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Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany

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Abstract

More than 30% of Germany's final energy consumption currently results from thermal energy for heating and cooling in the building sector. One possibility to achieve significant greenhouse gas emission savings in space heating and cooling is the application of aquifer thermal energy storage (ATES) systems. Hence, this study maps the spatial technical potential of shallow low-temperature ATES systems in Germany. Important criteria for efficient ATES operation considered in this assessment encompass suitable hydrogeological conditions, such as aquifer productivity and groundwater flow velocity, and balanced space heating and cooling demands. The latter is approximated by the ratio of heating and cooling degree days, which is incorporated as a time-dependent criterion to also evaluate the impact of climate change on the ATES potential. The hydrogeological and climatic criteria are combined within a spatial analysis revealing that, regarding the upcoming decades, about 54% of the investigated German area are very well or well suitable for ATES applications, largely concentrating on three regions: the North German Basin, the Upper Rhine Graben and the South German Molasse Basin. Considering time-dependent climatic conditions, the very well or well suitable areas will increase by 13% for the time period 2071–2100. This is mostly caused by a large relative area increase of the very well suitable regions due to an increasing cooling demand in the future. The sensitivity of the very well and well suitable regions to the criteria weightings is relatively low. Accounting for existing water protection zones shows a reduction of the country-wide share of very well or well suitable areas by around 11%. Nevertheless, the newly created potential map reveals a huge potential for shallow low-temperature ATES systems in Germany.

Keywords: Aquifer thermal energy storage, Potential study, Heating energy, Cooling energy, Climate change, Degree days

Introduction

Combating climate change poses a global challenge. To achieve the internationally formulated goal of limiting global warming to 1.5 °C above pre-industrial levels at best and 2 °C at most, far-reaching and fast reductions of greenhouse gas emissions are required worldwide (Rhodes 2016). On the COP 26 climate change conference in 2021, the 1.5 °C goal was restated in form of the Glasgow Climate Pact (COP26 2021). Furthermore, the German federal government has recently adapted the Federal Climate Change Act which now states an earlier deadline for achieving carbon neutrality by 2045 at the latest

(Bundesministerium der Justiz und für Verbraucherschutz 2021). In this context, decarbonization of the space heating and cooling sector is of great importance since this sector alone currently accounts for more than 30% of Germany's final energy consumption (AGEB 2021). However, compared to electricity generation, where the share of renewable energies is continuously increasing, decarbonization of space heating and cooling receives less attention (Fleuchaus et al. 2018), implying a large potential for greenhouse gas emission savings.

An environmentally friendly alternative for space heating and cooling supply, for which potential reductions in greenhouse gas (GHG) emissions of up to 75% compared to conventional space heating systems were shown, is the use of shallow groundwater as a seasonal storage medium of low-temperature (LT) thermal energy (Fleuchaus et al. 2018; Stemmle et al. 2021; Vanhoudt et al. 2011). Especially in temperate climates with distinct climatic seasons, using groundwater for storing excess heat in summer and cooling capacity in winter can efficiently mitigate temporal mismatches between availability and demand of thermal energy (Bloemendal et al. 2018; Fleuchaus et al. 2018; Schüppler et al. 2019). This technology is known as aquifer thermal energy storage (ATES), and consists of a warm and a cold storage volume in the subsurface, from which heated or cooled groundwater can be extracted depending on heating or cooling demands. In many cases a heat pump is used in heating mode, whereas cooling is often done without operating the heat pump according to a so-called direct cooling design. The majority of ATES systems are LT storage systems with maximum injection temperatures below 25 °C and are located in shallow depths (Bloemendal and Hartog 2018; Kunkel et al. 2019). LT storage systems typically store thermal energy arising from the ATES-connected building itself, i.e., heated groundwater during summerly cooling season and cooled groundwater during heating season. Accordingly, the intended purpose of LT-ATES as considered in this study is space heating and cooling of residential buildings, as well as larger building complexes such as office buildings, hospitals or shopping centers. Here, an ATES system is typically designed to meet both heating and cooling base loads. In addition, conventional auxiliary supply technologies such as gas boilers and compression chillers can serve for peak load supplies (Beernink et al. 2022; Jaxa-Rozen 2019; Schüppler et al. 2019). To ensure a long-term sustainable ATES operation, a balanced thermal charging and discharging of the aquifer, e.g., by balancing heating and cooling demands, is favorable. In the Netherlands, which have a pioneering role in ATES systems, the avoidance of thermal imbalances in the underground is even mandatory during permit process (Bloemendal et al. 2014; Bozkaya and Zeiler 2019; Fleuchaus et al. 2020a; Schüppler et al. 2019).

In contrast to LT-ATES, for high-temperature ATES systems, which store water at above 50 °C typically in deeper aquifers, the heat source and heat consumer often do not coincide. Exemplary heat sources include waste heat from industrial processes and power plants or excess solar thermal energy (Kunkel et al. 2019). High-temperature (HT) storage systems can also be connected to district heating networks operating at higher temperatures (Fleuchaus et al. 2020b). Due to greater storage depths and higher storage temperatures, HT-ATES partly have different requirements, challenges and risks regarding hydrogeological, hydrogeochemical and technical conditions than LT systems (Fleuchaus et al. 2020b).

ATES systems are typically characterized by larger storage volumes compared to other underground thermal energy storage (UTES) systems, such as borehole or pit thermal energy storage (BTES or PTES) systems. Thus, they are typically used for large-scale applications, such as space heating and cooling of hospitals, office buildings or airports. The integration of ATES systems into existing or planned district heating and cooling networks is also an option (Fleuchaus et al. 2018; Todorov et al. 2020). Our study, however, focuses on ATES systems connected to individual buildings or building complexes.

While there are currently more than 2800 ATES systems worldwide, they are mainly distributed among a few countries. Around 85% (2500 ATES systems) are located in the Netherlands, another 10% in Sweden (220), Belgium (30) and Denmark (55) (Fleuchaus et al. 2018). In Germany, there are only two installations in operation at the moment, which are located in Bonn and Rostock (Fleuchaus et al. 2021). According to Lu et al. (2019a), in many countries, the lack of potential evaluation is one of the main barriers for ATES applications. There are various types of shallow geothermal potential to distinguish. In the literature, the two most commonly evaluated types are the theoretical and the technical potentials. The theoretical potential is usually determined using simplified estimations for the total energy stored in a reservoir (e.g., Zhu et al. 2010). The technical potential on the other hand, assesses the thermal energy that can be extracted by a certain technology. It is usually smaller than the theoretical potential. Possible factors which constrain the technical potential of a certain technology are technical limitations, such as space restrictions, drilling depth or the maximum groundwater drawdown (Bayer et al. 2019). In this study, we do not consider any regulatory limitations to have an influence on the technical potential. Instead, we evaluate the impact of existing water protection zones on the spatial ATES applicability in a separate work step.

Previously published studies aimed to provide an overview of the qualitative technical LT-ATES potential following a very broad approach on a worldwide (Bloemendal et al. 2015; Lu et al. 2019a, b) or European scale (Bloemendal et al. 2016). In Bloemendal et al. (2015), the ATES potential is presented on a qualitative scale from one to ten regarding the worldwide ATES suitability, which is determined using hydrogeological and climatic criteria. The hydrogeological criteria mainly include aquifer characteristics and groundwater recharge rates. However, characteristics of the groundwater itself, such as its flow velocity or quality, are not considered, although they represent important criteria for ATES operation. Due to the global scale of the potential evaluation, the spatial resolution of the data and results is comparatively low, with some of the hydrogeological data being country-averaged. A similar problem can also be observed regarding the climatic data, which is included in Bloemendal et al. (2015) using only five distinct suitability scores based on prevailing heating or cooling demand. For many countries, including Germany, this coarse classification yields only one climate suitability score across the entire country, impeding a more detailed assessment.

Lu et al. (2019a, b) use a very similar approach for their global assessment of the technical ATES suitability, but consider a larger set of criteria including socio-economic criteria, such as the gross domestic product (GDP) per capita. Some of the criteria are represented again by country-averaged values, e.g., groundwater quality and total carbon emissions. The climatic conditions are included in the same manner as in Bloemendal et al. (2015) leading to the same poor spatial distinction of climatic variations.

The Europe-wide determination of the ATES suitability published in Bloemendal et al. (2016) is created using only groundwater recharge and information on the groundwater resources, such as the availability of a major groundwater basin or local aquifers. Thus, it omits any other criteria such as climatic conditions. However, the resulting ATES potential map with ten qualitative suitability levels is further evaluated by the authors with regard to climatic conditions representing heating and cooling demands.

On a national level, Ramos-Escudero and Bloemendal (2022) evaluate the qualitative ATES potential for Spain. Similar to the previous publications, this study considers aquifer characteristics and climatic conditions. The potential determination focuses on the identification of towns where ATES applications may be feasible due to favorable climatic conditions and the presence of thermally utilizable aquifers. However, this study lacks hydrogeological information of greater detail. Thus, smaller scale evaluations of distinct regions regarding ATES feasibility are required, two of which Ramos-Escudero and Bloemendal (2022) provide as examples considering further information, such as aquifer transmissivity and specific ATES design parameters.

The present study evaluates the qualitative technical suitability potential of shallow LT-ATES for space heating and cooling in Germany on a national level using significantly more detailed hydrogeological and climatic input data according to a weighted linear combination (WLC). This method is widely used in geographic information system (GIS) problems to support decision-making or to create composite maps from different underlying data sets (Malczewski 2000). Kiavarz and Jelokhani-Niaraki (2017) outline an example where weighted linear combination serves as a tool in multicriteria decision analysis (MCDA) in geothermal prospection. As a further example, in Ramos-Escudero et al. (2021), MCDA is used to create a suitability map of Spanish region Murcia for the application of ground source heat pump (GSHP) systems based on geological and climatic input criteria. In this study, we also establish a time-dependency of the climatic criteria in order to determine possible changes in ATES suitability caused by climate change. The ATES suitability is also analyzed regarding its sensitivity on different weightings when considering the different input data sets.

Material and methods

Criteria selection and input data

The qualitative technical potential in terms of the suitability of a given region for the application of shallow ATES in Germany is here determined based on several criteria, such as hydrogeological and climatic criteria, which influence the ATES suitability potential according to previous studies (Bloemendal et al. 2016; Lu et al. 2019a). In order to evaluate the impact of climate change on the ATES potential, we also incorporate climatic conditions as time-dependent data. The specific characteristics of each criterion are introduced in the following, while details on the data are provided in Table SD1 in the Additional file 1: Section S1. Figure 1 illustrates the basic ATES operation principle and the relevant input criteria.

Aquifer productivity

As groundwater is the storage medium used by ATES, a sufficient amount of extractable groundwater is a fundamental requirement for the operation of an ATES system.

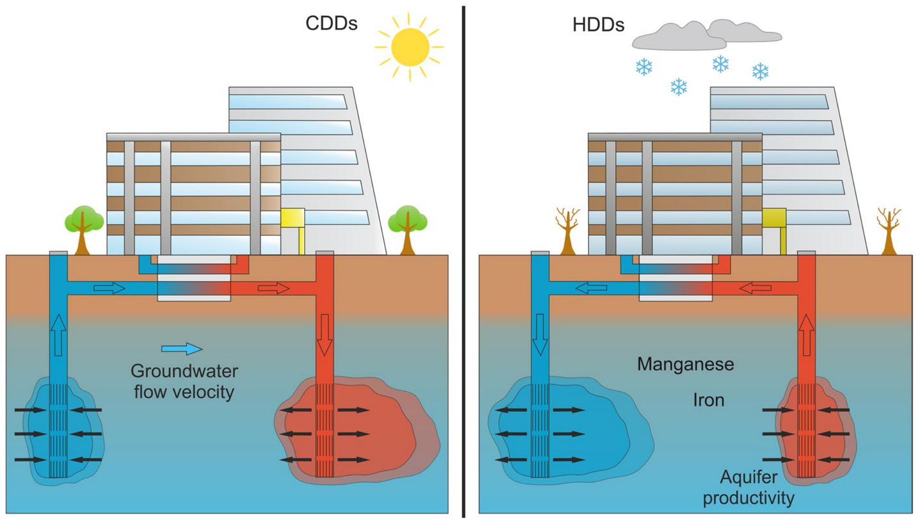

Fig. 1 Schematic operation principle of ATES in cooling mode (left) and in heating mode (right). The hydrogeological criteria aquifer productivity, iron and manganese contents in groundwater and groundwater flow velocity as well as the climatic criterion represented by cooling degree days (CDDs) and heating degree days (HDDs) are included for illustration purposes

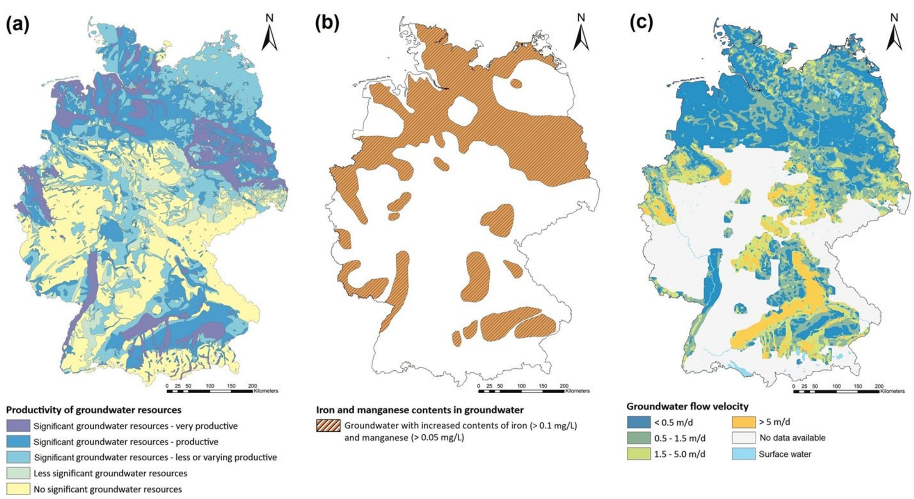

Fig. 2 Hydrogeological criteria of the ATES potential study for Germany: **a** aquifer productivity (BGR 2019a), **b** iron and manganese contents in groundwater (BGR 2019b), **c** mean groundwater distance velocity (Wendland et al. 1993)

The nationwide dataset "Groundwater Yields of Germany" from the BGR (2019a) divides the productivity of aquifers in five classes (Fig. 2a) allowing a qualitative description for every region in Germany. The classes range from *significant groundwater resources—very productive* to *no significant groundwater resources* based on possible average continuous groundwater extraction rates of existing wells and waterworks as well as on an aggregation of hydrogeological characteristics. The criterion thus indirectly includes information about hydraulic conductivity, drainable porosity and aquifer thickness. The last-mentioned criterion class describes regions without any large-scale contiguous groundwater resources. However, locally significant groundwater resources may still exist in these areas. For this reason, aquifer productivity is also a very relevant parameter on a site-specific scale for individual ATES systems with regard to pumping rate and number of wells.

Iron and manganese contents in groundwater

The operation of ATES systems can be impacted by hydrogeochemical processes such as shifted solution equilibria caused by temperature changes or mixing of groundwater with different chemical compositions (Hähnlein et al. 2013). While temperature-dependent effects are commonly of little importance for low-temperature ATES (Drijver et al. 2012), high contents of iron and manganese in the groundwater can lead to well clogging when it is mixed with groundwater of different composition during ATES operation (Bloemendal et al. 2016; Lu et al. 2019a). This can detrimentally influence the life expectancy and maintenance costs of ATES wells and has to be considered during system design and construction via technical designs, which prevent mixing groundwater of different chemical compositions (Bloemendal et al. 2016; Bonte et al. 2013) or water treatment technologies (e.g., Hellriegel et al. 2020). Thus, we include the dataset "Geogenic Groundwater Quality of Germany" (Fig. 2b) from the BGR (2019b) in our evaluation to designate regions with elevated levels of iron contents (> 0.1 mg/L) or manganese contents (> 0.05 mg/L) (Bannick et al. 2008).

Groundwater flow velocity

Groundwater flow velocity can significantly influence the efficiency of ATES systems due to potentially substantial heat losses in the subsurface caused by high flow velocities and correspondingly high advective heat transfer reducing storage efficiency. To some extent, these heat losses can be reduced by an adapted ATES design with downstream production wells in order to achieve high thermal recoveries (Bloemendal and Olsthoorn 2018; Sommer et al. 2013, 2014). Nevertheless, the groundwater flow velocity is an important criterion regarding ATES suitability due to its large impact on the necessary ATES design. Accordingly, we include this criterion in our analysis using a map of the average groundwater distance velocity (Fig. 2c) derived from hydraulic head contour maps of the upper aquifers, which accounts for the corresponding values of the hydraulic conductivity and the effective porosity (Wendland et al. 1993). The areas designated with *no data* do not allow the calculation of the flow velocity since large-scale hydraulic head contour maps were not available. These regions are mostly areas without large-scale porous aquifers (Wendland et al. 1993).

Heating and cooling demands

Climate conditions influence the building energy demands for heating and cooling, and are therefore a fundamental criterion for planning and dimensioning of ATES systems (Fleuchaus et al. 2020a; Ni et al. 2016). Besides climatic factors, other aspects such as set point temperatures, internal heat gains and building insulation also significantly influence the heating and cooling energy demands. The country-wide scope of our study, however, does not enable to easily integrate this kind of detailed building-specific information. We therefore use degree days to obtain a proxy for balanced heating and cooling demands, which is not limited to existing building stock and settlement areas.

Degree days are commonly used to estimate the influence of climatic conditions on the heating and cooling demands of buildings (Jakubcionis and Carlsson 2017). Here, we calculate the heating degree days (HDDs) and cooling degree days (CDDs) for Germany for past and future time periods based on surface air temperatures (SAT) to account for changing climatic conditions in the ATES potential.

Degree days relate the outdoor air temperature to a specified base temperature, typically 18.5 °C (Rosa et al. 2014). Thus, HDDs and CDDs indicate by how much and for how long the outside air temperature is below or above the base temperature, respectively. The calculation of degree days assumes that a building is heated when the outside air temperature falls below the base temperature and cooled when the base temperature is exceeded. The following approximation solution is commonly used for the calculation of the annual HDDs and CDDs (Mourshed 2012):

$$\mathrm{HDDs} = \sum_{i=1}^{365}\left(18.5^{\circ}\mathrm{C} - \frac{T_{\min,i} + T_{\max,i}}{2}\right) \tag{1}$$

and

$$\mathrm{CDDs} = \sum_{i=1}^{365}\left(\frac{T_{\min,i} + T_{\max,i}}{2} - 18.5^{\circ}\mathrm{C}\right) \tag{2}$$

with $T_{\min,i}$ and $T_{\max,i}$ being minimum and maximum outdoor SAT in °C on day i. The selection of the base temperature value should consider criteria such as the local climate conditions, the type of building (in terms of insulation, use, etc.), the expected occupant behavior and the desired indoor temperature (Spinoni et al. 2015). In this study, the base temperature is set to 18.5 °C since this value is a commonly used base temperature in the literature (Christenson et al. 2006; Rosa et al. 2014; Short et al. 2015; Wibig 2003).

The HDDs and CDDs are calculated based on SAT values from the statistical regionalization model WETTREG2010 (Kreienkamp et al. 2010). Statistical regionalization models aim to establish statistical relations between observed large-scale circulation patterns in the atmosphere and local or regional weather data measured in the past by a network of weather stations.

These identified relationships are then applied to global climate projections in order to draw conclusions on the changing climate on a local or regional scale. In the WETTREG dataset, this is realized for each station as individual synthesized transient time series of daily weather parameters from 1961 to 2100. For each station, these time series consist of sections of weather measurements which are stringed together by a stochastic weather generator used in the WETTREG model. The signatures of changing climate which serve as boundary conditions for the weather generator and thus influence the sequence of the measurement sections within one time series are obtained from the global circulation model ECHAM5 driven by the IPCC SRES emission scenario A1B. This way, temporal changes of frequency and other characteristics of distinct atmospheric patterns are translated to local climate projections (Kreienkamp et al. 2011). More information about the global model can be found in Roeckner et al. (2003, 2004). For a detailed description of the utilized emission scenario, the reader may refer to Nakićenović (2000).

The spatial resolution of the WETTREG dataset directly correlates with the number of available weather stations. In this study, we use the average result of an ensemble of ten alternative equivalent WETTREG model runs for each of the 383 measuring stations available in Germany as past and projected future climate data.

The WETTREG dataset contains values for the daily maximum and minimum SAT that are used for the calculation of HDDs and CDDs according to Eqs. (1) and (2), respectively. The average annual degree days for each weather station are calculated for four distinct time periods: the *far past* (1961–1990), the *near past* (1991–2020), the *near future* (2021–2050) and the *far future* (2071–2100).

In order to use the degree day data as an input for the spatial calculation of the ATES potential of Germany, a spatial interpolation of HDDs and CDDs between weather stations is conducted using ordinary cokriging in ArcGIS Desktop (Version 10.7.1). Cokriging is a geostatistical interpolation technique that allows to incorporate one or more secondary variables that are spatially correlated to the primary variable leading to a more accurate interpolation (Giraldo et al. 2020; Rivoirard 2001). The primary variables to be interpolated in this study are the HDDs and the CDDs, while ground elevation is chosen as secondary variable in order to account for the influence of altitude on building heating and cooling energy demands. Altitude data are obtained from the DGM1000 digital terrain model of BKG (2021) that has a grid width of 1000 m, a horizontal accuracy of ± 5 m and a vertical accuracy of ± 20 m to ± 30 m depending on the type of terrain (Additional file 1: Fig. S2).

Degree days are included into the calculation of the ATES suitability potential in form of the ratio of annual CDDs to HDDs, as this ratio allows a direct assessment of the thermal energy demand in terms of a balanced system operation. A more balanced ratio of heating and cooling demands implies a more balanced thermal charging and discharging of the aquifer which is favorable for a long-term sustainable operation of ATES systems (Bloemendal et al. 2014, 2018; Ramos-Escudero and Bloemendal 2022; Schüppler et al. 2019; Sommer et al. 2015; Todorov et al. 2020).

Determination of the suitability potential

The vast majority of ATES systems around the world are located in porous aquifers (Fleuchaus et al. 2018; Lu et al. 2019a). Fractured and karst aquifers on the other hand are not usually suited for an efficient ATES application due to frequent heterogeneous fissures which can cause substantial thermal losses (Bloemendal et al. 2015). Thus, the focus of the determination of the ATES suitability potential lies here on porous aquifers in Germany.

The nationwide calculation of the suitability potential is performed using a weighted linear combination (WLC) of the criteria listed in the previous chapter. The calculation involves four steps (Fig. 3), which are described in detail in the following paragraphs:

Step 1: Selection and pre-processing of the datasets to be included (see previous chapter).

Step 2: Normalization of the datasets to establish a comparable and uniform scale with criteria scores between zero and one.

Step 3: Determination of the weighting factor of each criterion via pairwise comparisons.

Step 4: Calculation of the suitability potential by a weighted linear combination of the criteria scores.

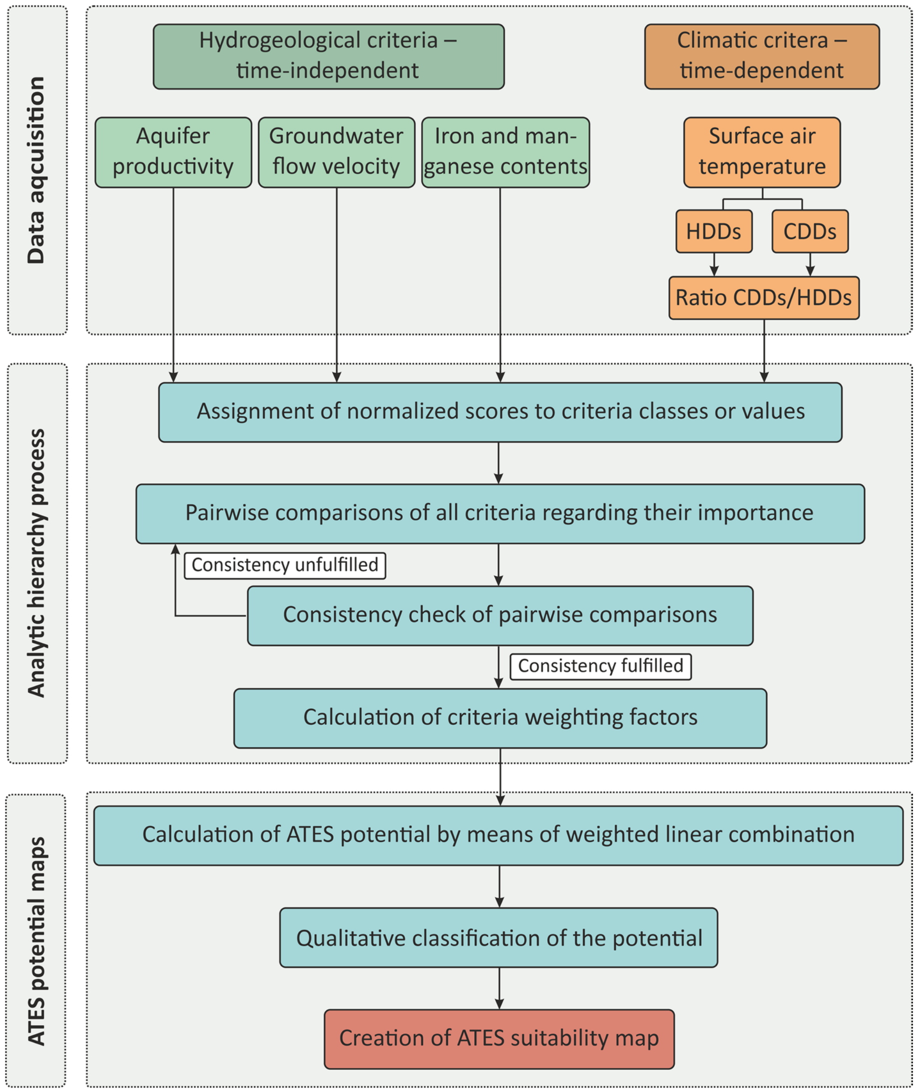

Fig. 3 Workflow for the creation of the ATES suitability potential map of Germany. Data sources and further details on the criteria are provided in Additional file 1: Table S1

Normalization of the criteria

Using different criteria with different ordinal or nominal class divisions or cardinal value ranges requires the establishment of a comparable and uniform scale for all criteria. Thus, normalization of the three time-independent hydrogeological criteria is conducted by allocating scores between 0 and 1 to all criteria classes, with criterion scores close to 1 representing favorable conditions for ATES and scores close to 0 indicating unsuitable conditions. The score allocation is done according to the authors' expert judgment based on existing shallow open geothermal systems and on previous studies such as thermo-hydraulic modeling in order to assess the impact of groundwater flow velocity on thermal recovery and storage efficiency (e.g., Sommer et al. 2013, 2014). For the criteria aquifer productivity and groundwater flow velocity, the score allocations are further explained below.

The time-dependent climate data consisting of the ratio CDDs/HDDs are normalized using the overall minimum and maximum values of all four selected time periods as scaling points (Kiavarz and Jelokhani-Niaraki 2017):

$$S_{\text{norm}} = \frac{S - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} \tag{3}$$

Here, S_{norm} represents the normalized score of the corresponding value S of the ratio CDDs/HDDs. S_{min} and S_{max} indicate the mutual minimum and maximum values of the four time periods. Table 1 provides an overview of the datasets with the respective classes or value ranges and the associated normalized scores.

The score allocation to the individual classes of the criterion aquifer productivity is based on information about the operational characteristics of about 100 Dutch ATES systems as well as a large number of conventional shallow open geothermal installations in the Upper Rhine Graben. According to this data, the pumping rates of typical systems are larger than 5 l/s. Many smaller systems with supply capacities below 500 kW supplying individual buildings have pumping rates in the range between 5 and 20 l/s (e.g., Ohmer et al. 2022). We therefore assign a score larger than 0.5 to the middle criterion class "Significant groundwater resources—less or varyingly productive" since this class promises good conditions for ATES operation with possible extraction rates of 5 l/s to 15 l/s via a single well (Table 1). The higher criteria classes receive larger scores to

Table 1 Overview of the criteria used to calculate the ATES suitability potential, their respective classes or value ranges and the corresponding normalized scores

Criterion	Class or value		Normalized score
Aquifer productivity		Possible average continuous extraction rates of single wells [l/s]	
	Significant groundwater resources—very productive	Mostly > 40	1
	Significant groundwater resources—productive	Mostly 15–40	0.8
	Significant groundwater resources—less or varyingly productive	Mostly 5–15	0.6
	Less significant groundwater resources	Mostly < 5	0.4
	No significant groundwater resources	Mostly < 2	0.1
Iron and manganese contents in groundwater	Groundwater without increased iron/manganese contents		1
	Groundwater with increased iron/manganese contents		0
Groundwater flow velocity	< 0.5 m/d		1
	0.5–1.5 m/d		0.6
	1.5–5.0 m/d		0.4
	> 5.0 m/d or no data available		0
Ratio CDDs/HDDs[a]	0.27		1
	[…]		[…]
	0		0

[a] Calculated according to Eq. (3)

account for the fact that large ATES system potentially could be realized with a smaller number of wells.

The scores for the criterion groundwater flow velocity are in part allocated based on experiences from heat transport modeling aimed at investigating the influence of groundwater flow velocity on thermal recovery and storage efficiency of ATES systems. For flow velocities above 0.5 m/days, significant heat losses occurred. Thus, we choose to establish a clear separation regarding the score of the most suitable class, i.e., the lowest flow velocity, and the other classes. The high suitability of low flow velocities is also demonstrated by Dutch ATES systems, many of which are situated in regions with low groundwater flow velocities < 0.25 m/days (Bloemendal and Hartog 2018). For higher groundwater flow velocities, the recovery of thermal energy gradually decreases. While these storage efficiency reductions can be alleviated to a certain extent by installing downstream production wells, this results in higher drilling and operational costs and potentially higher subsurface space requirements. For groundwater flow velocities of more than 5 m/days, the simulated storage efficiencies are too low even for an adapted ATES well arrangement.

Determination of weighting factors

The weighting factors of each criterion are determined based on pairwise one-on-one comparisons between the individual criteria following an MCDA approach known as analytic hierarchy process (AHP), which aims to establish a hierarchical order of the criteria based on experts' judgements (Lu et al. 2019a; Saaty 1977, 1980). The AHP method reduces the complexity of a decision-making process to a sequence of pairwise comparisons that are compiled in a ratio matrix to rank decision options from most desirable to least desirable.

In this study, the pairwise comparisons separately benchmark the relative importance of two criteria regarding their influence on the ATES suitability. The comparison of all possible criteria pairs is done using the comparison scale created by Saaty (1977) with values between 1/9 and 9 (Table 2). A criterion with a weighting of 1/9 relative to another criterion is *extremely less important* for ATES suitability than the other criterion. Conversely, a relative weighting of 9 means that the criterion is *extremely more important*.

The pairwise comparison matrix A of the $i=j$ criteria is set up following the form

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{pmatrix} \tag{4}$$

For the calculation of weighting factors with value ranges between 0 and 1, the comparison matrix A has to be normalized. The entries b_{ij} of the normalized matrix B with

Table 2 Comparison scale of relative weights for pairwise comparisons (Lu et al. 2019a; Saaty 1977)

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely Less important	Very strongly	Strongly	Moderately	Equally Important	Moderately More important	Strongly	Very strongly	Extremely

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & b_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ b_{i1} & b_{i2} & \cdots & b_{ij} \end{pmatrix} \quad (5)$$

can be calculated for n criteria as follows according to Drobne and Lisec (2009):

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (6)$$

Equation (6) means that the matrix entry b_{ij} can be calculated by dividing the corresponding entry a_{ij} by the sum of all entries in column j of matrix A. The weighting factors w_i of the criteria correspond to the arithmetic mean of the entries in a row of matrix B. They can therefore be understood as mean values of all possible criteria comparisons and are calculated according to:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \quad (7)$$

with

$$\sum_{\mathrm{i}=1}^{n} w_i = 1$$

Note that the vector w of the weighting factors $w_1 \cdots w_n$ is an approximation for the normalized eigenvector corresponding to the principal eigenvalue of the comparison matrix A. Due to the separated comparison approach, this method is prone to inconsistencies within the pairwise comparisons, which can be revealed by a consistency check. A detailed description of the consistency check is presented in Additional file 1: Section S3.

Calculation of suitability potential

The suitability potential SP of ATES systems in Germany is calculated for all time periods via WLC using the four criteria and their corresponding weighting factors w_i:

$$\mathrm{SP} = \sum_{i=1}^{n} (w_i x_i), \text{with } n = 4 \quad (8)$$

Here, x_i represents the normalized score of each criterion. The calculation is performed in ArcGIS Desktop (Version 10.7.1) for all cells of a grid covering the entire area of Germany. The calculated suitability potential of each cell is represented by a value between 0 and 1, with a cell value close to 1 indicating a high ATES suitability potential. For visualization purposes, the suitability potential is classified into four distinct classes based on mutual natural breaks within the calculated values of all time periods. For this purpose, we use the Jenks natural breaks algorithm implemented in ArcGIS, which strives to iteratively minimize value differences within one class and to maximize the differences between individual classes to separate possible data groupings inherent in the data.

Results and discussion

Ratio of degree days

Figure 4 shows the long-term average ratio of annual cooling and heating degree days in Germany calculated for the *near future* time period (2021 to 2050) as well as the change of the ratio from the *near future* to the *far future* (2071–2100). The low ratio values shown in Fig. 4a reflect the German climate conditions with significantly more HDDs than CDDs and thus a prevailing heating demand. The highest ratios of CDDs to HDDs can be observed in eastern Germany and in western Germany, especially in the south-west, which corresponds well with the predominant temperature gradient in Germany during the warm season from south to north and from east to west. This can be explained by an increasingly continental climate in the east and for the south additionally by a higher intensity of solar radiation and a more frequent occurrence of high-pressure weather conditions (Kappas et al. 2003). The Upper Rhine Graben region in south-west Germany shows the highest ratios of CDDs to HDDs and is accordingly among the warmest regions in Germany. For example, the city of Freiburg im Breisgau shows high yearly CDD numbers of more than 170 and at the same time a relatively low number of HDDs (Additional file 1: Fig. S5a). This matches a comparatively high mean temperature of 12.6 °C in 2020. In contrast, the mean temperature in Rostock in northern Germany was 11.0 °C in 2020. Accordingly, the ratio of CDDs to HDDs is much lower there. This also applies to the southeastern area of the German Alps. The ski resort Oberstdorf, for example, has very low CDD numbers of below 25, however a high number of HDDs of more than 4000, relating to a mean

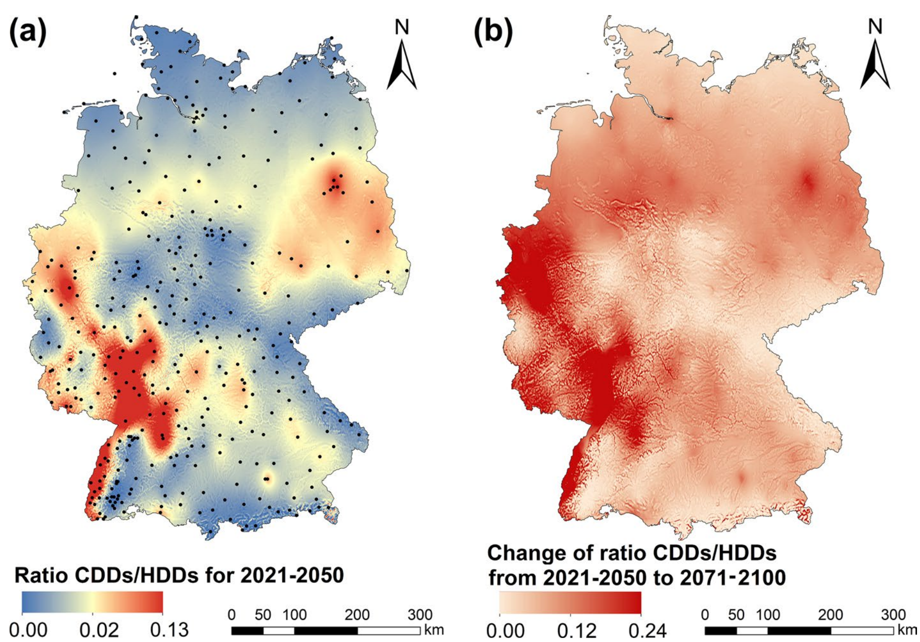

Fig. 4 **a** Mean ratio of CDDs to HDDs for 2021–2050, **b** change of mean degree days ratio from 2021–2050 to 2071–2100. The marks in **a** represent the weather stations utilized for the generation of country-wide degree days via cokriging

average temperature of 8.1 °C in the year 2020. Overall, the Germany-wide interpolation of degree days leads to a spatial distribution of CDDs and HDDs that are similar to previously published maps of degree days in Europe (Spinoni et al. 2018) and other publications, which provide information about large-scale climatic indicators across Germany (e.g., Frick et al. 2014; Kappas et al. 2003).

The maps show that the warmest areas of Germany which are characterized by the highest degree days ratios will also experience the greatest increase in the degree days ratio in the future. An increasing ratio of CDDs to HDDs is apparent in the vast majority of the country, which reflects global warming as incorporated in the WETTREG data. This also leads to an acceleration in the rate of increasing degree days ratios compared to the past time periods (Additional file 1: Fig. S6). This result is in good agreement with the study by Spinoni et al. (2018), who studied the expected change in CDDs and HDDs in Europe up to the year 2100. While the authors use different IPCC emission scenarios, the spatial patterns of increase in CDDs and decrease in HDDs in Germany reflect our results shown in Fig. 4b.

Besides the regional differences, a certain topographic influence (cf. Additional file 1: Fig. S2) on the degree days ratio can be observed in both maps. This influence originates from the cokriging method, which includes ground elevation data in order to estimate degree day values more accurately. However, this method can sporadically lead to interpolation artifacts that are most apparent in the alpine regions of Germany and especially in the most southeastern part of the country. This is due to strong altitude differences over relatively short distances, the impacts of which are overemphasized in the cokriging interpolation. However, since only a very small number of grid cells show such interpolation artifacts, they can be ignored without affecting the remaining map areas. Furthermore, the artifacts are located in hard rock areas, which are excluded from ATES utilization. The uneven spatial distribution of the weather stations across Germany shown in Fig. 4a also results in higher prediction errors in regions with a low density of measuring stations. As an example, Additional file 1: Fig. S5 shows the Germany-wide interpolation of HDDs for the period 2021–2050 and the corresponding prediction standard error (i.e., standard deviation).

Pairwise comparison results and weighting factors

The pairwise comparison matrix of the four criteria as well as the weighting factors for each criterion resulting from the comparison matrix and calculated according to Eq. (7) is shown in Table 3.

Table 3 Pairwise comparison matrix of the four criteria included in the potential study and their respective weighting factors

	Aquifer productivity	Iron and manganese contents in groundwater	Groundwater flow velocity	Ratio CDDs/HDDs	Weighting factor
Aquifer productivity	1	8	3	4	0.54
Iron and manganese contents in groundwater	1/8	1	1/7	1/6	0.04
Groundwater flow velocity	1/3	7	1	2	0.25
Ratio CDDs/HDDs	1/4	6	1/2	1	0.17

The highest weighted criterion is the aquifer productivity reflecting its status as a fundamental requirement for operating ATES systems. The lowest weighting factor is assigned to the criterion iron and manganese contents in groundwater, as problematic clogging caused by iron or manganese oxides or hydroxides can be prevented by a suitable design of the ATES system (Bloemendal et al. 2016; Ni et al. 2016). The consistency check reveals a high consistency among the comparisons (Additional file 1: Table S3). Thus, the weighting factors resulting from the pairwise comparisons can be used for determination of the suitability potential.

ATES suitability potential in Germany

Using the criteria weighting factors in Table 3, the ATES suitability potential for Germany for the time period *near future* (2021–2050) is calculated (Fig. 5a). About 35% of the area are hard rock regions or inland water surfaces (BGR and UNESCO 2019) for both of which the application of ATES is assumed to be not viable. Regarding the remainder of Germany, about 54% of the area is rated as very well or well suitable for the application of ATES systems in the time period from 2021 to 2050, revealing a high potential for the application of ATES systems in Germany. These areas can be largely assigned to the three geographical regions of the North German Basin, the Upper Rhine Graben and the South German Molasse Basin, which are characterized by the occurrence of thick Cenozoic unconsolidated rock sequences. Some of

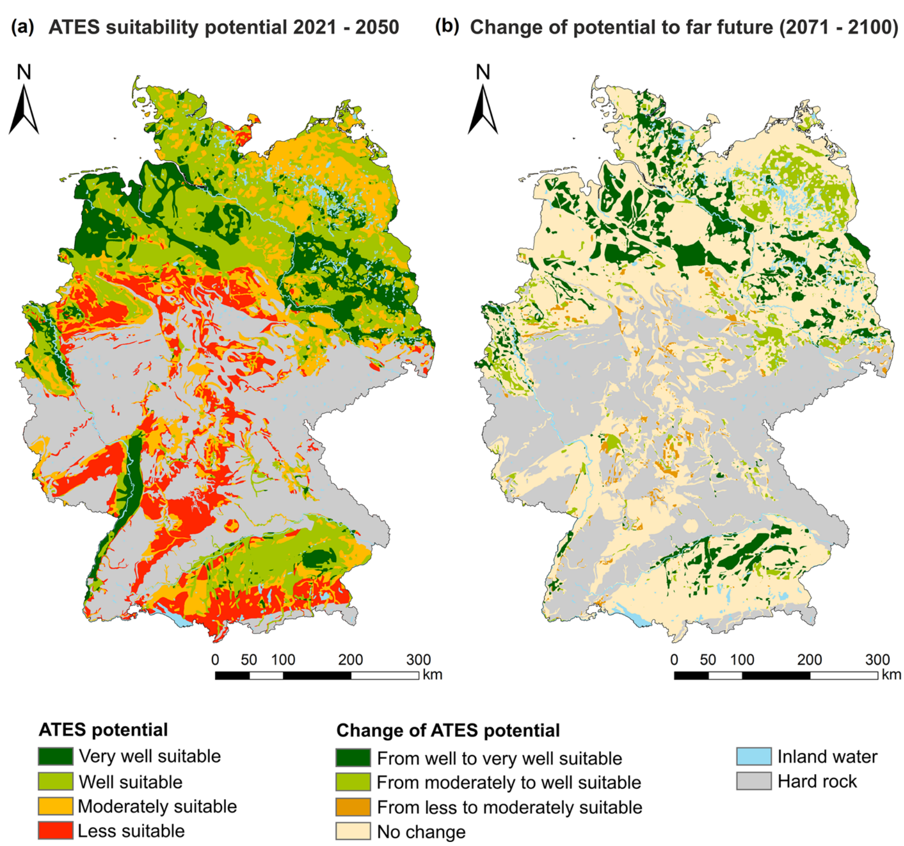

Fig. 5 **a** ATES suitability potential in Germany for the period *near future* (2021–2050), **b** change in potential from the *near future* to the *far future* (2071–2100)

these sequences form very productive porous aquifers over several groundwater levels (Schubert 2016). In addition to productive aquifer conditions, many areas within these regions show also low groundwater flow velocities of < 0.5 m/days further increasing the ATES suitability.

For the majority of the moderately suitable area, the basic requirements for a viable ATES operation in terms of aquifer productivity are fulfilled. However, other criteria show characteristics that are not favorable for the suitability of typical LT-ATES applications, e.g., a poor balance of heating and cooling energy demands (Fig. 4a). Another criterion causing these areas to be classified as moderately suitable is a higher groundwater flow velocity, as in Germany's northeastern regions (Fig. 2c). The detrimental impact of high flow velocities losses can be reduced by designing the ATES systems with downstream production wells in order to reduce possible heat losses and achieve higher thermal recoveries (Bloemendal and Olsthoorn 2018). Areas that are colored in red are less suitable for the ATES application. In most parts, this is largely caused by unfavorable hydrogeological conditions dominated by the absence of significant groundwater resources (Fig. 2a). Another aspect which can prevent ATES applications and has to be considered in site-specific planning are any legislative restrictions regarding the operation of ATES systems or open geothermal systems in general, such as water protection zones. Due to this study's focus on hydrogeological and climatic conditions, these aspects are not considered here.

Analyzing the change in ATES suitability potential from the *near future* period (2021–2050) to the *far future* (2071–2100), reveals that across Germany the potential does not change for about 76% of the country's area with shallow porous aquifers, meaning that the ATES suitability remains within the same respective classes as for the *near future* in most parts of Germany (Fig. 5b). However, within each suitability class, there are small increases of the absolute suitability potential score for all grid cells. The majority of suitability class changes coincides with a change from well suitable for ATES to very well suitable. The increasing ATES suitability is caused by a more balanced ratio of cooling and heating energy demands due to global warming. It should also be noted, that there are no regions in Germany with a decreasing suitability potential. For the past time periods, the suitability potential changes are lower since also the respective changes of the CDDs/HDDs ratio are lower (Fig. 6). For the time periods *far past* (1961–1990), *near past* (1991–2020) and *near future* (1961–2050), there is almost no change in the shares of the individual potential classes. Regarding the upcoming time period *near future*, about 16% of Germany's relevant area are very well suitable for ATES, 38% are well suitable, 26% are moderately suitable and 20% are not suitable.

More significant potential changes can be observed when moving to the *far future* (2070–2100), which again shows the increasing rate of global warming reflected by the IPCC emission scenario A1B used in this study. For this time period, the share of the very well or well suitable area increases from around 54% of the relevant parts of Germany to about 61%. The very well suitable area in particular almost doubles.

Our results are in good agreement with previous ATES potential maps presented in Bloemendal et al. (2016) and Lu et al. (2019a). They also indicate a high or very high suitability potential in most parts of Germany and central Europe in general.

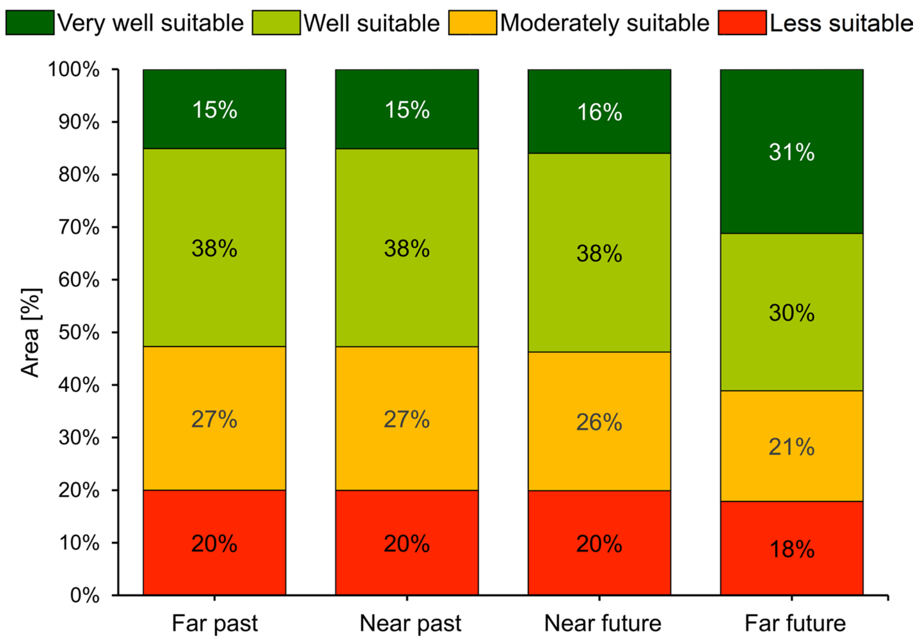

Fig. 6 Percentage shares of ATES suitability potential classes in Germany for the four considered time periods *far past* (1961–1990), *near past* (1991–2020), *near future* (2021–2050) and *far future* (2071–2100). The shares refer to the parts of Germany that are not covered by hard rock or inland water surfaces

In comparison, however, the potential map of Germany presented in Fig. 5a depicts regional differences of significantly smaller scale, reflecting the higher level of detail of the input data.

Besides the hydrogeological criteria, this also applies to the climatic conditions. The study by Bloemendal et al. (2015) also estimates the ATES suitability for future climate conditions (2051–2075). When compared to the time period 1976–2000, Bloemendal et al. (2015) predict a decreasing suitability potential in some parts of the world including central Europe. This is explained by the shift from balanced heating and cooling demands in these parts of the world towards a cooling dominated energy demand. This contradicts our conclusions in this regard (Fig. 5b) which, in fact, results from a contrary estimation of energy demand development towards a more balanced ratio of heating and cooling starting from a presently prevailing heating demand.

These differences can be explained by the utilized climate projections and the methods for estimating heating and cooling demands. The changing energy demand in Bloemendal et al. (2015) is based on the IPCC scenario A1FI, which represents the maximum climate shift expected with an ongoing emphasis on fossil fuels (Rubel and Kottek 2010). In contrast, the present study uses the scenario A1B reflecting a balanced utilization of all available energy sources resulting in less severe climatic changes. Thus, Bloemendal et al. (2015) use a more pessimistic climate scenario while also applying an assessment of the current heating and cooling demand situation that is more optimistic regarding ATES suitability.

In contrast to the classification schemes used in previous studies (Bloemendal et al. 2015, 2016; Lu et al. 2019a, b), the potential map in Fig. 5a presents the ATES suitability in only four classes to achieve a clear presentation. Considering the uncertainties of the input data and the variability of possible criteria weightings, which are further analyzed in the next chapter, a finer subdivision would gradually decrease the individual classes' significance and the informative value of class differences.

ATES suitability potential using different criteria weightings

The one-on-one comparisons between all possible pairs of individual criteria conducted to obtain the ATES potential map (Fig. 5a) is based on the authors' expert judgments, which implies a certain amount of ambiguity. One way to deal with this is to assemble more opinions of relevant experts via the questionnaire method (Lu et al. 2019a). Here, we generate three additional distinct comparison matrices, each of which represents a different perspective on the topic of ATES operation reflecting different professional backgrounds and motivations. This approach thus assesses the sensitivity of the suitability potential to different weighting schemes.

The first alternative perspective prioritizes groundwater protection resulting in a much higher weighting of the criterion on iron and manganese contents. A second alternative prioritizes more balanced heating and cooling demands (and supplies) representing a possible evaluation by a building energy consultant with a high weighting of the ratio CDDs/HDDs. The last alternative perspective stresses the importance of low subsurface thermal losses caused by groundwater flow with a high weighting of the groundwater flow velocity criterion. The alternative comparison matrices and their corresponding weighting factors are presented in Additional file 1: Table S4. All alternatives fulfill the consistency check.

Figure 7 shows the shares of the ATES suitability potential classes for the *near future* (2021–2050) depending on the applied weighting scheme. The reference bar refers to the weighting that was used to create the ATES potential map of Germany (Table 3, Fig. 5a). The class delimitation for the three alternative weighting schemes follows the same scheme as before. While the alternative weighting schemes are only evaluated for the *near future* period, this approach enables methodological consistency for the sake of a meaningful comparison of the weighting schemes.

In general, it is noticeable that there are no extreme changes regarding the regions that are well or very well suitable (Additional file 1: Fig. S7). The combined area of well and very well suitable regions varies between 48 and 59% of the considered parts of Germany. This implies a relatively low sensitivity of the both most suitable regions to the utilized weighting scheme. Thus, Germany shows a significant suitability for ATES application regardless of the criteria weighting. In fact, the reference weighting scheme used for creating the potential map of Germany (Fig. 5a) results in a rather conservative judgement of the country-wide ATES potential (Fig. 7).

The comparatively low sensitivity can also be observed regarding the combined share of the well and very well suitable regions projected for the *far future* (2070–2100) using the three alternative weighting schemes. With 61% of the relevant German area, the lowest combined share for this time period results from using the reference weighting scheme (Fig. 6). For the alternative schemes, the combined shares for the *far future* are 67% (Alternative 1), 69% (Alternative 3) and 77% (Alternative 2). Alternative 2 is characterized by a very high weighting of the climatic criterion (Additional file 1: Table S4) and

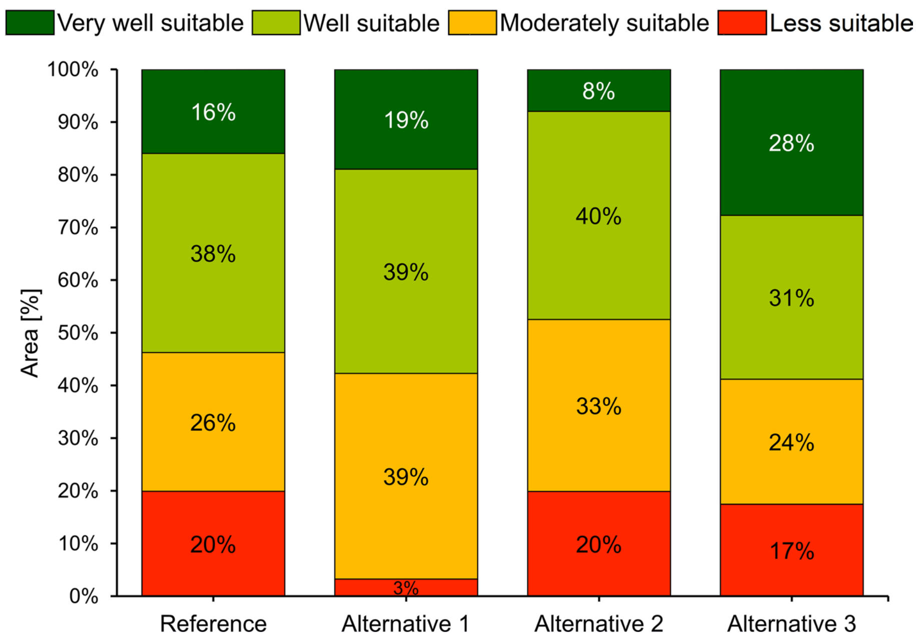

Fig. 7 Percentage shares of ATES suitability potential classes in Germany for the reference as well as the three alternative weighting schemes with regard to the time period *near future* (2021–2050). The shares refer to the parts of Germany that are not covered by hard rock or inland water surfaces (Additional file 1: Fig. S7)

therefore shows the highest suitability changes from the *near future* (2021–2050) to the *far future* (2071–2100).

Restrictions in water protection zones

The qualitative technical potential of ATES in Germany as shown in Fig. 5a is determined based on hydrogeological and climatic factors. In order to also consider legislative restrictions regarding the thermal use of groundwater which can possibly hinder ATES applications in well or very well suitable regions, existing water protection zones are overlaid on the created potential map (Fig. 8). Due to this study's focus on the technical potential, these zones are not removed from the potential map.

In order to avoid detrimental effects on water quality or quantity, protective rules and forbidden activities apply in these zones, which are further subdivided into zones I, II and III. While geothermal applications are strictly excluded for the immediate well head protection zones (I) and the closer protection zones (II), a conditional thermal utilization of groundwater in the wider protection zones (III) is in principle conceivable. However, possible exceptions to the stated restrictions in zones III still have to be decided upon by the responsible local water authority on case-by-case decisions (Neidig 2022).

For this study, we take a conservative approach and assume the exclusion of ATES applications in all zones I to III to evaluate the potential reduction of suitable regions due to drinking and spa water protection zones. The combined area of well and very well suitable regions across Germany reduces by around 11% when accounting for all water protection zones. Particularly in the Upper Rhine Graben, the very well suitable area is considerably reduced. A reduction by about 14% can also be observed for the

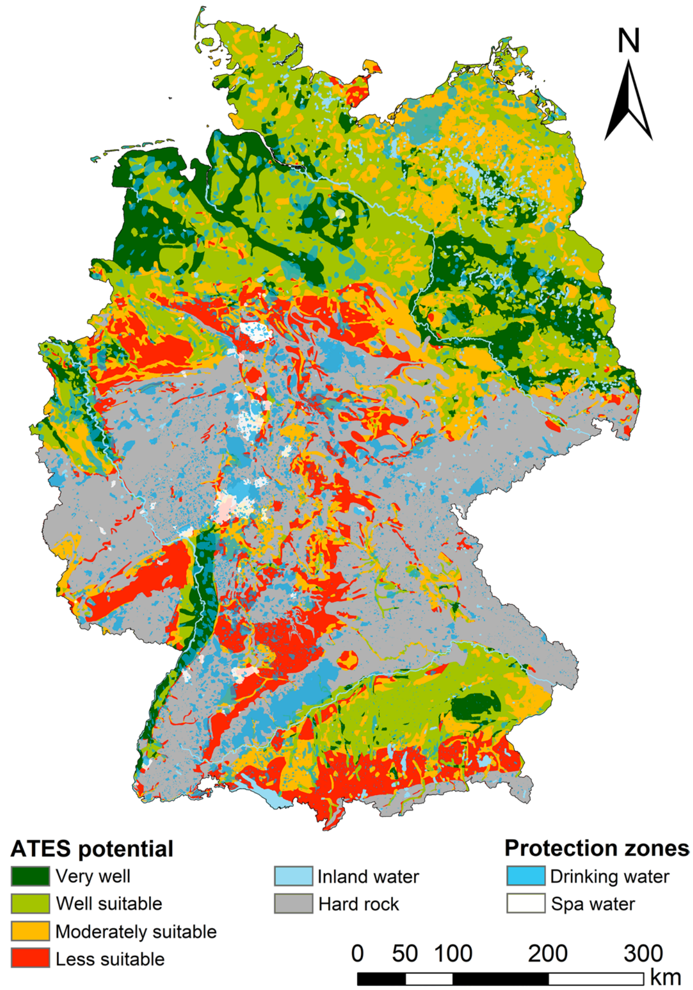

Fig. 8 ATES suitability potential in Germany for the period *near future* (2021–2050) based on the reference criteria weighting scheme. Drinking and spa water protection zones are included. Protection zone data from BfG (2021), LfU (2021), LUBW (2022a; b), HLNUG (2022), MULNV NRW (2022), NLWKN (2021)

nationwide area of moderately suitable regions. Given these numbers, the discussion arises whether installation of individual LT-ATES systems should be allowed in protection zones III. This is particularly true given the extent of the wider protection zone III which is usually much larger than zone I and II. Numerical modeling is conceivable as a suitable decision tool to check if thermal utilization of groundwater can possibly be reconciled with existing protection concepts, for example with regard to temperature or chemical changes. When combined with an environmental assessment, this could be part of a policy framework for a sustainable utilization of shallow groundwater as proposed in Blum et al. (2021).

Limitations of the ATES suitability potential map

The ATES suitability potential map (Fig. 5a) represents the most detailed Germany-wide assessment of the ATES potential yet, providing an overview of the suitability and its spatial distribution. However, it should be noted, that the map is not suitable for drawing local or site-specific conclusions for planning ATES systems. This is in part due to limitations in the resolution of the input data. As shown in Additional file 1: Table S1, the input data sets do not share a uniform resolution. The datasets aquifer productivity as well as iron and manganese contents in groundwater are available as vector data without a native resolution. However, the map scale of these datasets originally published in printed form is 1:1,000,000. The smaller scale of the groundwater flow velocity dataset (1:3,500,000) with a resolution of 3 km × 3 km thus constrains the resolution of the ATES suitability potential map (Fig. 5a).

Other hydrogeological characteristics that are not mapped on a country-wide scale can also affect ATES applicability. Examples of this are an increased occurrence of clay lenses, small-scale heterogeneities and local variations in groundwater flow velocity or chemical composition. In order to consider drilling costs, the inclusion of the depth of potential storage reservoirs could also be worthwhile. Planning a specific ATES system therefore requires detailed and accurate site-specific investigations and knowledge, such as hydrogeological exploration and thermo-hydraulic modeling. One should also be aware of the type of potential illustrated in the map. The suitability potential is a qualitative rating. Again, site-specific quantitative assessments and modeling are necessary to determine the optimal design of individual systems with respect to the amount of thermal energy that can be stored and extracted.

Heat transport models also enable the inclusion of more detailed information on heating and cooling demands, which in this study is estimated by country-wide interpolated data of heating and cooling degree days. Exemplary additional information in this regard such as auxiliary peak load supply or steadily increasing requirements for building insulation is crucial for planning individual ATES systems. The degree day interpolation itself is another uncertainty inducing factor affecting the accuracy of the ATES suitability potential map of Germany due to the limited number of available weather stations across Germany. A limited accuracy of the other input criteria and the respective datasets can also affect the accuracy of the generated ATES potential map. Parts of the results in form of the prevailing high suitability in northern Germany as identified in the potential map (Fig. 5a) can be checked regarding plausibility via a comparison with the neighboring Netherlands. Fleuchaus et al. (2018) showed that a high number of ATES systems are installed in the Netherlands. This is in part due to the very high suitability of the Dutch aquifers which have hydrogeological characteristics similar to northern Germany. Thus, the high ATES suitability in northern Germany appears plausible.

Another limitation of the generated map is that regulatory or legislative aspects other than water protection zones as well as conflicts with competing usage scenarios of shallow groundwater are not included. Such aspects can possibly impede the permission of ATES applications based on case-by-case decisions even in areas designated as well or very well suitable.

Conclusions

The aim of this study is to create a map of the qualitative suitability potential regarding shallow ATES applications in Germany. For this purpose, different hydrogeological and climatic data are compiled and their individual influence on the ATES suitability is evaluated. Restricting the study to shallow LT-ATES systems allows to narrow down the number of relevant input criteria as well as focusing on space heating and cooling as the considered ATES use case. The created map of the ATES suitability potential in Germany is the most detailed one yet and a useful tool to identify suitable regions and assess the country-wide ATES potential. It shows that about 54% of the country's area with shallow porous aquifers currently are well or very well suitable for low-temperature ATES systems. The large majority of these areas are located in the three geographical regions of the North German Basin, the Upper Rhine Graben and the South German Molasse Basin. The specific value of this share depends on the weighting assigned to each individual criterion during calculation of the potential. Evaluating several distinct schemes of input criteria weightings reveals that the combined shares of currently well or very well suitable areas varies between 48 and 59%. This indicates a relatively low sensitivity to the suitability classes. Considering climate change according to the IPCC SRES emission scenario A1B, the share of well or very well suitable areas is expected to increase to values between 61 and 77% of the relevant parts of Germany until the end of the century depending on the weighting scheme. This is due to a more balanced ratio of cooling and heating demands. When considering drinking water and spa water protection zones, the technical ATES potential is significantly reduced in many areas due to legislative restrictions related to water protection.

Future studies in this research field could build on this work by including additional data, such as updated climate projection scenarios and time-dependent data of aquifer productivity as well as input data of higher accuracy and resolution. The chosen workflow based on pairwise comparisons allows for an easy integration of such data. An adaptation of the workflow using more detailed spatial data in order to determine the qualitative potential for individual regions is also possible. In the future, this kind of potential evaluation could also serve as a tool for regional policy-makers to create the necessary framework for further advancing the application of this technology.

Abbreviations

AHP	Analytical Hierarchy Process
ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
CDD	Cooling degree days
COP	Conference of the Parties
DGM	Digitales Geländemodell (eng.: digital terrain model)
ECHAM	European Centre for Medium-Range Weather Forecasts, Hamburg
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information System
GSHP	Ground source heat pump
HDD	Heating degree days
HT	High-temperature
IPCC	Intergovernmental Panel on Climate Change
LT	Low-temperature
MCDA	Multicriteria Decision Analysis
PTES	Pit thermal energy storage
SAT	Surface air temperature
SRES	Special Report on Emissions Scenarios
UTES	Underground thermal energy storage
WETTREG	Wetterlagenbasierte Regionalisierungsmethode (eng.: weather situation-based regionalization method)
WLC	Weighted Linear Combination

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40517-022-00234-2.

Additional file 1: Table SD1. Data sets used for the potential study of ATES in Germany. **Fig. SD2**. Digital terrain model of Germany (DGM1000, modified from BKG (2021)). **Table SD3.1**. Values of RI in dependence of n according to Saaty (1980) and Lu et al. (2019). **Table SD3.2**. Values of CR for the reference and alternative pairwise comparison matrices. **Table SD4**. Pairwise comparison matrices and weighting factors representing three alternativeperspectives (A1, A2, A3) on the topic of ATES. **Fig. SD5**. HDDs for 2021-2050: (a) Germany-wide HDD values interpolated between 383 weatherstations (black marks) via cokriging, (b) Prediction standard error (i.e. standard deviation) of thecokriging interpolation. **Fig. SD6**. Change of mean ratio of CDDs to HDDs: (a) From far past (1961-1990) to near past (1991-2020), (b) from near past to near future (2021-2050), (c) from near future to far future (2071-2100). **Fig. SD7**. ATES suitability potential in Germany for the period near future (2021-2050) based on thethree alternative weighting schemes: (a) Alternative 1, (b) Alternative 2, (c) Alternative 3.

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Author contributions
RS: conceptualization, methodology, data collection, visualization, writing—original draft. VH: methodology, data collection, visualization. PB: conceptualization, supervision, writing—review and editing. KM: conceptualization, supervision, writing—review and editing. All authors read and approved the final manuscript.

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Declarations

Competing interests
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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