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Identifying aquifer thermal energy storage (ATES) key locations for hospitals in Lower Saxony, Germany

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ABSTRACT

In a decade of advancing energy transition, European countries, including Germany, face the challenge of managing seasonal imbalances in heating and cooling demands. Aquifer thermal energy storage (ATES), which uses groundwater as a storage medium in an open-loop geothermal system, offers a promising solution. Infrastructure requiring both heating and cooling, such as universities, data centers, shopping malls, office buildings, and hospitals, are particularly suited for ATES. Especially hospitals have high heating and cooling demands, making them promising candidates. This study evaluates the ATES suitability in the state of Lower Saxony, Germany, where geological conditions in many areas resemble those in the bordering Netherlands, the worldwide leader in the application of ATES. Hence, the study focuses on identifying ATES key locations in Lower Saxony by estimating the cooling capacities of 113 hospitals using visible compression chiller fans. Cooling capacities of up to 5.9 MW are detected, with a mean of 0.9 ± 1.2 MW. The results show that 57 % of the area with shallow porous aquifers in Lower Saxony is well or very well suited for ATES, with 60 hospitals located in these areas. ATES offers payback times of 2–10 years and CO_2 savings of up to 74 % compared to conventional systems, highlighting its economic and environmental advantages. However, no system is currently operating in Lower Saxony and the lack of specific regulation for ATES hinders their development. Establishing supportive and novel policy frameworks could unlock the potential of this sustainable thermal energy storage technology.

1. Introduction

Achieving widespread climate neutrality requires increasing decarbonization efforts across all sectors. This includes the heating and cooling sector, where low-carbon alternatives to conventional space heating and cooling based on fossil fuels and energy-intensive cooling machines are necessary. One such alternative is the thermal use of groundwater (Stauffer et al., 2014). Aquifer thermal energy storage (ATES) in particular promises great primary energy savings and reductions in CO_2 emissions (Godschalk et al., 2019; Ni et al., 2020; Stemmle et al., 2021). ATES is an open-loop geothermal system that deploys a bi-directional pumping scheme to store heated and cooled groundwater in the subsurface to decouple the demand and availability of heat and cold. Most commonly, the stored heat is used as an energy source for high-efficiency heat pumps while the stored cooled groundwater often enables direct cooling. ATES systems are therefore able to provide sustainable space heating and cooling (Bloemendal et al., 2016; Fleuchaus et al., 2018; Jackson et al., 2024; Lee, 2010; Sommer et al., 2014).

Favorable building types supplied by ATES are large complexes, such as university buildings, commercial centers, office buildings, and in particular hospitals and data centers due to their large cooling demands (Fleuchaus et al., 2018; Jackson et al., 2024; Paksoy et al., 2000; Schüppler et al., 2019; Vanhoudt et al., 2011). Hospitals are characterized by large heating and cooling demands with an average annual heating demand per patient of 29 MWh in Germany. This implies a large potential for energy and cost savings for hospitals that can be realized using ATES systems (Schüppler et al., 2019). Hence, in the current study hospitals are especially considered.

Paksoy et al. (2000) assessed the feasibility of an ATES system for the thermal energy supply of a hospital in Adana, Turkey. In winter, groundwater that is additionally chilled with lake water using heat pumps is stored. By this, the system design allows for direct cooling during summer. Additional groundwater heating during summer using

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solar thermal collectors has also been assessed. By replacing electrical chillers and oil-based heating, the described ATES operation scheme could save around 3000 MWh of electricity and around 1000 m^3 of heating oil per year.

Another ATES system for the energy supply of a hospital in Brasschaat, Belgium went into operation in 2000 (Vanhoudt et al., 2011). A central building monitoring system combined with external data logging of the groundwater flow rates and temperatures revealed primary energy savings of 71 % with reference to gas-fired boilers and compression cooling machines. These savings correspond to CO_2 emission reductions of 1280 tons over the monitoring period of three years. Furthermore, they determined a payback time of 8.4 years for the ATES system due to its lower operational costs compared to the reference technologies.

In a similar study, Schüppler et al. (2019) evaluated the conceptual design of an ATES system for the heating and cooling supply of a hospital in Karlsruhe, Germany. As for the Belgian system, the authors compare the ATES with a reference technology in terms of its economic and environmental performance. Here, the reference case consists of a connection to the local district heating grid while compression chillers supply the cooling demand. The comparison results in mean energy savings with ATES of 76 % accompanied by a short payback time of only 2.7 years. The potential savings in CO_2 emissions amount to around 262 tons per year.

As shown in these case studies, hospitals in Central Europe typically require both heating and cooling. Schüppler et al. (2019) reported a space heating power demand of 52 W/m^2 and a space cooling power demand of 75 W/m^2 for a hospital in Karlsruhe, Germany. Energy extraction and storage are ideally balanced in sustainable ATES systems. However, for reasons of limited data availability, in this study we consider only the cooling capacities. Furthermore, cost savings are mainly realized by replacing the conventional compression chillers.

Despite the environmental and economic benefits, only two ATES systems are currently operating in Germany (Fleuchaus et al., 2018, 2021; Stemmle et al., 2024a). This is despite the high potential for the application of ATES across Germany as shown by Stemmle et al. (2022). Bloemendal et al. (2015) and Lu et al. (2019) developed global ATES potential assessments using also hydrogeological parameters and the thermal energy demand approximated through climate data. However, these ATES potential assessments are only applicable for residential buildings and not for industrial, commercial and other building types such as hospitals and data centers. In addition, they do not include any specific sites or buildings for the potential ATES deployment. Hence, in this study we identify key locations for cooling by considering hospitals and their installed compression chillers, which can be detected by aerial images (Barth et al., 2023; Schüppler et al., 2021).

Hence, the objective of this study is to identify key locations for the deployment of ATES systems in Lower Saxony, Germany. By combining the spatial ATES suitability potential with estimations of the installed cooling capacities of hospitals, we develop a novel method that enables the identification of key locations, where an energy supply with ATES is most promising. The study area is constrained to the federal state of Lower Saxony in Northern Germany. However, the developed method could be employed to any other state or country as long as similar input data is available.

2. Materials and methods

2.1. *Criteria for ATES suitability*

The criteria for the ATES suitability determination were the transmissivity, groundwater velocity, and iron concentration of the upper aquifers. The choice of criteria was based on Stemmle et al. (2022). Contrary to this study, heating and cooling demands were not considered as a criterion as these were investigated for each hospital in the identification of key locations (see Section 2.3). Furthermore, we did not apply any future climate scenarios and resulting changes in heating and cooling demands. In contrast to Stemmle et al. (2022), who considered iron and manganese concentrations due to clogging risks, we only included data on iron concentrations as the effect of manganese on clogging risk can be considered negligible (Kang et al., 2020).

Aquifer salinization and the presence of water protection areas was not considered for the calculation of ATES suitability as this information is more of a regulatory concern than an indicator of site suitability. However, these factors remain crucial for the authorization of ATES systems and will therefore be discussed in Section 3.3. Data was retrieved from a publicly accessible server, provided by the state authority for Mining, Energy and Geology of the state of Lower Saxony (LBEG, 2024).

2.1.1. *Transmissivity*

As ATES is an open-loop geothermal system, it relies on groundwater as the storage medium for heat. Thus, the productivity of the wells is crucial for the successful operation of ATES systems. The productivity can be reflected by an aquifer's transmissivity (T in m^2/h) (Graham et al., 2009), which is the product of hydraulic conductivity (K) and aquifer thickness (d). Information on transmissivity was obtained from the map "*Extraction conditions in the groundwater-bearing rocks 1: 500, 000*" (LBEG, 2024) and shown in Fig. 1a. Only the total transmissivity was considered, even if two or more separate aquifers were present. According to LBEG (2024), there are not enough transmissivity determinations from hydraulic tests (such as pumping tests) to make a spatial determination. Instead, an estimate is made on the basis of geological data from exploratory and well drillings. Typical hydraulic conductivity values, which were determined by evaluating a large number of pumping tests, were derived from the lithology.

Transmissivity was divided into three classes, indicating the suitability for groundwater extraction. *Unfavorable* conditions ($T < 20$ m^2/h) are mainly encountered where thin Quaternary sediments overlie clayey Tertiary layers or in the marginal area of bedrock (LBEG, 2024). The aquifers in this class are generally not suitable for larger groundwater abstractions. Here, areas of highly variable transmissivity are also assigned to the class of *unfavorable* conditions, as no uniform characteristics of the extraction conditions can be determined. *Good* aquifer productivity ($T = 20$–100 m^2/h) exists mainly in the area of Quaternary glaciofluvial sediments, including gravel fillings of river valleys (LBEG, 2024). Aquifers in this category are potentially suitable for the extraction of large quantities of groundwater. *Very good* transmissivity ($T >$ 100 m^2/h) can be found wherever very thick layers with high hydraulic conductivities are present. These conditions exist in Lower Saxony in the areas of Lüneburg (NE Lower Saxony) and Aurich (NW Lower Saxony), where Quaternary and Tertiary predominantly sandy aquifers form a thick aquifer complex with Quaternary channel systems, filled with coarse sedimentary material (LBEG, 2024). In these areas, groundwater extraction rates are expected to be very high with minor drawdowns.

2.1.2. *Groundwater velocity*

The velocity of groundwater flow is of great importance for the recovery rate of ATES systems. Groundwater flow enables advective heat transport, which can greatly influence heat losses in geothermal storage systems (Bloemendal and Hartog, 2018). Thus, aquifers require low groundwater velocities to be well-suited for ATES applications (Stemmle et al., 2024b). The velocity of groundwater flow is typically expressed as v_a in m/d and calculated as follows: $v_a = (K \times i)/n_e$.

Hydraulic conductivity (K) and effective porosity (n_e) were derived from the lithology of the shallow subsurface. The required information was obtained from the map "*Geological overview map of Lower Saxony 1: 500,000*" (LBEG, 2024). Except for the southern part of Lower Saxony, where mainly hard rock can be found, the shallow subsurface comprises unconsolidated sediments of Tertiary and Quaternary origin. In the Tertiary period, predominantly marine sands and clays were deposited. In the Quaternary, large parts of Lower Saxony were glaciated and the ice left behind boulder clays and meltwater deposits (gravel, sand, and

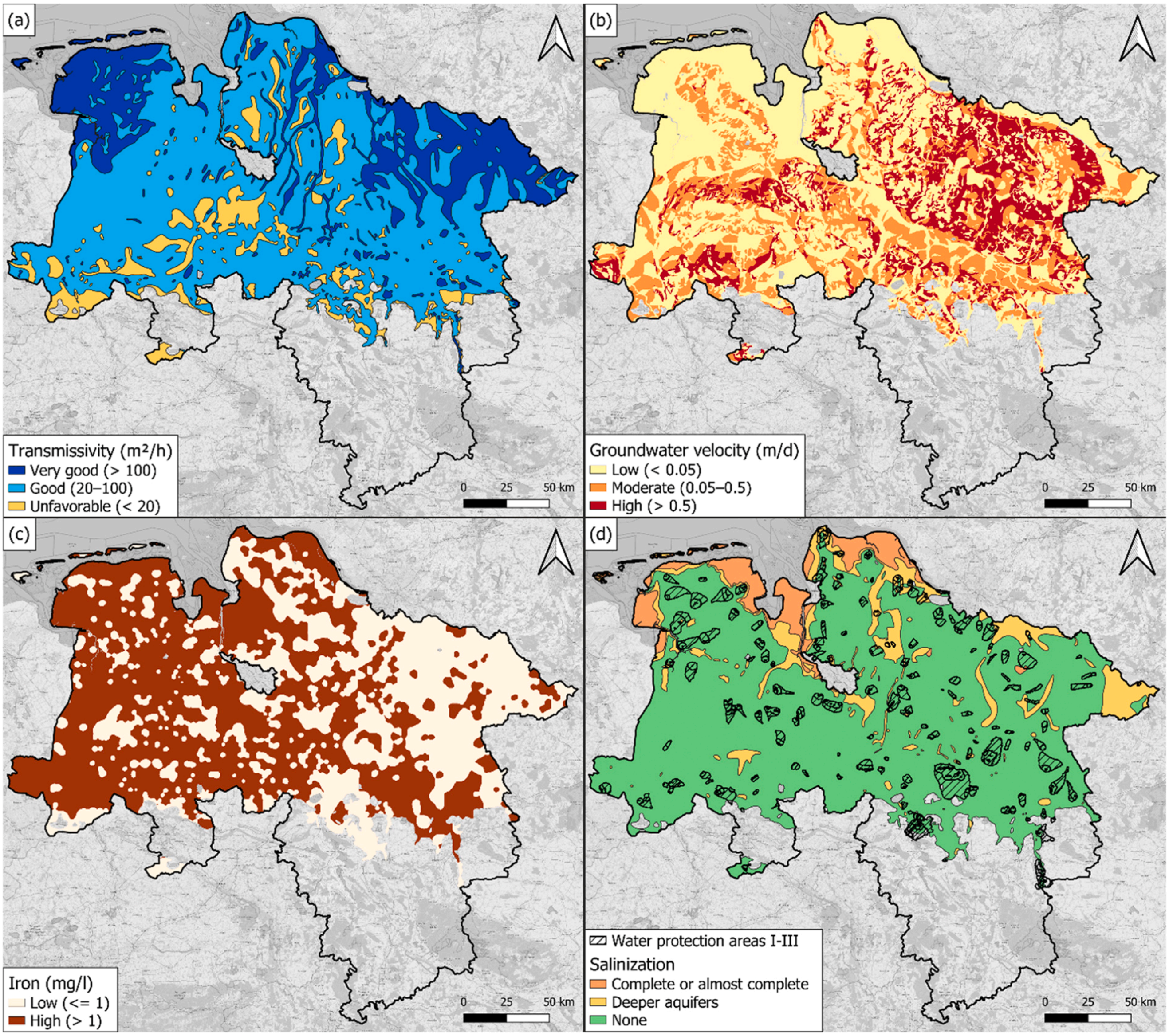

Fig. 1. Spatial distribution of the criteria for the determination of ATES suitability: (a) transmissivity, (b) groundwater velocity, and (c) iron concentration; subplot (d) shows water protection areas and salinized aquifers, which are not considered for ATES suitability determination but are important for legal considerations. Basemap: OpenStreetMap.

clay). During the interglacial and postglacial periods (Holocene), peat, mud and marl were formed (LBEG, 2024). These Tertiary and Quaternary sediments cover the majority of Lower Saxony today. The values for K and n_e are assigned to the different lithologies according to Hölting and Coldewey (2019). The hydraulic gradient (i) is calculated as the slope of the hydraulic head contours, taken from the map "*Position of the groundwater level 1: 200,000*" (LBEG, 2024). The resulting map is presented in Fig. 1b

We divided the groundwater velocity into three classes: *Low* velocities (< 0.05 m/d) can be found especially in the northern and northwestern parts of Lower Saxony, while *moderate* (0.05–0.5 m/d) velocities are mostly present in the central parts. Areas of *high* groundwater velocities (> 0.5 m/d) predominate the northeastern parts of the state.

Bloemendal and Hartog (2018) consider groundwater with a flow velocity above ~ 0.07 m/d (25 m/a) to be substantially affected by advection and subsequently, loss of efficiency for ATES systems occurs. With moderate velocities, advanced solutions, such as the alignment of injection and extraction wells along the groundwater flow direction, have to be pursued to decrease heat losses. However, the application is still viable (Bloemendal and Olsthoorn, 2018; Stemmle et al., 2024b) and we therefore propose a class for *moderate* velocities. When groundwater velocities are *high*, aquifer storage solutions become less effective. Instead, conventional open-loop geothermal systems should be considered.

2.1.3. Iron

Operating ATES systems in iron-rich aquifers increases the probability of well-clogging (Bloemendal et al., 2016). Especially injection wells are vulnerable to the deposition of iron oxides, which can be critical for the life expectancy of the system (Shi et al., 2024). Furthermore, mixing water of different chemical compositions should be avoided as this can lead to the precipitation of iron and, consequently, to well clogging. For this reason, aquifers of low iron concentrations are favorable for ATES application. The information on this criterion was retrieved from the map "*Groundwater quality: Iron content 1: 500,000*" for the depth level of 20–50 m and is shown in Fig. 1c. The map was generated by inverse distance weighting interpolation with point data

(LBEG, 2024). We distinguished between *low* (< 1 mg/l) and *high* (> 1 mg/l) iron concentrations. The latter could also be treated by in-situ de-ironing; however, this treatment would increase the capital costs and therefore increase the payback time of the ATES.

2.1.4. Salinization and water protection areas

Salinized groundwater can lead to scaling and corrosion of the equipment, reducing the system's efficiency and lifespan. However, if the system is constructed correctly, as demonstrated in an ATES application case in Rostock, Germany, these issues can be mitigated effectively (Bauer et al., 2009; Fleuchaus et al., 2021).

Water protection areas are important for the approval of any utilization of aquifers as they are designated to safeguard drinking water resources from contamination. Installing ATES systems in or near these zones requires careful management to prevent any risk of thermal pollution or disturbances, ensuring both environmental protection and compliance with regulations (Neidig, 2022), which is however possible to manage even in a water protection zone.

The data for salinization was obtained from "*Salinization of groundwater 1: 200,000*" (LBEG, 2024) and for the water protection areas from "*Drinking water protection areas (WSG) by protection zone*" (LBEG, 2024). Both salinization and water protection areas are depicted in Fig. 1d Complete or almost complete salinization of aquifers occurs in coastal areas, while the salinization of deeper aquifers is predominantly found in the northern part of Lower Saxony. The majority of the state, however, shows no signs of aquifer salinization. Water protection areas, in contrast, are distributed throughout Lower Saxony, indicating the groundwater extraction of regional waterworks.

2.2. Determination of ATES suitability

The determination of ATES suitability for the state of Lower Saxony was performed according to Stemmle et al. (2022). The methodology is primarily aimed at low-temperature ATES (LT-ATES), since we only consider shallow aquifers. High-temperature ATES (HT-ATES) have different requirements, such as greater storage depths and higher storage temperatures (Fleuchaus et al., 2020a).

We only considered porous aquifers, as fractured and karst aquifers are typically less suited for underground storage and are therefore typically not targeted for ATES application, in particular for LT-ATES (Bloemendal et al., 2015; Fleuchaus et al., 2018). The calculation involves four steps, which are described in detail in Stemmle et al. (2022):

1. Selection, processing, and definition of classes of the required datasets as explained in Section 2.1.
2. Normalization of the datasets according to the defined classes with scores between zero and one.
3. Conversion of the weighting factor of each criterion (adopted from Stemmle et al. (2022)) as — in contrast to the study mentioned — heating and cooling demands are not included in the ATES suitability calculation.
4. Calculation of the suitability potential with the platform QGIS, integrating the normalized scores and weighting factors of each criterion. The resulting suitability potential is spatially resolved (vectors) and represented by a value between zero and one.

The applied criteria and their allocated classes and values are summarized in Table 1 as well as their associated normalized scores and weighting factors.

For a clearer visualization of the resulting suitability potential score, we assign classes that qualitatively evaluate the suitability potential of ATES and apply a traffic light colour scheme. The suitability potential was categorized into *very well suitable* (> 0.8), *well suitable* (0.6–0.8), *moderately suitable* (0.4–0.6), and *less suitable* (< 0.4).

Table 1
Overview of the criteria applied in the ATES suitability determination as well as their respective classes, values, normalized scores, and weighting factors.

Criterion	Class	Value	Normalized score	Weighting factor
Transmissivity (m^2/h)	Unfavorable	< 20	0	0.65
	Good	20–100	0.5	
	Very good	> 100	1	
Groundwater velocity (m/d)	High	> 0.5	0	0.30
	Moderate	0.05–0.5	0.5	
	Low	< 0.05	1	
Iron (mg/l)	High	≥ 1	0	0.05
	Low	< 1	1	

2.3. Estimation of installed cooling capacities of hospitals

In comparison to previous ATES potential studies where spatial information on climatic conditions are incorporated (e.g., Lu et al., 2019; Ramos-Escudero and Bloemendal, 2022; Stemmle et al., 2022), here the heating and cooling demand is not included in the calculation of ATES suitability (Section 2.2). Instead, we directly estimate the cooling capacities of the hospitals using aerial images as a proxy for their cooling demands (Barth et al., 2023; Schüppler et al., 2021). Although the identified cooling capacities from compression chillers might be oversized for the actual cooling load. The detection of the installed cooling capacities is a suitable indicator for the actual cooling load and electricity demand of a building. Thus, the cooling-related peak electricity demand and annual electricity consumption could be estimated from the installed nominal capacity and annual cooling demand using typical seasonal energy efficiency ratings (SEER) for the different air-conditioning types and sizes (Barth et al., 2023).

Identification of hospitals is done with a document from the Statistical Office of Lower Saxony (LSN, 2019). This list also contains preventive care and rehabilitation facilities, which are not considered for this study. For the remaining 113 hospitals located in regions of porous aquifers, the installed cooling capacities are estimated with the number of visible compression chiller fans. The method was primarily established and validated for a university campus by Schüppler et al. (2021). The fans are counted manually using aerial images from Google Maps and Google Earth. The cooling capacity of the hospitals is then approximately calculated using the empirical linear correlation established by Barth et al. (2023) according to the following formula:

$$Q = 62.1 \times n - 63.8 \quad (1)$$

with Q (in kW) being the estimated installed cooling capacity and n the number of visual fans. This correlation was derived from a mix of different building types, whereas we use the equation for hospitals only. A determination of the correlation for hospitals only might result in a deviating equation. In this study, we could only identify air-cooled condensers and no cooling towers, which are estimated using a different correlation. Furthermore, it should be noted that the cooling capacities determined in this approach only represent a minimum estimate as a fraction of fans cannot be detected with aerial images, e.g., when they are covered by trees or when radial fans instead of axial fans are used (Barth et al., 2023; Schüppler et al., 2021).

3. Results and discussion

3.1. ATES suitability in lower Saxony

The result of the ATES suitability assessment for the porous aquifers of the state of Lower Saxony is shown in Fig. 2. The majority of the analyzed area can be considered as either *very well suitable* (18 %) or *well suitable* (39 %) for ATES application. The most promising areas are the northwestern and northeastern parts of the state where sandy sediments of Quaternary and Tertiary origin form thick aquifer complexes. In

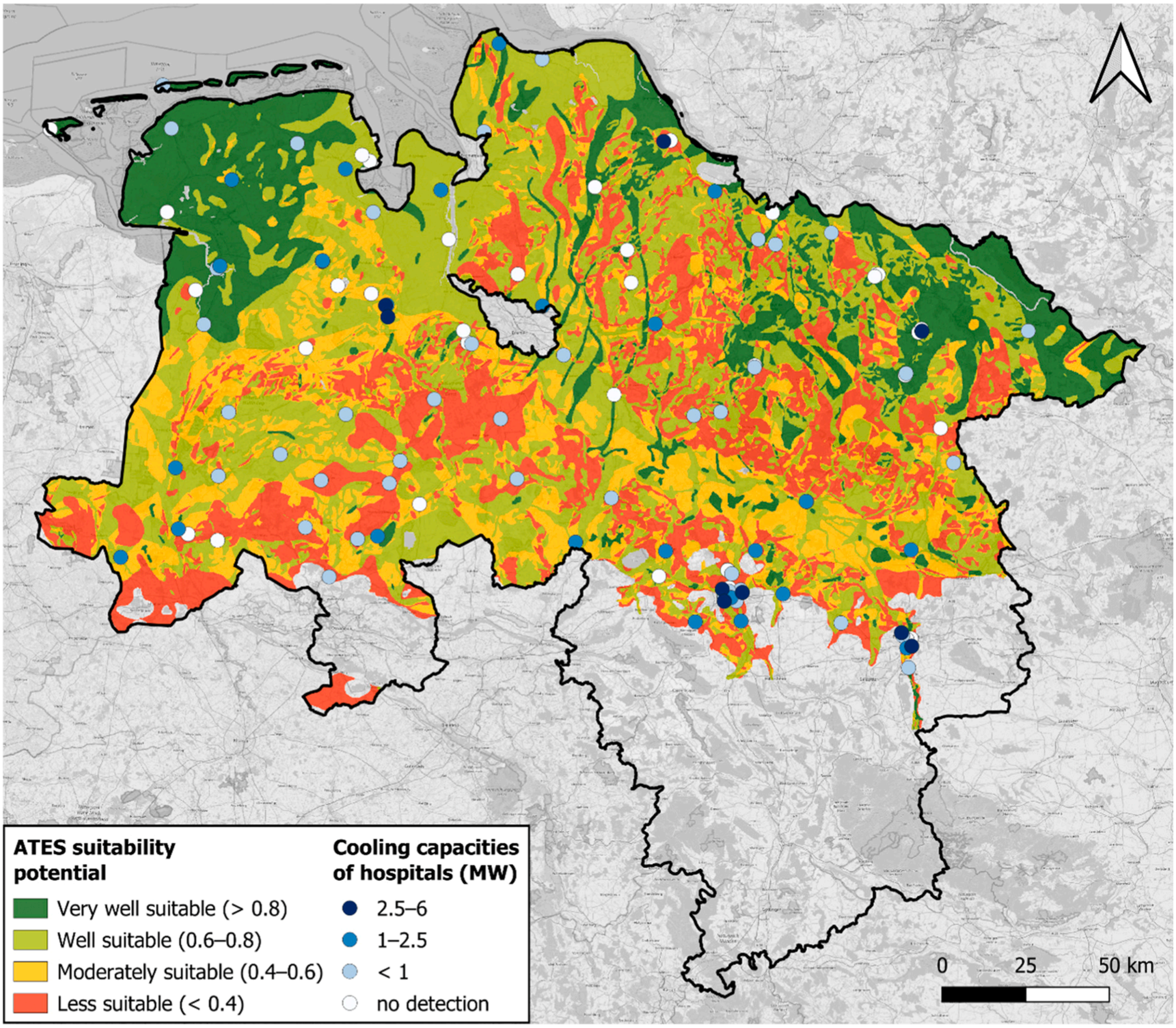

Fig. 2. Results of the ATES suitability analysis and estimation of cooling capacities for hospitals in Lower Saxony. Basemap: OpenStreetMap.

particular, the geology of the coastal areas in the northwestern part of Lower Saxony is similar to the favorable conditions in The Netherlands, where ATES systems are widely and successfully applied (Fleuchaus et al., 2020b). The ATES suitability in most other parts appears segmented due to the highly heterogeneous distribution of the criteria transmissivity and groundwater velocity. Especially the central and western parts of Lower Saxony are in many areas only *moderately suitable* (26 %) or *less suitable* (17 %) for ATES application. The arithmetic mean of the ATES suitability potential score for porous aquifers in Lower Saxony is 0.59 (standard deviation: 0.22).

While this ATES suitability potential gives a first assessment, it can only be as good as the input data, including its spatial resolution and accuracy. The uncertainty of the regionally resolved data on the local scale (i.e., size of an ATES system) can hardly be determined. We therefore recommend verifying the results of this study with site-specific data, such as drilling logs, geophysical measurements, and hydrogeological tests. The majority of the *moderately suitable* areas fulfill either the criterion of transmissivity or groundwater velocity well. This implies that the other criterion offers poor prerequisites for ATES application. Hence, *moderately suitable* areas could present challenging conditions for the successful implementation of an ATES system. For example, some areas classified as *moderately suitable* have *very good* transmissivities (> 100 m^2/h), whereas groundwater velocities are *high* (> 0.5 m/d). In this scenario, a successful ATES application can still be feasible, e.g., by designing the system with more downstream production wells (Bloemendal and Olsthoorn, 2018). However, this depends on the actual groundwater velocity, which has to be evaluated for the specific site. Generally, aquifers with high groundwater velocities should be avoided if possible as heat losses increase and thermal recovery rates decrease (Stemmle et al., 2024b).

The results of this study show good agreement with previous ATES potential studies, e.g., by Bloemendal et al. (2016) or Lu et al. (2019). For Lower Saxony, both studies show good or very good conditions for ATES application, which can be attributed to the extensive occurrence of thick porous aquifers. Less surprisingly, the ATES potential study of Germany provided by Stemmle et al. (2022) is in good accordance with our results presented in Fig. 2. Both studies use a similar methodology, except for the neglect of heating and cooling degree days in this study and different limit values of the classes. Differences exist due to the higher resolution of input data in our study, resulting in a more detailed map. In addition, a more conservative attribution of the criteria's classes in comparison to the study of Stemmle et al. (2022) leads to the assessment that more areas are only *moderately suitable* or *less suitable* for ATES application.

3.2. ATES key locations for hospitals

The analysis of hospitals' potential for ATES systems reveals a significant variability in cooling capacity and subsurface suitability. Among the 113 hospitals assessed in regions with porous aquifers, 33 % (37 hospitals) lack detectable air-cooled condensers. The mean estimated cooling capacity for all hospitals was calculated to be 0.85 MW (standard deviation: 1.17 MW).

Regarding subsurface suitability, 60 hospitals (53 %) are situated in areas deemed *very well suitable* or *well suitable* for ATES applications. To identify key locations for the installation of ATES systems, both the suitability potential of the subsurface and the hospital's cooling capacity must meet favorable conditions. These dual prerequisites are plotted for each hospital in Fig. 3, illustrating the distribution of the geological suitability potential and the estimated cooling capacity. In this figure, it becomes clear that of the 20 hospitals which are located in areas considered *very well suitable* for ATES application, 9 have no detectible cooling capacity. The same applies to the *well suitable* areas, where 14 of 39 hospitals have no visible air-cooled condensers. Even if these hospitals are not considered key locations in this study, due to their geological prerequisites, they can become primary targets for the development of ATES systems in the future, especially in the case of the construction of new buildings or extensions.

The four hospitals with the highest estimated cooling capacities, located in areas categorized as *well suitable* or *very well suitable* for ATES applications, are highlighted in Fig. 4. These hospitals represent priority sites for the implementation of ATES systems, combining optimal subsurface conditions with substantial cooling capacities.

The two sites in Hannover (Fig. 4a) and Braunschweig (Fig. 4b) are both characterized by *low* groundwater velocities and *good* transmissivities. The groundwater at the Hannover site has *low* iron concentrations, whereas in Braunschweig, it exceeds 1 mg/l. Due to transmissivities of only 20–100 m^2/h, both sites are considered as *well suitable* but not *very well suitable*. *Low* transmissivities may result in insufficient well productivity. In this case, it may be necessary to design the ATES system with multiple wells. However, this is especially challenging in urban environments where space is generally scarce, such as in the cities of Hannover or Braunschweig. In Hannover, the River Ihme, which is only 50 m away from the hospital, poses an additional challenge for subsurface heat storage as river deposits are often heterogeneous sediments with locally high groundwater flow rates. For this reason, site-specific investigations have to be performed to assess at which depth the aquifer is most suitable for ATES application.

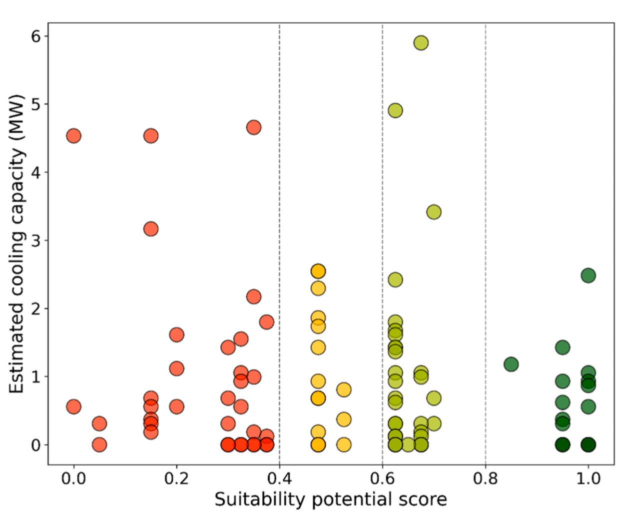

Fig. 3. Scatterplot showing the estimated cooling capacities of hospitals in Lower Saxony and the ATES suitability score at the locations of the hospitals. The colors correspond to the categorization used in Fig. 2: *very well suitable* (dark green), *well suitable* (light green), *moderately suitable* (yellow), and *less suitable* (red).

At the hospital in Bad Bevensen (Fig. 4c), there are *very good* transmissivities, however, the groundwater velocities are calculated to be *high* as well (about 2 m/d). Under these conditions, energy storage in an aquifer is challenging, and site investigations are required to validate the suitability for different depths. In contrast, hydrogeological conditions at the hospital in Leer (Fig. 4d) can be considered *very well suitable*. All criteria are deemed optimal at this site and an estimated cooling capacity of 2.5 MW indicates a high demand for cooling energy.

3.3. Discussion of further aspects

Besides the parameters used in the assessment above and local cooling demands, further hydrogeological aspects, as well as legislative requirements and economic aspects have to be carefully considered before the implementation of an ATES system at a potential site. At an optimal ATES site, the target aquifers should be confined by aquitards, which help reduce heat losses of the stored thermal energy (Gao et al., 2017). Additionally, sufficient space is necessary for the installation of multiple wells, ensuring efficient operation and scalability of the system. The presence of saline aquifers presents both challenges and opportunities for ATES systems, particularly for HT-ATES systems. Since these aquifers are less valuable for freshwater use, obtaining the necessary permits might be easier, as demonstrated by the HT-ATES system in the city of Rostock (Fleuchaus et al., 2021). The lower groundwater protection concerns in saline aquifers might simplify legislative requirements.

However, high salinity can also negatively affect ATES performance without appropriate measures, potentially reducing operational lifespan. Saline aquifers require the use of salinity-resistant equipment to mitigate risks of corrosion and maintain system durability (Bloemendal et al., 2015). Despite this, systems like the one in Rostock demonstrate that these challenges can be effectively addressed. Operating at a charging temperature of about 50 °C, the Rostock ATES system has performed reliably without technical failures, showcasing the viability of ATES in saline environments when designed with salinity-resistant features (Bauer et al., 2009; Fleuchaus et al., 2021). Among the 113 hospital locations studied, 94 do not encounter any saline aquifer. However, 9 hospitals are located in regions with saline conditions in deeper aquifers, and 8 are located where aquifers are nearly entirely saline. Hence, these hospitals are also suitable for HT-ATES systems with the possibility to operate at higher temperatures ($>> 20$ °C).

Water protection areas represent a critical legal aspect in ATES planning. Among the hospital sites analyzed, only 4 are within water protection areas (WPZ) — 3 in zone III and 1 with undefined protection status. The limited overlap with water protection areas likely reflects the urban location of most hospitals. Due to strict protection regulations, installations of open-loop geothermal systems, and therefore of ATES systems, are not allowed in WPZ I and II. WPZ III may allow ATES implementation following further evaluation and compliance with regulatory frameworks (Neidig, 2022).

In general, there is no specific legislation for ATES available in Lower Saxony, although feasibility studies for HT-ATES exist (Holstenkamp et al., 2017; Zhou et al., 2024). For the construction and operation of open-loop geothermal systems, permissions by the lower water authority are required, as specified in Jensen et al. (2022). The conditions include preventing negative impacts on groundwater quality and other geothermal systems, avoiding the mobilization of contaminants, preferably extraction from the uppermost aquifer, and the mandatory reinjection into the same aquifer. For open-loop geothermal systems, the permissible temperature change is limited to ± 6 K compared to the natural groundwater temperature, with absolute limits of 4 °C and 20 °C

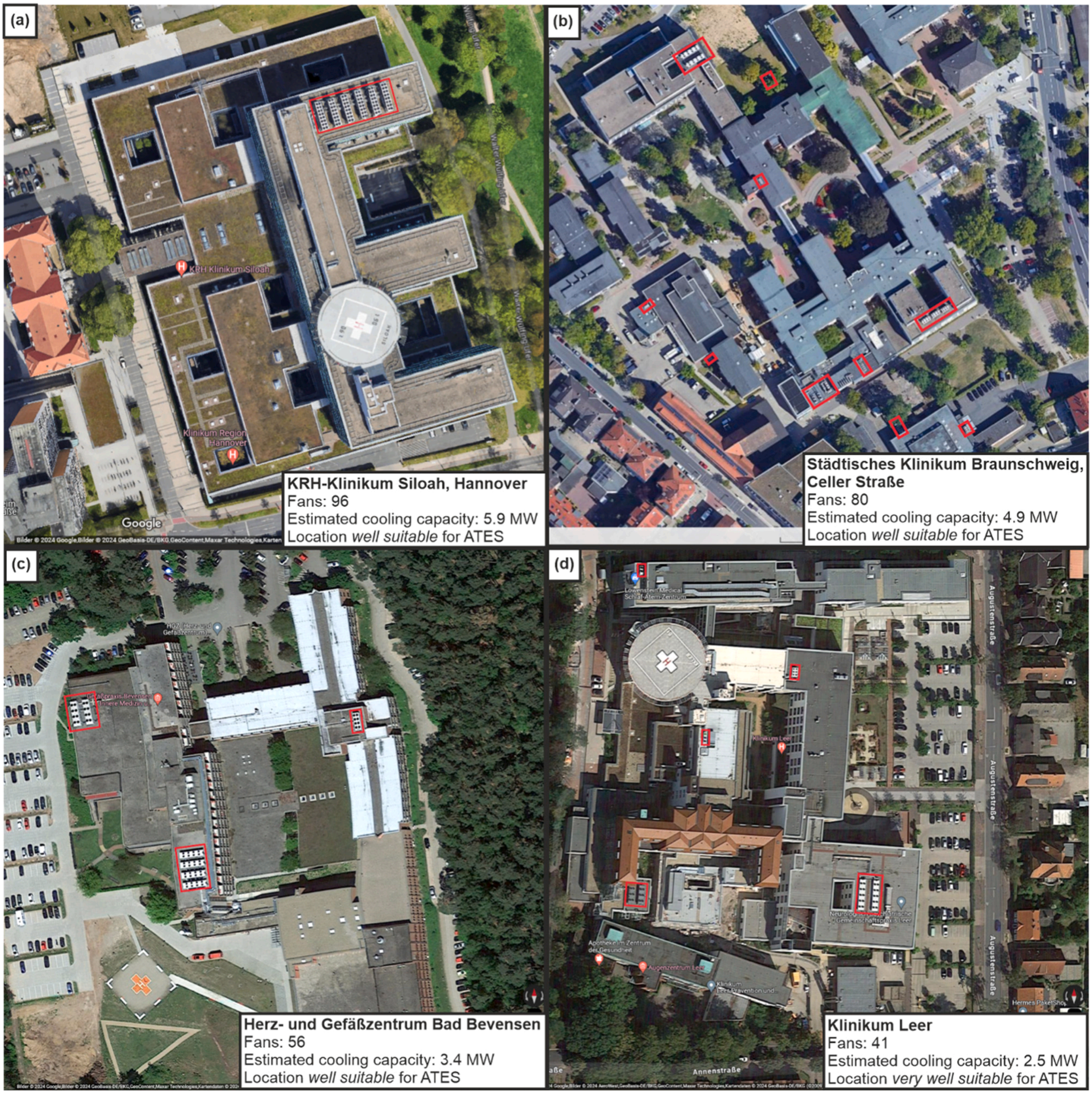

Fig. 4. Aerial images showing the four hospitals with the highest estimated cooling capacities that are *well* or *very well suitable* for ATES application. Red rectangles indicate the position of the identified compression chiller fans. Image sources: Google Maps (a, c, d) and Google Earth (b).

(Jensen et al., 2022). This legislation with strictly and narrowly defined temperature threshold hinders currently the successful uptake of ATES (Bayer et al., 2019; Hähnlein et al., 2010, 2013; Tsagarakis et al., 2020). In particular, HT-ATES systems are not feasible, even though saline aquifers are promising targets for HT-ATES (Fleuchaus et al., 2021). Hence, there is a need for specific regulatory frameworks and additional policies for ATES in Lower Saxony and all of Germany that establish clear and supportive conditions for their development (Stemmle et al., 2024a), as currently no ATES systems is in operation in Lower Saxony.

During the decision-making phase, economic factors such as capital costs and payback times of the systems are essential. The ATES systems for hospitals discussed by Schüppler et al. (2019) and Vanhoudt et al. (2011) have payback times of 2.7 and 8.4 years, respectively. Typical payback times ranging between two and ten years were also reported for other ATES systems (Bakema et al., 1995; Baxter et al., 2018; Fleuchaus et al., 2020b; Gao et al., 2017; Hoekstra et al., 2020; Midttomme et al., 2017). The study by Schüppler et al. (2019) estimated investment costs of about 1.3 million € for an ATES system with a combined heating and cooling capacity of 4.8 MW (i.e. 270 €/kW). The capital costs of the ATES system at the hospital in Brasschaat were about 700,000 € with a combined heating and cooling capacity of 1.2 MW (i.e. 583 €/kW) (Vanhoudt et al., 2011). A comprehensive study on capital costs of ATES systems by Herrmann et al. (under review) analyzes capital costs of 132 ATES systems from The Netherlands, Belgium, Denmark, and other countries. This study showed that with increasing heating and cooling capacities the capital costs of ATES systems converge to about 300 €/kW per installed capacity, ranging up to 1000 €/kW. Although the capital costs of ATES system are low in comparison with other seasonal thermal energy storages, other market aspects such us the availability of HVAC planners, drilling contractors and installers for energy systems might also currently hinder the uptake of ATES in Germany.

Besides this skills shortage, however, ATES can provide substantial CO_2 savings. The results of a life cycle assessment (LCA) conducted by Stemmle et al. (2021) show that a typical ATES system can avoid up to around 74 % of CO_2 emissions when compared to fossil fuel-based heating and electricity-driven cooling machines. This value coincides with savings between 40 % and 70 % reported in Fleuchaus et al. (2018). The ATES system investigated by Vanhoudt et al. (2011) that is used for the thermal energy supply of a Belgian hospital reduces CO_2 emissions by a comparable 77 % with reference to gas-fired boilers and compression cooling machines. Schüppler et al. (2019) also describe an ATES system supplying a hospital. Compared to the other studies, this system would result in lower CO_2 savings of around 36 %. This is due to a differing combination of reference technologies. While cooling demands are supplied again by compression chillers, the reference case for heating supply is the local district heating, which is characterized by a low emission factor at the respective study site. Nevertheless, these values clearly indicate that ATES systems can substantially contribute to the decarbonization of the heating and cooling sector.

4. Conclusions

This study investigated the suitability potential for the application of ATES systems in the state of Lower Saxony, Germany. The overall aim was the identification of hospitals as key locations for the deployment of ATES systems by estimating their installed cooling capacities combined with the hydrogeological properties at the site. For the ATES suitability potential, the transmissivity, groundwater velocity, and iron concentration were considered. Our results show predominantly *well suitable* or *very well suitable* conditions (57 %) for the porous aquifers in Lower Saxony. Especially, the northwestern region, which borders The Netherlands, and northeastern areas are exceptionally well suited. More than half (53 %) of the hospitals studied are located in areas that are *well suitable* or *very well suitable* for the application of ATES, with estimated cooling capacities of up to 5.9 MW. For 67 % of the 113 hospitals, rooftop compression chillers could be detected. The average detected and estimated cooling capacity of a hospital amounts to 0.9 ± 1.2 MW. 4 of the 113 hospitals are located in a water protection zone, which hinders the construction of an ATES. However, 17 hospitals are located above a saline aquifer, which might enable the application of HT-ATES systems that operates with higher storage temperatures of up to 50 °C like the HT-ATES system in Rostock. Despite the good hydrogeological prerequisites and numerous suitable facilities in Lower Saxony, no ATES has been implemented yet. This is surprising considering that environmental benefits such as CO_2 savings of up to 74 % and short payback times between 2 and 10 years can be achieved. Nevertheless, site-specific investigations, such as the determination of actual cooling loads, are still required to validate the high ATES potential identified on the state scale presented in this study. Finally, only pilot implementations can fully prove the technological feasibility of a system and demonstrate the expected economic and environmental benefits. Successful full-scale ATES operation would then motivate supportive legislation and regulatory boundaries tailored to the specifics of ATES systems in Northern Germany.

CRediT authorship contribution statement

Maximilian Noethen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Ruben Stemmle:** Writing – review & editing, Writing – original draft, Methodology. **Nick Siebert:** Writing – review & editing, Writing – original draft, Data curation. **Matthias Herrmann:** Writing – review & editing, Writing – original draft. **Kathrin Menberg:** Conceptualization, Methodology, Writing – review & editing. **Philipp Blum:** Writing – review & editing, Writing – original draft, Methodology. **Peter Bayer:** Writing – review & editing, Writing – original draft, Methodology.

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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Appendix

Table 2

Table 2
List of all 113 hospitals where an ATES suitability score was determined.

Name	City	Detected fans	Estimated cooling capacity (MW)	Suitability potential score
Klinikum Leer gGmbH	Leer (Ostfr.)	41	2.5	1.00
Elbe Klinikum Buxtehude	Buxtehude	18	1.1	1.00
Ubbo-Emmius-Klinik Norden	Norden	16	0.9	1.00
Krankenhaus Buchholz und Winsen gGmbH	Winsen (Luhe)	15	0.9	1.00
HELIOS Klinikum Uelzen GmbH	Uelzen	10	0.6	1.00
Krankenhaus Ginsterhof	Rosengarten	0	0	1.00
Inselkrankenhaus Borkum gGmbH	Borkum	0	0	1.00
KRH Psychiatrie Wunstorf GmbH	Wunstorf	0	0	1.00
OsteMed Klinik Bremervörde	Bremervörde	0	0	1.00
Diana-Klinik	Bad Bevensen	0	0	1.00
Aller-Weser-Klinik Krankenhaus Verden	Verden (Aller)	0	0	1.00
HELIOS Klinik Cuxhaven GmbH	Cuxhaven	24	1.4	0.95
Borromäus Hospital Leer gGmbH	Leer (Ostrfr.)	16	0.9	0.95
Marienkrankenhaus Papenburg-Aschendorf GmbH	Papenburg	11	0.6	0.95

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Table 2 (*continued*)

Name	City	Detected fans	Estimated cooling capacity (MW)	Suitability potential score
Krankenhaus Wittmund gGmbH	Wittmund	7	0.4	0.95
Krankenhaus Norderney	Norderney	6	0.3	0.95
Psychiatrische Klinik Uelzen gGmbH	Uelzen	0	0	0.95
Klinikum Emden Hans-Susemihl-Krankenhaus gGmbH	Emden	0	0	0.95
Gisunt-Klinik für integrative Medizin	Wilhelmshaven	0	0	0.95
Klinik Lilienthal	Lilienthal	20	1.2	0.85
Herz- und Gefäßzentrum Bad Bevensen	Bad Bevensen	56	3.4	0.70
Capio Elbe-Jeetzel-Klinik Dannenberg	Dannenberg (Elbe)	12	0.7	0.70
Krankenhaus Buchholz und Winsen gGmbH	Buchholz i. d. Nordheide	6	0.3	0.70
KRH-Klinikum Siloah	Hannover	96	5.9	0.68
KRH-Klinikum Agnes Karll Laatzen	Laatzen	18	1.1	0.68
DIAKOVERE Friederikenstift gGmbH	Hannover	17	1.0	0.68
HELIOS Klinik Wittingen GmbH	Wittingen	6	0.3	0.68
Paracelsus Klinik am Silbersee	Langenhagen	4	0.2	0.68
Klinik Fallingbostel Fachklinik für Herz- und Kreislauferkrankungen	Bad Fallingbostel	3	0.1	0.68
Klinikum Wilhelmshaven gGmbH	Wilhelmshaven	1	0	0.68
Stenum Fachklinik für Orthopädie	Ganderkesee	0	0	0.68
Klinikum Region Hannover GmbH Psychiatrie Langenhagen	Langenhagen	0	0	0.68
Klinikum Region Hannover GmbH Geriatrie Langenhagen	Langenhagen	0	0	0.68
MediClin Seepark Klinik Akutpsychosomatik Schwerpunkt Essstörung	Bad Bodenteich	0	0	0.68
Caduceus-Klinik	Bad Bevensen	0	0.0	0.65
Städtisches Klinikum Braunschweig c	Braunschweig	80	4.9	0.63
Allgemeines Krankenhaus Celle	Celle	40	2.4	0.63
Ammerland Klinik GmbH	Westerstede	30	1.8	0.63
HELIOS Klinik Wesermarsch Nordenham GmbH	Nordenham	28	1.7	0.63
Krankenhaus Ludmillenstift Meppen	Meppen	27	1.6	0.63
Herzogin-Elisabeth-Hospital	Braunschweig	24	1.4	0.63
Nordwest-Krankenhaus Sanderbusch GmbH	Sande	24	1.4	0.63
Euregio Klinik Albert-Schweitzer-Straße GmbH	Nordhorn	23	1.4	0.63
HELIOS Kliniken Mittelweser GmbH Klinik Stolzenau	Stolzenau	18	1.1	0.63
Heidekreis Klinikum GmbH Krankenhaus Soltau	Soltau	16	0.9	0.63
St. Johannes-Hospital	Varel	12	0.7	0.63
Städtisches Klinikum Braunschweig a	Braunschweig	11	0.6	0.63
Capio Krankenhaus Land Hadeln	Otterndorf	6	0.3	0.63
St. Vinzenz-Hospital	Haselünne	6	0.3	0.63
Bundeswehrkrankenhaus	Westerstede	3	0.1	0.63
Clemens-August-Klinik	Neuenkirchen-Vörden	3	0.1	0.63
St. Josefs-Hospital Cloppenburg gGmbH	Cloppenburg	3	0.1	0.63
Augenklinik Dr. Hoffmann	Braunschweig	1	0	0.63
Ev.-luth. Diakonissenanstalt Marienstift	Braunschweig	0	0	0.63
Median Reha-Zentrum Gyhum	Gyhum	0	0	0.63
Karl-Jaspers-Klinik für Psychosomatische Medizin und Psychotherapie	Westerstede	0	0	0.63
Elisabeth-Krankenhaus	Thuine	0	0	0.63
Psychiatrisch-Psychosomatische Klinik Celle	Celle	0	0	0.63
Krankenhaus Rheiderland	Weener	0	0	0.63
St. Bernhard-Hospital	Brake (Unterweser)	0	0	0.63
Hümmling-Krankenhaus-Sögel	Sögel	14	0.8	0.52
St. Anna-Klinik gGmbH	Löningen	7	0.4	0.52
Klinik Dr. Havemann	Lüneburg	0	0	0.52
Klinikum Oldenburg gGmbH	Oldenburg (Oldb.)	42	2.5	0.47
Evangelisches Krankenhaus Oldenburg	Oldenburg (Oldb.)	42	2.5	0.47
AGAPLESION Diakonieklinikum Rotenburg (Wümme) gGmbH	Rotenburg (Wümme)	38	2.3	0.47
Ubbo-Emmius-Klinik Aurich	Aurich (Ostfr.)	31	1.9	0.47
Pius-Hospital	Oldenburg (Oldb.)	29	1.7	0.47
Krankenhaus St. Elisabeth gGmbH	Damme	24	1.4	0.47
AMEOS Klinikum Seepark Geestland GmbH	Geestland	16	0.9	0.47
Klinikum Peine	Peine	12	0.7	0.47
Aller-Weser-Klinik Krankenhaus Achim	Achim	12	0.7	0.47
St. Marienhospital Vechta gGmbH	Vechta	4	0.2	0.47
Karl-Jaspers-Klinik	Bad Zwischenahn	1	0	0.47
St. Marien-Hospital gGmbH	Friesoythe	0	0	0.47
Privatklinik Bad Zwischenahn Fachklinik für Psychotherapeutische Medizin und Psychosomatik	Bad Zwischenahn	0	0	0.47
Klinik Diepholz	Diepholz	0	0	0.47
KRH-Klinikum Lehrte	Lehrte	30	1.8	0.38
Waldklinik Jesteburg	Jesteburg	3	0.1	0.38
Orthoklinik Lüneburg GmbH	Lüneburg	0	0	0.38
OsteMed Martin-Luther-Krankenhaus Zeven	Zeven	0	0	0.38
KRH-Klinikum Nordstadt	Hannover	76	4.7	0.35
KRH-Klinikum Robert Koch Gehrden	Gehrden	36	2.2	0.35
Krankenhaus Johanneum	Wildeshausen	17	1.0	0.35
Niels-Stensen-Kliniken Bramsche	Bramsche	4	0.2	0.35
Eilenriede Klinik Hannover	Hannover	0	0	0.35
Kreiskrankenhaus Osterholz	Osterholz-Scharmbeck	0	0	0.35

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Table 2 (*continued*)

Name	City	Detected fans	Estimated cooling capacity (MW)	Suitability potential score
St. Bonifatius Hospital	Lingen (Ems)	26	1.6	0.32
KRH-Klinikum Großburgwedel	Burgwedel	18	1.1	0.32
HELIOS Kliniken Mittelweser GmbH Klinik Nienburg	Nienburg (Weser)	16	0.9	0.32
Heidekreis Klinikum GmbH Krankenhaus Walsrode	Walsrode	10	0.6	0.32
MediClin Klinikum Soltau	Soltau	0	0	0.32
MediClin Hedon-Klinik	Lingen (Ems)	0	0	0.32
HELIOS Klinikum Gifhorn GmbH	Gifhorn	24	1.4	0.30
Christliches Krankenhaus Quakenbrück	Quakenbrück	12	0.7	0.30
Klinik Sulingen	Sulingen	6	0.3	0.30
Klinik für Kinder- und Jugendpsychiatrie und -psychotherapie Wichernstift gGmbH	Ganderkesee	0	0	0.30
Klinik Dr. Witwity	Stade	0	0	0.30
DIAKOVERE Krankenhaus gGmbH	Hannover	27	1.6	0.20
KRH-Klinikum Neustadt am Rübenberge	Neustadt am Rbge.	19	1.1	0.20
DRK-Krankenhaus Clementinenhaus	Hannover	10	0.6	0.20
Städtisches Klinikum Braunschweig b	Braunschweig	74	4.5	0.15
Medizinische Hochschule Hannover	Hannover	52	3.2	0.15
Delme Klinikum Delmenhorst	Delmenhorst	12	0.7	0.15
Städtisches Klinikum Wolfenbüttel gGmbH	Wolfenbüttel	10	0.6	0.15
Niels-Stensen-Kliniken Marienhospital Ankum-Bersenbrück	Ankum	7	0.4	0.15
INI -International Neuroscience Institute Hannover	Hannover	6	0.3	0.15
Klinik Bassum	Bassum	4	0.2	0.15
Kinder- und Jugendkrankenhaus auf der Bult	Hannover	6	0.3	0.05
Sophien-Klinik GmbH	Hannover	0	0	0.05
Elbe Klinikum Stade	Stade	74	4.5	0
St. Franziskus-Hospital	Lohne (Oldb.)	10	0.6	0

Data availability

Data will be made available on request.

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