Contribution of Aquifer Thermal Energy Storage (ATES) to the Energy Transition in Germany

Zur Erlangung des akademischen Grades eines

Doktors der Naturwissenschaften (Dr. rer. nat.)

von der KIT-Fakultät für
Bauingenieur-, Geo- und Umweltwissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte

Dissertation

von

M.Sc. Ruben Stemmle

Tag der mündlichen Prüfung: 02. Februar 2024

Referentin: PD Dr. Kathrin Menberg
Korreferent: Prof. Dr. Jasper Griffioen
Korreferent: Prof. Dr. Philipp Blum

Karlsruhe 2024

Abstract

Around half of Germany's final energy consumption is caused by heating and cooling processes. Decarbonizing the heating and cooling sector is therefore an important part of a successful energy transition in Germany. Aquifer Thermal Energy Storage (ATES) represents a promising solution for sustainable and climate-friendly heating and cooling in the building sector using groundwater and the geological subsurface as a storage medium for thermal energy. This storage technology can overcome the temporal mismatch between the availability of thermal energy and the demand for heating and cooling, increasing the share of renewable energy sources and previously unused waste heat in the heating and cooling sector. Nevertheless, the deployment of ATES in Germany, as in many other countries, has so far been very limited. This thesis aims to answer the question of how ATES can contribute to the energy transition in Germany, taking into account hydrogeological, technical, political, and societal factors.

The first study of this cumulative thesis aims to determine potential greenhouse gas emission savings that can be achieved with ATES. For this purpose, a low-threshold life cycle analysis regression model is created that can be applied to a wide range of possible ATES configurations. Due to its parametric structure, the model represents a quick-to-use alternative to conventional life cycle analyses. Significant savings in greenhouse gas emissions of up to 74 % are possible with ATES compared to conventional heating technologies based on fossil fuels. These savings are expected to rise in the future due to increasing shares of renewably generated electricity used for ATES operation. Compared to electrically powered compression chillers, typical ATES systems can achieve greenhouse gas emission savings of up to around 59 %.

To achieve large-scale realization of these greenhouse gas emission savings, sufficiently large areas with suitable hydrogeological and climatic conditions for ATES are necessary. The second study therefore identifies suitable regions for ATES based on important criteria such as aquifer productivity, groundwater flow velocity, and climate-based estimates of heating and cooling demands. The resulting ATES potential map of Germany shows that around 54 % of Germany, excluding hard rock areas, is well or very well suitable for ATES. Overall, Germany therefore has a substantial potential for ATES applications. High ATES suitability is shown for three regions in particular: the North German Basin, the Upper Rhine Graben, and the South German Molasse Basin. Considering climatic changes up to the year 2100, the study shows that future increases in suitable areas are to be expected.

In addition to the qualitative investigation of ATES suitability, the third study develops an approach for quantifying the technical ATES potential on the city scale. The city of Freiburg im Breisgau in Southwest Germany serves as an exemplary study area for thermo-hydraulic 3D numerical simulation of ATES systems with different well layouts that are adapted to the local groundwater flow velocity. Comparing ATES power densities determined from these simulations with the urban heating and cooling demands reveals that ATES could supply significant shares of the city’s thermal energy demand. For half of all residential buildings in the study area, heating supply rates of more than 60 % are shown. ATES could even completely supply the cooling demand of 92 % of the buildings. The developed modeling approach could also be used in other cities in the future to include the potential of ATES in city-scale urban energy planning.

Beyond hydrogeological and technical feasibility, appropriate national policies for ATES are essential in driving deployment. By means of a comprehensive online survey and expert interviews, the fourth study of this thesis therefore identifies successful, but also often missing, policy measures aimed at increasing ATES utilization. From these insights, recommendations for a sophisticated ATES policy are derived to overcome legislative, regulatory, and socio-economic barriers to a wider ATES deployment. Besides legislative and regulatory measures, the recommendations include actions to increase awareness and expertise regarding ATES as well as the potentially significant role of ATES in urban energy planning.

The environmental benefits and substantial application opportunities of ATES systems at national and city scales shown in this thesis demonstrate the great transformative potential of ATES for a successful energy transition in Germany. The recommendations for action developed for a sophisticated ATES policy can help to bring this potential closer to realization.

Kurzfassung

Etwa die Hälfte des deutschen Endenergieverbrauchs wird durch Heiz- und Kühlprozesse verursacht. Die Dekarbonisierung des Heiz- und Kühlsektors ist somit ein wichtiger Bestandteil einer erfolgreichen Energiewende in Deutschland. Thermische Aquiferspeicher (Aquifer Thermal Energy Storage, ATES) stellen eine vielversprechende Möglichkeit für nachhaltiges und klimafreundliches Heizen und Kühlen im Gebäudesektor dar und nutzen den geologischen Untergrund und insbesondere das darin enthaltene Grundwasser als Speichermedium für thermische Energie. Diese Speichertechnologie ermöglicht es, den zeitlichen Versatz zwischen Verfügbarkeit thermischer Energie und dem Bedarf an Wärme und Kälte zu überbrücken und so den Anteil erneuerbarer Energien sowie bisher ungenutzter Abwärme im Heiz- und Kühlsektor zu erhöhen. Dennoch ist ATES in Deutschland wie auch in vielen anderen Ländern bislang nur wenig verbreitet. Unter Berücksichtigung hydrogeologischer, technischer sowie politischer und gesellschaftlicher Faktoren soll diese Arbeit die Frage beantworten, wie thermische Aquiferspeicher zur Energiewende in Deutschland beitragen können.

Die erste Studie dieser kumulativen Arbeit zielt darauf ab, mögliche Treibhausgaseinsparungen zu bestimmen, die durch Aquiferspeicher erreicht werden können. Hierzu wird ein niederschwelliges Lebenszyklusanalysenregressionsmodell erstellt, das für die Ökobilanzierung einer großen Bandbreite möglicher ATES-Konfigurationen genutzt werden kann. Dank seiner parametrisierten Struktur stellt das Modell eine schnell zu verwendende Alternative zu konventionellen Lebenszyklusanalysen dar. Im Vergleich zu konventionellen, auf fossilen Brennstoffen basierenden Heiztechnologien zeigen sich bedeutende Einsparungen an Treibhausgasemissionen durch ATES von bis zu 74 %. Diese Einsparungen werden in Zukunft aufgrund eines zunehmenden Anteils erneuerbar generierten Stroms für den Betrieb der Aquiferspeicher weiter steigen. Verglichen mit elektrisch betriebenen Kompressionskältemaschinen zur Gebäudekühlung können typische Aquiferspeicher Treibhausgaseinsparungen von bis zu etwa 59 % erreichen.

Für eine bedeutende Realisierung dieser Treibhausgaseinsparungen sind ausreichend große Areale mit hydrogeologischen und klimatischen Bedingungen erforderlich, die für den ATES-Betrieb geeignet sind. Die zweite Studie nutzt daher wichtige Kriterien wie die Aquiferproduktivität, die Grundwasserströmungsgeschwindigkeit und klimabasierte Abschätzungen von Heiz- und Kühlbedarf, um für Aquiferspeicher geeignete Regionen zu identifizieren. Die resultierende Deutschlandkarte des qualitativen ATES-Potentials zeigt, dass etwa 54 % Deutschlands unter Ausschluss der Festgesteinsgebiete gut oder sehr gut für ATES geeignet sind, sodass Deutschland insgesamt ein hohes Potential für die Anwendung thermischer Aquiferspeicher bescheinigt werden kann. Insbesondere das Norddeutsche Becken, der Oberrheingraben und das Süddeutsche Molassebecken weisen eine sehr hohe Eignung auf. In Zukunft ist außerdem eine Zunahme der geeigneten Flächen zu erwarten, wie durch die Berücksichtigung klimatischer Veränderungen bis zum Jahr 2100 gezeigt werden kann.

Über die qualitative Untersuchung der ATES-Eignung hinausgehend wird in der dritten Studie ein Ansatz zur Quantifizierung des technischen ATES-Potentials auf der Stadtskala entwickelt. Die Stadt Freiburg im Breisgau in Südwestdeutschland dient dabei als exemplarisches Untersuchungsgebiet für die thermohydraulische 3D-numerische Simulation thermischer Aquiferspeicher mit unterschiedlichen, an die lokale Grundwasserströmungsgeschwindigkeit angepassten Brunnenkonfigurationen. Der Vergleich der so ermittelten ATES-Leistungsdichten mit dem bestehenden städtischen Heiz- und Kühlenergiebedarf zeigt, dass sich bedeutende Anteile des thermischen Energiebedarfs durch ATES decken ließen. Während sich für die Hälfte aller Wohngebäude im Untersuchungsgebiet Deckungsgrade des Heizenergiebedarfs von mehr als 60 % ergeben, könnten Aquiferspeicher den Kühlenergiebedarf von 92 % der Gebäude sogar vollständig decken. Der entwickelte Modellierungsansatz könnte in Zukunft auch in anderen Städten eingesetzt werden, um das Potential von Aquiferspeichern in der kommunalen Wärmeplanung zu berücksichtigen.

Neben der hydrogeologisch-technischen Machbarkeit ist eine zunehmende Verbreitung von Aquiferspeichern in hohem Maße von nationalen ATES-Policies abhängig. Die vierte Studie dieser Arbeit identifiziert daher mithilfe einer breit angelegten internationalen Onlineumfrage sowie Experteninterviews einige erfolgreiche, aber auch oftmals fehlende Policymaßnahmen, die auf einen verstärkten Einsatz thermischer Aquiferspeicher abzielen. Basierend auf den erlangten Erkenntnissen präsentiert die Studie Empfehlungen, wie eine geeignete ATES-Policy legislative, regulatorische und sozioökonomische Barrieren überwinden kann. Diese Empfehlungen betreffen neben legislativen und regulatorischen Anpassungen unter anderem Maßnahmen zur Steigerung des Bewusstseins und der Expertise bezüglich ATES sowie die potentiell bedeutsame Rolle von Aquiferspeichern in der kommunalen Wärmeplanung.

Die in dieser Arbeit gezeigten ökologischen Vorteile sowie substantiellen Einsatzmöglichkeiten thermischer Aquiferspeicher auf nationaler und auf kommunaler Ebene belegen ein großes transformatives Potential von ATES für eine erfolgreiche Energiewende in Deutschland. Die entwickelten Handlungsempfehlungen für eine geeignete ATES-Policy können dabei behilflich sein, dieses Potential seiner Ausschöpfung näher zu bringen.

Table of contents

Abbreviations

AHP	Analytical Hierarchy Process
ASHP	Air Source Heat Pump
ATES	Aquifer Thermal Energy Storage
BC	Boundary Condition
BTES	Borehole Thermal Energy Storage
CDD	Cooling Degree Days
CO_2eq	Carbon Dioxide equivalents
COP	Coefficient Of Performance
CTES	Cavern Thermal Energy Storage
DHC	District Heating and Cooling
FEM	Finite Element Method
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information System
GSA	Global Sensitivity Analysis
GSHP	Ground Source Heat Pump
GWHP	Groundwater Heat Pump
HDD	Heating Degree Days
HT-ATES	High-Temperature Aquifer Thermal Energy Storage
HVAC	Heating, Ventilation and Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LT-ATES	Low-Temperature Aquifer Thermal Energy Storage
MC	Monte Carlo
MCDA	Multicriteria Decision Analysis
PTES	Pit Thermal Energy Storage
RHC	Renewable Heating and Cooling
SAT	Surface Air Temperature
SGE	Shallow Geothermal Energy
SUHI	Subsurface Urban Heat Island
TAZ	Thermally Affected Zone
TES	Thermal Energy Storage
URG	Upper Rhine Graben
UTES	Underground Thermal Energy Storage
WLC	Weighted Linear Combination

1 Introduction

1.1 Motivation

In recent years, man-made global warming reached 1.1 °C relative to the long-term mean of 1850 to 1900, according to the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Lee et al., 2023). The consequences are widespread and substantial adverse effects on people and nature. Increasing frequencies of weather extremes, an accelerating sea level rise, and the irreversible loss of species are examples from the atmosphere, hydrosphere, and biosphere (Ablain et al., 2017; Habibullah et al., 2022; Nerem et al., 2018; Román-Palacios and Wiens, 2020; Stott, 2016). Far-reaching and ambitious climate action measures are necessary to prevent further damage and limit global warming to a maximum of 1.5 °C. This internationally agreed goal was restated in 2021 at the COP 26 climate change conference in the form of the Glasgow Climate Pact. Replacing today's carbon-intensive energy system with sustainable alternatives based on renewable energies is essential for reaching this goal. Until now, this energy transition mainly focused on the transformation of the power sector, where a share of renewable energies of around 30 % has been reached globally (Enerdata, 2023). Decarbonizing the heating and cooling sector is of high importance, too, since this sector accounts for about half of the global final energy consumption (IRENA et al., 2020). However, a mere 10 % of this energy is currently supplied by renewable energies, such as solar thermal energy, sustainable bioenergy, or geothermal energy, with only small increases in recent years (IRENA et al., 2020). A comparable situation can be seen in Germany, where the share of renewable energies in the heating and cooling sector is currently only around 18 % due to the slow pace of this sector's decarbonization in recent years (Umweltbundesamt, 2023). These numbers illustrate the importance and the so far largely unused potential of renewable heating and cooling (RHC) for reaching climate protection targets in Germany and around the world.

Energy storage can greatly benefit future sustainable energy systems with high shares of renewable energies (Barns et al., 2021; Cabeza and Palomba, 2022; IRENA, 2020). In the heating and cooling sector, thermal energy storage (TES) systems can act as a key enabler for the optimal and sustainable utilization of available sources of heat and cold and can reduce primary energy consumption (Alva et al., 2018; Bott et al., 2019; Heier et al., 2015; Zhang et al., 2016). Compared to electricity demand, energy demands for heating and cooling often vary more strongly in line with seasonal outside air temperature variations during a year (Watson et al., 2019). Seasonal discrepancies between periods of highest capacity for RHC generation and times of highest thermal energy demand therefore pose one of the main challenges for a more widespread decarbonization of the heating and cooling sector (Bott et al., 2019; Narula et al., 2020; Paulus et al., 2021; Pavlov et al., 2012). Long-term seasonal TES systems can convert the fluctuating energy availability into a reliable and steadily accessible source of heating and cooling energy, thus decoupling RHC generation from environmental conditions (Bott et al., 2019). Figure 1.1 exemplarily shows the seasonal mismatch between the availability of solar thermal energy and a typical heating demand curve which are highest in summer and winter, respectively, illustrating the purpose of seasonal TES.

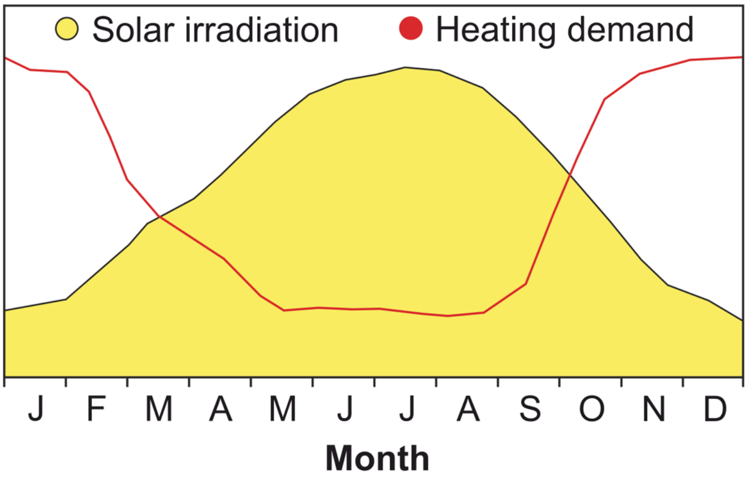


Figure 1.1: Schematic variations of solar irradiation and heating demand during a year. Seasonal TES can be used to store surplus solar thermal energy in summer and time-shift its availability to the heating period in winter.

TES systems can be classified by their storage medium as well as by the charging and discharging mechanism and are typically divided into sensible, latent, and thermochemical heat storages (Pinel et al., 2011; Rosen and Koohi-Fayegh, 2017; Xu et al., 2014). While latent and thermochemical storage types commonly have higher specific energy storage capacities with respect to the storage volume, sensible heat storage is at the highest development level and most frequently applied (Pinel et al., 2011; Rundel et al., 2013). Different types of sensible heat storage include closed artificial storage systems and Underground Thermal Energy Storage (UTES). The former group consists of isolated tanks or pits made of steel or concrete and thus offers a high flexibility regarding the storage installation site (Bott et al., 2019; Xu et al., 2014). In contrast, the different types of UTES, which are Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), and Cavern Thermal Energy Storage (CTES), have distinct geological and hydrogeological requirements. While therefore being confined to areas of suitable subsurface conditions, UTES has the advantage of storage volumes typically exceeding those of closed artificial storage solutions. ATES in particular is characterized by large storage volumes and at the same time low space requirements at the surface (Fleuchaus et al., 2018). Thus, in areas with suitable aquifers, ATES is a promising technology for contributing to a sustainable supply of heat and cold. The assessment of the possible contribution of ATES to the decarbonization of the heating and cooling sector, however, requires consideration of a variety of hydrogeological, technical as well as political, and societal factors. To this end, this thesis presents a thorough evaluation of the potential role of ATES in the energy transition regarding these aspects, with a focus on Germany. The individual objectives including more specific research questions are presented in Chapter 1.3 with the structure of this thesis being provided in Chapter 1.4. First, however, the following Chapter 1.2 explains the working principle of ATES in more detail.

1.2 Basic principle and application cases of Aquifer Thermal Energy Storage

ATES is an open-loop geothermal system that uses groundwater as a medium for seasonal storage of thermal energy at different temperature levels. ATES is commonly classified into Low-Temperature ATES (LT-ATES) and High-Temperature ATES (HT-ATES). LT-ATES systems are typically characterized by maximum storage temperatures of 25 °C (Fleuchaus et al., 2018; Fleuchaus et al., 2020a). Besides storing warm water at these temperature levels, LT-ATES systems also create a cold storage volume in the subsurface to provide both heat and cold for space heating and cooling applications. The most basic form to achieve this is a single ATES well doublet consisting of two groundwater wells operating in a seasonal mode with reversing water pumping direction (Figure 1.2). During the heating period, i.e. the cold season, groundwater from the warm storage area is extracted to heat the building that is connected to the ATES system. A heat pump commonly further raises the temperature to levels required by the building heating system. After the extracted warm groundwater has supplied part of its thermal energy to the building, the now cooled groundwater is reinjected into the ATES system's cold storage area. Reversing pumping direction then enables the extraction of the stored cooled groundwater during the following cooling period, i.e. in the summer season. In many cases, the groundwater extracted from the cold storage area is cold enough for direct space cooling without the need for operating the heat pump. The waste heat from the cooling process in the form of heated groundwater is then reinjected into the warm aquifer storage area, completing a storage cycle. This seasonal operation benefits from well-balanced space heating and cooling demands leading to even charging and discharging of the warm and the cold storage areas, which ensures a sustainable system operation (Bozkaya et al., 2018; Fleuchaus et al., 2020b; Sommer et al., 2014). In case of demand imbalances, the application of solar thermal collectors or free coolers allows to store additional summer heat or winter cold in order to achieve a thermal balance in the subsurface (Beernink et al., 2022; Schüppler et al., 2019).

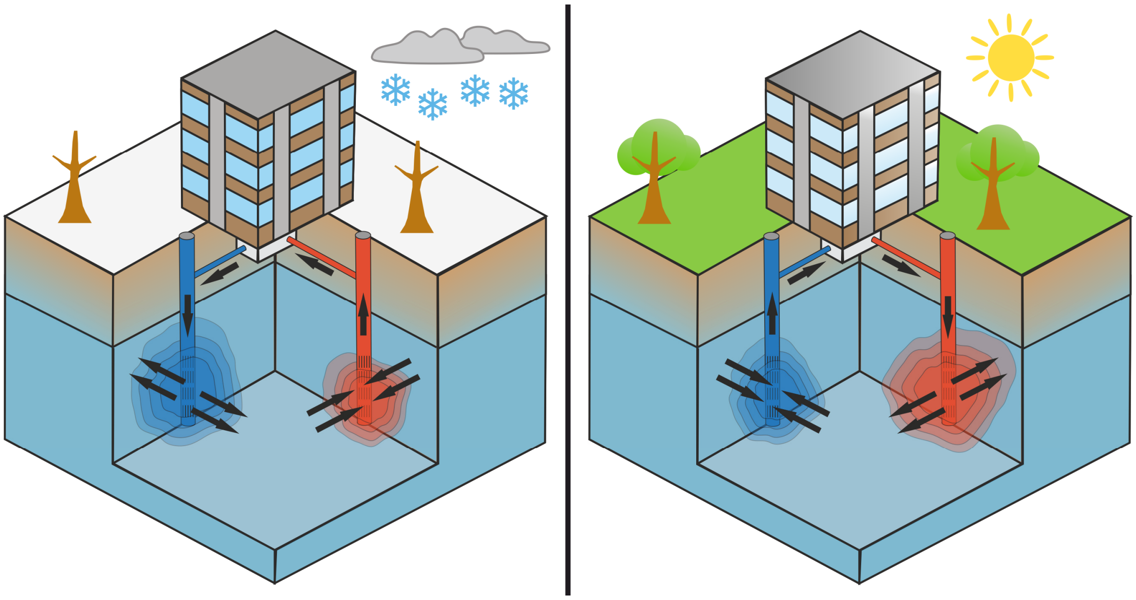


Figure 1.2: Schematic operation principle of LT-ATES in heating mode (left) and in cooling mode (right).

HT-ATES systems store groundwater at higher temperatures typically exceeding 40 °C and thus potentially have higher storage capacities compared to LT-ATES (Drijver et al., 2019; Fleuchaus et al., 2020a; Heldt et al., 2023; Vidal et al., 2022). While LT-ATES systems most often store waste heat and cold from the cooling and heating process itself as described above, HT-ATES is used to store thermal energy generated independently from the energy consumer, i.e. from external heat sources (Figure 1.3). Possible sources include industrial waste heat, excess heat from cogeneration plants and renewable energy sources, such as surplus solar thermal energy and geothermal energy (Fleuchaus et al., 2020a; Wesselink et al., 2018).

ATES is commonly used for large-scale space heating and cooling applications in large building complexes such as airports, office buildings, hospitals, universities, or high-density residential housings (Birhanu et al., 2015; Fleuchaus et al., 2018; Lu et al., 2019b). Another application case is the integration of ATES into district heating and cooling (DHC) networks to compensate for fluctuations in energy supply and demand as well as to increase the share of renewable energies and waste heat sources feeding into the network (Schmidt et al., 2018; Todorov et al., 2020; Wesselink et al., 2018).

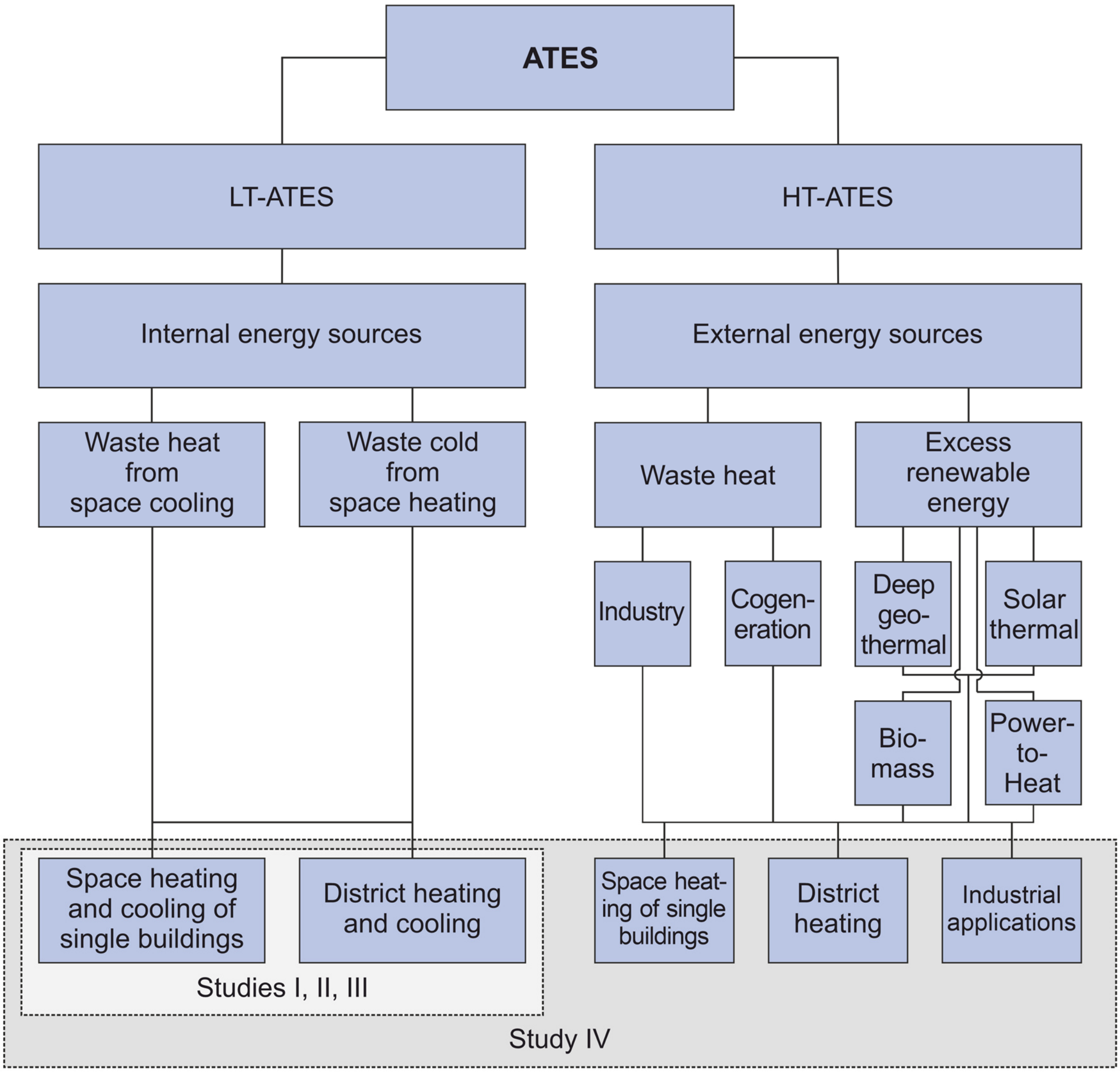


Figure 1.3: Classification of ATES into LT-ATES and HT-ATES with further characterization of both types. The chart presents a common classification; variations and mixed forms of ATES are possible. Studies I to III address LT-ATES, while Study IV considers all types of ATES. Further information on the individual studies compiled in this thesis is presented in Chapter 1.4.

1.3 Objectives

The first applications of ATES date back to the 1960s. Still, despite suitable subsurface and climate conditions being present in many countries and the technology being considered technically proven, ATES has yet to face extensive utilization across the world. So far, the global application has been very limited, with ATES systems primarily being used in four countries: the Netherlands, Sweden, Denmark, and Belgium (Fleuchaus et al., 2018; Lu et al., 2019b). In Germany, only four systems have been installed to date, some of which are no longer in operation according to Fleuchaus et al. (2021). The objective of this thesis is therefore to evaluate how ATES can contribute to the ongoing energy transition focusing on Germany and on LT-ATES systems, which represent the large majority of installed systems worldwide (Fleuchaus et al., 2018). To this end, the thesis aims to determine possible environmental advantages, application opportunities on different spatial scales, and ways to overcome barriers to a more widespread deployment of ATES. It answers the following research questions:

- *To what extent can LT-ATES systems contribute to reducing greenhouse gas emissions compared to other types of space heating and cooling?*
  Reducing the amount of greenhouse gas emissions from the heating and cooling sector is an important pillar of a successful energy transition. The first goal is thus to determine greenhouse gas emission savings achievable with ATES.
- *Where are suitable regions for LT-ATES located in Germany?*
  Large-scale realization of the determined greenhouse gas emission savings through the use of ATES on the national scale requires the existence of sufficiently large areas suitable for ATES. The second goal of this thesis is to identify these regions in Germany.
- *To what extent can LT-ATES supply existing energy demands for space heating and cooling in an urban setting?*
  Besides qualitative suitability, sufficient system performance is important for a practical ATES deployment. Thus, a further goal is to quantify heating and cooling supply rates achievable with ATES on the city scale.
- *What is the current international status of ATES policies and which aspects should a sophisticated ATES policy include that can contribute to increasing ATES deployment?*
  Expanding on the hydrogeological-technical focus of the prior research questions, the final goal is to provide a comprehensive overview of the current international status of policies relevant to ATES. Based on this, the thesis aims to derive policy recommendations that can contribute to promoting ATES in the context of the energy transition.

1.4 Structure of the thesis

This cumulative thesis presents four individual studies, which are enclosed in Chapters 2 - 5. All studies were submitted to international peer-reviewed journals. Studies I, II and III presented in Chapters 2 - 4 are already published, while Study IV in Chapter 5 is currently under review. The thesis is structured according to the research goals outlined above:

- **Chapter 2:** *"Environmental impacts of aquifer thermal energy storage (ATES)"*, published in *Renewable and Sustainable Energy Reviews*
  This chapter provides insights into the environmental benefits achievable with LT-ATES. Based on an existing ATES system, a novel life cycle assessment regression model is developed. It presents a low-threshold and quick-to-use tool to estimate greenhouse gas emissions of a large variety of ATES system configurations. A comparison with other types of

heating and cooling, such as gas boilers and compression chillers, reveals the greenhouse gas emission savings of ATES. The findings of a global sensitivity analysis show which system parameters should be optimized in particular when planning new ATES systems.

- **Chapter 3:** *"Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany"*, published in *Geothermal Energy*
  This chapter aims to determine the overall qualitative potential of LT-ATES across all of Germany in terms of subsurface and climatic suitability. A nationwide spatial multicriteria decision analysis implemented in a geographic information system (GIS) combines hydrogeological and climatic criteria to identify regions suitable for LT-ATES. The results are presented as a Germany map of the ATES suitability. To evaluate future suitability changes due to global warming, climate conditions are considered in a time-dependent way.
- **Chapter 4:** *"City-scale heating and cooling with aquifer thermal energy storage (ATES)"*, published in *Geothermal Energy*
  This chapter quantifies the technical potential of LT-ATES in an urban setting. To this end, 3D numerical subsurface heat transport models are created to simulate extensive ATES operation on the city scale. Power densities of different ATES configurations determined from the models relate the storable and retrievable thermal energy to the required horizontal Earth surface area, thus accounting for storage losses and space restrictions. Comparing the power densities with existing energy demands for space heating and cooling enables the determination of urban heating and cooling supply rates which can be achieved with ATES.
- **Chapter 5:** *"Policies for Aquifer Thermal Energy Storage: International comparison, barriers and recommendations"*, submitted to *Clean Technologies and Environmental Policy*
  This chapter aims to compile international experience in the use of policies that may help to encourage a wider uptake of ATES. For this purpose, views from international experts on this topic are invited. In a two-step process consisting of an online survey and subsequent semi-structured interviews, an extensive set of data is collected highlighting best practices and revealing missing measures to tackle identified ATES market barriers. Building on these findings, policy recommendations are derived that may contribute to increasing ATES deployment.
- **Chapter 6:** *Synthesis*
  This chapter summarizes the main results of Studies I to IV (Chapters 2 to 5) and draws conclusions regarding the contribution of ATES to the energy transition in Germany. Finally, an outlook on possible future research addresses pending research questions.

2 Environmental impacts of Aquifer Thermal Energy Storage (ATES)

Reproduced from: Stemmle, R., Blum, P., Schüppler, S., Fleuchaus, P., Limoges, M., Bayer, P., Menberg, K., 2021. Environmental impacts of aquifer thermal energy storage (ATES). Renewable and Sustainable Energy Reviews 151, 111560. https://doi.org/10.1016/j.rser.2021.111560.

Abstract

Aquifer Thermal Energy Storage (ATES) is an open-loop geothermal system allowing long-term storage of thermal energy in groundwater. It is a promising technology for environmentally friendly energy generation that can reduce greenhouse gas (GHG) emissions. In the literature, there are few studies on the greenhouse gas emissions caused by ATES systems over their entire life cycle. Thus, this study presents a novel life cycle assessment (LCA) regression model that can be used for a wide range of ATES configurations due to its parametric structure. This model is a fast alternative to conventional time-consuming LCAs. Combined with a Monte Carlo simulation, it enables the analysis of the environmental impacts of a large variety of hypothetical ATES systems and therefore the evaluation of the technology as a whole. Compared to conventional heating systems based on heating oil and natural gas, the median value of the Monte Carlo simulation results in GHG savings of up to 74 %. In comparison to cooling techniques using today's electricity mix, ATES can save up to about 59 % of GHG emissions, while also being economically competitive. When considering a projected electricity mix for the year 2050, the GHG emission savings resulting from a second LCA regression model are as high as 97 %. The findings of our sensitivity analysis show which ATES design parameters should be optimized when planning new systems. In particular, the most important design parameters *operating time cooling* and *coefficient of performance* (COP) of the heat pump should be carefully considered.

2.1 Introduction

Aquifer Thermal Energy Storage (ATES) is a technology for long-term storage of thermal energy using groundwater. These open-loop geothermal storage systems take advantage of the high heat capacity of groundwater and its large volumes that are widely available (Fleuchaus et al., 2020b; Stauffer et al., 2014).

Typically, ATES systems are used for large-scale applications due to their high storage capacities. Exemplary use cases of ATES systems are the heating and cooling supply of office buildings, hospitals, airports or universities. ATES has also been deployed for supply of district heating networks (Fleuchaus et al., 2018; Schüppler et al., 2019). Suitable hydrogeological conditions are required for the application of ATES, including a highly permeable aquifer and low groundwater flow velocities, among others (Fleuchaus et al., 2018).

Climatic factors are also relevant for an efficient use of ATES. Particularly in regions with a moderate climate and distinct seasonal temperature differences ATES is well suited to mitigate the seasonal mismatch between the availability and the demand of heating and cooling energy to supply buildings (Bloemendal et al., 2018; Collignon et al., 2020; Fleuchaus et al., 2018; Schüppler et al., 2019; Todorov et al., 2020). Similar to ground source heat pump (GSHP) systems, it is therefore a promising technology for environmentally friendly energy generation that can reduce CO_2 emissions (Bayer et al., 2012; Blum et al., 2010).

ATES systems are based on the long-term creation of a warm and a cold storage volume in the subsurface. Depending on the heating or cooling demand, the groundwater can be extracted from the corresponding storage volume to supply the buildings with energy. Typically, in heating mode a heat pump is used whereas with cooling mode a so-called direct cooling loop without using the heat pump is often designed (Fleuchaus et al., 2018; Stauffer et al., 2014). The vast majority of ATES systems are classified as low-temperature-ATES (LT-ATES) with maximum injection temperatures of below 25 °C and are usually using shallow groundwater of the upper few tens to hundreds of meters (Bloemendal and Hartog, 2018; Kunkel et al., 2019; Schüppler et al., 2019).

More than 2800 ATES systems have been successfully implemented worldwide (Fleuchaus et al., 2018). Most of these systems are located in the Netherlands, which is characterized by suitable climate and underground conditions with a predominantly homogeneous subsurface with slow groundwater velocities. There are ongoing efforts to find similar conditions in other countries in favor of ATES (Anibas et al., 2016; Bayer et al., 2019; Gao et al., 2019; Todorov et al., 2020). However, to pave the way for an increasing spread of the technology, a main determinant is also its environmental performance such as the capability to reduce greenhouse gas (GHG) emissions.

Life Cycle Assessment (LCA) is a common and standard method to evaluate GHG emissions and other environmental impacts of technologies (Guinée et al., 2011; Lacirignola et al., 2014; Menberg et al., 2016b; Padey et al., 2013). Until now, comprehensive LCAs that evaluate the GHG performance of ATES systems are scarce. Tomasetta (2013) and Tomasetta et al. (2015) conducted an LCA of a Dutch ATES system consisting of two boreholes reaching to a depth of 80 m. However, in contrast to the common bimodal ATES application for heating and cooling, only the heating was investigated. Its heating capacity is stated as 250 kW with an annual full-load operation time of 2000 hours. A main finding is that the Dutch system has considerably lower environmental impacts than a conventional heating system, such as a natural gas boiler. Unfortunately, no specific numbers for possible reductions of GHG emissions are provided.

The LCA in the study by Moulopoulos (2014) also refers to a Dutch ATES system, again consisting of two wells that supply an office building complex with an approximate area of 6,000 m^2. It is used for combined heating and direct cooling operation and thus complies with the typical ATES utilization scenario. In heating mode, a heat pump is required that is supported by a natural gas boiler. The LCA is based on a data survey presented as a Life Cycle Inventory (LCI) and its results are divided into several life cycle phases. The author also states that the described ATES system can save up to 45 % of GHG emissions compared to a conventional heating and cooling system. Due to the LCA's inclusion of an elaborate waste water treatment, it can be assumed that these savings are lower than for a typical ATES system without incurring waste water.

Ni et al. (2020) carried out two LCAs for comparing an ATES system with a conventional heating and cooling system that are both situated at a hypothetical location in China. A special feature investigated in this study is the combination of both technologies with in-situ bioremediation using a biological medium containing dechlorinating bacteria that is added into the aquifer. As stated in Ni et al. (2020), the thermally altered subsurface in case of ATES should enhance the bioremediation effect. The result of the comparison of both LCAs is a considerably lower environmental impact for ATES and bioremediation. Over all impact categories, it is about 50 % less than for the conventional system and bioremediation. Regarding the GHG emissions, the ATES produced about 67 % less CO_2eq. A sensitivity analysis conducted for the ATES investigates various life cycle stages such as material acquisition, construction and operation. It revealed that the system operation is the most important stage. A detailed sensitivity analysis of individual system design parameters like ATES capacity or well depth was however not performed. Furthermore, the combination of ATES with in-situ bioremediation is a very uncommon application that is not representative of the typical and standard ATES use.

Thus far, the limited work available in this field is insufficient for assessing the environmental potential of ATES in a rigorous manner. Our study aims to generally assess the GHG emissions of ATES systems and possible GHG savings compared to conventional heating and cooling systems. We therefore refer to a real application that serves to carry out LCAs for many different hypothetical ATES systems defined by varying combinations of characteristic parameters. The execution of a detailed LCA study – especially the collection of reliable input and output data during the LCI – is a time-consuming process and it may not be possible to consider all the uncertainties, especially those of geological parameters. This study presents a way to carry out LCAs of ATES systems in a streamlined and time-saving way, concentrating on the systems' GHG emissions. An LCA regression model enables a quick execution of a large number of LCAs by including only a limited number of variable input parameters. This provides a fundamental knowledge base for a more comprehensive evaluation of the ATES technology in terms of environmental performance. The median value of a Monte Carlo (MC) simulation is considered as a typical ATES system which is used to determine possible GHG savings achievable by the technology when compared to conventional heating and cooling systems. Furthermore, the most influential parameters regarding GHG emissions are identified by using a global sensitivity analysis (GSA). This enables for a targeted optimization of existing and planned ATES. The underlying idea for the selected workflow originates from Padey et al. (2013) and Lacirignola et al. (2014), who presented LCAs for wind power and enhanced geothermal systems (EGS), respectively. In addition, results from previous studies on the economic performance of ATES systems are reviewed in order to evaluate the overall benefits of this technology in comparison to conventional energy systems.

2.2 Materials and methods

2.2.1 Study site

Although a substantial potential of ATES was shown for central Europe, only a small number of systems have been realized in Germany due to the technology's low level of awareness and legislative barriers (Bloemendal et al., 2016; Fleuchaus et al., 2018). Being one of the few German systems, an LT-ATES has been in operation at the "Bonner Bogen" area since 2009 supplying a hotel with a congress center, office buildings, a data center and a medical center (Figure 2.1). The system is one of Europe's largest heat pump systems with an authorized flow rate of up to 1,455,000 m^3/a. Here, six wells with a maximum depth of about 28 m are used for the heating and cooling supply of a usable area of around 60,000 m^2 (Table 2.1). In the cold season, a heat coverage of 60 % to 80 % is achieved using the water from the warm storage in combination with heat pumps. Two gas boilers are available to cover peak loads during very low outside air temperatures (Mands et al., 2010). In summer, the water circulation is reversed in order to extract the cold groundwater allowing for the area's direct cooling supported by refrigeration machines. The year-round cooling of the data center causes an increased cooling demand at the site resulting in an elevated heat input into the aquifer. Further constructional and operational details of the "Bonner Bogen" ATES are given in Table 2.1.

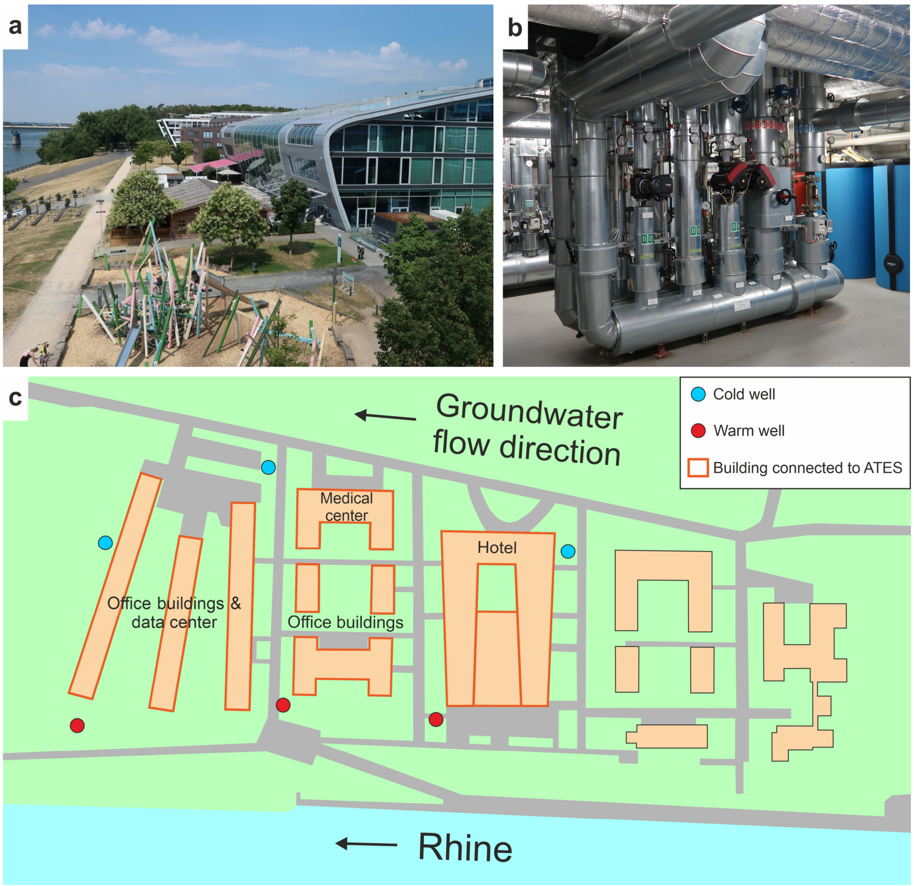


Figure 2.1: Impressions of the ATES site “Bonner Bogen”: Hotel building connected to the ATES (**a**) and technical center of the aquifer storage system (**b**). Figure (**c**) shows a site map of the “Bonner Bogen”.

Table 2.1: Main characteristics for the LCA of the ATES system at the “Bonner Bogen”.

	Parameter	**Value**	**Unit**	**Source**
Subsurface	Depth of boreholes	22 - 28	m	Mands et al. (2010)
	Number of boreholes	6	-	Mands et al. (2010)
	Energy demand of the submersible pumps[a]	167.6	MWh$_{el}$/a	EcoVisio GmbH
Surface	Installed capacity[b]	-	MW$_{th}$	
	Energy demand of the heat pump[a]	808.1	MWh$_{el}$/a	EcoVisio GmbH
Operation	Maximum production rate	300	m^3/h	EcoVisio GmbH
	Heat production[a]	2,164	MWh$_{th}$/a	EcoVisio GmbH
	Cold production with heat pump[a]	3,188	MWh$_{th}$/a	EcoVisio GmbH
	Direct cold production[a]	812	MWh$_{th}$/a	EcoVisio GmbH

[a] The given values refer to the year 2016.
[b] No information available. Instead, the base case LCA of the ATES system at the “Bonner Bogen” was conducted using the provided numbers for heating and cooling.

2.2.2 Life cycle assessment

Life cycle assessment (LCA) is a standardized methodology to determine the environmental impacts of products, processes or technical systems (ISO norms DIN EN ISO 14040 and DIN EN ISO 14044). An LCA study is based on the establishment of an LCI including all inputs (materials, processes, etc.) and outputs (e.g. energy as heat and cold) that are required or produced during the considered life cycle from a ‘cradle to grave’ perspective. Within an LCA, environmental impacts are allocated from the LCI data to impact categories by means of an impact assessment.

The main focus regarding the LCA in the present work is on the system’s GHG emissions in relation to the amount of heating and cooling energy provided by the system. Hence, the functional unit of the LCA is ‘gCO_2eq/kWh_{th}’. Establishing this functional unit allows a comparison between ATES and other heating and cooling technologies. The ATES system boundaries regarded in the LCA reach from the groundwater conditions over the subsurface construction to the heat pump. The buildings’ energy distribution system connected to the aquifer storage is not included as it is a basic requirement regardless of the energy system.

2.2.2.1 Life cycle inventory

The base case LCA model used as a foundation for the developed LCA regression model examines the environmental impacts of the ATES system at the “Bonner Bogen”. The LCI of the base case LCA model is subdivided into five related life-cycle stages: (1) well construction, (2) surface construction, (3) subsurface construction, (4) operation and (5) decommissioning. The life-cycle stage ‘well construction’ consists of the construction materials and processes for well drilling, well piping and well development as well as construction of the well chamber.

A complete compilation of the LCI is presented in detail in the Supplementary data (Section S2.1). The input and output components are collected from the ecoinvent 3.5 database (Steubing et al., 2016; Wernet et al., 2016). For each component, the listed amount is related to one well. Due to the uniform depth of all six wells at the site, the total amounts can be calculated by multiplication. The amount of each material or process is derived or calculated from manufacturing specifications and considering the constructional details such as borehole depth or size of the well chamber. Underlying information was provided by the two companies EcoVisio GmbH and Knauber Contracting GmbH, which are responsible for planning, realization and operation. Regarding the LCI entries, several assumptions and estimations had to be made where no constructional and operational details were available. These are based on literature information (Frick et al., 2010) or comparable projects (e.g. Aquadrom Hockenheim, Germany) (Supplementary data, Section S2.2).

The uncertainties specified in the Supplementary data (Section S2.1) are mainly caused by the absence of precise specifications regarding some constructional or operational details. Furthermore, in some cases there are no items in the LCI database that are able to exactly represent the situation on site. In these cases, the most appropriate database product or process was chosen.

2.2.2.2 Life cycle impact assessment

Within an LCA, the allocation of quantified environmental impacts to each LCI item is done during the life cycle impact assessment (LCIA) phase. Here, characterization factors are applied to all input and output data collected in the LCI. The characterization results are then aggregated to various impact categories according to the used impact allocation method providing the characterization factors (Menberg et al., 2016b).

The impact allocation method used in this study is IMPACT 2002+ V2.10 (Jolliet et al., 2003). The main focus of the present work is on the systems' GHG emissions represented by the impact category 'climate change' (functional unit: gCO_2eq/kWh_{th}). However, the base case "Bonner Bogen" LCA model was also evaluated for the additional impact categories 'human health' ($DALY/kWh_{th}$) covering human toxicity and respiratory effects and 'ecosystem quality' ($PDF \times m^2 \times yr/kWh_{th}$) referring to aquatic acidification and aquatic eutrophication. Furthermore, it was evaluated for the category 'resources' (kJ primary/kWh_{th}) such as non-renewable energy consumption (Jolliet et al., 2003). Similar to the compilation of the LCI, the impact assessment was carried out with the LCA software SimaPro (Version 9.0.0.35) using the above-mentioned allocation method.

2.2.2.3 Interpretation

The interpretation phase of an LCA aims for delivering results relevant to the defined goal and scope of the study. This is done by a combined consideration of the inventory analysis and the impact assessment. Thus, the interpretation phase serves the purpose to provide understandable and consistent conclusions able to explain limitations and to derive recommendations.

2.2.3 Creation of the LCA regression model

The workflow for generating the LCA regression model can be divided into the following steps (Figure 2.2):

Step 1: Creating the base case LCA model at the "Bonner Bogen" including selected input parameters that define the system configuration.

Step 2: Parametric LCAs of 70 hypothetical ATES configurations using the LCA model.

Step 3: Design of the LCA regression model and generation of an ATES GHG distribution profile using Monte Carlo (MC) simulations.

Step 4: Identification of important key parameters by means of a global sensitivity analysis (GSA).

The workflow presented in this study is adapted from the studies by Padey et al. (2013) and Lacirignola et al. (2014).

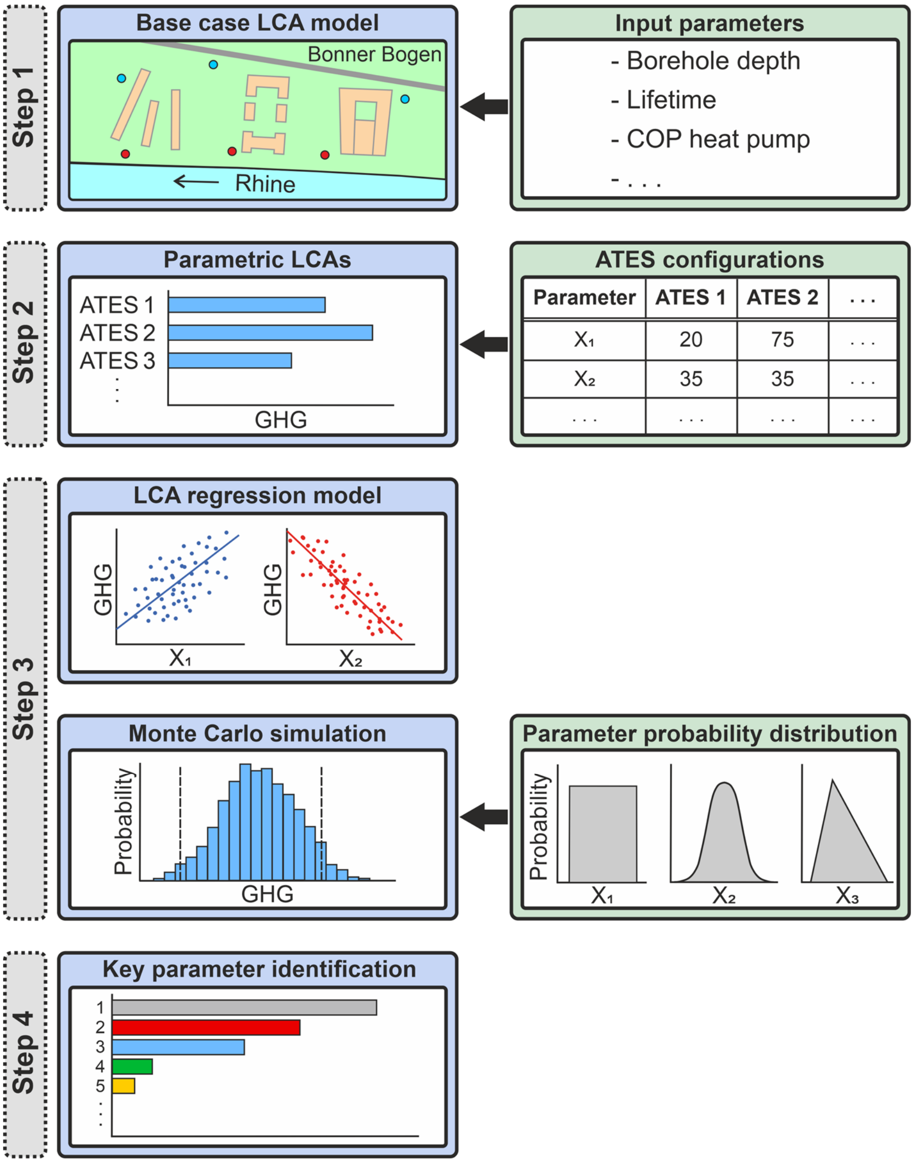


Figure 2.2: Workflow for creating the LCA regression model for ATES systems.

2.2.3.1 Base case LCA model

While the base case LCA model of the ATES at the "Bonner Bogen" is site-specific for this system's configuration, the independent variation of ten included system-characterizing parameters allows the model's application to a wide range of different ATES configurations. Accordingly, the included parameters function as scaling factors to adjust the amount of LCI items (e.g. amount of filter gravel, length of electrical cables, fuel needed for drilling) that were initially specified for the study site (see also Supplementary data, Section S2.1). The selected parameters represent characteristics generally required to describe the dimension, construction and operation of an ATES system. The parameter *COP heat pump* does not only represent the operation conditions of the building heating system that is connected to an aquifer storage but serves as an indicator for the overall performance of the ATES systems' subsurface components including effects of underground heat loss.

Table 2.2 provides an overview of the ten included parameters and the respective ranges within which they can be varied. Based on information from literature, a probability distribution for each parameter is specified for use in Monte Carlo (MC) simulations. Also, mathematic independence of the model parameters is a necessary condition that allows for the correct application of the global sensitivity analysis which has to be conducted to identify the key parameters in the last of the above listed steps.

Table 2.2: Input parameters included in the LCA model.

Parameter	**Symbol**	**Unit**	**Characteristic value**	**Probability distribution**	**Main references**
Depth of boreholes	*d*	m	185	Uniform (20, 350)	Fleuchaus et al. (2018)
Flow rate (whole system)	*fr*	m^3/h	365	Uniform (10, 720)	Fleuchaus et al. (2018)
Number of wells	*Nw*	-	2	Half-normal (2, 64)	Fleuchaus et al. (2018)
Fuel for drilling	*fd*	t/m	0.12	Uniform (0.07, 0.16)	Lacirignola et al. (2014)
Operating time heating (full load equivalent)	*Th*	h/a	2500	Uniform (1500, 3500)	Härdtlein et al. (2018), Stauffer et al. (2014)
Operating time cooling (full load equivalent)	*Tc*	h/a	1600	Normal (1600, 4×10^6)	Eicker (2006)
Lifetime	*L*	a	35	Normal (35, 25)	Bloemendal et al. (2014), Sommer (2015)
Specific power of well pumps (per pump)	*Pp*	kW/(l/s)	0.6	Uniform (0.3, 0.9)	Beck et al. (2018), Haque et al. (2017)
COP heat pump	*COP*	-	3.5	Triangular (3, 3.5, 7)	Barrios (2015), Saner et al. (2010)
ATES capacity	*Cap*	kW	2000	Uniform (200, 2×10^4)	Fleuchaus et al. (2018)

2.2.3.2 Parametric LCAs

In order to create the LCA regression model, the parameterized LCA model is used to evaluate the environmental impacts of 70 dissimilar ATES configurations. Each hypothetical ATES system corresponds to a different combination of the ten parameters listed in Table 2.2. The generation of the 70 parameter sets is done following a one-at-a-time (OAT) approach, thus only one parameter is changed at a time, while all other parameters are kept at their characteristic values (arithmetic mean, expected value or mode). Each of the ten parameters is varied in seven equidistant steps within its respective range leading to a total number of 70 different parameter sets and associated LCA results.

2.2.3.3 LCA regression model

Using the 70 LCA results obtained with the parameterized LCA model, a multiple linear regression analysis is conducted in order to create the LCA regression model. It aims to quantitatively describe the LCA results in the form of GHG emissions as a function of the ten system-specific parameters from Table 2.2. The regression model follows a simple linear form:

$$GHG_{ATES}\left[\mathrm{gCO_{2eq}/kWh_{th}}\right] = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i \qquad \text{with } n = 10 \tag{2.1}$$

Here, α_0 represents the regression constant and α_i the regression coefficients obtained from the regression analysis. X_i marks the ten included parameters (Table 2.2). The regression analysis is conducted using the statistics software SPSS. More detailed information about the principles of multiple linear regression analysis can be found in Montgomery et al. (2012).

Due to its simple form, the regression model can be used in a straightforward way in MC simulations to obtain the GHG emissions of 10,000 different ATES configurations. Again, each configuration consists of a unique combination of values of the ten input parameters that are randomly generated according to the respective probability distribution from Table 2.2. In this way, the GHG emissions from a large variety of possible ATES systems can be evaluated making up for the lack of explicit LCA studies in literature. This panel of GHG emission results obtained with the MC simulation is also compared to specific LCA results published in the literature to verify the robustness of the LCA regression model.

In addition, a second regression model is created to evaluate the impact of a different electricity mix on the overall GHG performance of ATES systems over their lifetime. This second model is also derived from the base case LCA model with a modified LCI considering the projected German electricity mix for the year 2050 with a significantly higher share of renewable energies (Table 2.3).

Table 2.3: Estimated shares of different types of energy of the utilized current German electricity mix (ecoinvent 3.5) and the projected German electricity mix in 2050.

Type of energy	**Share of the current electricity mix[a] (%)**	**Share of the 2050 electricity mix (%)** (Hecking et al., 2018; Matthes et al., 2017)
Lignite	26	0
Hard coal	20	0
Nuclear	17	0
Wind power – onshore	10	42
Natural gas	7	4
Imports	7	10
Biogas	6	0
Hydropower	5	3
Biomass	1	4
Wind power – offshore	0.3	19
Photovoltaics	0	18

[a] The German electricity mix provided in ecoinvent 3.5 refers to the year 2014. A more recent mix is not available in the LCI database.

2.2.3.4 Global sensitivity analysis

The ten input parameters included in the LCA regression model (Equation (2.1)) do not contribute equally to the variance of the model output, i.e. the GHG performance. Hence, a global sensitivity analysis (GSA) is performed to identify the key parameters that contribute the most to the model's output variance. In this study, the GSA is carried out using the Sobol method over a large sample of different ATES configurations. This method enables the calculation of estimated values for Sobol indices of first, higher and total order (Padey et al., 2013; Saltelli et al., 2008). Here, the mathematical independence of the ten input parameters allows a complete variance decomposition and leads to a formulation of the total variance as a sum of the variance contributions of each individual parameter as well as their respective interactions with each other (Saltelli et al., 2008).

These parameter interactions are represented by the higher and total order Sobol indices. Due to the design of the regression model as a linear and additive model, no higher order parameter interactions are to be expected (Menberg et al., 2016a). Thus, only the first order Sobol indices are calculated (see also Supplementary data, Section S2.3).

2.3 Results and discussion

2.3.1 Environmental impacts

The results of the LCA model for the base case ATES system at the “Bonner Bogen” are shown in Figure 2.3. The LCA model was evaluated for the four impact categories ‘human health’, ‘ecosystem quality’, ‘climate change’ and ‘resources’. For each impact category, Figure 2.3 also illustrates the share of the individual life cycle phases using the current German electricity mix (Figure 2.3a) and the projected German electricity mix for the year 2050 (Figure 2.3b). When using the current electricity mix, it is apparent that the operation of the ATES system is the dominating life cycle phase regarding the first three impact categories ‘human health’, ‘ecosystem quality’ and ‘climate change’. The impact on ‘climate change’ which represents the GHG emissions is almost solely caused by the operation phase. A more detailed evaluation of the LCA results also reveals that within the operation phase, the electricity supply for running the ATES is the most influential factor (not shown in Figure 2.3). Regarding the ‘resources’ category, it can be seen that the subsurface construction phase has the largest share in the overall impact of the study site. This is mainly due to the material demand in form of high-density polyethylene water pipes that were embedded into the ground.

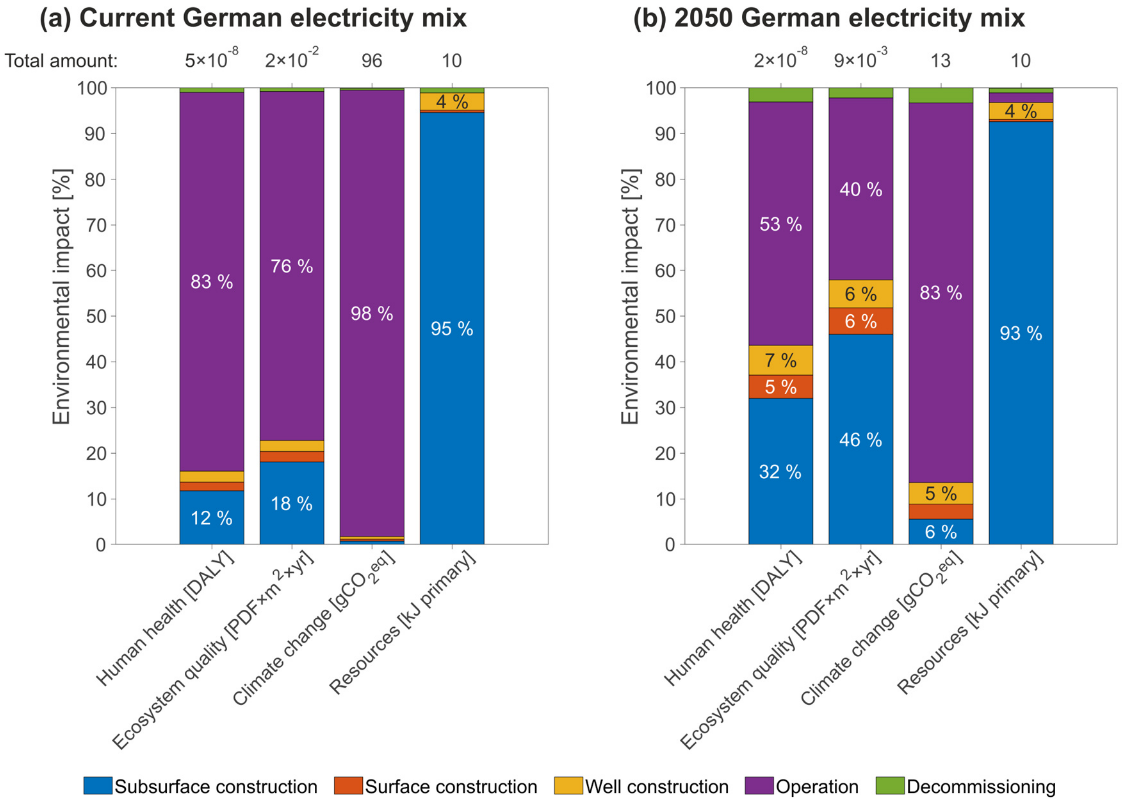


Figure 2.3: LCA results per kWh$_{th}$ of the base case scenario at the “Bonner Bogen” using the current German electricity mix (**a**) and a projected German electricity mix for the year 2050 (**b**).

If the projected 2050 electricity mix is considered, the share of the operating phase in the categories ‘human health’, ‘ecosystem quality’ and ‘climate change’ decreases while particularly the share of the subsurface construction phase increases. Regarding the ‘resources’ category, there are only minor changes, and the subsurface construction phase still accounts for the largest share of this impact.

Previous ATES studies found in the literature often present overall lifetime environmental impacts without a detailed comparison. Tomasetta (2013) and Tomasetta et al. (2015) focus on the relative environmental benefits of the considered ATES system compared to a conventional heating system (i.e. a natural gas boiler). Moulopoulos (2014) also states that the operation phase is dominant in most impact categories including climate change, even though this LCA includes a waste water treatment within the end-of-life phase that is also influential regarding GHG emissions.

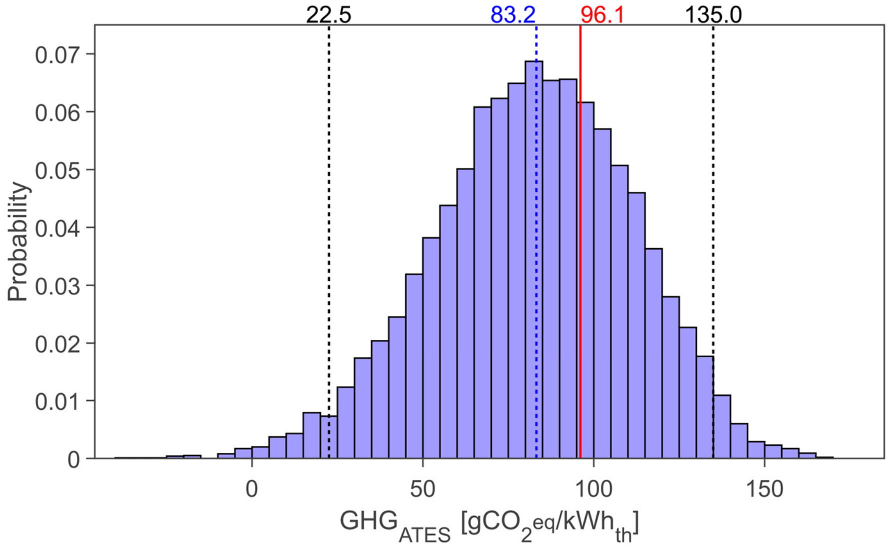
The most recent study performed by Ni et al. (2020) is an LCA of a combination of ATES and in-situ bioremediation. The results are presented with regard to a similar life cycle, yet refer to a different impact assessment method. Similar to the present study and the aforementioned studies, the authors demonstrated that the operation phase is by far the most impactful phase regarding climate change (here termed as global warming potential). The second most impactful life cycle phase across all impact categories in Ni et al. (2020) is the material acquisition phase. It should be noted, however, that most of this impact is due to the production of the biological medium necessary for the in-situ bioremediation and is therefore not directly comparable to a standard ATES system without any bioremediation. A quantitative comparison with the results from previous studies is shown subsequently after the formulation of the regression model.

2.3.2 LCA regression models

Based on the design of the regression model for GHG emissions of the ATES systems in Equation (2.1), the fully formulated LCA regression models referring to the current and the 2050 German electricity mix are obtained by means of a multiple linear regression analysis. The models are presented in the Supplementary data (Section S2.4).

Figure 2.4 illustrates the LCA results of the MC simulation from the regression models using 10,000 randomly generated ATES configurations. The blue dashed lines mark the median values of the distribution at 83.2 gCO_2eq/kWh_{th} when using the current German electricity mix (Figure 2.4a) and at 10.5 gCO_2eq/kWh_{th} for the projected 2050 electricity mix (Figure 2.4b).

(a) Current German electricity mix



(b) 2050 German electricity mix

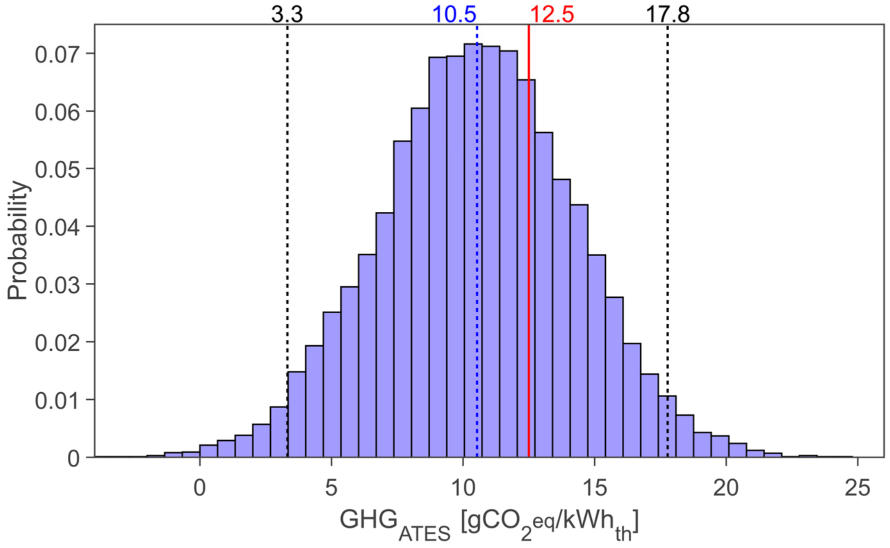


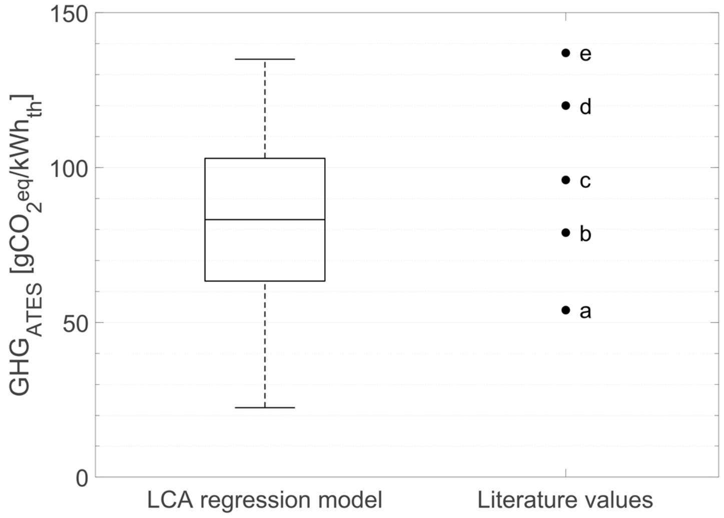
Figure 2.4: Histogram of the results of the MC simulation using the LCA regression model based on the current German electricity mix (**a**) and on the projected 2050 German electricity mix (**b**). The blue dashed lines mark the median of each distribution. The red lines show the LCA results of the respective base case scenario at the study site “Bonner Bogen”. Quantiles 2.5 % and 97.5 % are represented by black dashed lines.

The random generation of each of the 10,000 different parameter sets, i.e. ATES configurations, can sporadically lead to parameter combinations that are unlikely to correspond to a viable ATES system in terms of technical and economic feasibility. One example would be a parameter combination with both a very low ATES capacity and very high flow rate. The negative LCA results shown in Figure 2.4 can be explained by these unlikely parameter combinations and the formulation of the regression model as a linear combination including both positive and negative coefficients. However, with far less than 1 % of the total number of individual model runs during the MC simulation, the impact of the negative results on the overall MC result can be neglected. The LCA results of the unlikely parameter sets as well as the negative results are dealt with by disregarding statistical outliers below quantile 2.5 % and above quantile 97.5 % for the further analysis (Figure 2.4). The unlikely parameter combinations described above could be suppressed by including mathematical relationships between the parameters, such as dependencies or mutual constraints. A suitable tool for this could be the use of copula functions in the regression models. However, there is currently not enough data on existing systems to exactly formulate such relationships between the parameters.

The red lines in Figure 2.4 present the results of the base case LCA model regarding the GHG performance at the study site. At 96.1 gCO_2eq/kWh_{th} when considering the current electricity mix, the base case GHG emissions are higher than for a typical ATES system represented by the median value of the MC distribution. This can possibly be explained by the fact that the heat pump at the “Bonner Bogen” ATES system is used for both heating and cooling while the LCA regression model is based on direct cooling without the need of a heat pump. Furthermore, the system’s heat pump operation partially shows low COP values of below 2.5 (Knauber Contracting GmbH, personal communication, May 11, 2018).

Figure 2.5 shows a boxplot of the GHG emission results obtained with the MC simulation using the LCA regression model. The upper and lower whiskers indicate the quantiles 97.5 % and 2.5 %, respectively. Next to the box plot, the figure shows the GHG emissions of specific ATES systems reported in the literature. The comparison reveals that the GHG emission range marked by the whiskers matches the emission values from the literature. This observation verifies the robustness of the regression model and the suitability of the utilized parameters to give reliable estimations for GHG emissions of ATES systems. Thus, the regression model can serve as a simple and fast to use but still robust LCA tool for decision makers.

The ability of the regression models to be easily implemented within a Monte Carlo simulation framework results from their simple linear form (Equation (2.1)). The combination of Monte Carlo simulation and regression models offers a time-saving way to gain an overview of GHG emission results from 10,000 different ATES configurations. Obtaining the same number of results using conventional LCA frameworks would be rather time-consuming, particularly the collection of adequate input and output data for creating the LCIs is labor-intensive. Instead, the purpose-built parameterized LCA on which the LCA regression models are based uses variable parameters to adjust the amount of individual LCI items, allowing easy adaptation to other ATES configurations. In addition, the regression models speed up and simplify the applicability for a large number of configurations by alleviating the computational costs of the life-cycle impact assessment. This is shown by the difference in computation time when using the parameterized LCA model in SimaPro and the LCA regression model. The computation time of the parameterized LCA model is about 34 minutes, while the regression model takes less than a second to complete the generation of 10,000 different ATES configurations and the calculation of their respective GHG emissions. Both computational times refer to the same workstation with 8 CPU cores with a base clock of 3.6 GHz and 128 GB of RAM. It should be noted, however, that the parameterized LCA model in SimaPro calculates other types of environmental impacts in addition to GHG emissions.



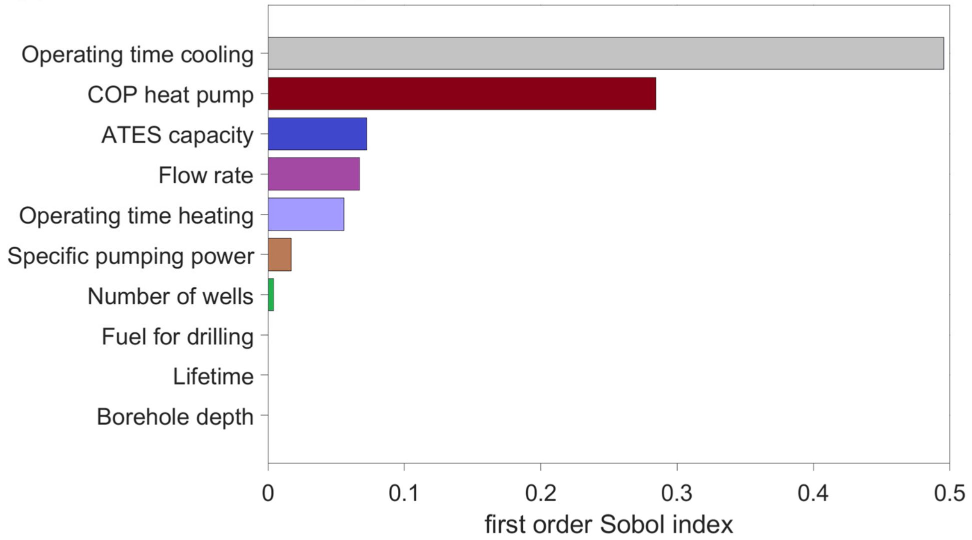
	Reference	GHG_{ATES} [gCO_{2eq}/kWh_{th}]
a	Schüppler et al. (2019)	54 (mean)
b	Vanhoudt et al. (2011)	79
c	Base case “Bonner Bogen” [this study]	96
d	Tomasetta (2013)	120
e	Moulopoulos (2014)	137

Figure 2.5: Comparison of the GHG emission results of the MC simulation using the LCA regression model and GHG emissions of ATES systems described in the literature.

2.3.3 Sensitivity analysis

Figure 2.6a shows the first order Sobol indices of the ten parameters included in the LCA regression model (Equation (2.1)) considering the current German electricity mix determined by GSA. The two parameters with the highest Sobol indices are *operating time cooling* and *COP heat pump*. It is important to emphasize that a Sobol index of around 0.5 does not mean that the respective parameter is mainly responsible for the emission of greenhouse gases, but it has the greatest influence on the variance of GHG emissions per kilowatt hour of thermal energy that is provided by the ATES system. The parameters *ATES capacity*, *flow rate (whole system)* and *operating time heating* also contribute a relevant proportion to the output variance. Together, these five key parameters are responsible for more than 95 % of the variance of the GHG results. Thus, when using the regression model for the LCA of a specific ATES system, it is particularly important to use accurate values for these five key parameters in order to obtain reliable results. The findings of the GSA also show which parameters in particular should be optimized when planning new systems.

(a) Current German electricity mix



(b) 2050 German electricity mix

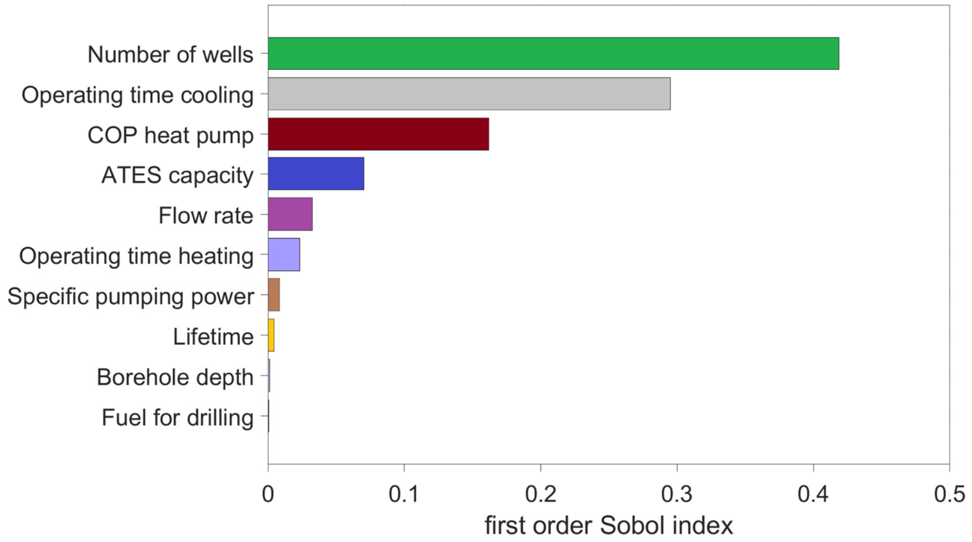


Figure 2.6: First order Sobol indices of the ten model input parameters from the LCA regression models using the current German electricity mix (**a**) and the projected 2050 electricity mix (**b**). The top five parameters cause more than 95 % of the model output variance.

It is noticeable that the five most influential parameters in Figure 2.6a are related to the operation phase of an ATES system. The high Sobol index of the parameter *operating time cooling* is related to its very wide value range (Table 2.2). An increase in this parameter causes the specific

GHG emissions per kilowatt hour of thermal energy to decrease. This is due to the direct cooling without the use of a heat pump as assumed in the present study. The findings therefore confirm that ATES cooling should be done directly whenever possible. The importance of an appropriate design for the heat pump while planning an ATES system is demonstrated by the high influence of the parameter *COP heat pump*. The decreasing demand of electrical power when increasing the heat pump's COP causes lower specific GHG emissions. The LCA regression model confirms this effect. In contrast, the parameters *flow rate* and *operating time heating* have a detrimental effect on the GHG emissions when increased. Regarding the *flow rate*, this can be explained by the additional electrical power needed for a higher volume of produced groundwater. One possibility to reduce the required flow rate is to increase the difference between production and injection temperatures in order to obtain a higher amount of thermal energy per flow rate.

While a higher operating time in the heating mode increases the amount of thermal energy provided by the ATES system, this also leads to a higher amount of electrical energy needed for operating the heat pump. Both effects considered, according to the LCA regression model an increase in the parameter *operating time heating* causes higher specific GHG emissions.

The GSA results of the LCA regression model incorporating the 2050 electricity mix are illustrated in Figure 2.6b. The parameter with the highest Sobol index is now *number of wells*. The Sobol indices of the five previously identified most influential parameters in Figure 2.6a are accordingly lower. This reflects the decreased importance of the electrical power necessary for ATES operation due to the much lower specific GHG emissions of the projected 2050 electricity mix.

The LCA regression models could now be further simplified by including only the key parameters with high Sobol indices. However, this step is beyond the scope of this study. Due to the very high percentage of variance explainable by the upper five parameters in Figure 2.6, only minor deviations in the GHG emissions would be expected from such simplified models.

2.3.4 Greenhouse gas savings

Figure 2.7 compares the GHG emissions of different types of ATES and conventional heating systems in order to determine possible GHG savings. The value shown for ATES systems determined in this study corresponds to a typical ATES system, i.e. the median of the MC distribution when using the current German electricity mix (blue dashed line in Figure 2.4a). It should be noted that the functional unit of the LCA regression model refers to the combined heating and cooling output of ATES systems, and therefore it does not allow separate assessments of the heating and the cooling phases. Thus, the value of 83.2 gCO_2eq/kWh_{th} for the typical ATES system comes from a bimodal system employed for heating and for cooling.

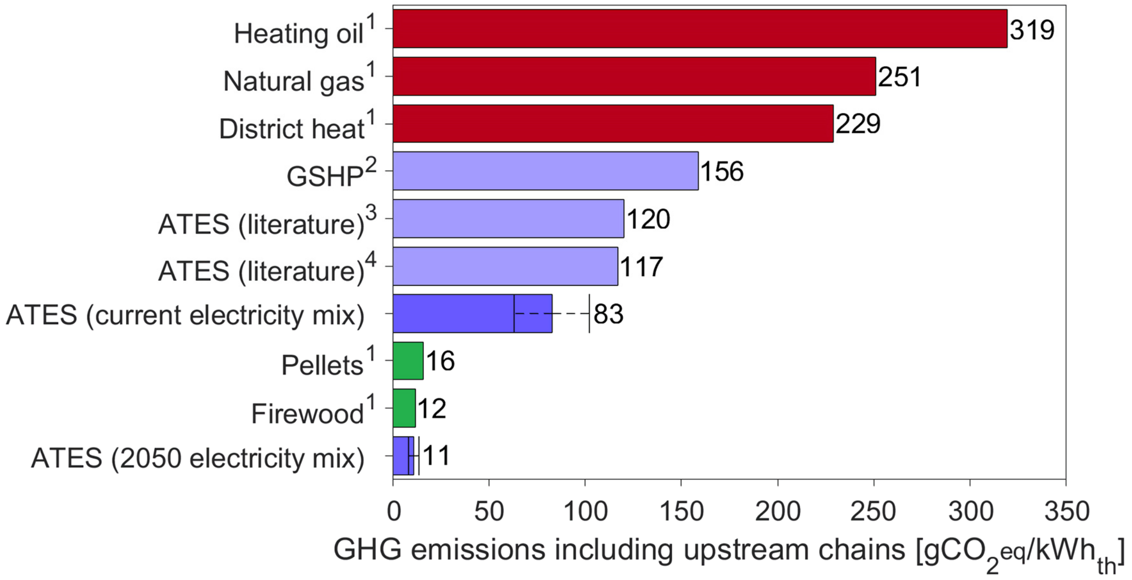


Figure 2.7: Specific GHG emissions of different types of heating systems. The two results for ATES determined in this study correspond to the median value of the respective MC results distribution and their interquartile range. [1] Bettgenhäuser and Boermans (2011); [2] Bonamente and Aquino (2017); [3] Tomasetta (2013); [4] Moulopoulos (2014).

The two types of heating energy that cause the highest GHG emissions are also the ones with the highest shares of the German heating energy mix. Heating oil and natural gas provide around 70 % of the heating energy in the German building sector (Fraunhofer IWES/IBP, 2017). According to the values in Figure 2.7, a typical ATES system can save around 74 % of GHG emissions compared to heating oil, and 67 % with respect to natural gas. Thus, the use of ATES systems can significantly reduce the GHG emissions in the building sector. The values agree well with the study by Fleuchaus et al. (2018), in which the possible savings of ATES systems compared to conventional technologies are between 40 % and 70 %. The investigations of the ATES of a Belgian hospital by Vanhoudt et al. (2011) showed an annual reduction in CO_2 emissions of up to 77 % compared to the reference technology comprising of a gas-powered boiler and a compression refrigeration machine.

When comparing the environmental performance of a typical ATES system with wood pellets and firewood, it is important to note that those values also account for the uptake of CO_2 into the biomass. Hence, burning pellets and firewood only releases CO_2 that was previously bound during the plants‘ growth leading to extremely low GHG emissions which are solely caused by upstream processes such as transportation and necessary processing steps (Bettgenhäuser and Boermans, 2011).

Figure 2.7 also shows the LCA results regarding GHG emissions of two specific ATES systems discussed in the literature (Moulopoulos, 2014; Tomasetta, 2013). It is important to note that the environmental impact of the auxiliary gas boiler and the waste water treatment originally included as separate LCA stages in Moulopoulos (2014) were disregarded here in order to allow for an appropriate comparison with the other ATES LCAs in Figure 2.7. The values of both Moulopoulos (2014) and Tomasetta (2013) are higher than the GHG emissions of a typical ATES system as determined in this study, even exceeding the upper limit of the interquartile range of this study's LCA results. Possible explanations for the higher GHG emissions compared to this study's result are different LCI databases and impact assessment methods. Furthermore, non-ideal operation of the two systems elaborated in the corresponding studies could also cause higher GHG emissions. This is particularly true for the ATES system described by Tomasetta (2013), which is only used for heating and thus deviates from the combined operating principle assumed in this study. This deviation illustrates the problematic lack of a precise and universal definition of ATES. In fact, one can argue that the system evaluated by Tomasetta (2013) is not even an ATES but merely a groundwater heat pump (GWHP) system.

When using the projected 2050 German electricity mix to operate the ATES systems, the median of the MC distribution (blue dashed line in Figure 2.4b) is around 11 gCO_2eq/kWh_{th}. This is the lowest value shown in Figure 2.7, further demonstrating the outstanding significance of the chosen electricity mix regarding the systems' GHG performance.

Bonamente and Aquino (2017) conducted an LCA of a GSHP system used for heating and cooling. The obtained results show considerably higher GHG emissions compared to the typical ATES system from the present study. It should be noted that the authors provide no information about the electricity mix used to operate the GSHP system. A mix largely consisting of fossil fuels, however, is strongly implied. Similar to this study they showed the importance of utilizing electricity resulting from carbon-neutral fuels.

Another evaluation of possible GHG emission savings by GSHP systems was performed by Blum et al. (2010) (not shown in Figure 2.7) for the southwestern part of Germany. When using the German electricity mix at the time of the study, the resulting GHG emissions of a typical GSHP system are 149 gCO_2eq/kWh_{th}. The utilization of a regional mix largely consisting of nuclear and renewable energies reduces the emissions to 65 gCO_2eq/kWh_{th}. It should be pointed out however, that the authors did not consider any upstream chain processes or materials and the emissions solely result from the operation of the GSHP systems.

Figure 2.7 and the above stated results refer to possible GHG savings when comparing ATES with other types of heating systems. In the case of cooling, the variety of different systems is much smaller, as most of the space cooling demand is currently provided by electricity-driven vapor compression systems (Braungardt et al., 2018). Hence, to be able to estimate possible GHG savings in cooling mode, the median value for ATES systems of 83.2 gCO_2eq/kWh_{th} must be compared with the utilized electricity mix and the COP of the cooling system needs to be considered. The most recent numbers from 2019 for the German electricity mix state an emission factor of 401 gCO_2/kWh_{el} (Umweltbundesamt, 2020). Assuming typical COP values for vapor compression systems ranging between 2 and 4, the possible GHG savings are between 59 % and 17 %.

The German climate protection policy targets carbon neutrality by 2045 (Bundesregierung, 2021). One pillar of the German energy transition is an increased share of renewable energies in the heating energy mix, which at present is dominated by natural gas and heating oil. Currently, about 70 % of the energy for space heating in Germany is provided by these two energy sources (Fraunhofer IWES/IBP, 2017). The average energy demand of a German household for space heating and hot water is about 15,600 kWh per year (Statistisches Bundesamt, 2020). Assuming that heating oil and natural gas were to be completely replaced by thermal energy supplied by ATES, the average absolute GHG emission savings would amount to about 2100 $kgCO_2eq$ per household and year. This amount is equal to a distance of 22,100 km travelled by car, assuming the average fleet emission target value of 95 gCO_2/km that was set by the European Union from 2020 onwards. The high emission savings shown here could be used as an incentive to include ATES in climate protection policies, next to other types of renewable energy supply. An example of a successful energy market penetration of ATES are the Netherlands where market incentive programs and low legislative barriers lead to a high attractiveness of ATES (Fleuchaus et al., 2018).

2.3.5 Economic comparison

Here, a brief overview of existing economic analyses of ATES is provided, focusing on comprehensively described ATES systems for which information about capital and operational costs are available. This allows the calculation of payback times when comparing ATES to a reference heating and cooling technology. Figure 2.8 shows these costs for ATES systems and reference technologies that are described in the literature (see also Supplementary data, Section S2.5).

Vanhoudt et al. (2011) studied an existing ATES system used for the heating and cooling of a Belgian hospital and performed a cost comparison with a conventional reference system consisting of a compression chiller and a gas-fired boiler. Compared to the reference system, the operational costs of the ATES system are 85 % and 55 % lower in cooling and in heating mode, respectively. The operational costs are expressed as specific energy costs in €-ct per kWh_{th} of heating or cooling energy that is provided by the considered system. Taking into account the capital costs of the ATES system and the lower operational costs compared to the reference system, a payback time of 8.4 years was determined (Vanhoudt et al., 2011).

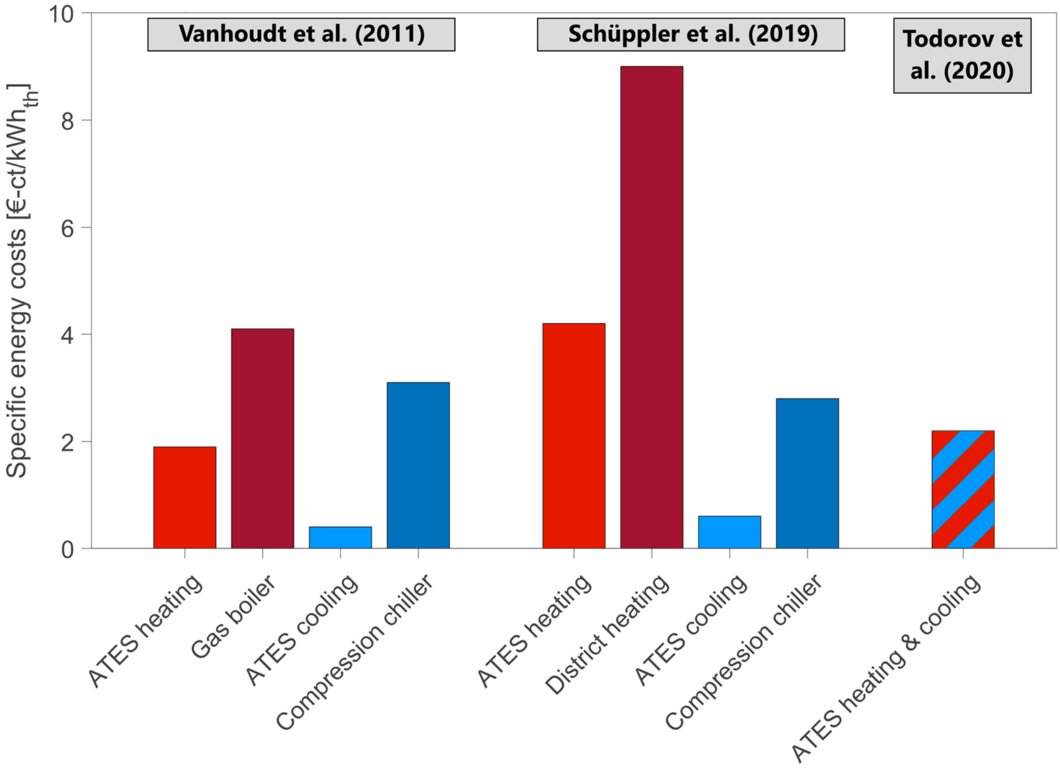


Figure 2.8: Specific energy costs of several ATES systems described in the literature compared to the costs of typical conventional heating and cooling systems.

Schüppler et al. (2019) described an ATES system that was considered to supply a hospital in Germany with heating and cooling energy. Like in the system studied by Vanhoudt et al. (2011), the cooling is done directly, while the heat supply is supported by a heat pump. The average specific energy costs were calculated as 4.2 €-ct/kWh$_{th}$ in heating mode and 0.6 €-ct/kWh$_{th}$ for cooling. Thus, they are again significantly lower than the operational costs of the reference system consisting of district heating and cooling using compression chillers (Figure 2.8). The calculated average payback time of 2.7 years is significantly lower than for the ATES system described by Vanhoudt et al. (2011). This can be explained by the low heating costs of the gas boiler which was considered as a reference system for the Belgian hospital as well as the relatively high capital costs of the Belgian ATES system. It should also be noted that the payback time in Schüppler et al. (2019) does not only result from lower specific energy costs, but also considers the maintenance and replacement costs. The payback time of 2.7 years is in good agreement with the ATES system described by Ghaebi et al. (2017), whose payback time related to the reference technology (compression chiller and gas boiler) is about 2.9 years.

The combined specific energy costs for heating and cooling using an ATES system described in Todorov et al. (2020) are 2.2 €-ct/kWh$_{th}$, corresponding well to the costs of the other ATES systems in Figure 2.8.

The energy cost savings and resulting short payback times of reported ATES systems clearly demonstrate that ATES systems not only help to reduce greenhouse gas emissions but are also an economically viable alternative to conventional heating and cooling technologies. This is further supported by other ATES systems reported in the literature and compiled by Schüppler et al. (2019). The average payback time of the systems used for both heating and cooling is about 6 years. Fleuchaus et al. (2018) state that typical payback times of ATES systems reported in the literature range from 2 to 10 years when compared to conventional technologies such as gas or oil boilers and compression chillers.

2.4 Conclusions

Using a base case LCA of the ATES system at the “Bonner Bogen”, an LCA regression model is created including ten relevant system parameters. Due to the parametric structure of the model, it can be applied for the LCA of a wide range of different ATES configurations. Hence, the model is a fast alternative to conventional time-consuming and labor-intensive LCAs. The combination of a Monte Carlo simulation with the LCA regression model enables for the analysis of environmental impacts of a large variety of hypothetical ATES systems and therefore the evaluation of the technology as a whole. Based on our simulations, the median GHG emission of an ATES system is 83 gCO_2eq/kWh_{th}. Compared to conventional heating systems using heating oil and natural gas, 74 % and 67 % of GHG savings can be achieved, respectively. In comparison to cooling techniques using the current German electricity mix, an ATES system can save up to 59 % of GHG emissions. These savings clearly demonstrate that the ATES technology can make an important contribution to more climate-friendly heating and cooling supply in the future. It is also revealed that these GHG savings will significantly increase with the expected growing share of renewable energies in the electricity mix. Thus, in the future, GHG savings of up to 97 % are achievable when compared to conventional oil heating.

Besides GHG emissions, future research should also be directed towards other environmental impacts. Especially in case of an unbalanced system operation with an elevated heat input into the ground, detrimental effects on the groundwater ecosystem are to be expected that are difficult to investigate with available LCA frameworks.

A brief overview of relevant studies shows that ATES can also offer economic advantages compared to conventional heating and cooling systems. The reported payback times of various ATES systems are significantly lower, ranging between 2 and 10 years. A combined utilization of LCA and a life cycle cost analysis could further quantify CO_2 abatement costs and reveal possible economic advantages of ATES in comparison to other technologies in a more comprehensive way.

Acknowledgements

The authors would like to thank Steffen Große (EcoVisio GmbH) and Konrad Maul (Knauber Contracting GmbH) for providing constructional and operational details of the "Bonner Bogen" ATES system.

This work was supported within the project "Geoenergy" by the Helmholtz Association of German Research Centers [grant number 38.04.04, POF IV]. The financial support for Ruben Stemmle via the Scholarship Program of the German Federal Environmental Foundation (DBU) is also gratefully acknowledged.

Supplementary data

S2.1 Complete LCI used for the base case LCA of the ATES system at the "Bonner Bogen".

Table S2.1: Complete LCI used for the base case LCA of the "Bonner Bogen" ATES system.

	Component	Material/process	Amount per well	Uncertainty
Well construction – well chamber	Entry ladder	steel, chromium steel 18/8 | market for | cut-off, U	37 kg	±20 %
	Ventilation pipe	steel, chromium steel 18/8 | market for | cut-off, U	348.9 kg	±20 %
	Well chamber	concrete, normal | market for | cut-off, U	5,2 m^3	±20 %
	Transport	transport, freight, lorry 16-32 metric ton, euro 5	93 tkm	±10 %
		transport, freight, lorry > 32 metric ton, euro 5	4775 tkm	±20 %
		operation, lorry 20-28t, empty, fleet average	7.5 km	±10 %
		operation, lorry > 28t, empty, fleet average	63.7 km	±20 %
	Diesel for excavation	diesel | market for | cut-off, U	5.6 kg	±20 %
Well construction – well development	Submersible power cable	copper wire, technology mix, at plant	377 kg	±5 %
		synthetic rubber | market for | cut-off, U	112.1 kg	±5 %
	Submersible pump	steel, chromium steel 18/8 | market for | cut-off, U	147 kg	±20 %
	Transport	transport, freight, lorry 3.5-7.5 metric ton, euro5	130.3 tkm	±20 %
		operation, lorry 3.5-20t, empty, fleet average	85 km	±20 %
Well construction – well drilling	Diesel for well drilling	diesel | market for | cut-off, U	3.4 t	±20 %
	Transport	transport, freight, lorry 16-32 metric ton, euro5	663 tkm	±5 %
		transport, freight, lorry 16-32 metric ton, euro 5	1288 tkm	±20 %
		operation, lorry 20-28t, empty, fleet average	45 km	±5 %

Well construction – well piping	Bottom cap	steel, chromium steel 18/8 | market for | cut-off, U	37.8 kg	±20 %
	Bentonite grout	activated bentonite | market for | cut-off, U	1256 kg	±5 %
	Full pipe (incl. sump pipe)	reinforcing steel | market for | cut-off, U	1518 kg	±10 %
	Well screen	steel, chromium steel 18/8 | market for | cut-off, U	843.4 kg	±10 %
	Standpipe	steel, chromium steel | market for | cut-off, U	290.8 kg	±10 %
	Filter gravel	gravel, round | market for gravel, round | cut-off, U	22.9 t	±5 %
	Filter pipe (observation pipe)	PVC pipe E	8.8 kg	±10 %
	Full pipe (observation point)	PVC pipe E	15.4 kg	±10 %
	Well head	steel, chromium steel 18/8 | market for | cut-off, U	500 kg	±50 %
	Transport	transport, freight, lorry 16-32 metric ton, euro 5	458.2 tkm	±5 %
		transport, freight, lorry >32 metric ton, euro 5	4482.5 tkm	±20 %
		transport, freight, lorry 7.5-16 metric ton, euro 5	75.4 tkm	±20 %
		operation, lorry 20-28t, empty, fleet average	46.7 km	±5 %
		operation, lorry >28t, empty, fleet average	173.8 km	±20 %
		operation, lorry 3.5-20t , empty, fleet average	60 km	±20 %
Surface construction	Heat pump	heat pump, brine-water, 10kW | market for | cut-off, U	10 p	±20 %
		refrigerant R134a | market for | cut-off, U	24.3 kg	-
	Heat exchanger	steel, chromium steel 18/8 | steel production, electric, chromium steel 18/8 | cut-off, U	999 kg	±10 %
	Insulation heat exchanger	polyurethane, rigid foam | market for polyurethane, rigid foam | cut-off, U	30.4 kg	±50 %
	Groundwater filter unit	steel, chromium steel 18/8 | steel production, electric, chromium steel 18/8 | cut-off, U	30 kg	-
		galvanized steel sheet, at plant/RNA	4 kg	-
	Sound insulation panel	polyurethane, flexible foam | market for polyurethane, flexible foam | cut-off, U	51 kg	-
	Transport	transport, freight, lorry 7.5-16 metric ton, euro5	730.1 tkm	±20 %
		transport, freight, lorry 7.5-16 metric ton, euro5	480.7 tkm	±20 %
		operation, lorry 3.5-20t, empty, fleet average	80.3 km	±20 %
		operation, lorry 3.5-20t, empty, fleet average	80.3 km	±20 %
Subsurface construction	Horizontal water pipes	HDPE pipes E	3275 kg	±20 %
	Electrical wiring	copper | market for | cut-off, U	3525.4 kg	±10 %
		polyvinylchloride, suspension polymerised | market for | cut-off, U	525.3 kg	±10 %
	Empty conduit	PVC pipe E	212.4 kg	±10 %

	Diesel for excavation	diesel | market for | cut-off, U	39.8 kg	±20 %
	Transport	transport, freight, lorry 16-32 metric ton, euro 5	268.3 tkm	±20 %
		transport, freight, lorry > 32 metric ton, euro 5	202.5 tkm	±20 %
		operation, lorry 20-28t, empty, fleet average	20 km	±20 %
		operation, lorry >28t, empty, fleet average	8.3 km	±20 %
Operation	Submersible pump operation over lifetime	electricity, low voltage {DE} | market for | cut-off, U	838 MWh	-
	Refrigerant leakage over lifetime	refrigerant R134a | market for | cut-off, U	14.6 kg	-
		R134a_CO2eq	14.6 kg	-
	Heat pump operation over lifetime	electricity, low voltage {DE} | market for | cut-off, U	4.04 GWh	-
Decommissioning	Disposal electrical wiring	disposal, treatment of cables/GLO U	637.3 kg	-
		scrap copper | treatment of scrap, municipal incineration | cut-off, U	3902.3 kg	-
	Disposal steel	scrap steel | treatment of scrap steel, municipal incineration | cut-off, U	5029.9 kg	-

S2.2 Assumptions made in the LCI of the “Bonner Bogen” ATES system

- The vehicles used for transportation meet the Euro 5 emission standard.
- Well drilling is done with a fuel consumption of 6 GJ/m and a fuel energy density of 38.6 GJ/t.
- Fuel consumption for excavation is 6 l/h, excavation rate is 25 m^3/h, fuel density is 0.832 kg/l.
- Excavated material (sandy gravel) has a density of 1,540 kg/m^3.

S2.3 Additional information about the Sobol method global sensitivity analysis

The Sobol method (Sobol, 2001) is based on variance decomposition which aims to formulate the total variance $V(Y)$ of the model output Y as the sum of independent variance contributions of the individual parameters and all parameter interactions (Menberg et al., 2016a):

$$V(Y) = \sum_i V_i + \sum_i \sum_{j>i} V_{ij} + \cdots + V_{12\ldots k}$$

Here, V_i denotes the variance contribution of the parameter X_i and V_{ij} marks the variance of the interaction between the parameters X_i and X_j.

Due to the regression models' linear and additive design, only variance contributions of individual parameters are to be expected (Menberg et al., 2016a). Thus, only the calculation of first order Sobol indices S_i are described here using a generally formulated depiction of the regression model f (after Menberg et al. (2016a), Saltelli et al. (2008)):

$$Y = f(X_1, X_2, \dots, X_k)$$

Assuming a fixed value x_i^* for the parameter X_i, the term $V_{\boldsymbol{X}_{\sim i}}(Y|X_i = x_i^*)$ denotes the conditional variance of Y that is caused by $\boldsymbol{X}_{\sim i}$. Here, $\boldsymbol{X}_{\sim i}$ represents a matrix of all parameters except for X_i. The mean of the conditional variance $V_{\boldsymbol{X}_{\sim i}}(Y|X_i = x_i^*)$ over all possible values x_i^* can be written as $E_{X_i}(V_{\boldsymbol{X}_{\sim i}}(Y|X_i))$. This expression is a measure for the relative significance of the parameter X_i. It is always smaller than or equal to the total non-conditional variance $V(Y)$ because a fixed parameter X_i eliminates a possible contribution to the total variance. Therefore, a small value of the mean conditional variance $E_{X_i}(V_{\boldsymbol{X}_{\sim i}}(Y|X_i))$ implies a high significance of the parameter X_i to the total variance $V(Y)$. This means that a large value for

$$V_{X_i}\left(E_{\boldsymbol{X}_{\sim i}}(Y|X_i)\right) = V(Y) - E_{X_i}(V_{\boldsymbol{X}_{\sim i}}(Y|X_i))$$

represents a significant parameter X_i in teams of its contribution to the total variance $V(Y)$.

The normalized sensitivity measure of the parameter X_i in the form of the first order Sobol index is calculated as:

$$S_i = \frac{V_{X_i}(E_{\boldsymbol{X}_{\sim i}}(Y|X_i))}{V(Y)}$$

Different numerical estimators for the first order Sobol exist. In this study, the following formula is utilized that is described in detail in Saltelli et al. (2010):

$$V_{X_i}\left(E_{\boldsymbol{X}_{\sim i}}(Y|X_i)\right) = \frac{1}{N}\sum_{j=1}^{N} f(\boldsymbol{B})_j \left(f\left(\boldsymbol{A}_{\boldsymbol{B}}^{(i)}\right)_j - f(\boldsymbol{A})_j\right) \qquad \text{for } S_i$$

The sample matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ are generated using Monte Carlo samples and represent hypothetical ATES systems in the form of $N = 10{,}000$ combinations of the $k = 10$ input parameters. The matrices thus consist of 10 columns and 10,000 rows. The term $\boldsymbol{A}_{\boldsymbol{B}}^{(i)}$ is a matrix that includes all columns of $\boldsymbol{A}$ except for the *i*-th column. The *i*-th column of $\boldsymbol{A}_{\boldsymbol{B}}^{(i)}$ equals the *i*-th column of $\boldsymbol{B}$. Generating the matrices $\boldsymbol{A}$ and $\boldsymbol{B}$ is done via Latin Hypercube Sampling.

S2.4 Fully formulated LCA regression models

The fully formulated LCA regression model referring to the current German electricity mix is obtained as follows (with the variables corresponding to those in Table 2.2):

$$GHG_{ATES}[\mathrm{gCO_{2eq}/kWh_{th}}] = \alpha_0 + \alpha_1 \times d + \alpha_2 \times fr + \alpha_3 \times Nw + \alpha_4 \times fd + \alpha_5 \times Th + \alpha_6 \times Tc + \alpha_7 \times L + \alpha_8 \times Pp + \alpha_9 \times COP + \alpha_{10} \times Cap$$

with

α_0 = 130.323 $\mathrm{gCO_2eq/kWh_{th}}$

α_1 = 2.076 × 10^{-3} $\mathrm{gCO_2eq/(kWh_{th}\ m)}$

α_2 = 4.896 × 10^{-2} $\mathrm{gCO_2eq\ h/(kWh_{th}\ m^3)}$

α_3 = 0.255 $\mathrm{gCO_2eq/kWh_{th}}$

α_4 = 18.138 $\mathrm{gCO_2eq\ m/(kWh_{th}\ t)}$

α_5 = 1.648 × 10^{-2} $\mathrm{gCO_2eq\ a/(kWh_{th}\ h)}$

α_6 = −1.152 × 10^{-2} $\mathrm{gCO_2eq\ a/(kWh_{th}\ h)}$

α_7 = −4.193 × 10^{-2} $\mathrm{gCO_2eq/(kWh_{th}\ a)}$

α_8 = 29.786 $\mathrm{gCO_2eq\ l/(kWh_{th}\ kW\ s)}$

α_9 = −17.767 $\mathrm{gCO_2eq/kWh_{th}}$

α_{10} = −1.841 × 10^{-3} $\mathrm{gCO_2eq/(kWh_{th}\ kW)}$

The corresponding procedure for the projected 2050 electricity mix results in the following LCA regression model:

$$GHG_{ATES}[\mathrm{gCO_{2eq}/kWh_{th}}] = \beta_0 + \beta_1 \times d + \beta_2 \times fr + \beta_3 \times Nw + \beta_4 \times fd + \beta_5 \times Th + \beta_6 \times Tc + \beta_7 \times L + \beta_8 \times Pp + \beta_9 \times COP + \beta_{10} \times Cap$$

with

β_0 = 15.791 $\mathrm{gCO_2eq/kWh_{th}}$

β_1 = 2.076 × 10^{-3} $\mathrm{gCO_2eq/(kWh_{th}\ m)}$

β_2 = 4.953 × 10^{-3} $\mathrm{gCO_2eq\ h/(kWh_{th}\ m^3)}$

β_3 = 0.366 $\mathrm{gCO_2eq/kWh_{th}}$

β_4 = 3.240 $\mathrm{gCO_2eq\ m/(kWh_{th}\ t)}$

β_5 = 1.415 × 10^{-3} $\mathrm{gCO_2eq\ a/(kWh_{th}\ h)}$

β_6 = −1.298 × 10^{-3} $\mathrm{gCO_2eq\ a/(kWh_{th}\ h)}$

β_7 = −4.193 × 10^{-2} $\mathrm{gCO_2eq/(kWh_{th}\ a)}$

β_8 = 3.013 $\mathrm{gCO_2eq\ l/(kWh_{th}\ kW\ s)}$

β_9 = −1.900 $\mathrm{gCO_2eq/kWh_{th}}$

β_{10} = −2.581 × 10^{-4} $\mathrm{gCO_2eq/(kWh_{th}\ kW)}$

S2.5 Overview of existing economic analyses of ATES

Table S2.2: Relevant details on ATES and reference systems described in literature and used for the economic comparison in Chapter 2.3.5.

	Vanhoudt et al. (2011)		Schüppler et al. (2019)		Todorov et al. (2020)
	ATES	**Reference system**	**ATES**	**Reference system**	**ATES**
Capital costs	695 k€	241 k€	1259 k€	667 k€	1,056,250 €
Operational costs per year	28.7 k€ (electricity)	82.4 k€ (electricity & gas)	238.5 k€ (electricity, maintenance & replacement)	525.6 k€ (electricity, district heating, maintenance & replacement)	112,936 € (electricity & maintenance)
Payback time of ATES	8.4 years		2.7 years		–

3 Potential of Low-Temperature Aquifer Thermal Energy Storage (LT-ATES) in Germany

Reproduced from: Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geothermal Energy 10, 24. https://doi.org/10.1186/s40517-022-00234-2.

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 areas 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.

3.1 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 environmental-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., 2020b; 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., 2020a). 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., 2020a).

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. (2019b), 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 (Zhu et al., 2010). The technical potential on the other hand, assesses the thermal energy that can be extracted by a certain technology. It usually is 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; Lu et al., 2019b) 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) and Lu et al. (2019b) 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 regards 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.

3.2 Materials and methods

3.2.1 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., 2019b). 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 S3.1 in the Supplementary data (Section S3.1). Figure 3.1 illustrates the basic ATES operation principle and the relevant input criteria.

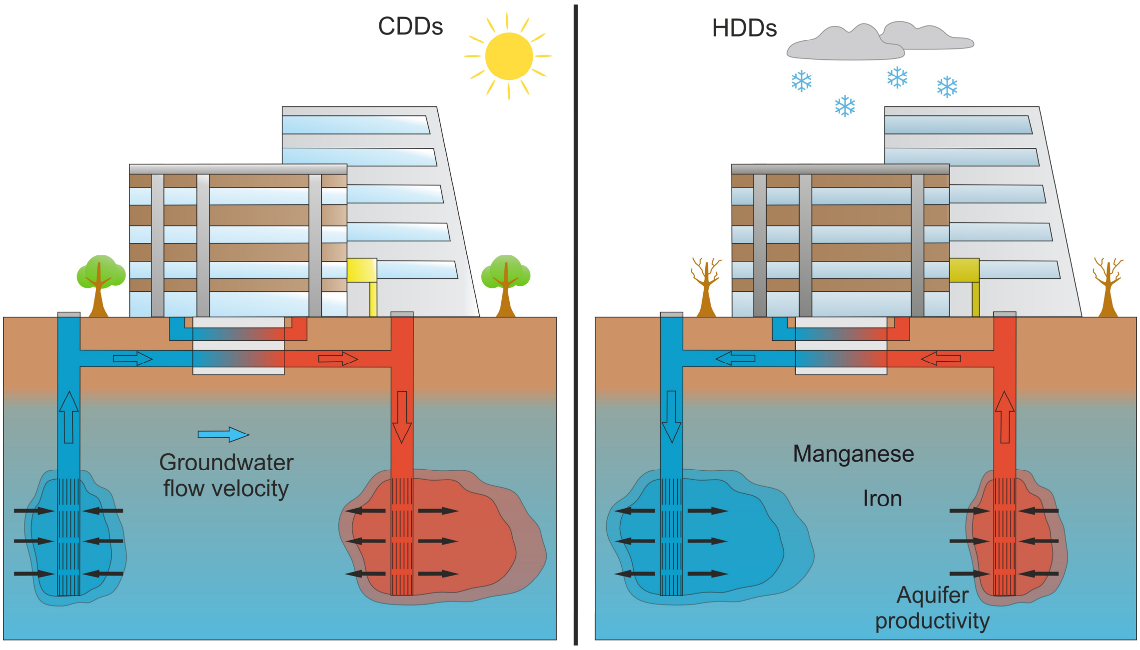


Figure 3.1: Schematic operation principle of ATES in cooling mode (left) and in heating mode (right). The hydrogeological criteria aquifer productivity, iron and manganese contents in groundwater and groundwater flow velocity as well as the climatic criterion represented by cooling degree days (CDDs) and heating degree days (HDDs) are included for illustration purposes.

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. The nationwide dataset “Groundwater Yields of Germany” of BGR (2019a) divides the productivity of aquifers in five classes (Figure 3.2a) 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 regards 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., 2019b). 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 (Hellriegel et al., 2020). Thus, we include the dataset “Geogenic Groundwater Quality of Germany” (Figure 3.2b) of 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; Sommer et al., 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

(Figure 3.2c) 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).

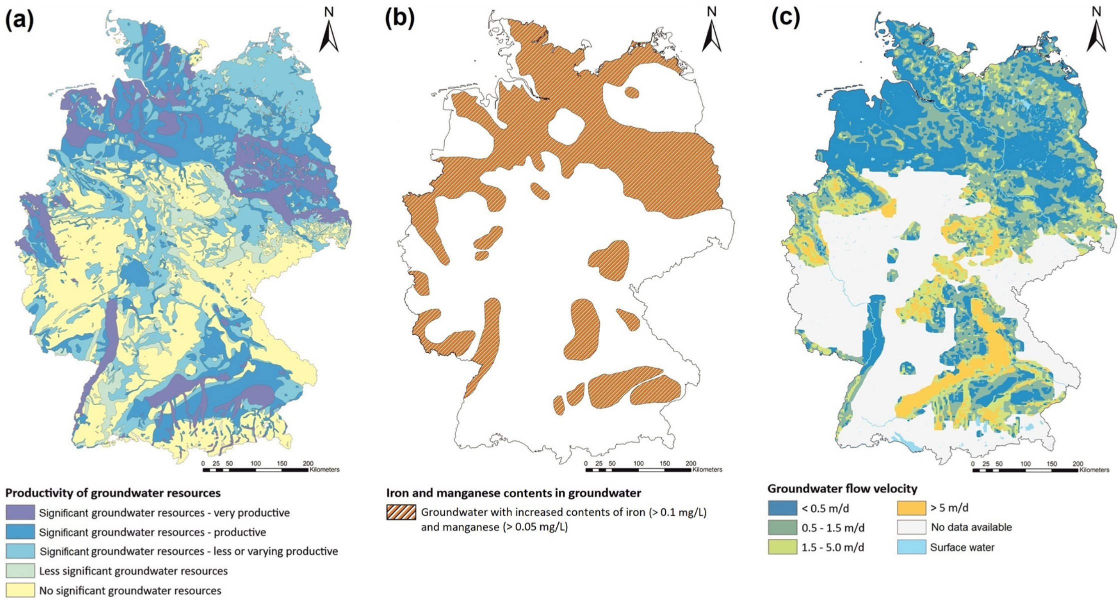


Figure 3.2: Hydrogeological criteria of the ATES potential study for Germany: (**a**) Aquifer productivity (BGR, 2019a), (**b**) iron and manganese contents in groundwater (BGR, 2019b), (**c**) mean groundwater distance velocity (Wendland et al., 1993).

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., 2020b; 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):

$$HDDs = \sum_{i=1}^{365} \left(18.5\,°\mathrm{C} - \frac{T_{min,i} + T_{max,i}}{2}\right) \tag{3.1}$$

and

$$CDDs = \sum_{i=1}^{365} \left(\frac{T_{min,i} + T_{max,i}}{2} - 18.5\,°\mathrm{C}\right) \tag{3.2}$$

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) and

Roeckner et al. (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 surface air temperature that are used for the calculation of HDDs and CDDs according to Equations (3.1) and (3.2), 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 is 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 (Figure S3.1, Supplementary data).

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., 2018; Bloemendal et al., 2014; Ramos-Escudero and Bloemendal, 2022; Schüppler et al., 2019; Sommer et al., 2015; Todorov et al., 2020).

3.2.2 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., 2019b). 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 nation-wide 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 (Figure 3.3), 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.

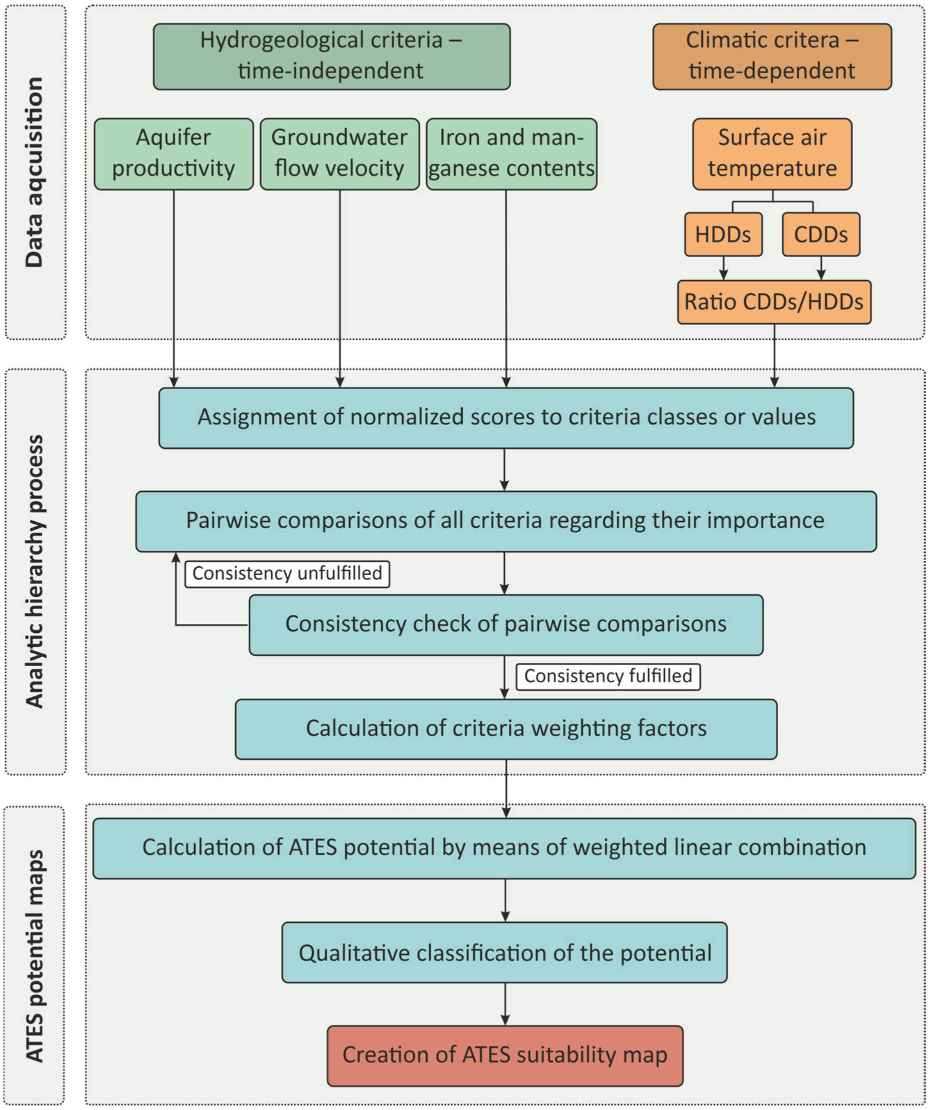


Figure 3.3: Workflow for the creation of the ATES suitability potential map of Germany. Data sources and further details on the criteria are provided in Table S3.1 (Supplementary data).

3.2.2.1 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 (Sommer et al., 2013; Sommer et al., 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 is normalized using the overall minimum and maximum values of all four selected time periods as scaling points (Kiavarz and Jelokhani-Niaraki, 2017):

$$S_{norm} = \frac{S - S_{min}}{S_{max} - S_{min}} \tag{3.3}$$

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 3.1 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 l/s and 20 l/s (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 3.1). The higher criteria classes receive larger scores to account for the fact that large ATES system potentially could be realized with a smaller number of wells.

Table 3.1: 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 Equation (3.3).

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/d, 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/d (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/d, the simulated storage efficiencies are too low even for an adapted ATES well arrangement.

3.2.2.2 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., 2019b; 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 3.2). 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*.

Table 3.2: Comparison scale of relative weights for pairwise comparisons (Lu et al., 2019b; Saaty, 1977).

1/9	1/7	1/5	1/3	1	3	5	7	9
Extremely	Very strongly	Strongly	Moderately	Equally	Moderately	Strongly	Very strongly	Extremely
less important				important	more important			

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

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{pmatrix} \tag{3.4}$$

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

$$B = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1j} \\ b_{21} & b_{22} & \cdots & b_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ b_{i1} & b_{i2} & \cdots & b_{ij} \end{pmatrix} \tag{3.5}$$

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

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{3.6}$$

Equation (3.6) 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:

$$w_i = \frac{\sum_{j=1}^{n} b_{ij}}{n} \qquad \text{with} \qquad \sum_{i=1}^{n} w_i = 1 \tag{3.7}$$

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 the Supplementary data (Section S3.3).

3.2.2.3 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:

$$SP = \sum_{i=1}^{n} (w_i \, x_i) \qquad \text{with} \qquad n = 4 \tag{3.8}$$

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.

3.3 Results and discussion

3.3.1 Ratio of degree days

Figure 3.4 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 Figure

3.4a 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 (Figure S3.2, Supplementary data). 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 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 (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 (Figure S3.3, Supplementary data). 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 however reflect our results shown in Figure 3.4b.

Besides the regional differences, a certain topographic influence (Figure S3.1, Supplementary data) 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 artefacts 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 artefacts, they can be ignored without affecting the remaining map areas. Furthermore, the artefacts are located in hard rock areas, which are excluded from ATES utilization. The uneven spatial distribution of the weather stations across

Germany shown in Figure 3.4a also results in higher prediction errors in regions with a low density of measuring stations. As an example, Figure S3.2 (Supplementary data) shows the Germany-wide interpolation of HDDs for the period 2021-2050 and the corresponding prediction standard error (i.e. standard deviation).

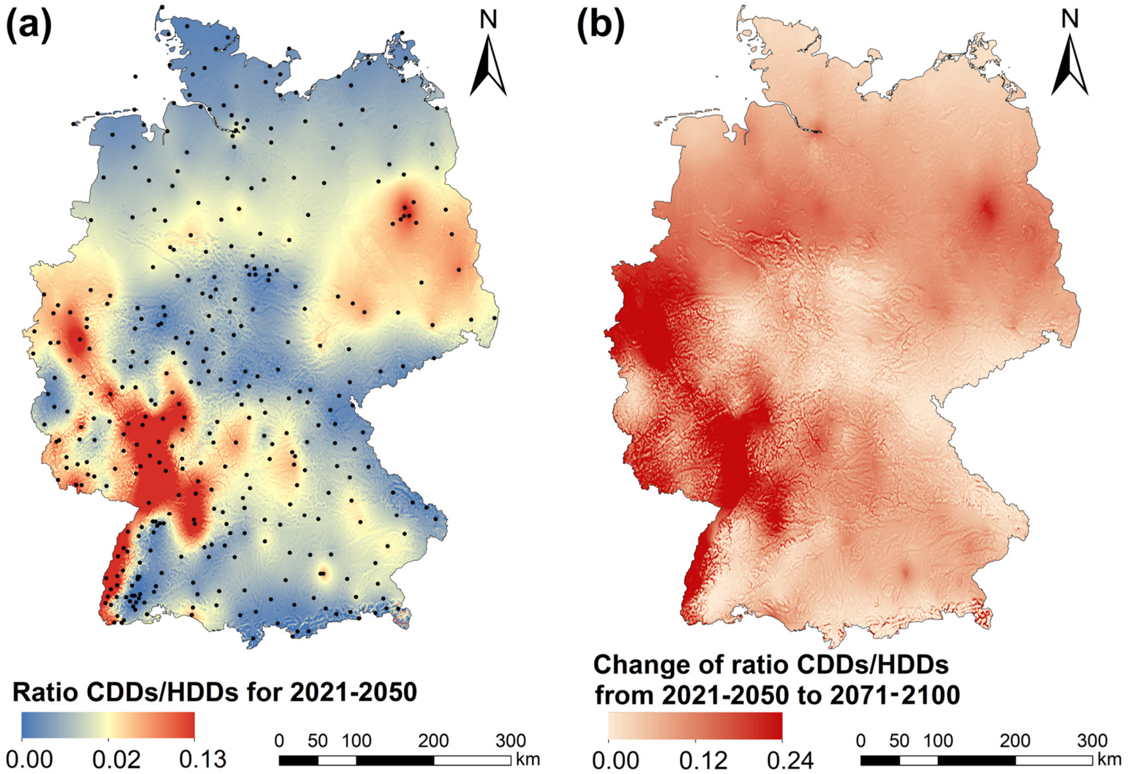


Figure 3.4: (**a**) Mean ratio of CDDs to HDDs for 2021-2050, (**b**) change of mean degree days ratio from 2021-2050 to 2071-2100. The marks in (**a**) represent the weather stations utilized for the generation of country-wide degree days via cokriging.

3.3.2 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 Equation (3.7) are shown in Table 3.3. 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 (Supplementary data, Section S3.3). Thus, the weighting factors resulting from the pairwise comparisons can be used for determination of the suitability potential.

Table 3.3: 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

3.3.3 ATES suitability potential in Germany

Using the criteria weighting factors in Table 3.3, the ATES suitability potential for Germany for the time period *near future* (2021-2050) is calculated (Figure 3.5a). 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 2021-2050, 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 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/d 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 (Figure 3.4a). Another criterion causing these areas to be classified as moderately suitable is a higher groundwater flow velocity, as in Germany's northeastern regions (Figure 3.2c). 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 (Figure 3.2a). 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.

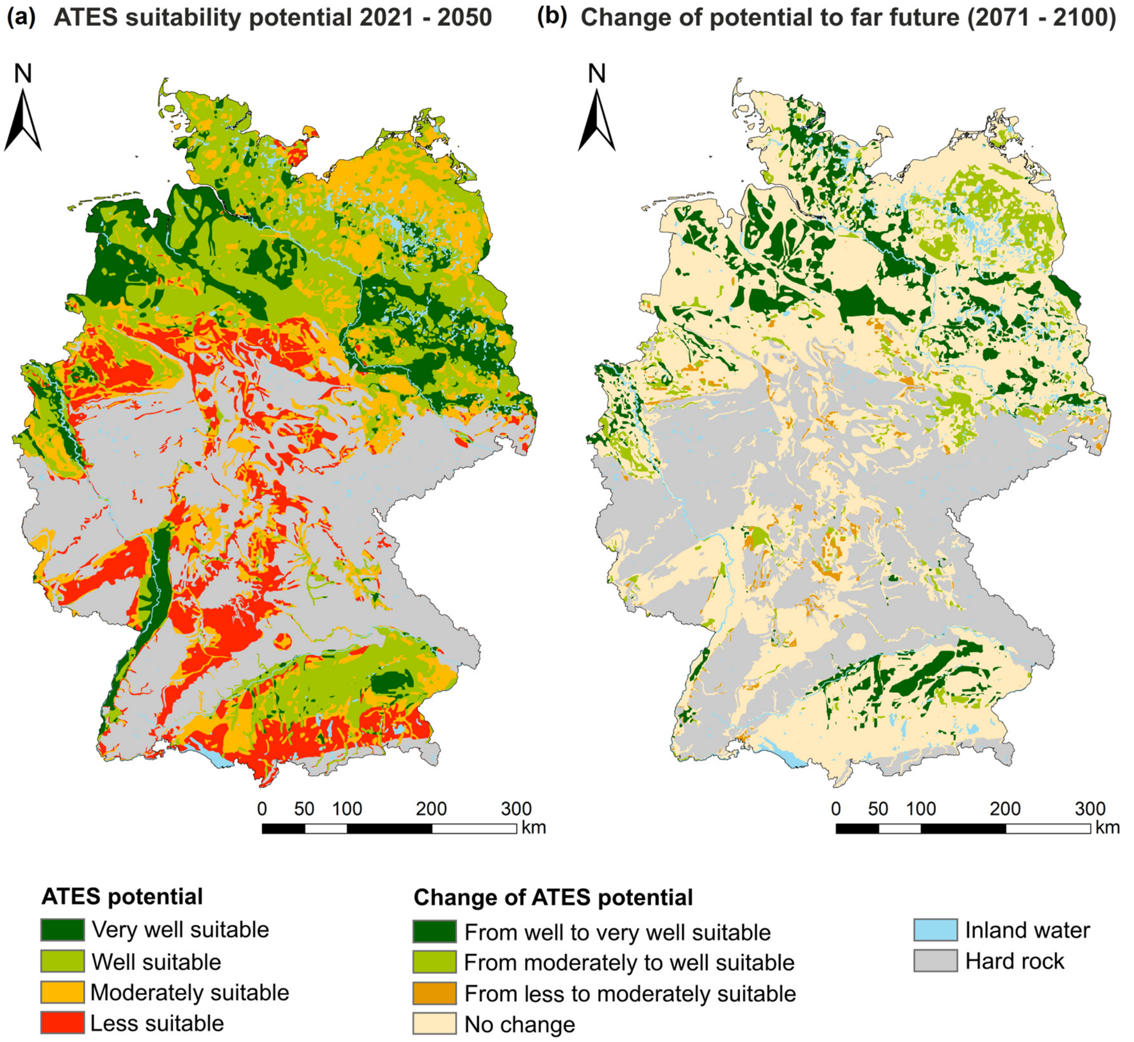


Figure 3.5: (**a**) ATES suitability potential in Germany for the period *near future* (2021-2050), (**b**) change in potential from the *near future* to the *far future* (2071-2100).

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 (Figure 3.5b). 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 (Figure 3.6). 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.

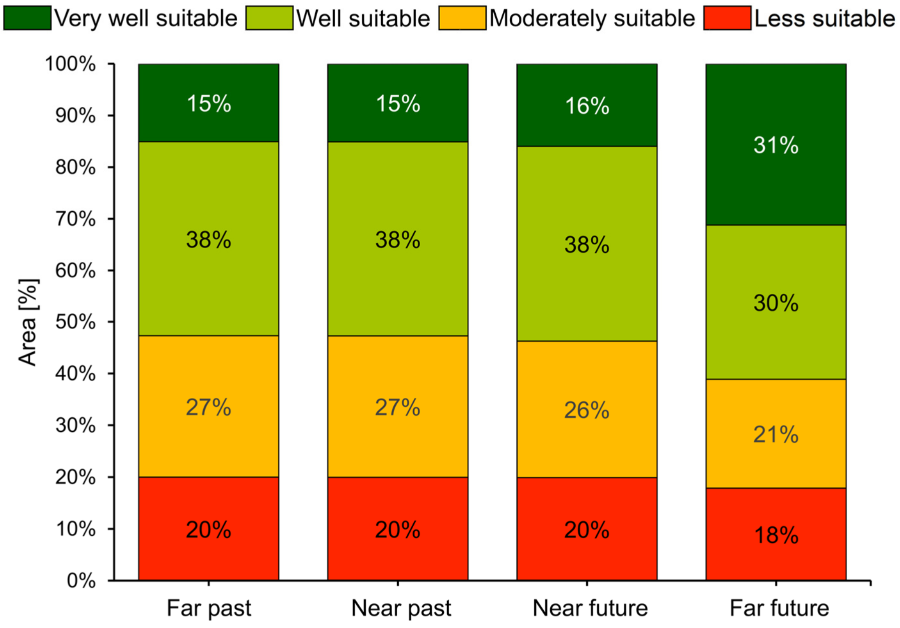


Figure 3.6: Percentage shares of ATES suitability potential classes in Germany for the four considered time periods *far past* (1961-1990), *near past* (1991-2020), *near future* (2021-2050) and *far future* (2071-2100). The shares refer to the parts of Germany that are not covered by hard rock or inland water surfaces.

Our results are in good agreement with previous ATES potential maps presented in Bloemendal et al. (2016) and Lu et al. (2019b). They also indicate a high or very high suitability potential in most parts of Germany and central Europe in general. In comparison, however, the potential map of Germany presented in Figure 3.5a 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 (Figure 3.5b) 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., 2016; Bloemendal et al., 2015; Lu et al., 2019a; Lu et al., 2019b), the potential map in Figure 3.5a 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 is further analyzed in the next chapter, a finer subdivision would gradually decrease the individual classes' significance and the informative value of class differences.

3.3.4 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 (Figure 3.5a) 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., 2019b). 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 Table S3.4 (Supplementary data). All alternatives fulfill the consistency check.

Figure 3.7 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 3.3, Figure 3.5a). 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 (Figure S3.4, Supplementary data). 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 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 (Figure 3.5a) results in a rather conservative judgement of the country-wide ATES potential (Figure 3.7).

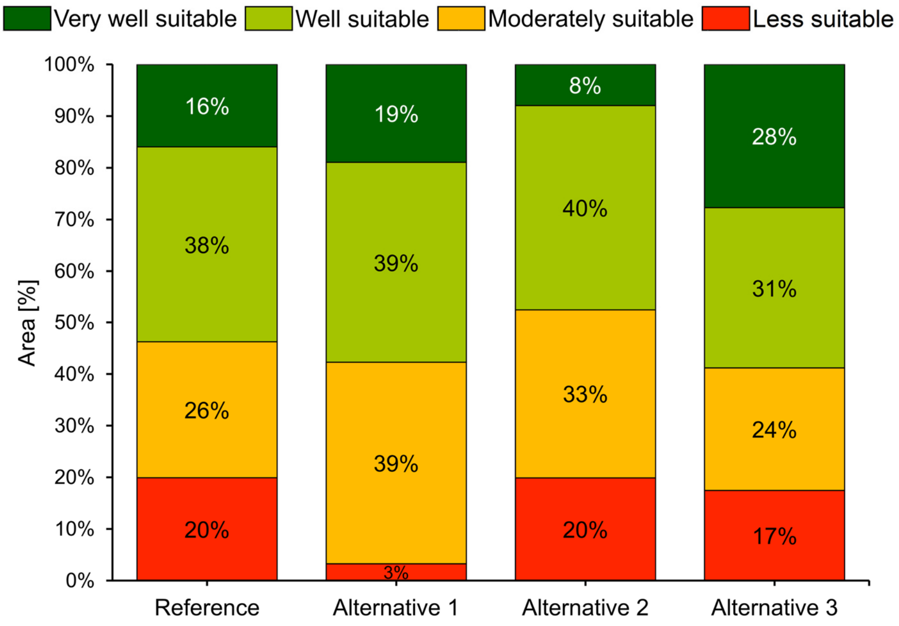


Figure 3.7: Percentage shares of ATES suitability potential classes in Germany for the reference as well as the three alternative weighting schemes with regard to the time period *near future* (2021-2050). The shares refer to the parts of Germany that are not covered by hard rock or inland water surfaces (Figure S3.4, Supplementary data).

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 (Figure 3.6). 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 (Table S3.4, Supplementary data) and therefore shows the highest suitability changes from the *near future* (2021 – 2050) to the *far future* (2071 – 2100).

3.3.5 Restrictions in water protection zones

The qualitative technical potential of ATES in Germany as shown in Figure 3.5a 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 (Figure 3.8). Due to this study's focus on the technical potential, these zones are however 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 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).

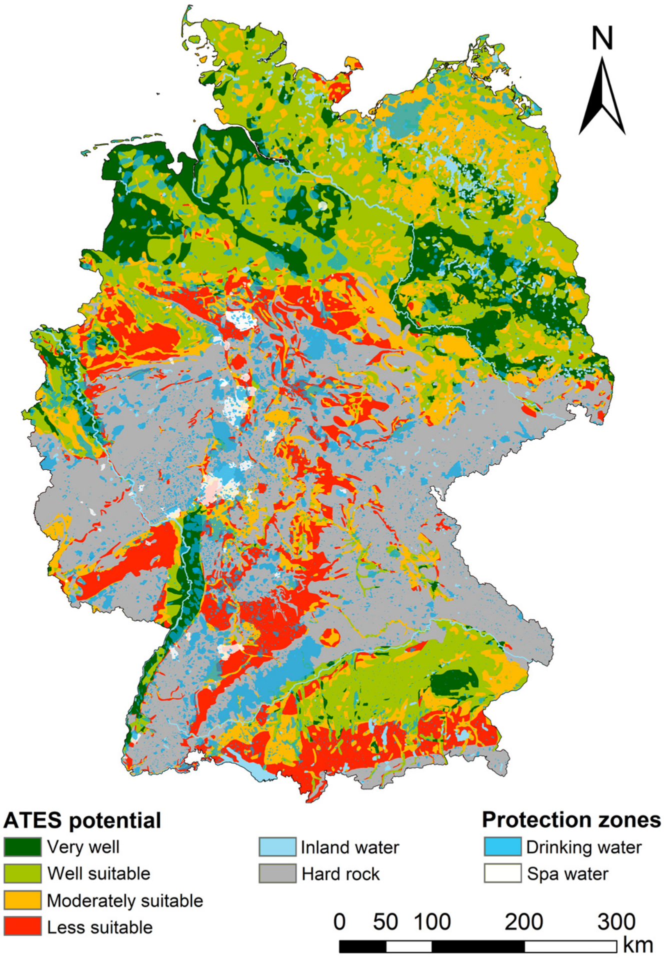


Figure 3.8: ATES suitability potential in Germany for the period *near future* (2021-2050) based on the reference criteria weighting scheme. Drinking and spa water protection zones are included. Protection zone data from BfG (2021), HLNUG (2022), LfU (2021), LUBW (2022a, 2022b), MULNV NRW (2022), NLWKN (2021).

3.3.6 Limitations of the ATES suitability potential map

The ATES suitability potential map (Figure 3.5a) 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 Table S3.1 (Supplementary data), 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 (Figure 3.5a).

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 are 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 (Figure 3.5a) can be checked regarding plausibility via a comparison with the neighboring Netherlands. Fleuchaus et al. (2018) showed that a high number of ATES systems is 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.

3.4 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.

Acknowledgements

The authors would like to thank Paul Fleuchaus (formerly KIT) and Simon Schüppler (formerly EIFER) for valuable discussions regarding ATES operation. The authors would also like to thank Anna Albers, Christoph Bott, Paul Fleuchaus, Marco Fuchs, Fabien Koch, Gabriel Rau, Simon Schüppler, Robin Seyfarth, Hagen Steger and Patrick Winkler for providing their opinion on the pairwise comparisons to raise awareness of different perspectives on this topic. Finally, the constructive comments of three anonymous reviewers are also gratefully acknowledged.

The financial support for Ruben Stemmle via the Scholarship Program of the German Federal Environmental Foundation (DBU) and the funding of Kathrin Menberg via the Margarete von Wrangell program of the Ministry of Science, Research and the Arts (MWK) of the State of Baden-Württemberg are gratefully acknowledged.

Supplementary data

S3.1 Hydrogeological and climatic criteria

Table S3.1: Data sets used for the potential study in Germany.

	Criterion	Description	Data source	Comments	Resolution or scale
Time-independent	Aquifer productivity	Productivity of groundwater resources in Germany	BGR (2019a)	-	Vector data. Scale of the map originally published in print: 1:1,000,000
	Iron and manganese contents in groundwater	Areas with increased Fe or Mn contents in the groundwater	BGR (2019b)	-	Vector data. Scale of the map originally published in print: 1:1,000,000
	Groundwater flow velocity	Mean groundwater velocity	Wendland et al. (1993)	Data available for most areas in Germany with an unconsolidated shallow subsurface. The data set was manually digitized and georeferenced, since no digital version is available.	3 km × 3 km. Scale of the map originally published in print: 1:3,500,000
Time-dependent	Daily surface temperatures	WettReg2010 data set with daily surface temperatures (1961 - 2100) for 383 climate stations in Germany	Kreienkamp et al. (2010)	Basis for calculating heating and cooling degree days.	Limited by the number of weather stations used for interpolation (383). Digital terrain model used in cokriging: 1 km × 1 km

S3.2 Digital terrain model of Germany

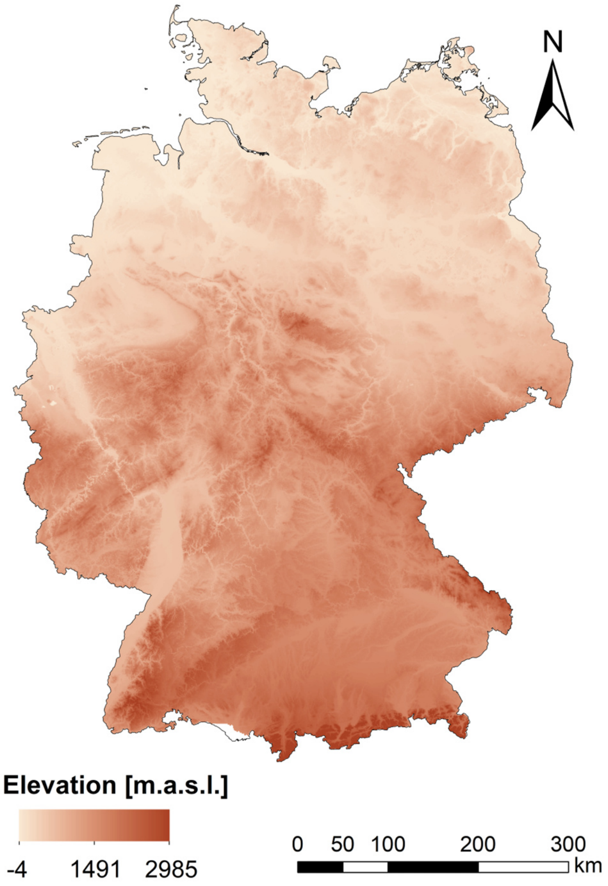


Figure S3.1: Digital terrain model of Germany (DGM1000, modified from BKG (2021)).

S3.3 Consistency check of the pairwise comparison matrix

The consistency check is used to identify possible contradictions in the execution of the pairwise comparisons and is based on calculating the so-called consistency ratio *CR*. The approach described here is based on Bunruamkaew (2012) and Lu et al. (2019b).

First, the consistency vector v is calculated from the comparison matrix A of the n criteria and the vector w of the weighting factors as:

$$v = A \cdot w$$

with

$$w = \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix}$$

and has the form

$$v = \begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix}$$

The entries v_i of the consistency vector v are divided by the corresponding entries w_i of the weighting vector w:

$$\mathrm{c}_i = \frac{v_i}{w_i} \qquad \text{with } i = 1,2,\ldots,n$$

The so calculated consistency measure c_i can be used to determine an approximate solution of the principal eigenvalue λ_{max} of the comparison matrix A:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n} c_i$$

The consistency of matrix A can be assessed using the consistency index CI, which is a measure of deviation from perfect consistency (Drobne and Lisec, 2009). It is calculated as:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

The final step of the consistency check consists of calculating the consistency ratio CR which is defined as:

$$CR = \frac{CI}{RI}$$

RI represents a random index, which corresponds to the consistency index of a comparison matrix of randomly generated pairwise comparison of n criteria. The value of *RI* depends on the criteria number n and can be found in Table S3.2.

Table S3.2: Values of *RI* in dependence of *n* according to Saaty (1980) and Lu et al. (2019b).

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.46	1.49

A widely used threshold value for *CR* is 0.10, which is also adopted in this study. *CR* values below this threshold indicate an acceptable consistency of the pairwise comparison matrix (Chen et al., 2010; Lu et al., 2019b). *CR* values greater than 0.10, on the other hand, require the reevaluation of the assigned relative weightings.

Table S3.3 shows the *CR* values for the reference pairwise comparison matrix (Table 3.3) that is used to create the ATES potential map of Germany (Figure 3.5), as well as the *CR* values of each of the three alternative weighting schemes (Table S3.4). All *CR* values are below 0.10 and thus the respective criteria weighting factors are suitable to be used for further steps in the MCDA.

Table S3.3: Values of *CR* for the reference and alternative pairwise comparison matrices.

	Reference	**Alternative 1**	**Alternative 2**	**Alternative 3**
CR	0.06	0.004	0.09	0.04

S3.4 Alternative weighting schemes

Table S3.4: Pairwise comparison matrices and weighting factors representing three alternative perspectives (A1, A2, A3) on the topic of ATES.

	Aquifer productivity			**Iron and manganese contents in groundwater**			**Groundwater flow velocity**			**Ratio CDDs/HDDs**			**Weighting factor**		
	A1	**A2**	**A3**	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**	**A1**	**A2**	**A3**
Aquifer productivity	1	1	1	2	7	7	3	3	1	3	1/3	3	0.45	0.31	0.39
Iron and manganese contents in groundwater	1/2	1/7	1/7	1	1	1	2	1/3	1/8	2	1/5	1/7	0.26	0.06	0.04
Groundwater flow velocity	1/3	1/3	1	1/2	3	8	1	1	1	1	1/3	2	0.14	0.14	0.36
Ratio CDDs/HDDs	1/3	3	1/3	1/2	5	7	1	3	1/2	1	1	1	0.14	0.48	0.20

S3.5 Heating Degree Days for 2021-2050 and corresponding cokriging prediction standard error

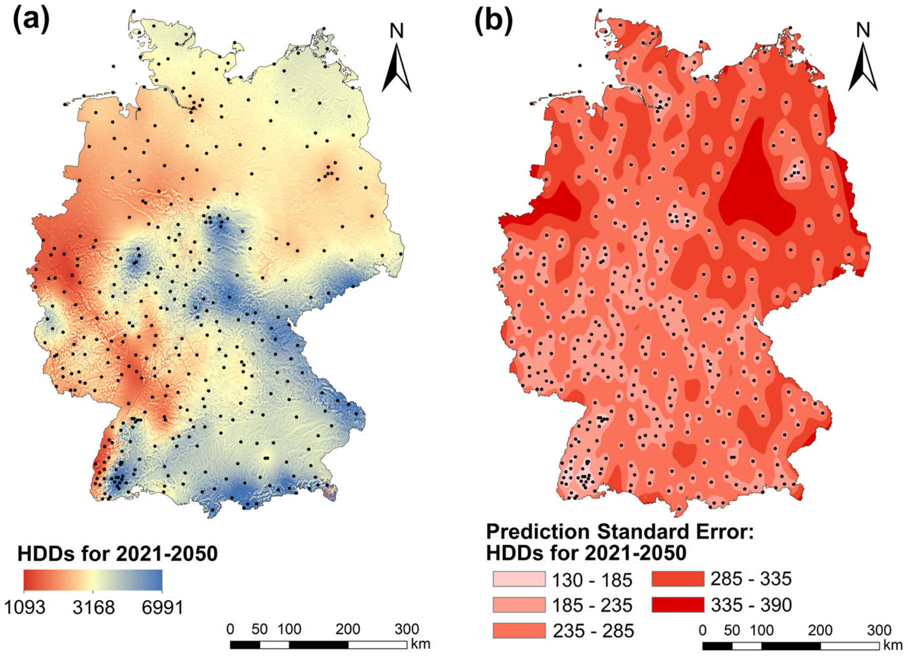


Figure S3.2: HDDs for 2021-2050: (**a**) Germany-wide HDD values interpolated between 383 weather stations (black marks) via cokriging, (**b**) Prediction standard error (i.e. standard deviation) of the cokriging interpolation.

S3.6 Change of mean degree days ratio for all time periods

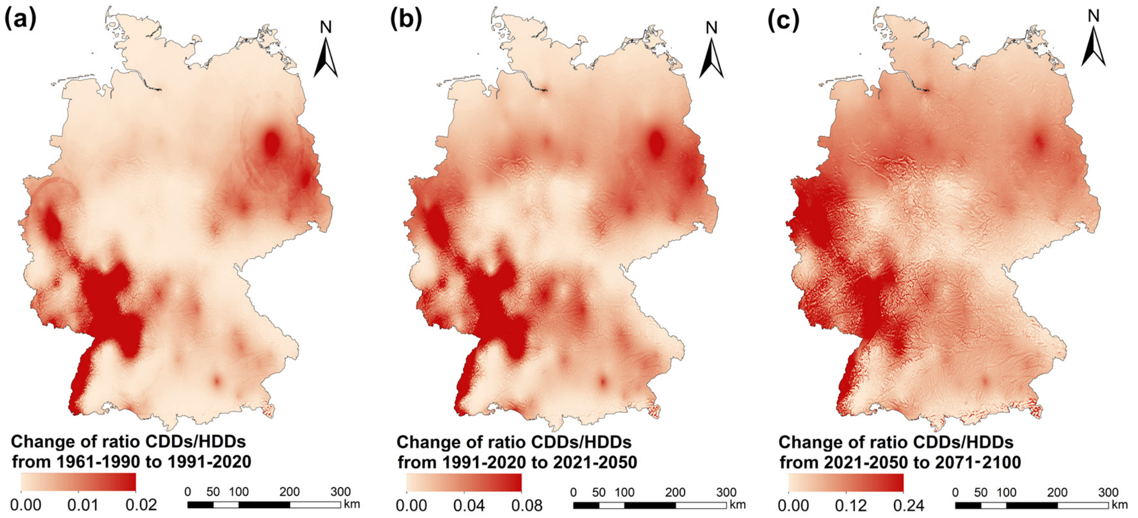


Figure S3.3: Change of mean ratio of CDDs to HDDs: (**a**) From *far past* (1961-1990) to *near past* (1991-2020), (**b**) from *near past* to *near future* (2021-2050), (**c**) from *near future* to *far future* (2071-2100).

S3.7 Alternative ATES suitability potential maps of Germany for 2021-2050

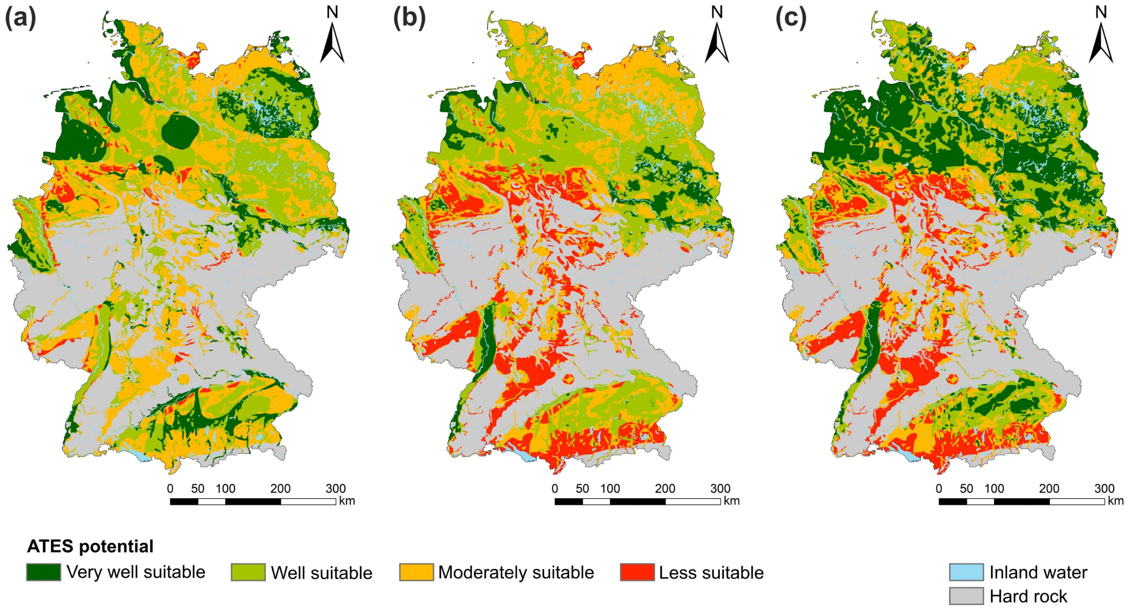


Figure S3.4: ATES suitability potential in Germany for the period *near future* (2021-2050) based on the three alternative weighting schemes: (**a**) Alternative 1, (**b**) Alternative 2, (**c**) Alternative 3.

4 City-scale heating and cooling with Aquifer Thermal Energy Storage (ATES)

Reproduced from: Stemmle, R., Lee, H., Blum, P., Menberg, K., 2024. City-scale heating and cooling with aquifer thermal energy storage (ATES). Geothermal Energy 12, 2. https://doi.org/10.1186/s40517-023-00279-x.

Abstract

Sustainable and climate-friendly space heating and cooling is of great importance for the energy transition. Compared to conventional energy sources, Aquifer Thermal Energy Storage (ATES) systems can significantly reduce greenhouse gas emissions from space heating and cooling. Hence, the objective of this study is to quantify the technical potential of shallow low-temperature ATES systems in terms of reclaimable energy in the city of Freiburg im Breisgau, Germany. Based on 3D heat transport modeling, heating and cooling power densities are determined for different ATES configurations located in an unconsolidated gravel aquifer of varying hydrogeological subsurface characteristics. High groundwater flow velocities of up to 13 m d^{-1} cause high storage energy loss and thus limit power densities to a maximum of 3.2 W m^{-2}. Nevertheless, comparison of these power densities with the existing thermal energy demands shows that ATES systems can achieve substantial heating and cooling supply rates. This is especially true for the cooling demand, for which a full supply by ATES is determined for 92 % of all residential buildings in the study area. For ATES heating alone, potential greenhouse gas emission savings of up to about 70,000 $tCO_2eq\ a^{-1}$ are calculated, which equals about 40 % of the current greenhouse gas emissions caused by space and water heating in the study areas' residential building stock. The modeling approach proposed in this study can also be applied in other regions with similar hydrogeological conditions to obtain estimations of local ATES supply rates and support city-scale energy planning.

4.1 Introduction

One of the overarching goals formulated at the COP 26 climate change conference in 2021 is the global net zero emission of greenhouse gases by mid-century in order to limit climate warming to 1.5 °C compared to pre-industrial levels (COP26, 2021). Besides international and national policies, climate change protection is also driven forward at the city and municipal level as many cities are developing sustainable and climate-friendly energy planning concepts (Epting et al., 2020; Lim et al., 2019; Pulselli et al., 2021). Integrated urban energy planning strategies are a suitable tool to achieve municipal climate protection plans and to reduce greenhouse gas (GHG) emissions. Since space heating and cooling in the building sector alone make up more than 30 % of Germany's final energy consumption (AGEB, 2021), climate-friendly heating and cooling solutions are of great importance.

One alternative to conventional space heating and cooling based on fossil fuels and cooling machines, respectively, are geothermal applications using the shallow subsurface and groundwater as a renewable source of thermal energy, such as groundwater heat pump (GWHP) systems. By seasonally reversing the pumping direction of GWHP systems, groundwater can also serve as a seasonal storage medium for heated and cooled water. This type of shallow geothermal energy is known as Aquifer Thermal Energy Storage (ATES) and allows to reduce seasonal mismatches between demand and availability of thermal energy by storing waste heat in summer and excess cooling capacities in winter (Bakr et al., 2013; Dickinson et al., 2009; Fleuchaus et al., 2018; Schüppler et al., 2019). This results in a more efficient operation of the heat pump system. For cooling, it is often possible to utilize the cooled water directly without any heat pump operation (Banks, 2009; Bloemendal et al., 2018; Fleuchaus et al., 2018; Sommer et al., 2014).

A quantification approach revealing the potentially achievable heating and cooling power can facilitate the integration of ATES into city-scale energy planning (Bayer et al., 2019). Thus, this study uses the concept of power density, which relates the amount of power generated by a specific technology to the required horizontal Earth surface area to quantify the ATES potential. In recent years, the unit of power density has been increasingly used to highlight space requirements as a potential limiting factor for the transition to renewable energies, which typically have much lower power densities than fossil fuels or nuclear energy (Kammen and Sunter, 2016; Smil, 2015). Power density can also serve as a universal mean for comparing different electricity generation technologies (Kammen and Sunter, 2016; van Zalk and Behrens, 2018). For instance, according to van Zalk and Behrens (2018), nuclear power plants and coal-fired power plants have median power densities of around 241 W m^{-2} and 135 W m^{-2}, respectively. Lower median power density values of around 7 W m^{-2} and 2 W m^{-2} are stated for solar and wind power, respectively.

With regard to thermal energy, the power density concept was previously used to quantify the technical potential of shallow geothermal applications (Bayer et al., 2019; Kammen and Sunter, 2016). The technical potential, as referred to in this study, relates to a specific extraction technology, such as open GWHP or closed ground source heat pump (GSHP) systems. It is therefore constrained by technical factors, such as space restrictions and temperature limits (Hähnlein et al., 2013; Tissen et al., 2019; Tissen et al., 2021). Bayer et al. (2019) compiled an overview of relevant studies from the literature and revealed a wide range of normalized power densities for

GSHP systems with values from less than 10 W m^{-2} up to more than 400 W m^{-2}. These discrepancies result from a variety of underlying assumptions and approaches.

Other studies regarding the technical potential of shallow geothermal energy often do not explicitly use the term power density while having similar objectives. For example, Tissen et al. (2019) and Tissen et al. (2021) used guideline values of achievable energy extraction rates to quantify the potential of closed geothermal systems with respect to determined space requirements on the district- and city-scale. Other studies present similar quantitative calculation approaches to estimate the thermal potential of groundwater and compare it to the energy demand as a means for subsurface thermal planning in urban settings (Epting et al., 2018; Miocic and Krecher, 2022; Zhu et al., 2010). Böttcher et al. (2019) and Epting et al. (2020), for example, determined the technical geothermal potential of open GWHP systems based on 2D numerical box models considering groundwater flow conditions and different pumping rates as well as temperature changes of the extracted groundwater. However, their box models only considered hydraulic effects of GWHP systems on the aquifer, while plume propagation of thermal anomalies was not considered. For the determination of meaningful space requirements of open geothermal installations, however, modeling the thermal plume propagation is crucial to avoid thermal interactions.

In this study, we develop a novel methodology to assess the technical potential of low-temperature Aquifer Thermal Energy Storage (LT-ATES), which is commonly characterized by storage temperatures between 5 °C and 25 °C (Fleuchaus et al., 2018). To this end and for the first time, heating and cooling power densities of LT-ATES are determined considering advective heat transport and multiple adapted ATES well configurations in dependence on the local ambient groundwater flow velocity. For the power density determination, thermo-hydraulic 3D numerical box models are created using the German city of Freiburg im Breisgau (hereafter referred to as Freiburg) as an exemplary application region. These models simplify the modeling process compared to comprehensive city-scale models by using a simplified geometry and representative hydrogeological and thermal underground characteristics. The 3D box models are checked against the city-scale model of the study area to evaluate the box models' representativeness. Their simple design and short simulation runtimes make the box models suitable for potential future applications in other study areas. Comparing the obtained power density values from the box models to the existing heating and cooling demand in the city of Freiburg then allows estimating heating and cooling supply rates that could be realized by ATES applications. Furthermore, this study compares GHG emissions of the potential ATES application in the city of Freiburg to those from conventional technologies, which are currently in operation.

4.2 Materials and methods

4.2.1 Study area

The study area is located within the municipality of Freiburg in Southwest Germany with a population of about 230,000. The city of Freiburg has been regarded as a ‘green city’ role model for more than three decades due to the city’s efforts to promote ecological urbanization, environmental policies and high quality of life (Fastenrath and Braun, 2018; Medearis and Daseking, 2012; Rohracher and Späth, 2014). It covers a total area of about 153 km^2 and is located at the transition of the Upper Rhine Graben (URG) to the Black Forest mountain range (Figure 4.1a). The upper graben fill sediments consisting of Pliocene and Quaternary gravel deposits from the Alps and uplifted rift flanks form productive porous aquifers, and thus provide a major portion of the regional drinking water supply as well as industrial and irrigation water demands (Geyer and Gwinner, 2011; Villinger, 1999). In the area of Freiburg, the upper graben fill developed as an alluvial fan of the Dreisam River (Figure 4.1b) and by glacial meltwater from the Black Forest. The shallow aquifer in this area consists of two unconfined groundwater bodies, which are hydraulically connected (Figure 4.1c).

The upper groundwater body in the study area is formed by the Neuenburg Formation consisting of predominantly unweathered and loosely bedded gravels with varying sand and low silt contents. The underlying Breisgau Formation consists of partially weathered sandy-silty gravels and has a lower hydraulic conductivity (Table 4.1). However, there is no distinct transition between these two Pleistocene formations which have a combined thickness of mostly less than 100 m (Geyer and Gwinner, 2011; LUBW, 2006; Villinger, 1999; Wirsing and Luz, 2005). In accordance with the hydraulic head contour lines in Fig. 1b, the direction of regional groundwater flow is Northwest towards the river Rhine. The contour lines are interpolated from a total of 118 groundwater monitoring wells using each well’s five-year mean hydraulic head.

The two areas in Figure 4.1b marked as hydraulically isolated are known as ‘Lehener Bergle’ (in the north) and ‘Honigbuck’ (in the south). They are tectonic horst structures that remained at the surface during subsidence of the surrounding rift system. These Mesozoic sedimentary rocks are hydraulically not connected to the Pliocene and Quaternary sand and gravel deposits (Villinger, 1999).

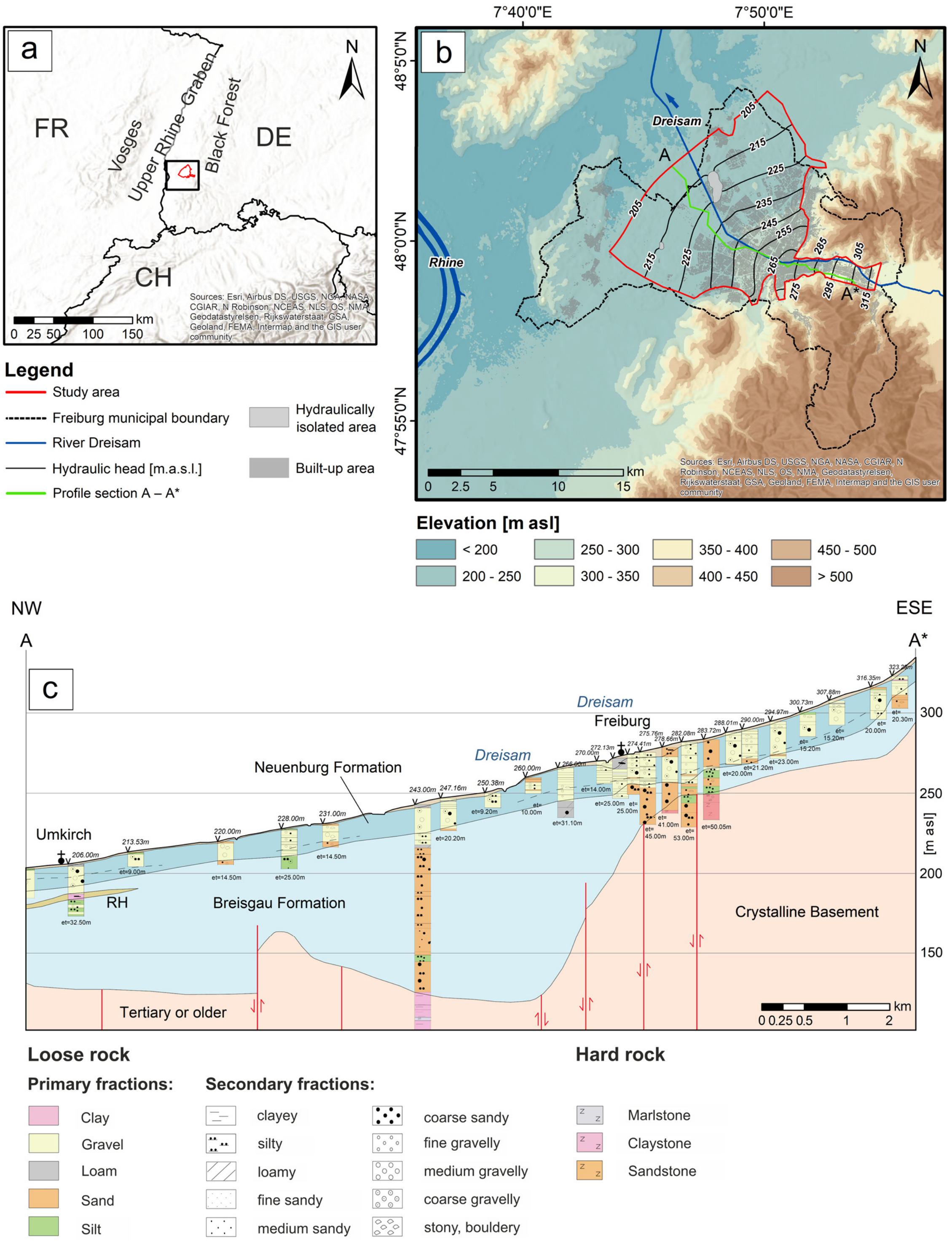


Figure 4.1: (**a**), (**b**): Location of the city of Freiburg im Breisgau with the highlighted study area in Southwest Germany. (**c**): Profile section A – A*. The Riegel Horizon (RH) shown in the profile section is not regarded in the numerical models. Data from GDI-BW (2015), Geofabrik (2022), USGS (2017). Hydraulic head data from the Environmental Protection Authority Freiburg and the Baden-Württemberg State Institute for the Environment, Survey and Nature Conservation (LUBW). Profile section modified from Wirsing and Luz (2005).

4.2.2 City-scale model

A city-scale numerical 3D finite element method (FEM) subsurface model of the Freiburg study area is built in COMSOL. Details on the thermo-hydraulic numerical modeling in this study including the required basic equations are given in the Supplementary data (Section S4.1). The Freiburg subsurface flow and heat transport model discretized by about 1.5 million tetrahedral elements covers an area of about 72 km^2 and has a vertical extent of about 290 m (Figure 4.1). In this study, the city-scale model serves as a baseline benchmark for the evaluation of the box models' representativeness when determining the power density in the city of Freiburg.

Table 4.1 shows the hydraulic and thermal parameters assigned to the city-scale model including the hydraulic conductivity of the Neuenburg Formation, which is implemented as a spatially varying parameter and used for model calibration. Section S4.2 in the Supplementary data provides further information regarding the subsurface model's geometry and boundary conditions (BCs), as well as its calibration.

The characteristics of longitudinal and transverse dispersivities in transport phenomena are a field of active and current research (Di Dato et al., 2022; Park and Lee, 2021; Pophillat et al., 2020b; Younes et al., 2020). For this study focusing on the development of a novel methodology for city-scale assessment of the technical ATES potential, we assume commonly used thermal dispersivities (Table 4.1).

Table 4.1: Subsurface parameters and their corresponding values used in the numerical Freiburg city-scale model and box models.

Parameter	Value	Unit	Reference
Hydraulic properties			
Porosity	0.15	-	Typical value for the study area (Geyer and Gwinner, 2011)
Fluid density	1000	kg m^{-3}	Stauffer et al. (2014)
Solid density	2650	kg m^{-3}	Stauffer et al. (2014)
Horizontal hydraulic conductivity (ratio horizontal to vertical hydraulic conductivity = 10)	Neuenburg F.: calibrated[a] (range: 1.0×10^{-4} – 4.42×10^{-3}) Breisgau F.: 6.0×10^{-5}	m s^{-1}	Baden-Württemberg State Office for Geology, Raw Materials and Mining (LGRB) (personal communication)
Thermal properties			
Ambient aquifer temperature (initial condition)	12	°C	Environmental Protection Authority Freiburg (personal communication)
Fluid heat capacity	4200	J kg^{-1} K^{-1}	Meng et al. (2018), Stauffer et al. (2014)
Solid heat capacity	750	J kg^{-1} K^{-1}	Meng et al. (2018), Stauffer et al. (2014)
Fluid thermal conductivity	0.6	W m^{-1} K^{-1}	Stauffer et al. (2014)
Solid thermal conductivity	Neuenburg F.: 6.5 Breisgau F.: 4.6	W m^{-1} K^{-1}	Menberg et al. (2013b), Stauffer et al. (2014)
Longitudinal dispersivity	10	m	Baden-Württemberg (2009), Beims (1983)
Transverse dispersivity	1	m	Baden-Württemberg (2009), Beims (1983)
Fluid heat capacity ratio	1	-	COMSOL (2020a)

[a] The reader is referred to the Supplementary data (Section S4.2) for further information.

4.2.3 Box models

4.2.3.1 Model geometry and hydrogeological subsurface data

In order to simplify and speed up the modeling process aimed at determining the power density of ATES systems within the study area, we utilize simplified numerical 3D finite element box models based on the complex city-scale subsurface model. Based on the spatial distribution of the hydraulic conductivity and hydraulic gradient in the calibrated city-scale subsurface flow model, the study area is divided into four homogeneous hydrogeological regions with the aim of minimizing differences of these parameters within a single region (Figure 4.2, Table 4.2). These two parameters, the multiplication of which results in the Darcy velocity, are chosen for the delineation since the groundwater velocity highly influences thermal plume spreading (Piga et al., 2017; Pophillat et al., 2020a; Pophillat et al., 2020b).

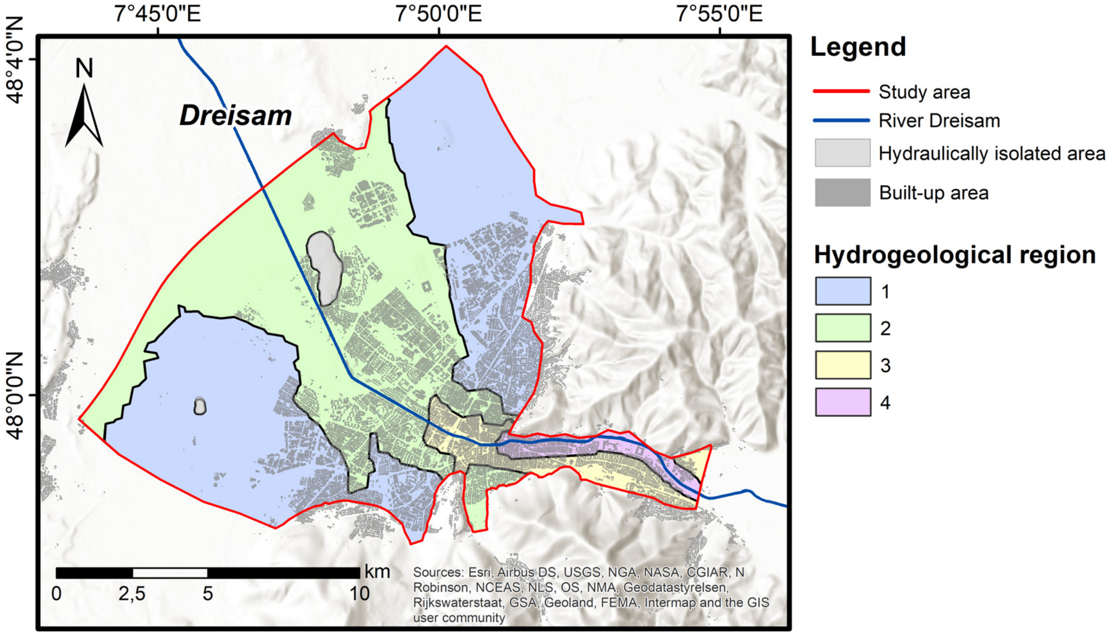


Figure 4.2: Delineated representative hydrogeological regions within the study area of Freiburg. Region delineation is based on the horizontal hydraulic conductivity and the hydraulic gradient.

Table 4.2: Representative hydraulic conductivities and hydraulic gradients of the four defined hydrogeological regions in Freiburg.

Region	**Horizontal hydraulic conductivity**[a] **[m s^{-1}]**	**Hydraulic gradient [‰]**	**Groundwater flow velocity [m d^{-1}]**
Region 1	Neuenburg F.: 6.6×10^{-4}	6.0	Neuenburg F.: 2.3 Breisgau F.: 0.2
Region 2	Neuenburg F.: 1.38×10^{-3}	7.5	Neuenburg F.: 6.0 Breisgau F.: 0.3
Region 3	Neuenburg F.: 2.01×10^{-3}	11.0	Neuenburg F.: 12.7 Breisgau F.: 0.4
Region 4	Neuenburg F.: 4.4×10^{-3}	11.5	Neuenburg F.: 29.1 Breisgau F.: 0.4

[a] Ratio horizontal to vertical hydraulic conductivity = 10

Due to very high groundwater flow velocities (29.1 m d^{-1} as calculated from horizontal hydraulic conductivity, hydraulic gradient and porosity) for the hydrogeological region 4 and the anticipated detrimental influence of the river Dreisam, ATES applications are assumed to be not feasible in region 4. Accordingly, no box models are created for that region.

For regions 1 to 3, numerical box models are generated as parallelepipeds with a length of 3500 m and a width of 600 m (Figure 4.3). They consist of two layers, the upper of which represents the Neuenburg Formation with a uniform thickness of 20 m. The lower layer represents the Breisgau Formation, which is implemented with a uniform thickness of 50 m. The hydraulic conductivities for both formations are set to the region-specific values given in Table 4.2. The slopes of the box models' surfaces and layer boundaries correspond to the respective region's representative hydraulic gradient (Table 4.2), while accounting for the assumption of a uniform groundwater table depth of 3 m throughout the box models. The hydraulic gradient along a model's longitudinal extent is implicitly implemented using 1st kind constant-head BCs on both sides of the box models. As for the city-scale model, a 2nd kind no heat flux BC, i.e. a thermal insulation BC at the top of each box model (Figure 4.3) leads to more conservative values for the power density (Ohmer et al., 2022). 2nd kind no heat flux BC are also applied at the model bottom as well as at the upstream and downstream sides. The remaining hydraulic and thermal parameters populating the box models correspond to those from the city-scale model (Table 4.1). The spatial discretization of each box model comprises about 55,000 tetrahedral elements with a finer discretization around the ATES wells.

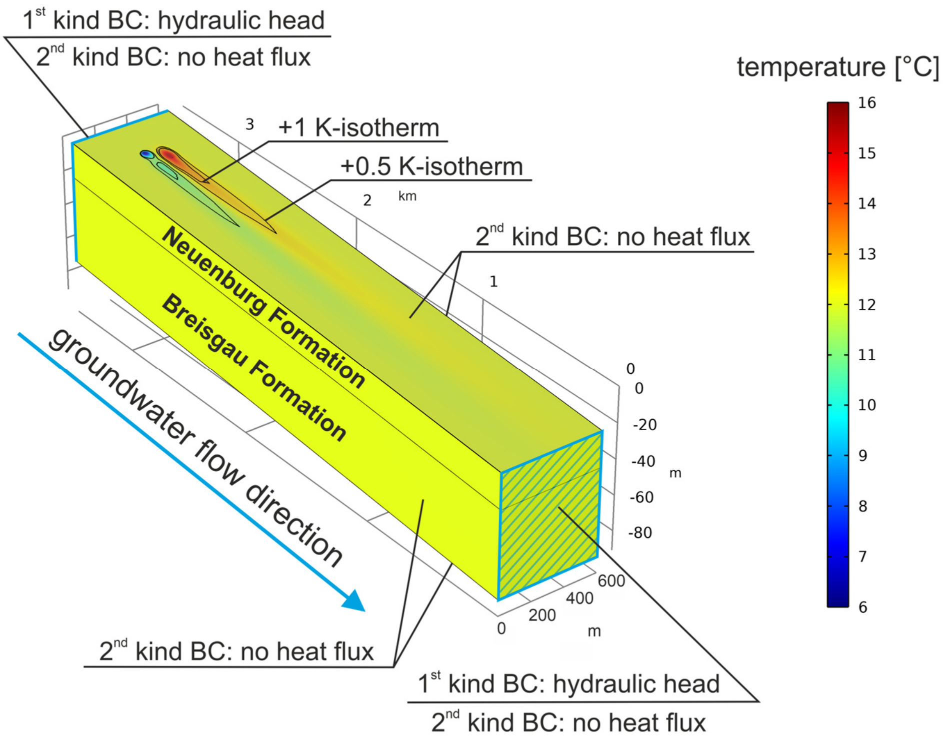


Figure 4.3: Exemplary box model of a 2-doublet ATES system in the Neuenburg Formation in hydrogeological region 1. The injection wells are implemented via 1st kind BCs (temperature) and 2nd kind BCs (mass flow rate). The extraction wells are implemented using 2nd kind BCs (mass flow rate). The black lines mark the ±1 K-isotherms and ±0.5 K-isotherms, respectively.

4.2.3.2 ATES configurations and model implementation

Under high groundwater flow velocities, substantial loss of stored thermal energy can occur, caused by the displacement of the injected water volume along the hydraulic gradient leading to low ATES efficiencies (Bloemendal and Hartog, 2018; Bloemendal and Olsthoorn, 2018). Installing two well doublets per ATES system in a line parallel to the direction of the ambient groundwater can reduce these thermal energy losses (Figure 4.4). The appropriate pumping scheme then involves injecting the heated or cooled water at the upstream wells. In the following season, the stored and since displaced heated or cooled water is extracted from the corresponding downstream wells. To further improve recovery of stored thermal energy, ATES configurations with three doublets are also possible. In this case, the ATES system consists of an upstream injection well doublet, a downstream extraction doublet and a middle well doublet operating in an alternating way comparable to single-doublet systems. For 2-doublet and 3-doublet systems, the iterative adaptation of the distance between the individual ATES doublets achieves the highest possible recovery rates of stored thermal energy in each box model.

Six different ATES configurations were simulated for each of the regions 1 to 3. ATES systems with one, two and three doublets were either placed in the Neuenburg Formation or in the Breisgau Formation leading to a total of 18 distinct box models. All wells are implemented with fully penetrating well screens over the entire thickness of the respective formation as proposed by Bloemendal et al. (2018). Each box model is run for 30 years according to the typical expected lifetime of ATES applications (Bloemendal et al., 2014; Sommer et al., 2015).

The distance between the warm and the cold wells of a well doublet equals two times the thermal radius R_{th} of the individual wells which can be computed as (Doughty et al., 1982):

$$R_{th} = \sqrt{\frac{c_w V}{c_{aq} \pi L}} \tag{4.1}$$

Here c_w and c_{aq} represent the thermal capacities of water and the aquifer. V marks the volume of water that is injected during one injection period. The filter screen length of the ATES wells is represented by L. The lateral inter-well distance of two times R_{th} ensures that no thermal interference between the warm and the cold wells of a well doublet occurs, which would lead to storage losses.

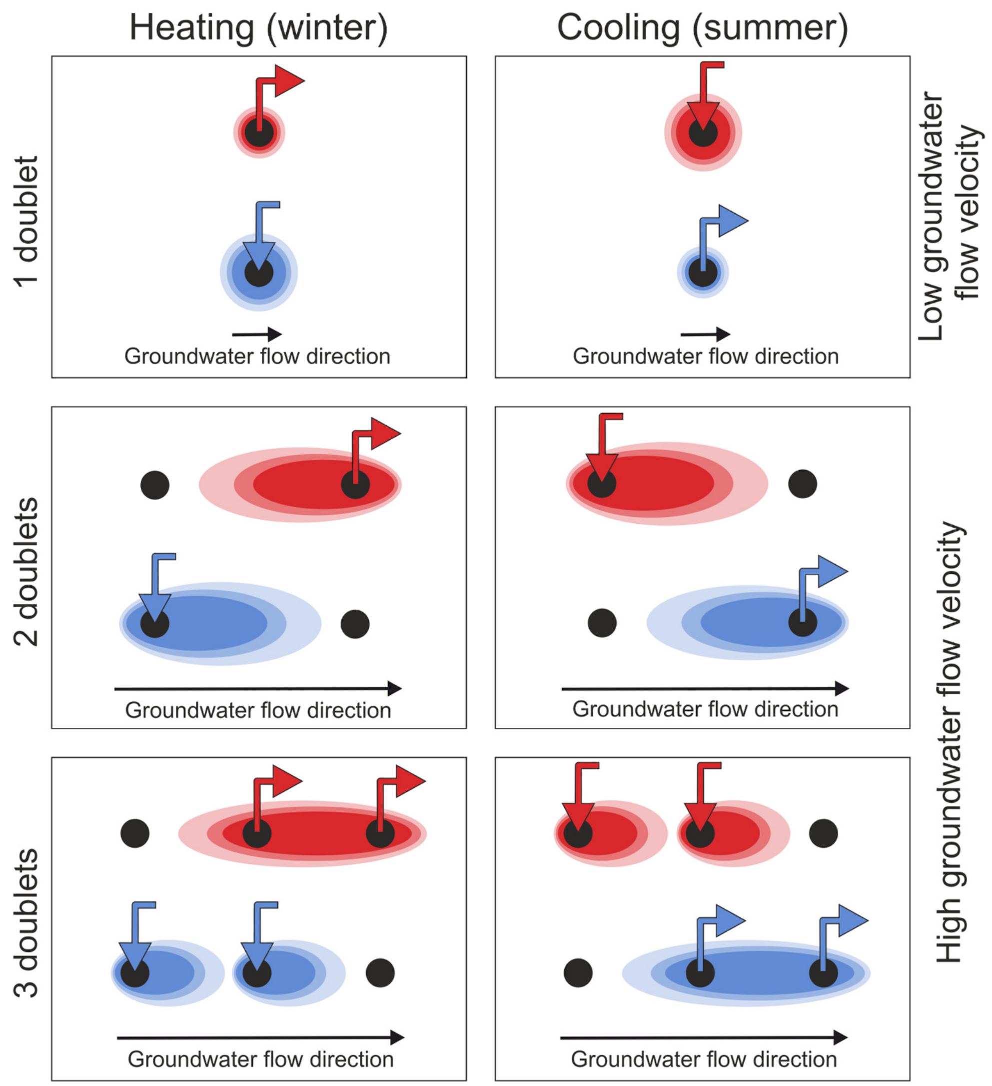


Figure 4.4: Schematic ATES configurations showing top view illustrations of ATES systems with one, two and three well doublets.

Typical seasonal ATES systems are used in heating mode in winter and in cooling mode in summer. However, short-term variations in energy demand may cause the system operation to shut down temporarily. Frequent switching between heating and cooling operation can also occur due to diurnal variations. In this study, these short-term fluctuations are not regarded since they presumably do not affect the long-term, overall characteristics of the thermal impact on the aquifer (Sommer et al., 2015). Accordingly, an ATES pumping scheme consisting of a 4-months period of heating during winter and a cooling period of the same length during summer is implemented in the box models. During the 2-months interim periods, the simulated ATES systems are not in active operation. This operation scheme corresponds to existing Dutch ATES systems (Sommer et al., 2013; Sommer et al., 2014). In the box models, the pumping scheme is implemented as time varying 2nd kind specified-flux BCs with flow rates of 600 m^3 d^{-1} according to typical existing GWHP systems in the city of Freiburg (Table 4.3).

The injection temperature at the warm and cold wells are defined as 1st kind BCs. Warm water is injected with a constant temperature of 18 °C, while cold water injection is set to a temperature of 6 °C. These temperatures result from assumed temperature differences during ATES operating of ±6 K with respect to the ambient temperature of 12 °C. In Germany, this difference of ±6 K is considered as the maximum acceptable change of groundwater temperature caused by open geothermal installations such as ATES and GWHP systems (Hähnlein et al., 2013; Hähnlein et al., 2011).

Table 4.3: ATES design parameters and respective values used in the box models.

Parameter	Value	Unit	Reference
Injection temperature cold water (1st kind BC)	6	°C	Hähnlein et al. (2011)
Injection temperature warm water (1st kind BC)	18	°C	Hähnlein et al. (2011)
Pumping rate (2nd kind BC)	600	$m^3\ d^{-1}$	According to typical existing GWHP systems in Freiburg.
Well diameter	0.5	m	According to typical existing GWHP systems in Freiburg.

4.2.4 Calculation of thermal recovery

The efficiency of individual ATES wells or doublets of ATES wells of the same kind (i.e. warm or cold) in terms of storage loss is commonly quantified by the thermal recovery *TR* (Gao et al., 2017). This quantity is the ratio of extracted thermal energy and the thermal energy injected during the previous injection period, both with respect to the ambient aquifer temperature. *TR* accordingly describes thermal loss due to advective, conductive and dispersive heat transport as well as potential thermal interferences (Abuasbeh et al., 2021; Birhanu et al., 2015; Fleuchaus et al., 2020b; Sommer et al., 2013; Sommer et al., 2014). It can be calculated as (Abuasbeh et al., 2021):

$$TR = \frac{E_{extr}}{E_{inj}} = \frac{\int_{extr\ start}^{extr\ end} \dot{V}_{extr} \cdot (T_{extr} - T_{amb})\ dt}{\int_{inj\ start}^{inj\ end} \dot{V}_{inj} \cdot (T_{inj} - T_{amb})\ dt} \tag{4.2}$$

Here, E_{extr} and E_{inj} represent the extracted and injected thermal energy with respect to the ambient aquifer temperature T_{amb}. T_{extr} and T_{inj} indicate the temperatures of the extracted and injected groundwater, respectively. $\dot{V}_{extr}$ and $\dot{V}_{inj}$ are the extraction and injection flow rates, which are identical and constant over time according to Table 4.3. The values of extracted and injected thermal energy are calculated in COMSOL for both the warm and the cold ATES well(s). The corresponding energy ratio *TR* is then determined for each complete pumping cycle consisting of injection, passive storage and extraction.

Since the temperature of the surrounding aquifer progressively adopts the comparatively higher or lower temperature of the injected water, early storage and recovery cycles typically exhibit higher conductive storage loss and therefore show lower *TR* values (Sommer et al., 2013). After the tenth cycle, however, no further increase of *TR* was observed during simulations. This is in good agreement with statements from previous studies (Bakr et al., 2013; Duijff et al., 2021; Sommer et al., 2013). Accordingly, the representative *TR* value used for further evaluation equals the average of *TR* for the warm and the cold well(s) for the tenth complete cycle, i.e. in the tenth year of operation.

4.2.5 Calculation of ATES power density

ATES power density values, which relate the amount of thermal power supplied by ATES systems to the required horizontal Earth surface area, are calculated for the city of Freiburg using the 18 box models based on the assumption that ATES systems are installed in the city as dense as possible without individual systems thermally influencing adjacent systems. For this purpose, we use the so-called thermally affected zone (TAZ) around the ATES wells in each box model after 30 years of ATES operation (Lo Russo et al., 2012). In the literature, the TAZ is commonly defined as the area where the absolute value of the temperature increase or decrease caused by ATES or GWHP systems exceeds 1 K, i.e. by the ±1 K-plumes (Gizzi et al., 2020; Lo Russo et al., 2012; Piga et al., 2017). However, this limit for adverse thermal interferences lacks scientific justification and seems to be chosen almost arbitrarily (Pophillat et al., 2020a). Given these uncertainties, we choose the more spacious ±0.5 K-isotherms after 30 years to delineate the TAZ in the block models. While this approach ensures even smaller thermal influences between adjacent systems, it also leads to more conservative power density values. For calculating the power density in this study, the space requirements with respect to the horizontal earth surface, i.e. the TAZ surface area, are determined as the smallest possible rectangle around the ±0.5 K-isotherms after 30 years as shown in Figure 4.5. The impact of choosing the ±0.5 K-isotherms is briefly evaluated by also calculating the power densities based on the ±1 K-isotherms for comparative purposes.

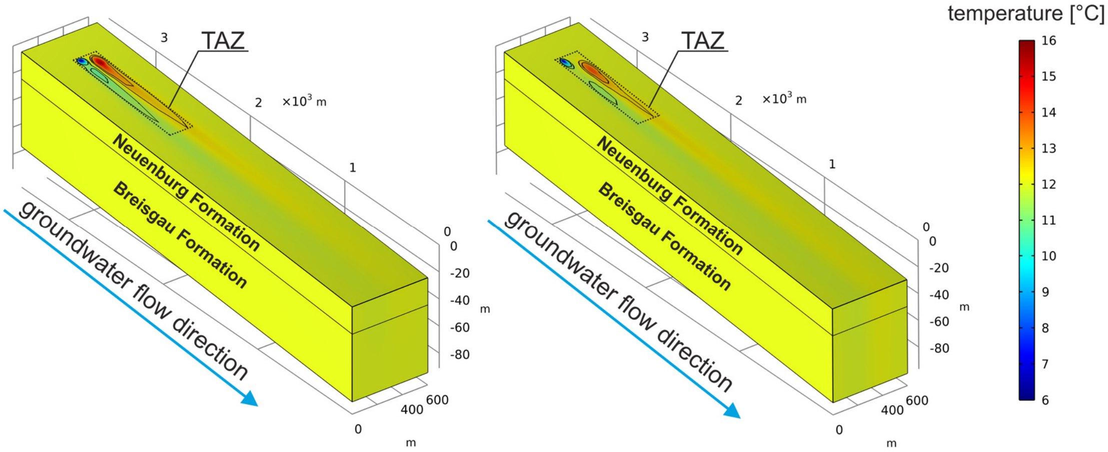


Figure 4.5: Exemplary box models of two 2-doublet ATES systems in the Neuenburg Formation in hydrogeological region 1 (left) and hydrogeological region 2 (right). The TAZ around the ±0.5 K-isotherms after 30 years of operation are highlighted. The smaller ±1 K-isotherms are also shown (black solid lines).

Based on the TAZ surface area A_{TAZ}, the power density values for heating mode $PD_{heating}$ and cooling mode $PD_{cooling}$ can be calculated as:

$$PD_{heating} = \frac{\bar{P}_{heating} \cdot f_{ava}}{A_{TAZ} \cdot 0.5} \tag{4.3}$$

and

$$PD_{cooling} = \frac{\bar{P}_{cooling} \cdot f_{ava}}{A_{TAZ} \cdot 0.5} \tag{4.4}$$

Here, it should be noted that the calculated power densities are the annual mean power densities for heating and cooling via ATES and therefore also incorporate the periods of a year in which the system does not operate in the respective mode. This is accounted for by the availability factor f_{ava} resulting from the 4-months' time period per year in which the system operates in heating or in cooling mode, respectively. Thus, the factor is $f_{ava} = 4/12$. Calculating the power density this way allows for a meaningful comparison with the existing heating and cooling demand, which is given as the total energy demand per area and year.

The mean values of heating power $\bar{P}_{heating}$ and cooling power $\bar{P}_{cooling}$ during heating and cooling periods in Equations (4.3) and (4.4), are calculated according to:

$$\bar{P}_{heating} = \dot{V}_{extr} \cdot \rho_f c_{p,f} \cdot [(T_{inj,warm} - T_{amb}) \cdot TR + (T_{amb} - T_{inj,cold})] \cdot f_{HP} \tag{4.5}$$

and

$$\bar{P}_{cooling} = \dot{V}_{extr} \cdot \rho_f c_{p,f} \cdot [(T_{amb} - T_{inj,cold}) \cdot TR + (T_{inj,warm} - T_{amb})] \tag{4.6}$$

Here, the inclusion of the thermal recovery TR allows to utilize the constant injection temperatures $T_{inj,warm}$ and $T_{inj,cold}$ at the warm and the cold ATES storage, respectively, instead of the respective extraction temperatures which vary throughout the extraction phase.

The factor f_{HP} considers the operation of a heat pump during heating mode, which adds heating power originating from the electricity grid to the thermal energy stored in the groundwater. Cooling, on the other, is assumed to be feasible without the operation of a heat pump (i.e. direct cooling). The factor f_{HP} can be determined from the coefficient of performance COP of the heat pump according to:

$$f_{HP} = \frac{COP}{COP - 1} \tag{4.7}$$

In this study, we assume a typical coefficient of performance $COP = 3.5$ (Bayer et al., 2012; Born et al; Duijff et al., 2021; Saner et al., 2010). This results in the factor $f_{HP} = 1.4$.

4.2.6 Determination of ATES heating and cooling supply rates

This study follows the nomenclature by Tissen et al. (2019), who defined ATES heating and cooling supply rates as the shares of residential heating and cooling energy demands, respectively, that can potentially be supplied by ATES applications.

The residential heating energy demand for the city of Freiburg is available at building block level, calculated based on building characteristics, such as energetic classification, living space and building age (LUBW, 2017). Besides space heating demand, the heating demand also includes thermal energy needed for residential water heating. The data set presents the heating demand referring to the original building conditions as well as lower demand values assuming building refurbishment. Since energetic building refurbishment is an important pillar of the German energy transition in the building sector (Grossmann, 2019), the supply rates in this study refer to the heating demand after refurbishment. These demand values are related to each building block's areal extent resulting in the heating energy demand given in MWh ha^{-1} a^{-1}.

In contrast to the heating energy demand, no such detailed data is available for the cooling energy demand in the city of Freiburg. Thus, we estimate the cooling energy demand by using a ratio of 5 to 1 for heating demand to cooling demand. This demand ratio is obtained from the study by Werner (2016), who determined living space specific cooling demands of residential buildings in the European Union countries including Germany. The ratio of 5 to 1 also corresponds well to the heating and cooling energy demand in Freiburg from the European hotmaps project datasets (Mueller, 2019; Mueller and Fallahnejad, 2020).

The calculation of ATES heating and cooling supply rates requires the conversion of the energy demand data to the power density's physical unit W m^{-2}. Due to its universal nature, the power density *PD* determined with the ATES box models allows for its straightforward comparison with the thermal energy demand *ED* in order to calculate possible supply rates *SR* as follows (similar to e.g. Epting et al. (2018), Tissen et al. (2019)):

$$SR = \frac{PD}{ED} \tag{4.8}$$

4.3 Results and discussion

4.3.1 Thermal recovery

The thermal recovery *TR* is an important parameter describing the storage efficiency of ATES systems and quantifying thermal energy loss in the subsurface. In this study, it is determined using numerical 3D box models, each of which represents a distinct hydrogeological region of the city-scale subsurface model of Freiburg. For each ATES configuration the thermal recoveries are calculated according to Equation (4.2). As shown in Figure 4.6, thermal recoveries of ATES systems in the deeper aquifer, i.e. the Breisgau Formation, are consistently higher for all ATES configurations and all regions compared to systems in the upper aquifer (Neuenburg Formation), which is characterized by higher groundwater flow velocities (Table 4.4). In order to mitigate the detrimental effects of the groundwater flow on the energy storage efficiency, different ATES configurations with one, two or three well doublets are modeled as described above. For the Breisgau Formation, 3-doublet ATES configurations show the highest thermal recoveries with up to *TR* = 59 % in hydrogeological region 1 (Figure 4.6). In contrast, 1-doublet systems recover the lowest share of thermal energy. This system configuration also shows the lowest recovery values for ATES in the Neuenburg Formation, while the highest thermal recoveries for the Neuenburg Formation can be observed for systems with 2 well doublets with up to 42 %.

These results demonstrate the strong influence of the ambient groundwater flow velocity on the thermal recovery and the suitable ATES design. High advective heat transport rates caused by high groundwater flow velocities of up to 12.7 m d^{-1} entail significant subsurface energy loss (Figure 4.6, Table 4.4). Thus, thermal recovery values for 1-doublet systems in the Neuenburg Formation are very low with the maximum being *TR* = 4 % in hydrogeological region 1. By adding a second downstream extraction well doublet, thermal recoveries substantially increase up to *TR* = 42 %. However, the thermal recovery values for 2-doublet ATES configurations are still significantly lower than typical recovery values reported in the literature and discussed below. This is especially true for regions 2 and 3 with *TR* = 27 % and *TR* = 13 %, respectively, indicating that at high groundwater flow velocities the 2-doublet configuration type can mitigate thermal losses only to a limited extent. The use of three well doublets in the upper aquifer does not improve thermal recovery but instead leads to recovery values which are slightly lower than for 2-doublet systems. Compared with the groundwater flow velocity, variations of other parameters, such as the ambient groundwater temperature and the solid thermal conductivity, have been shown to have a negligible effect on the thermal recovery. Further details on this are provided in the Supplementary data (Section S4.3).

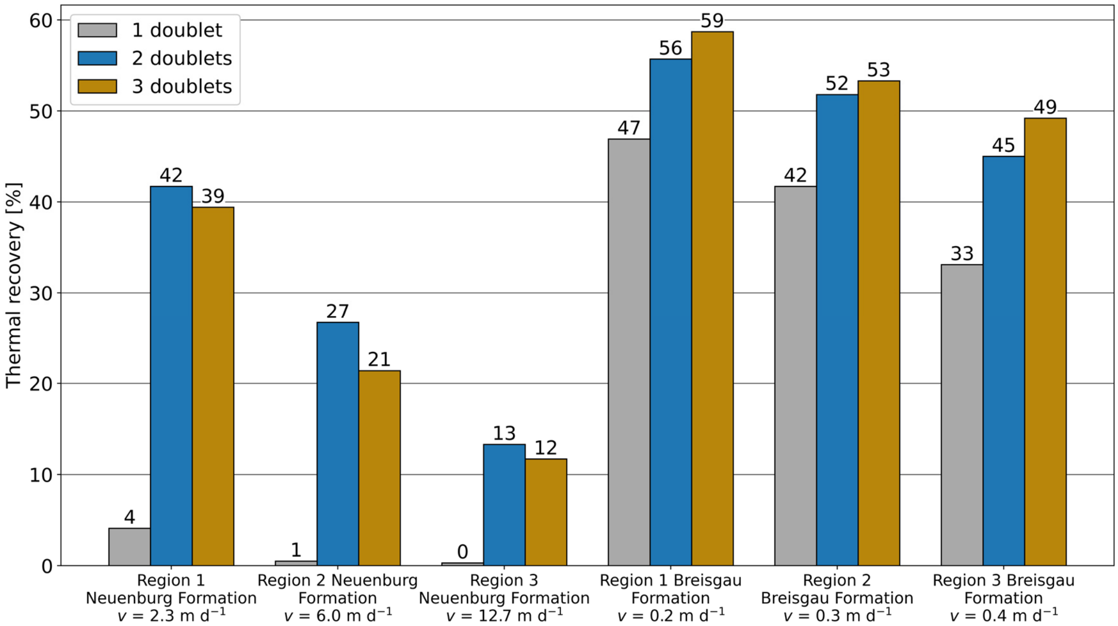


Figure 4.6: Thermal recovery values for various ATES configurations in different groundwater flow regimes. Ambient groundwater flow velocities v in the Neuenburg and the Breisgau Formations in hydrogeological regions 1 to 3 are also shown.

Table 4.4: Groundwater flow velocities in hydrogeological regions 1 to 3.

	Groundwater flow velocity [m d^{-1}]		
	Region 1	Region 2	Region 3
Neuenburg Formation	2.3	6.0	12.7
Breisgau Formation	0.2	0.3	0.4

Previous studies of LT-ATES systems revealed thermal recoveries of 47 % up to 90 % for ambient groundwater flow velocities ranging from 0.01 m d^{-1} to 1.6 m d^{-1} further demonstrating this parameter's influence on the storage efficiency (Abuasbeh et al., 2021; Bloemendal and Olsthoorn, 2018; Kangas and Lund, 1994; Sommer et al., 2014). Figure 4.7 shows the relation between thermal recoveries of ATES systems from the literature as well as from this study and the corresponding ambient groundwater flow velocities. The recovery values from this study correspond to the maximum recoveries of each hydrogeological region as shown in Figure 4.6.

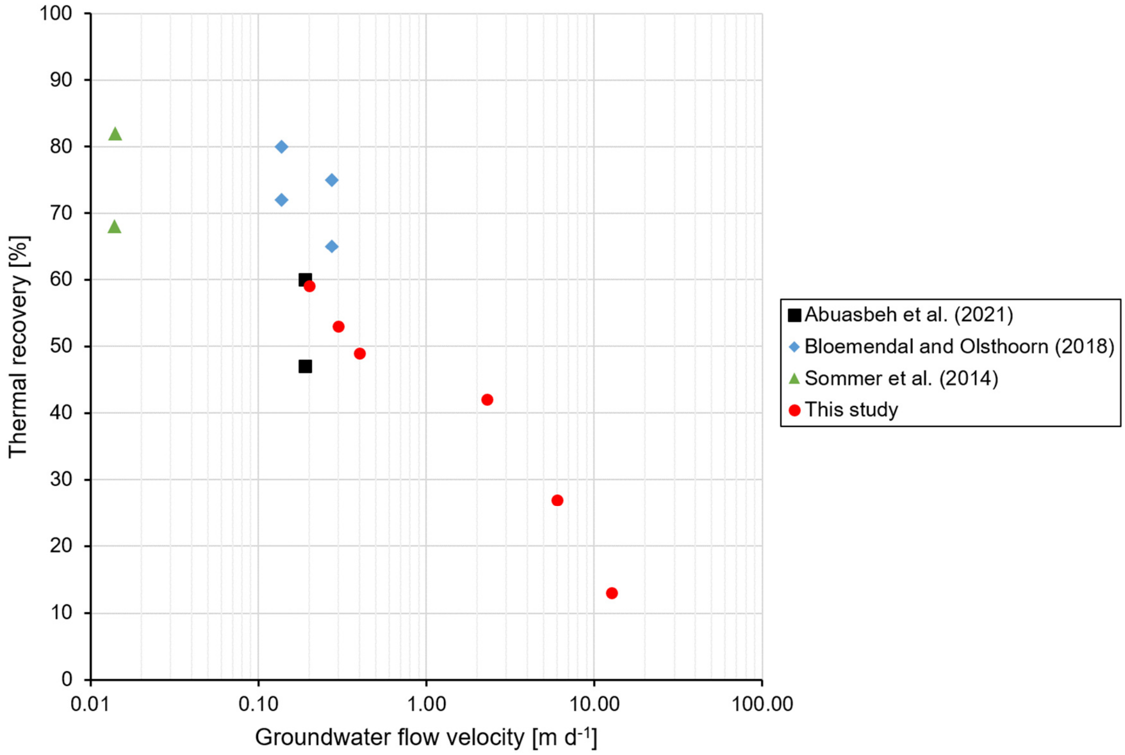


Figure 4.7: Thermal recoveries of ATES systems from this study and previous publications plotted against the corresponding ambient groundwater flow velocities. Data points from Abuasbeh et al. (2021), Bloemendal and Olsthoorn (2018), Sommer et al. (2014).

Sommer et al. (2014) analyzed an LT-ATES in Utrecht, the Netherlands, where the flow velocity is a mere 0.01 m d^{-1} and therefore significantly lower than in the Freiburg study area (Table 4.4). A thorough monitoring showed mean thermal recoveries during a seven-year operation period of 68 % and 82 % for the warm storage area and the cold storage area, respectively. Drijver et al. (2012) state values between 70 % and 90 % as typical range of thermal recoveries for LT-ATES systems in aquifers with low flow velocities. Similar recovery values are reported in Bakr et al. (2013) for multiple densely placed LT-ATES systems in the Dutch city of The Hague using thermo-hydraulic modeling. The minimum thermal recovery amongst all ATES systems was 68 % in the first year. Over the course of the ten years modeling period, the recovery values showed an increasing trend towards steady state values with the maximum thermal recovery being 87 % in the tenth year. The above-mentioned studies all refer to Dutch systems operating under conditions of very low ambient groundwater flow velocities.

Other publications studied ATES systems located in aquifers with higher ambient groundwater flow velocities. Numerically computed thermal recoveries of mostly between 73 % and 80 %

are stated for 2-doublet ATES systems and an ambient groundwater flow velocity of 0.1 m d^{-1} in Bloemendal and Olsthoorn (2018). For a flow velocity of 0.3 m d^{-1}, which entails higher subsurface heat loss, the same study gives recovery values ranging mostly from 65 % to 75 %. Flow velocities of about 0.1 m d^{-1} and 0.2 m d^{-1} are stated for a Swedish LT aquifer storage system, which result in mean thermal recovery values of 47 % and 60 % for the warm and the cold storage areas, respectively (Abuasbeh et al., 2021). These numbers are in line with this study's thermal recoveries for 3-doublet systems in the Breisgau Formation ranging from $TR = 49$ % to $TR = 59$ % corresponding to groundwater flow velocities between 0.2 m d^{-1} and 0.4 m d^{-1} (Table 4.4). In the literature, it was also demonstrated that LT-ATES systems can be possible with ambient flow velocities of up to 1.6 m d^{-1} when using multi-doublet configurations (Kangas and Lund, 1994).

4.3.2 Power density of ATES

The heating and cooling power densities achievable with ATES systems in the city of Freiburg are calculated according to Equations (4.3) and (4.4), respectively, for the ATES designs with the highest thermal recoveries (Figure 4.6). For the Neuenburg and the Breisgau Formation, these are the 2-doublet and 3-doublet configurations, respectively.

The highest power densities for ATES systems placed in the Neuenburg Formation are calculated for hydrogeological region 3 with $PD_{heating} = 1.6$ W m^{-2} and $PD_{cooling} = 1.2$ W m^{-2}, while aquifer storage systems in region 1 lead to the lowest power densities of $PD_{heating} = 1.3$ W m^{-2} and $PD_{cooling} = 0.9$ W m^{-2} (Figure 4.8). This is in contrast to the thermal recovery, which is highest for region 1 and lowest for region 3 (Figure 4.6) and shows the high influence of the thermally affected zone's area on the power density according to Equations (4.3) and (4.4). Due to the Neuenburg Formation's high ambient groundwater flow velocities in region 2 and 3 relative to region 1 (Table 4.4), the injected thermal plume undergoes a more pronounced dispersive spread in regions 2 and 3 leading to shorter ±0.5 K-isotherms. In region 1, on the other hand, the comparatively low flow velocity results in more stable and thus much more elongated ±0.5 K-isotherms. Accordingly, the TAZ for region 1 is about 58 % larger than for region 3 and about 30 % larger than for region 2 resulting in the lowest power density for ATES systems in region 1.

These effects are similar for the utilization of the deeper Breisgau Formation. There, however, the ambient groundwater flow velocity and accordingly the extent of the TAZ vary much less between regions 1 to 3. The highest and lowest heating power densities of ATES systems placed in the Breisgau Formation are calculated to $PD_{heating} = 3.2$ W m^{-2} and $PD_{heating} = 2.7$ W m^{-2} for hydrogeological regions 2 and 1, respectively (Figure 4.8). As for the systems in the Neuenburg Formation, due to free cooling without the use of a heat pump, the power density values for cooling mode are uniformly smaller by the factor $f_{HP} = 1.4$.

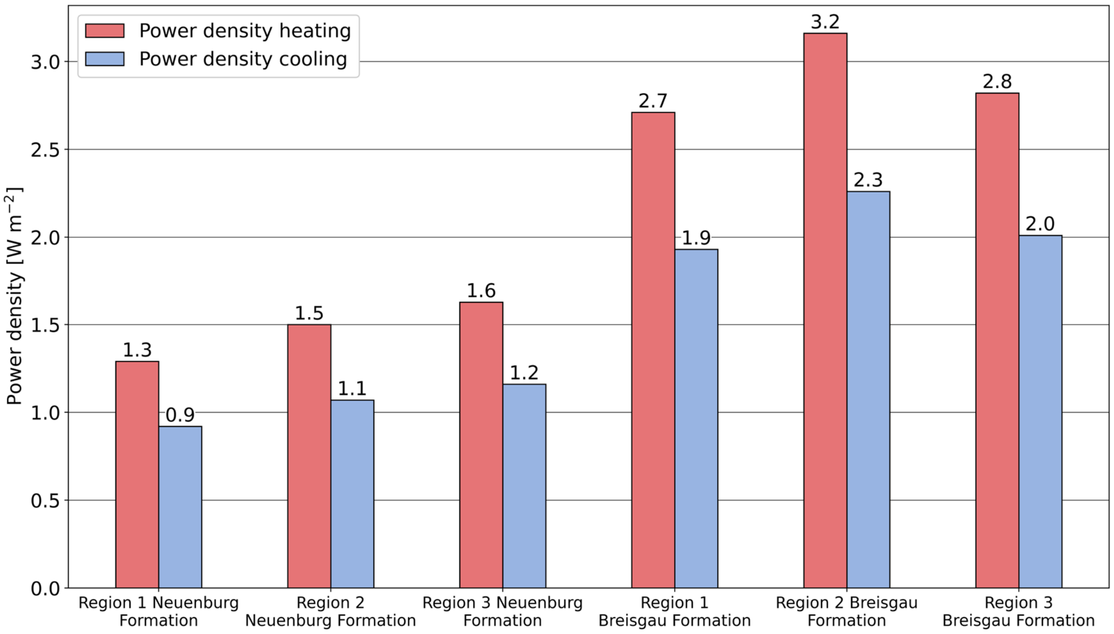


Figure 4.8: ATES power densities for Neuenburg and Breisgau Formations. ATES systems in the Neuenburg Formation are simulated as 2-doublet configurations. ATES systems in the Breisgau Formation use a 3-doublet configuration.

Previous studies on the technical potential of shallow geothermal applications were compared regarding their power density in Bayer et al. (2019). However, they only covered studies on closed geothermal systems such as GSHP systems. The compiled power density values range from about 7 W m^{-2} up to a 460 W m^{-2} reflecting a large variety of underlying assumptions and methodological approaches (Bayer et al. (2019) and references therein). Power densities of GSHP systems in an urban quarter ranging from 14 W m^{-2} to 93 W m^{-2} can be inferred from Tissen et al. (2019). GSHP systems typically induce much smaller thermal anomalies in the subsurface (Perego et al., 2022) explaining these consistently higher power densities compared to the values of the open systems in this study.

Power density values for open GWHP systems in an urban quarter described in the literature were calculated similarly to the approach described in this study, i.e. using the areal extents of the thermal plumes (Tissen et al., 2019). However, these were determined analytically, and may therefore deviate significantly from numerically simulated thermal plumes (Pophillat et al., 2020a). Nevertheless, with values of about 3 W m^{-2}, the power densities for two GWHP scenarios are similar to the power density values from this study (Figure 4.8). It should be noted, however, that Tissen et al. (2019) used the ±1 K-isotherms to delineate the TAZ compared to our more conservative approach of using the ±0.5 K-isotherms. For further comparisons, Figure S4.4 in the Supplementary data presents the less conservative power density values calculated from the box models using the ±1 K-isotherms after 30 years. On average, these power densities are about 2.1 times as high as the values shown in Figure 4.8. The strong sensitivity of the thermal recoveries of open systems to the groundwater flow velocity discussed above also contributes to the differences in reported power densities.

Open GWHP systems were also evaluated regarding their thermal potential in Epting et al. (2020) in the Swiss city of Basel. In an exemplary city quarter, power densities between 12 W m^{-2} and 720 W m^{-2} can be inferred for various well distances and temperature differences of up to 8 K. These power densities are significantly higher than in this study and in Tissen et al. (2019). This is because Epting et al. (2020) only considered hydraulic effects resulting from groundwater extraction and injection rather than accounting for thermal plume propagation. The power densities' reference to surface area therefore also refers to the much smaller inter-well distances of between 10 m and 50 m leading to higher power densities.

The heating and cooling power densities calculated in this study are annual mean values resulting from the used ATES pumping scheme, i.e. a 4-months period each for the heating and cooling modes and two 2-months passive periods in between. This is in contrast to the cited studies, where the power density only refers to the periods when the system is actually in operation. In the mentioned studies of closed systems, this period is a fixed operating time per year of 2400 h a^{-1} or 1700 h a^{-1} (Bayer et al., 2019; Tissen et al., 2019), while the power density for the open GWHP systems studied in Tissen et al. (2019) relates to a year-round operation.

Our study's results refer to a specified technology used in well-defined hydrogeological conditions. Model-implemented characteristics, such as specified pumping rates or hydraulic gradients, lead to more realistic power density values constrained by technical restrictions. This is in contrast to many previous studies on the topic of shallow geothermal power densities, several of which are based on more general assumptions or ignore the influence of groundwater flow (Bayer et al., 2019). The present study also for the first time distinguishes between power densities for heating and cooling modes. In this respect, it is also important to stress the influence of the 2nd kind no heat flux BC applied to the top side of the numerical models. As shown by Ohmer et al. (2022) this can significantly increase the lateral thermal plume propagation as it impedes any dissipation or input of thermal energy to or from the atmosphere.

4.3.3 Heating and cooling supply rates with ATES

The spatial distribution of ATES power densities is shown in Figure 4.9 for ATES systems placed in the Breisgau Formation, which have higher thermal recoveries (Figure 4.6) and power densities (Figure 4.8), indicating that ATES systems in this formation are more feasible regarding heating and cooling supply rates. The figure also presents the supply rates calculated according to Equation (4.8) for each block of residential buildings. The bar charts in Figure 4.9 show the percentages of residential buildings in the study area for which ATES systems placed in the Breisgau Formation could supply a certain share of their heating or cooling energy demand.

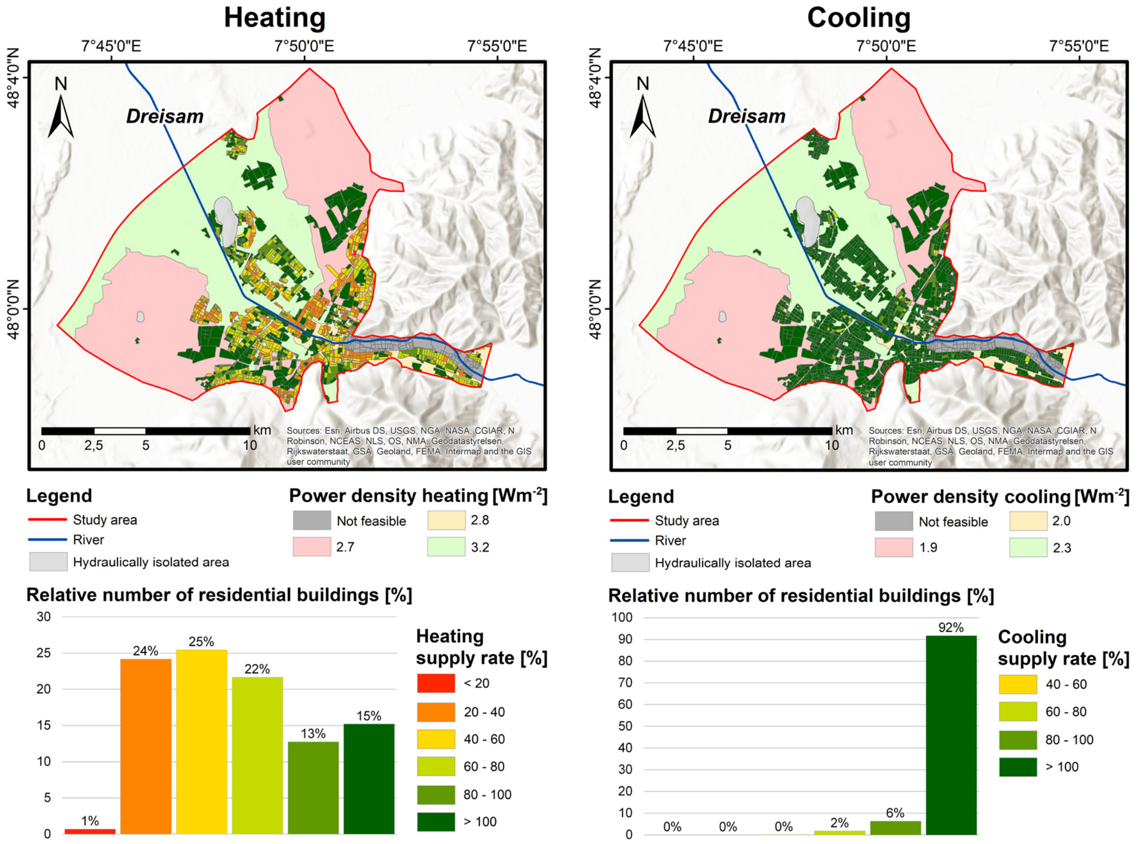


Figure 4.9: ATES supply rates in the city of Freiburg for heating (left) and cooling (right) using the Breisgau Formation. The bar charts illustrate the share of the total residential buildings within each individual supply rate class.

For about 28 % of the residential buildings, the heating supply rate is above 80 %. Heating demand supply rates of 60 % or more could be achieved for about 50 % of the residential buildings. Especially for residential buildings located in suburban or commercial and industrial districts, such as the commercial and industrial area in the northern part of the study area, ATES could supply the entire heating demand. In contrast, ATES systems in the Breisgau Formation can completely supply about 92 % of all residential buildings with cooling energy (Figure 4.9).

Similar to this study, Schiel et al. (2016) showed in a previous study on urban space heating with GSHP systems that the highest supply rates were located in suburban areas rather than the city's center. For Southwest Germany, calculations of the technical potential of GSHP systems showed that the heating demand of 65 % to 93 % of all buildings could be completely supplied by such systems with the highest supply rates again concentrating on rural and suburban areas (Miocic and Krecher, 2022). This is in line with a study of western Switzerland revealing that a complete supply of heating demand by GSHP systems is possible in many rural and suburban areas as opposed to densely populated cities for which a supply rate deficit is to be expected (Walch et al., 2021). These findings from previous publications match the spatial distribution of the ATES heating supply rates in Freiburg, which are lower in more densely populated areas (Figure 4.9).

The above-mentioned studies refer to heating energy supplied by GSHP systems. Besides GSHP systems, Tissen et al. (2019) and Tissen et al. (2021) also calculated heating supply rates of GWHP systems for urban settings in two different cities. For both cities, the supply rates of GSHP systems are significantly higher than of GWHP systems. GSHP systems could potentially supply the total heating demand, i.e. 100 %, after refurbishment in more than half of all districts in one of the cities. In contrast, the highest supply rate of GWHP systems was determined to be 83 % among all districts. The numbers for GWHP systems are in line with this study's heating supply rates of ATES systems, which are also open shallow geothermal systems.

4.3.4 Greenhouse gas emission savings with ATES

In the year 2020, the final energy demand for residential space and water heating in the city of Freiburg was around 1,000 GWh a^{-1} (GEF Ingenieur AG et al., 2021). The energy was mostly supplied by a mix of natural gas, district heating and heating oil (further details in Supplementary data, Section S4.5). In order to evaluate possible GHG emission savings achievable with ATES, two different scenarios are considered using ATES systems in the Breisgau Formation. These calculations are based on the emission factors of the Freiburg heating energy mix as well as on an ATES emission factor of 0.083 $tCO_2eq\ MWh^{-1}$ adopted from Stemmle et al. (2021).

Scenario 1 assumes an ATES supply limited to the residential building blocks for which a heating supply rate of 100 % or more was calculated in the previous chapter. This is true for about 15 % of all residential buildings (Figure 4.9). In scenario 2, ATES systems supply all residential buildings according to the building block specific supply rates. Buildings located in the study area's hydrogeological region 4 are excluded.

Figure 4.10 shows the resulting annual GHG emission savings. Scenario 1 yields savings of about 17,023 $tCO_2eq\ a^{-1}$, which equals about 10 % of the estimated current annual GHG emissions caused by space and water heating of all considered residential buildings in the study area. Higher GHG emission savings result for scenario 2. They amount to about 70,398 $tCO_2eq\ a^{-1}$ or 40 % of the total residential space and water heating related GHG emissions in the study area. Installing individual ATES systems for buildings with small supply rates is unlikely to be implemented in practice. However, integration of ATES in the existing district heating network in Freiburg poses a promising option to make use of the full technical potential.

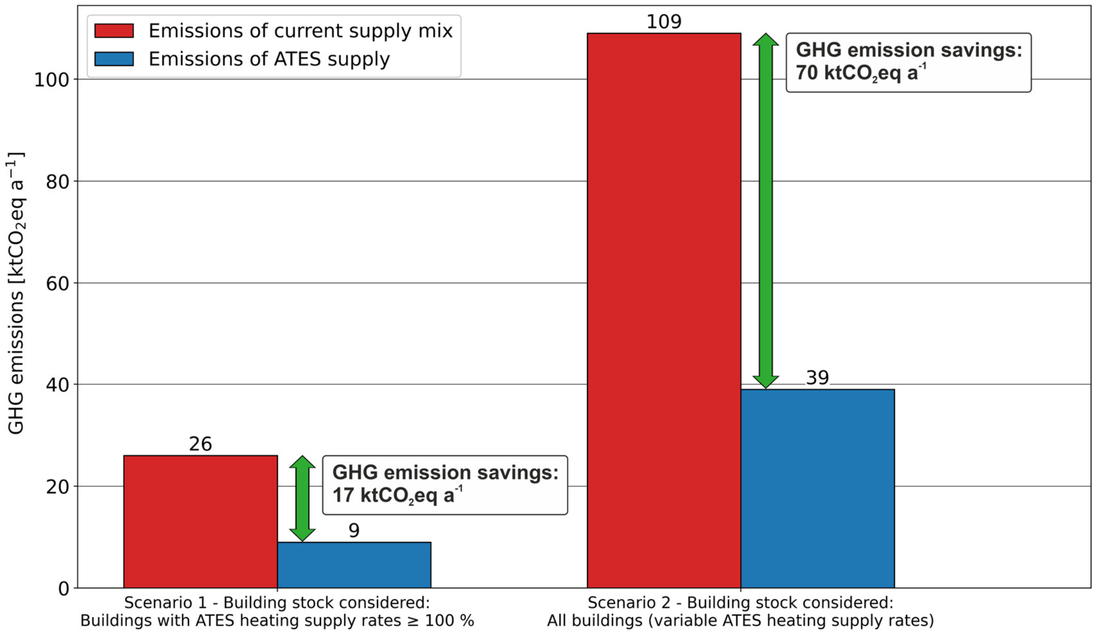


Figure 4.10: Possible GHG emission savings from ATES heating compared to the current heating energy mix in Freiburg. Calculated for two scenarios based on data from GEF Ingenieur AG et al. (2021).

For space cooling, lack of information on emission factors and the current structure of supply in Freiburg prevents calculation of GHG emission savings. The high cooling supply rates (Figure 4.9), however, indicate a large unused potential for sustainable space cooling and high GHG emission savings compared to conventional cooling technologies, such as compression chillers.

Like ATES, air source heat pumps (ASHP) are systems that can provide both, heating and cooling energy. In contrast to ATES, ASHP systems typically have lower coefficients of performance (COP) due to much stronger temperature variations of the heat source, i.e. the outside air, throughout the year (Esen et al., 2007; Gao et al., 2021; Sarbu and Sebarchievici, 2014). Thus, ATES systems typically require less electricity for the same amount of thermal output than ASHP systems. These energy savings are another advantage of ATES besides the possibility of using otherwise unused waste thermal energy.

4.3.5 Limitations of the box model approach

The box model approach used in this study prevents any thermal interferences between ATES systems, which impedes detrimental effects on the thermal recoveries. Various studies showed, however, that a holistic planning framework based on the coordinated placement of ATES systems can maximize subsurface utilization in contrast to separate planning of individual systems. This is of great importance in dense urban areas with a high ATES adoption rate and other subsurface infrastructure, such as sewage and traffic tunnels. A central component of such energy planning framework is the identification of an optimal trade-off between the combined energetic benefits across all ATES systems and the efficiency of individual systems. Furthermore, deliberate thermal interferences between wells of the same type, i.e. wells of either the warm or the cold storage areas, can decrease thermal loss at the storage volume boundaries due to a better ratio of storage surface area to storage volume (Bloemendal et al., 2018; Duijff et al., 2021; Pellegrini et al., 2019). Expanding on this study's modeling approach aimed at ATES potential determination, a city specific optimization of ATES placement in Freiburg could account for such positive thermal interferences, while also including existing shallow GWHP systems.

Utilizing a uniform mean ambient groundwater temperature of 12 °C across all box models, i.e. in all hydrogeological regions, does not allow to study the influence of different thermal regimes on thermal plume propagation. Due to the ambient groundwater flow velocity's strong influence on the plume propagation, using a mean value for this parameter seems reasonable in the context of a city-level potential assessment. This assumption is further supported by Figure S4.3 in the Supplementary data, which shows a very small influence of ambient groundwater temperatures ranging between 10 °C and 13 °C on the thermal recovery. Nevertheless, future studies using a similar approach of representative box models could potentially achieve more accurate potential estimations by including information on ambient groundwater temperature variations.

Reasons for spatial variations of the ambient groundwater temperature in urban areas include heat fluxes caused by anthropogenic heat sources and sinks, such as basements, subway infrastructure, sewage systems, and district heating grids (Benz et al., 2015). The presented model approach does not account for these heat fluxes due to the box models not being spatially localized within the study area besides their allocation to one of the hydrogeological regions (Figure 4.2).

Figure 4.11 exemplarily shows the temperature distribution after 30 years in the city-scale model with ATES systems implemented in the Neuenburg Formation. The distances between individual ATES systems along the groundwater flow direction correspond to the lengths of the TAZ in the box models and thus depend on the hydrogeological region (Figure 4.2). Along the Dreisam River the ATES placement is less dense, and hydrogeological region 4 is again excluded. Most of the modeled ±0.5 K-isotherms shown in Figure 4.11 are shorter than the length of the TAZ in the respective box model, while some of them are longer. This is to be expected since the box models are only approximations for each hydrogeological region. The differences of the thermal plume lengths between the city-scale subsurface model and the box models could be reduced by increasing the number of hydrogeological regions or the number of variable parameters in the box models, e.g. the site-specific formation thickness of the aquifers.

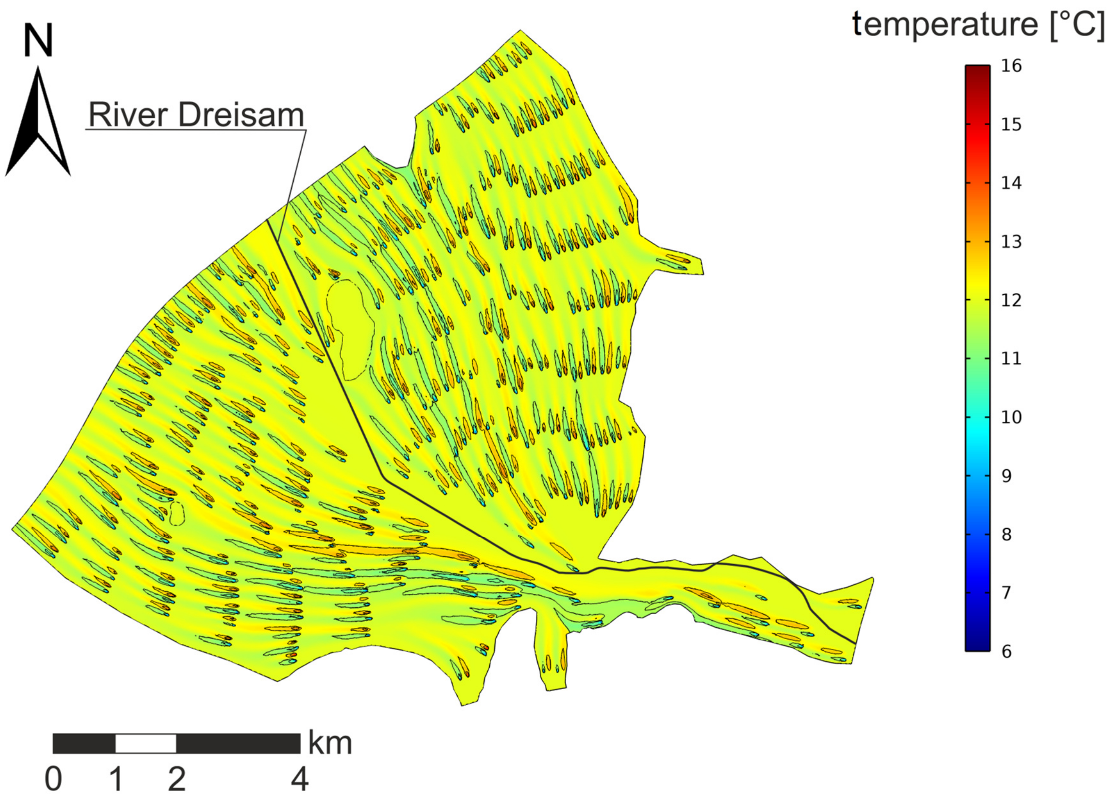


Figure 4.11: Top view of the city-scale subsurface model of Freiburg with ±0.5 K-isotherms after 30 years of ATES operation in the Neuenburg Formation. The smaller ±1 K-isotherms are also shown.

The use of representative box models has a number of advantages compared to using the city-scale subsurface model. Provided that a reasonable delineation of sufficiently homogeneous hydrogeological subsurface regions is possible, the approach allows a fast approximation of power density values for ATES operation in different cities or regions. In this study, they took an average of about 55 minutes to simulate the ATES operation over 30 years. In contrast, the Freiburg city-scale model took about 50 hours in order to complete the task on the same computer (8 CPU cores with a base clock of 3.6 GHz and 128 GB of RAM). This also means that adaptation and evaluation of different ATES system configurations are less time-consuming.

4.4 Conclusions

Using representative numerical 3D thermo-hydraulic models of a simple geometry, this study assesses the technical potential of low-temperature Aquifer Thermal Energy Storage (LT-ATES) applications in the city of Freiburg. For this purpose, the power density, which relates the amount of power generated by a specific technology to the required surface area, of space heating and cooling energy supply using ATES systems is quantified.

Simulating various ATES configurations with multi-doublet designs reduces energy storage loss. Using two or three well doublets consistently increases thermal recoveries compared to single-doublet systems. Nonetheless, relatively high groundwater flow velocities of up to about 13 m d^{-1} considerably reduce the recovery of stored thermal energy. This is especially true for ATES in the upper aquifer, the so-called Neuenburg Formation, where the maximum thermal recovery is 42 %. For ATES operation in the deeper Breisgau Formation with lower groundwater flow velocities of less than 1 m d^{-1}, thermal recovery values of up to 59 % are obtained.

Accordingly, ATES in the Breisgau Formation leads to higher power densities of up to 3.2 W m^{-2}, while the highest power density for the Neuenburg Formation is only 1.6 W m^{-2}. For the Breisgau Formation, this also enables considerably higher ATES supply rates with respect to the existing residential heating and cooling demand in Freiburg. While heating energy supply rates of larger than 60 % are determined for about 50 % of all residential buildings in the study area, the cooling energy demand could be supplied entirely by ATES systems for 92 % of the buildings.

Based on the calculated supply rates and today's final energy mix for space and water heating in Freiburg, potential GHG emission savings of up to about 70,000 $tCO_2eq\ a^{-1}$ for ATES heating alone can be estimated. This equals about 40 % of the current overall GHG emissions caused by space and water heating in the study area's residential buildings. While the extensive utilization of all the available subsurface space using ATES systems is not realistic, these numbers still show promising opportunities for ATES applications in the city of Freiburg.

In the future, this modeling approach could be expanded upon with the aim of integrating ATES into more specific and practice-oriented urban energy planning. This way, the technology could face an increasing use and could help to achieve climate protection goals at the municipal level and beyond. A brief comparison of our study results with power densities and supply rates from the literature reveals that closed GSHP systems should also be considered in urban energy planning scenarios since this type of shallow geothermal systems can potentially lead to higher power densities and supply rates. Numerical models as proposed in this study could help to identify the suitable type of shallow geothermal system for regions with similar hydrogeology.

Acknowledgements

The constructive comments of two anonymous reviewers are gratefully acknowledged. The financial support for Ruben Stemmle via the Scholarship Program of the German Federal Environmental Foundation (DBU) and the funding of Kathrin Menberg via the Margarete von Wrangell program of the Ministry of Science, Research and the Arts (MWK) of the State of Baden-Württemberg are gratefully acknowledged.

Supplementary data

S4.1 Thermo-hydraulic numerical modeling

In order to determine the power density of ATES systems in the city of Freiburg, 3D numerical models are created using a finite element approach. The software COMSOL Multiphysics (Version 5.6) is used to study the conductive and advective heat transport in the subsurface originating from implemented ATES wells. The heat transfer can be formally expressed by the following governing equation (Bidarmaghz et al., 2019; COMSOL, 2020a):

$$(\rho c_p)_{eff}\frac{\partial T}{\partial t} + \rho_f c_{p,f} u \cdot \nabla T + \nabla \cdot q = Q_h \tag{S4.1}$$

with

$$(\rho c_p)_{eff} = \varphi \cdot \rho_f c_{p,f} + (1-\varphi) \cdot \rho_s c_{p,s} \tag{S4.2}$$

and

$$q = -\lambda_{eff} \cdot \nabla T \tag{S4.3}$$

where ρ_s represents the density of the solid and ρ_f the density of the fluid, i.e. the groundwater. Due to the low range of temperatures between 6 °C and 18 °C, this study does not account for fluid density variations (Bridger and Allen, 2014; Regnier et al., 2022; Sommer et al., 2014). $c_{p,f}$ and $c_{p,s}$ represent the specific heat capacities of the fluid and the solid phase, respectively, while the term Q_h accounts for possible heat sources or sinks. The effective thermal conductivity λ_{eff} which quantifies the conductive heat flux q is calculated from the fluid (λ_f) and the solid (λ_s) thermal conductivities according to their geometric mean using the porosity φ (Menberg et al., 2013b) and is modified with the dispersive thermal conductivity λ_{disp} (COMSOL, 2020a):

$$\lambda_{eff} = \lambda_f{}^{\varphi} \cdot \lambda_s{}^{1-\varphi} + \lambda_{disp} \tag{S4.4}$$

with

$$\lambda_{disp} = \rho_f \cdot c_{p,f} \cdot D \tag{S4.5}$$

where D represents the dispersion tensor calculated as (Burnett and Frind, 1987):

$$D = \frac{1}{u} \cdot \begin{pmatrix} \alpha_L u_x{}^2 + \alpha_T\left(u_y{}^2 + u_z{}^2\right) & (\alpha_L - \alpha_T)u_x u_y & (\alpha_L - \alpha_T)u_x u_z \\ (\alpha_L - \alpha_T)u_x u_y & \alpha_L u_y{}^2 + \alpha_T(u_x{}^2 + u_z{}^2) & (\alpha_L - \alpha_T)u_y u_z \\ (\alpha_L - \alpha_T)u_x u_z & (\alpha_L - \alpha_T)u_y u_z & \alpha_L u_z{}^2 + \alpha_T\left(u_x{}^2 + u_y{}^2\right) \end{pmatrix} \tag{S4.6}$$

Here, α_L and α_T represent the longitudinal and transverse dispersivity, respectively, while u_x, u_y and u_z are the directional components of the Darcy velocity field u.

The heat transfer is coupled to the groundwater flow using the Darcy velocity field u. Darcy's law describes a single phase fluid flow in a porous medium and can be expressed as (Bidarmaghz et al., 2019; COMSOL, 2020b):

$$u = -K \cdot \nabla h \tag{S4.7}$$

Darcy's law relates the Darcy velocity u to the gradient of the hydraulic head h using fluid and soil matrix properties represented by the hydraulic conductivity K. The hydraulic head gradient is numerically computed by inserting Darcy's law (Equation (S4.7)) into the following continuity equation:

$$\frac{\partial}{\partial t}(\varphi \rho_f) + \nabla \cdot (\rho_f u) = Q_m \tag{S4.8}$$

where Q_m is a mass source or sink term. Solving Equations (S4.7) and (S4.8) obtains the Darcy velocity field u, which allows to computationally couple heat transfer to fluid flow using Equation (S4.1).

S4.2 Numerical subsurface model of Freiburg

The numerical 3D finite element flow and heat transport subsurface model of the study area serves as a baseline to evaluate the representativeness of the box models regarding ATES power density in the city of Freiburg. The exact delineation of the study area is done in a way so that the majority of the built-up area of Freiburg is included and considers the hydraulic and topographic conditions. The model covers an area of about 72 km^2 and includes the Dreisam valley in the southeastern part and a large portion of the Dreisam alluvial fan in the northwest. The southeastern boundaries are defined based on the topographic transition from the Upper Rhine Graben to the Black Forest. This is also reflected in the 2nd kind constant-flux boundary conditions (BCs) set at these boundaries (Figure S4.1) which represent the inflow into the study area from the adjacent Black Forest. The remaining model boundaries in the southeast as well as the northwestern boundary of the study area correspond to hydraulic head contour lines (Figure 4.1) and accordingly feature 1st kind constant-head BCs. The southwestern as well as the northeastern boundaries are set up perpendicular to the groundwater hydraulic head contour lines. The Dreisam River flowing through the study area is implemented as a 3rd kind head-dependent flux BC with a flow rate dependent on the Dreisam water level in order to account for the losing stream regime present in the study area (Villinger, 1999). A 2nd kind no-heat flux BC is applied on the top surface of the Freiburg model. This approach of thermally insulating the top surface and thus impeding any exchange of thermal energy with the atmosphere is consistent with the box models and results in larger thermal plumes and thus in more conservative power density estimations (Ohmer et al., 2022).

The Freiburg model consists of two layers representing the Neuenburg Formation and the Breisgau Formation. The bottom of the model is formed by the base of the Breisgau Formation (data from Wirsing and Luz (2005)), whereas the model's top side is created from the digital elevation model shown in Figure 4.1. According to Villinger (1999) and as shown in Figure 4.1c, the Neuenburg Formation is covered by a thin loess layer of mostly less than 1 m thickness in some parts of the study area. However, this layer is not implemented in the Freiburg subsurface model due to its location above the saturated zone in most parts of the area. The hydraulic and thermal parameters used in the model are listed in Table 4.1.

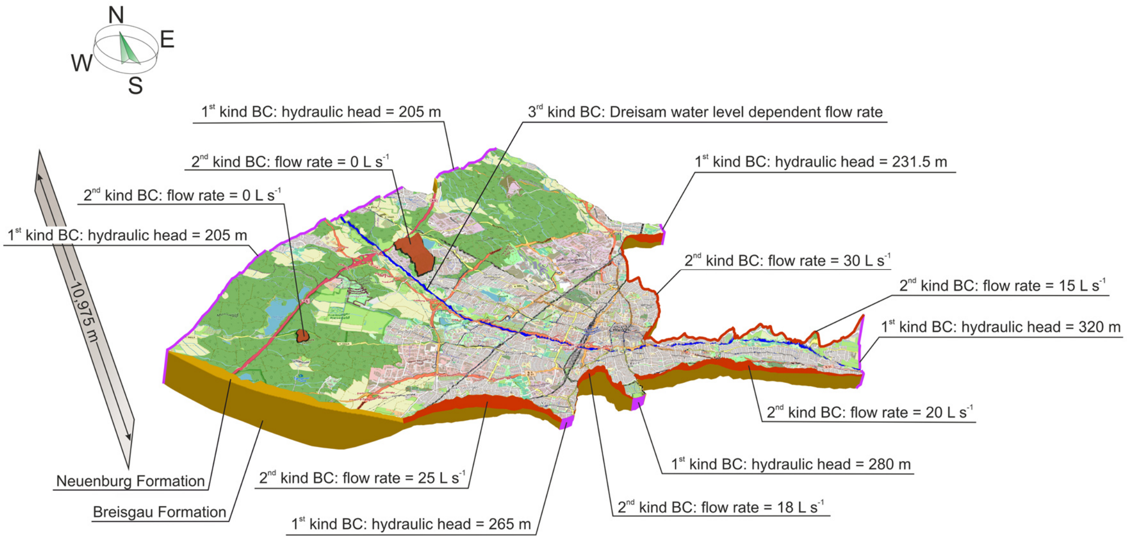


Figure S4.1: Numerical subsurface model of Freiburg consisting of the Neuenburg Formation (upper layer) and the Breisgau Formation (lower layer). The model illustration is ten times stretched in vertical direction. © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

In order to achieve a hydraulic head distribution in the Freiburg model best fitting to the hydraulic head contour lines shown in Figure 4.1, the stationary flow model is calibrated using the hydraulic conductivity of the Neuenburg Formation. Starting from the initial hydraulic conductivity distribution given by Wirsing and Luz (2005), the calibration is done using existing hydraulic head measurement data across the study area. Figure S4.2 shows the calibration results. The coefficient of determination of 0.998 and a root mean square deviation of 1.21 m indicate a high capability of the model to reproduce the hydraulic head measurements.

Based on the calibrated stationary flow model, a transient subsurface flow and heat transfer model is created with implemented ATES systems in either the Neuenburg or the Breisgau Formation. Using the areal extents of the thermally affected zones (TAZ) around individual

ATES systems as determined from the box models allows a systematical ATES placement in the Freiburg subsurface model. The final model consists of about 1.5 million tetrahedral elements. This number increases during the modeling runtime due to the utilization of the adaptive mesh refinement option implemented in COMSOL Multiphysics. Starting from an already finer discretization around the implemented ATES wells, this option dynamically increases the number of mesh elements in the relevant model areas, i.e. along the propagation paths of the thermal plumes coming from the implemented ATES wells. The modeling results are shown in Chapter 4.3.5, Figure 4.11 of the main manuscript and discussed regarding the box models' representativeness.

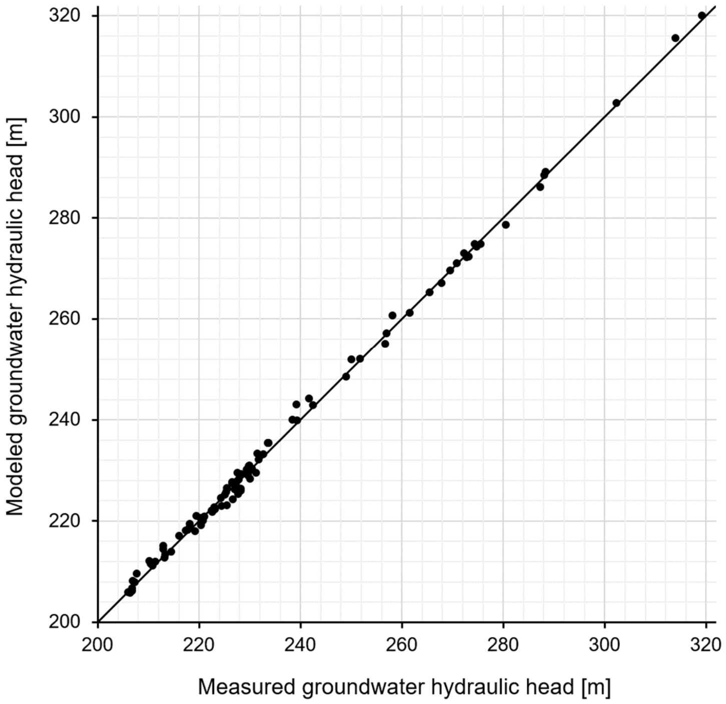


Figure S4.2: Modeled groundwater hydraulic heads plotted against measured groundwater hydraulic heads. The calibration results in a high coefficient of determination of 0.998. The root mean square deviation is 1.21 m.

S4.3 Influence of ambient groundwater temperature and thermal conductivity on the thermal recovery

In order to evaluate the influence of the ambient groundwater temperature and the thermal conductivity of the solid material of the Neuenburg and the Breisgau Formations on the ATES simulation, we determined the thermal recoveries of 1-, 2- and 3-doublet systems as a function of variations in these parameters. Figure S4.3 shows very minor impacts of the ambient groundwater temperature and the thermal conductivity on the thermal recovery.

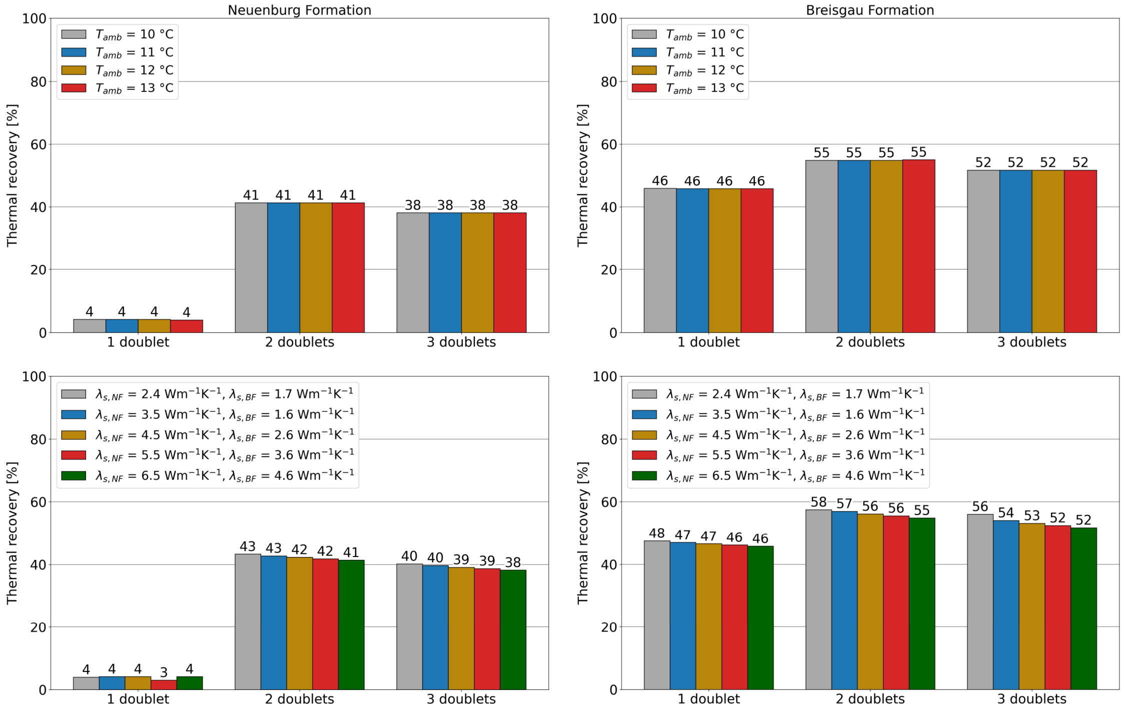


Figure S4.3: Thermal recoveries of 1-, 2- and 3-doublet ATES systems in the Neuenburg Formation (left) and the Breisgau Formation (right) depending on the ambient groundwater temperature T_{amb} (top) and the solid thermal conductivities $\lambda_{s,NF}$ and $\lambda_{s,BF}$ of the Neuenburg Formation and the Breisgau Formation, respectively (bottom).

S4.4 Power density results when using the ±1 K-isotherms

Contrary to many previous publications on the topic of thermal plume propagation in the subsurface, we use the ±0.5 K-isotherms from the box models to delineate the TAZ and calculate the power densities. However, as an additional information, Figure S4.4 shows the power density values calculated from the TAZ as defined by the ±1 K-isotherms after 30 years of ATES operation. On average, these values are about 2.1 times as high as the power densities shown in Figure 4.8.

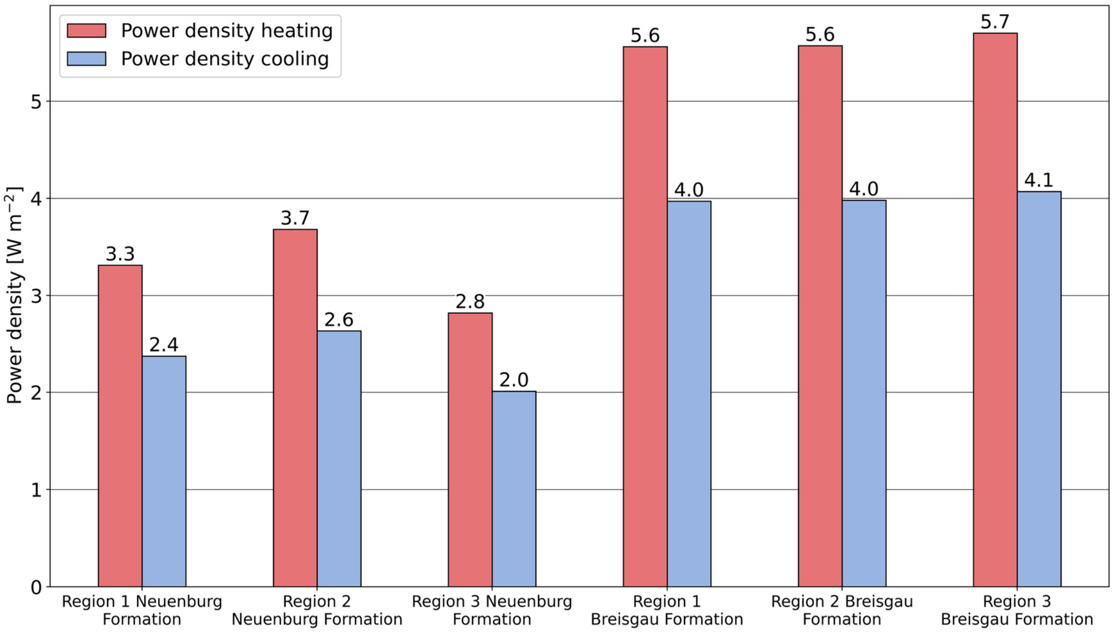


Figure S4.4: ATES Power densities for Neuenburg and Breisgau Formations when using the ±1 K-isotherms after 30 years for delineating the TAZ. ATES systems in the Neuenburg Formation are modeled as 2-doublet configurations. Systems in the Breisgau Formation use a 3-doublet configuration.

S4.5 Heating energy mix in Freiburg

Table S4.1 provides information about the final energy mix for space and water heating in the city of Freiburg for the year 2020.

Table S4.1: Final energy mix for space and water heating in Freiburg in 2020 with the respective emission factors for each energy source. Data from GEF Ingenieur AG et al. (2021).

Energy source	Final energy mix for space and water heating [%]	Emission factor [$tCO_2eq\ MWh_{th}^{-1}$]
Natural Gas	54	0.247
District heating	22	0.193[a]
Heating oil	17	0.318
Biomass	6	0.025
Heat pumps	1	0.118[b]
ATES	0	0.083[c]

[a] Freiburg mix.
[b] Calculated using seasonal COP = 3.5 and electricity emission factor of 0.412 $tCO_2eq\ MWh_{el}^{-1}$.
[c] Stemmle et al. (2021).

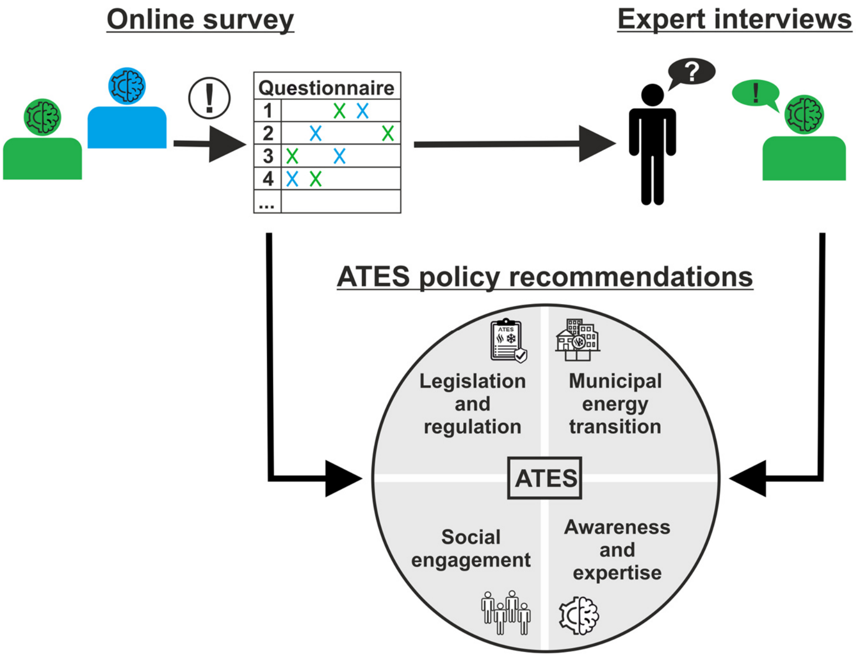
5 Policies for Aquifer Thermal Energy Storage: International comparison, barriers and recommendations

Reproduced from: Stemmle, R., Hanna, R., Menberg, K., Østergaard, P.A., Jackson, M., Staffell, I., Blum, P. Policies for Aquifer Thermal Energy Storage: International comparison, barriers and recommendations. Clean Technologies and Environmental Policy (submitted).

Abstract

Aquifer Thermal Energy Storage (ATES) represents a promising solution for heating and cooling, offering lower greenhouse gas emissions and primary energy consumption than conventional technologies. Despite these benefits and the widespread availability of suitable aquifers, ATES has yet to see widespread utilization, with uptake highly concentrated in select countries (Netherlands, Belgium, Sweden and Denmark). Beyond technical and hydrogeological feasibility, appropriate national policies are paramount in driving ATES deployment. This study provides an international comparison of ATES policies, highlighting best practices and revealing where measures are missing. It sources insights from a survey of experts across academia, industry and governmental bodies in 30 countries, complemented by semi-structured expert interviews. We reveal significant differences in the existence and strength of supportive policy environments between countries with different ATES market maturity. The interviews provide details on creating supportive environments (e.g. through facilitators like pre-existing groundwater technology use and building energy efficiency standards), and further barriers to ATES deployment. We derive ten recommendations for ATES policies to address the following areas: legislative and regulatory issues, raising public awareness, ATES' role in local energy transitions, and social engagement. This work aims to steer global policy towards better harnessing the potential of ATES to decarbonise buildings.

Graphical Abstract



5.1 Introduction

Aquifer Thermal Energy Storage (ATES) is an open-loop and most often shallow geothermal system that uses groundwater for seasonal storage of thermal energy. ATES systems exploit the wide availability and high heat capacity of groundwater to supply heating and/or cooling previously stored in the subsurface to mitigate temporal mismatches between energy demand and availability (Bloemendal et al., 2015; Fleuchaus et al., 2020b). ATES systems supplying both heat and cold are commonly used in large building complexes, such as offices, airports, universities or hospitals (Birhanu et al., 2015; Fleuchaus et al., 2018; Lu et al., 2019b). This kind of ATES typically stores waste heat and cold from the cooling and heating process itself and therefore benefits from balanced heating and cooling demands of the connected buildings, which ensures sustainable system operation.

Another type of ATES operation is to store excess heat from external sources, such as industrial waste heat and surplus solar thermal energy. These systems can also be used in a decentralised way as described above or in centralised applications in district heating and/or cooling (DHC) networks. This allows to compensate for fluctuating energy supply and to increase the share of renewable energy sources in the network which can further contribute to the energy transition at the municipal level (Fleuchaus et al., 2018; Schmidt et al., 2018; Todorov et al., 2020).

Compared to conventional heating and cooling technologies, such as gas boilers and compression chillers, ATES can reduce greenhouse gas emissions by up to 75 %. Similar reductions were shown regarding primary energy consumption (Fleuchaus et al., 2018; Stemmle et al., 2021; Vanhoudt et al., 2011). These environmental benefits are accompanied by lower operational costs compared to conventional technologies leading to typical payback times of ATES systems ranging from 2 to 10 years (Fleuchaus et al., 2018; Ghaebi et al., 2017; Schüppler et al., 2019). Nevertheless, ATES uptake remains limited. The more than 3000 systems installed globally are highly concentrated in the Netherlands with 85 % and further 10 % in Sweden, Denmark and Belgium (Fleuchaus et al., 2018), despite suitable aquifers being widespread across the globe (Bloemendal et al., 2015; Lu et al., 2019b; Ramos-Escudero and Bloemendal, 2022; Stemmle et al., 2022).

Like other technologies such as wind and solar power (Best and Burke, 2018; Saidur et al., 2010; Timilsina et al., 2012), international adoption of ATES requires appropriate energy policies. This is evident from the high number of Dutch ATES systems, supported by a sophisticated ATES legislative and regulatory framework. Building on successful government-subsidised pilot projects in the late 1980s, Dutch ATES numbers grew rapidly post-2000. These first systems required permits governed mainly by the Dutch Water Act (Drijver and Godschalk, 2018). By the early 2010s growing adoptions in the Netherlands required a revised legislative and regulatory framework for ATES, leading to a more specific ATES policy. The resulting Geo Energy Systems Amendment (Dutch: *Wijzigingsbesluit bodemenergiesystemen*) features a simplified eight-week permit process, company certifications to ensure high system quality and standardized system monitoring requirements (Bloemendal et al., 2023; Drijver and Godschalk, 2018; Dutch ATES, 2016). More specific operational regulations were also established, including upper and lower storage temperature limits of 25 °C and 5 °C, respectively, and a required energetic balance between injected heat and cold.

Besides ensuring efficient system operation, these regulations aim to protect the subsurface environment (Drijver and Godschalk, 2018; Drijver et al., 2010; Dutch ATES, 2016). As systems numbers grew, authorities also addressed increasing scarcity of subsurface space in urban areas and potentially detrimental thermal interferences between systems. They introduced geothermal energy master plans for coordinated spatial subsurface and energy planning of ATES systems in dense urban areas, ensuring optimal and sustainable use of the available subsurface (Beernink et al., 2022; Bloemendal et al., 2014; Drijver and Godschalk, 2018; Sommer et al., 2015). An interactive online map by the Dutch Ministry of Economic Affairs and Climate Policy allows municipalities to mark designated areas for geothermal use, aiding ATES planning (Dutch ATES, 2016).

The extensive Dutch ATES legal and regulatory framework stands out internationally, while for countries with a limited ATES deployment available literature, reports or other pieces of information about country-specific ATES policies is often lacking. While not specifically dealing with ATES, some publications discuss the legislative framework for shallow geothermal energy (SGE) utilization in European countries. These studies highlight a heterogeneous landscape of country-specific legislation and regulations governed by a plethora of national and regional laws, decrees and guidelines. This diversity hinders the uptake of SGE systems, suggesting a need for standardized policy approaches and regulations (García-Gil et al., 2020; Hähnlein et al., 2010; Hähnlein et al., 2013; Somogyi et al., 2017; Tsagarakis et al., 2020). ATES faces similar constraints as other SGE systems, and inadequate policy can also stifle uptake of ATES.

This study presents an international comparison of market barriers, policies and regulations for ATES. It highlights best practices for policy approaches, explores success factors and challenges in increasing ATES adoption, and identifies areas where appropriate policies are missing. From these insights, recommendations are derived for a comprehensive ATES policy approach to overcome legislative, regulatory and socio-economic barriers to wider international ATES deployment.

5.2 Methodology

To gather comprehensive information on the current status of ATES policies and regulations internationally, we conducted an online survey and a series of online interviews (Figure 5.1). The survey was sent to experts and practitioners in ATES, geothermal energy and geoscience. Additional contacts were compiled from publicly available membership lists of European heating and cooling industry and trade associations. Given that all recipients were identified for their relevant expertise, it is appropriate to assume that they possessed sufficient knowledge to answer the survey questions, and in cases where they did not, they were instructed to answer 'don't know'. The survey was emailed to 333 contacts from academia, consultancies, installation companies, government authorities, national geological surveys and industrial associations working on geothermal energy and ATES from 47 countries. 82 experts across 30 countries completed the survey, yielding a 25 % response rate. We followed recommendations in survey methods literature (Dillman et al., 2015; Frandell et al., 2021) on maximising the sample size by emailing a pre-notification letter[1], initial survey invitation and three reminders to recipients over one month.

---

[1] Pre-notification emails may however be less effective in raising web survey response rates compared to pre-notification postal letters (Clark et al., 2021; Daikeler et al., 2020).

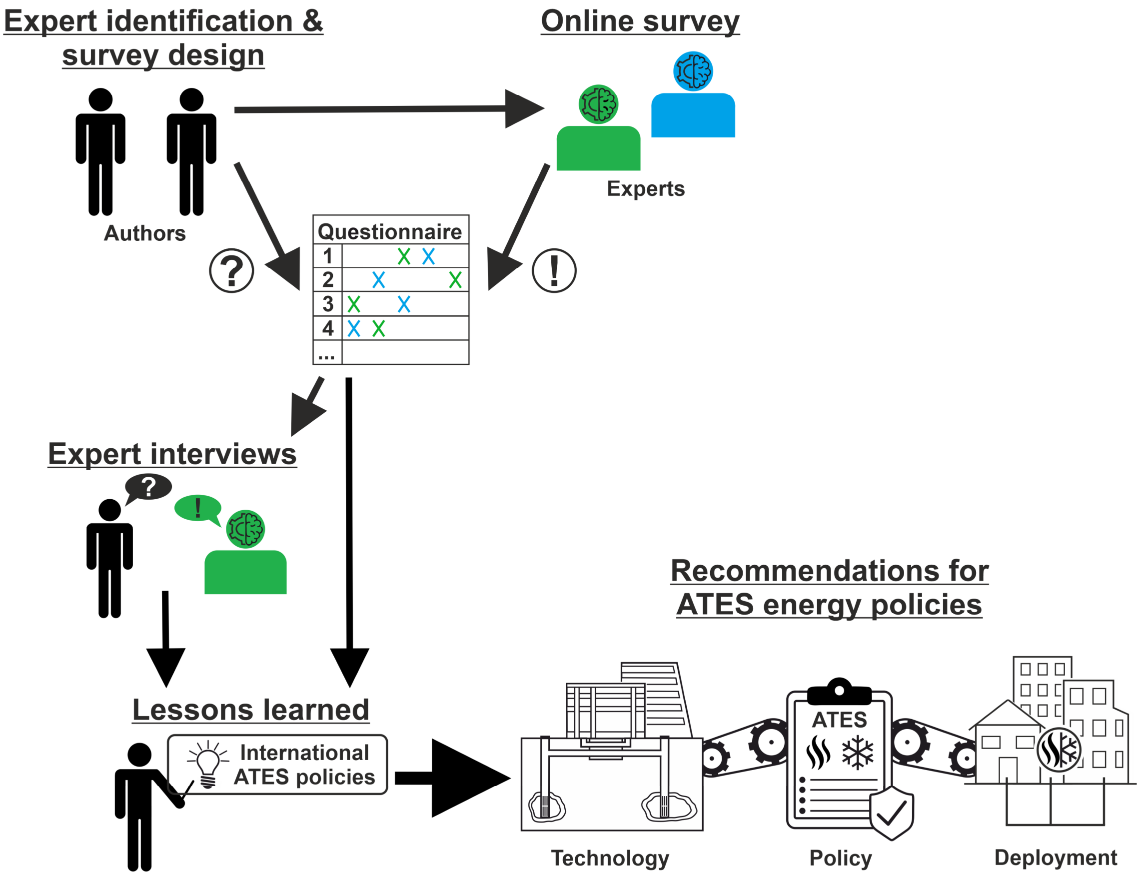


Figure 5.1: Overview of this study's workflow.

The survey's questionnaire was sent via Qualtrics (version March 2023) and sought information on country-specific policies, legal, technical, economic and societal conditions relevant to ATES, important market enablers and barriers and the existence of laws and regulations governing ATES installation and operation. Following good practice in survey design (Clark et al., 2021; Dillman et al., 2015), we developed closed questions with fixed-choice responses and open-ended questions allowing respondents to write their own answers. The phrasing of questions, fixed responses and Likert scales were formulated carefully to avoid leading answers in a particular direction. At the end of the survey, respondents were asked if they would be willing to participate in a follow-up interview. Subsequently, we conducted a set of 16 semi-structured interviews with a set of these experts to collect further country-specific information. The selection criteria for potential interviewees were based on the survey findings. Most interviews were conducted using Microsoft Teams or Zoom. Respondents consented to take part and to be audio and video recorded. Interviews were recorded, transcribed and detailed notes taken. Quotations and attributions used in this paper were sent to interviewees to obtain their permission to include them. The online survey's questionnaire and the interview guide are presented in Appendix A and Appendix B.

Insights and lessons learned from the survey and interviews were used as a basis for developing recommendations for a sophisticated ATES policy that aims to foster a wider international ATES deployment.

5.3 Results and discussion

5.3.1 Results of the online survey

A total of 82 experts from different countries and types of organisations completed the survey (Figure 5.2, Appendix C). For 17 countries, no responses were received. While not complete, the collected set of data is the most extensive to have been produced.

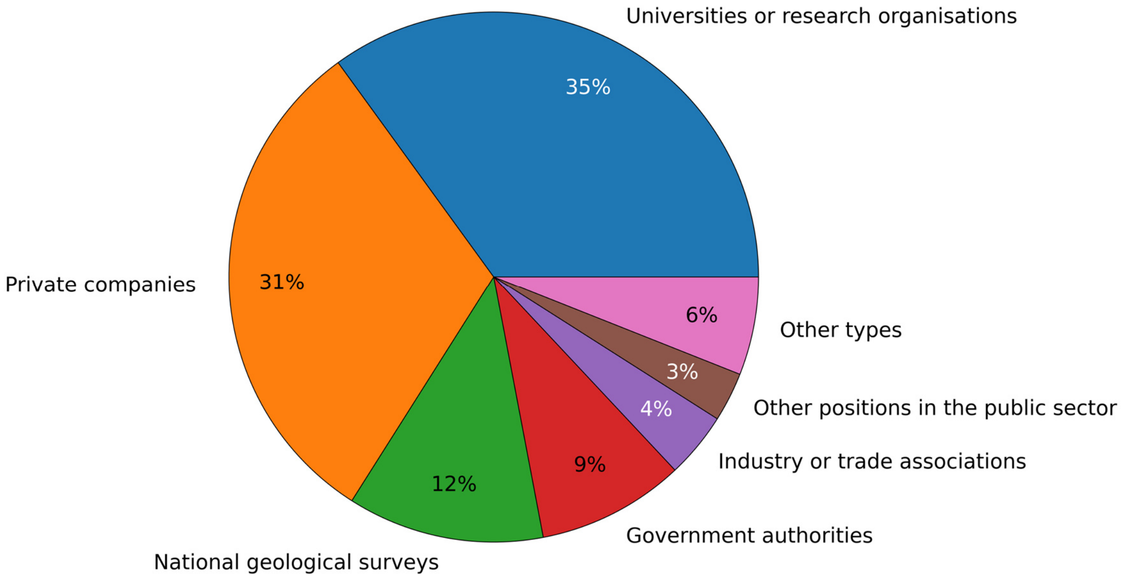


Figure 5.2: Pie charts showing the shares of the survey respondents' type of organisation. It should be noted that respondents were able to select more than one type of organisation. Appendix C states the absolute numbers of survey responses on a country per country basis.

A key finding is that legislative and regulatory frameworks relevant to ATES vary widely among different countries in both their existence and design. This confirms earlier findings from broader studies of shallow geothermal energy (García-Gil et al., 2020; Haehnlein et al., 2010; Hähnlein et al., 2013; Somogyi et al., 2017; Tsagarakis et al., 2020).

Chapters 5.3.1.1 to 5.3.1.8 highlight specific survey questions in more detail. For these analyses, we categorize countries by ATES market development levels to identify potential influences on market factors, policy and regulatory frameworks, and other survey aspects (Table 5.1). The categorization is based on Fleuchaus et al. (2018) and extended from survey results. With only 7 responses from the Netherlands, the only mature ATES market, Dutch responses were combined with those from growing markets into a *"mature & growing markets"* group with 4 countries. The *"emerging markets"* group includes 14 countries, while the *"countries without ATES"* group includes 12 countries. To facilitate more straightforward comparisons, responses of 'don't know' are omitted from the following evaluations. Chapter 5.3.1.9 compares results from the Netherlands, Denmark and Germany being mature, growing and emerging markets, respectively. These countries also had the highest response numbers.

Table 5.1: Countries represented in the survey results grouped according to their ATES market development levels. Number of ATES systems based on survey responses and Fleuchaus et al. (2018).

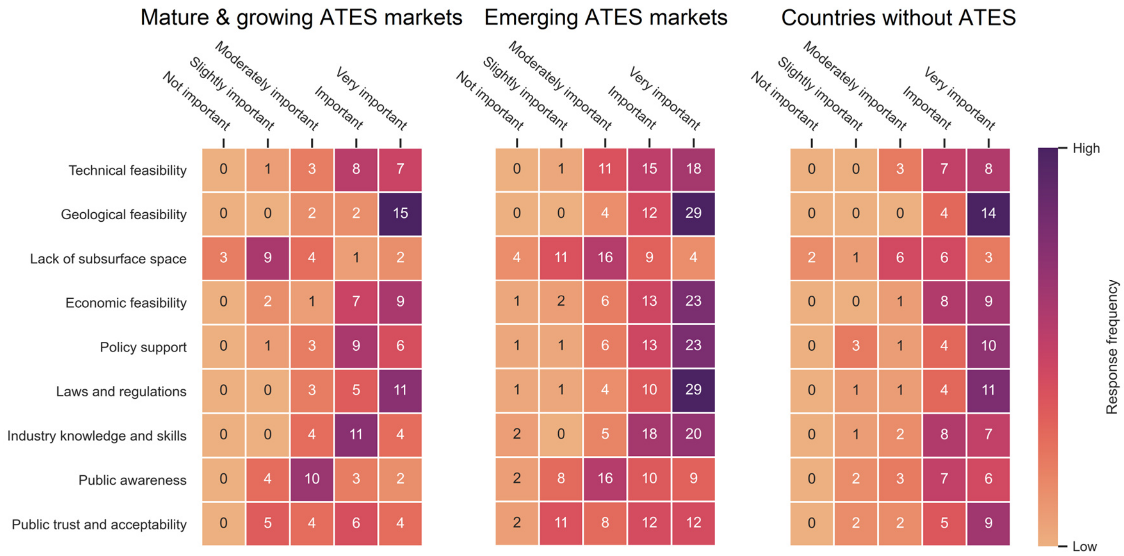
Mature & growing markets		**Emerging markets**		**Countries without ATES**
	ATES systems		ATES systems	
Mature:		Australia	< 10	Albania
Netherlands	> 3000	China	6 – 10	Austria
		Finland	1	Czech Republic
Growing:		France	unknown	Estonia
Belgium	100 – 340	Germany	2 – 4	Greece
Denmark	50 – 80	Hungary	unknown	Italy
Sweden	220 – 300	Norway	25 – 40	Lithuania
		Poland	unknown	Portugal
		Romania	unknown	Russia
		Slovakia	unknown	Serbia
		South Korea	< 10	Slovenia
		Switzerland	2 – 3	Spain
		UK	11 – 12	
		USA	2	

5.3.1.1 Importance of market factors

Survey questions 4 (& 4.a): *"At the present time and in your view, how important are the following market factors in influencing the uptake (the potential adoption) of ATES in your country?"*

Different market factors can act as barriers or enablers for a wider use of ATES. The influence of these factors on technology progression varies based on the country-specific market development level (Fleuchaus et al., 2018). Respondents' importance ratings of ATES market factors are therefore presented as a function of the ATES market development level (Figure 5.3). *Geological feasibility* and *laws and regulations* were rated as the most critical factors for the uptake or the adoption of ATES across all country groups (Table 5.2). In contrast, *lack of subsurface space* and *public awareness* received the lowest ratings across all groups, suggesting that the two most and two least important market factors are universal, rather than country-specific.

However, the importance ratings of other market factors differ between country groups. *Countries without ATES* have relatively uniform ratings, with most factors classed *important* or *very important*. In contrast, *mature & growing markets* and *emerging markets* see more differentiated views on ATES market factors (Figure 5.3).



Mature & growing ATES markets

	Not important	Slightly important	Moderately important	Important	Very important
Technical feasibility	0	1	3	8	7
Geological feasibility	0	0	2	2	15
Lack of subsurface space	3	9	4	1	2
Economic feasibility	0	2	1	7	9
Policy support	0	1	3	9	6
Laws and regulations	0	0	3	5	11
Industry knowledge and skills	0	0	4	11	4
Public awareness	0	4	10	3	2
Public trust and acceptability	0	5	4	6	4

Emerging ATES markets

	Not important	Slightly important	Moderately important	Important	Very important
Technical feasibility	0	1	11	15	18
Geological feasibility	0	0	4	12	29
Lack of subsurface space	4	11	16	9	4
Economic feasibility	1	2	6	13	23
Policy support	1	1	6	13	23
Laws and regulations	1	1	4	10	29
Industry knowledge and skills	2	0	5	18	20
Public awareness	2	8	16	10	9
Public trust and acceptability	2	11	8	12	12

Countries without ATES

	Not important	Slightly important	Moderately important	Important	Very important
Technical feasibility	0	0	3	7	8
Geological feasibility	0	0	0	4	14
Lack of subsurface space	2	1	6	6	3
Economic feasibility	0	0	1	8	9
Policy support	0	3	1	4	10
Laws and regulations	0	1	1	4	11
Industry knowledge and skills	0	1	2	8	7
Public awareness	0	2	3	7	6
Public trust and acceptability	0	2	2	5	9

Figure 5.3: Relative survey response frequencies of the importance ratings grouped by ATES market factors. The three heat maps show responses for the three groups of countries outlined in Table 5.1. Inset numbers inside each grid square give the numbers of responses.

Table 5.2: Average score of the importance ratings of ATES market factors for each country group. Scores are the arithmetic means across all survey responses. Scores correspond to ratings as 1: *not important*; 2: *slightly important*; 3: *moderately important*; 4: *important*; 5: *very important*.

Mature & growing markets		**Emerging markets**		**Countries without ATES**	
ATES market factor	**Importance rating**	**ATES market factor**	**Importance rating**	**ATES market factor**	**Importance rating**
Geological feasibility	4.68	Geological feasibility	4.56	Geological feasibility	4.78
Laws and regulations	4.42	Laws and regulations	4.44	Laws and regulations	4.47
Economic feasibility	4.21	Policy support	4.27	Economic feasibility	4.44
Technical feasibility	4.11	Economic feasibility	4.22	Technical feasibility	4.28
Policy support	4.05	Industry knowledge and skills	4.20	Industry knowledge and skills	4.17
Industry knowledge and skills	4.00	Technical feasibility	4.11	Policy support	4.17
Public trust and acceptability	3.47	Public trust and acceptability	3.47	Public trust and acceptability	4.17
Public awareness	3.16	Public awareness	3.36	Public awareness	3.94
Lack of subsurface space	2.47	Lack of subsurface space	2.95	Lack of subsurface space	3.39

5.3.1.2 Existence of ATES policies

Survey questions 5 (& 5.a): *"Are there any policies being applied currently in your country to increase the installation and use (to encourage the adoption and use) of ATES?"*

33 % of respondents state that policies exist in their country to increase or adopt ATES use (Figure 5.4). These responses all came from *mature & growing ATES markets* or *emerging ATES markets*. For *countries without ATES*, all responses indicate no policies to promote its adoption. Fisher's exact test with a 0.05 significance level indicates a statistically significant dependence between ATES market maturity and policy existence. As response numbers vary between countries (Appendix C), countries with many responses, such as Germany, have a greater impact on the significance assessment than countries with single responses.

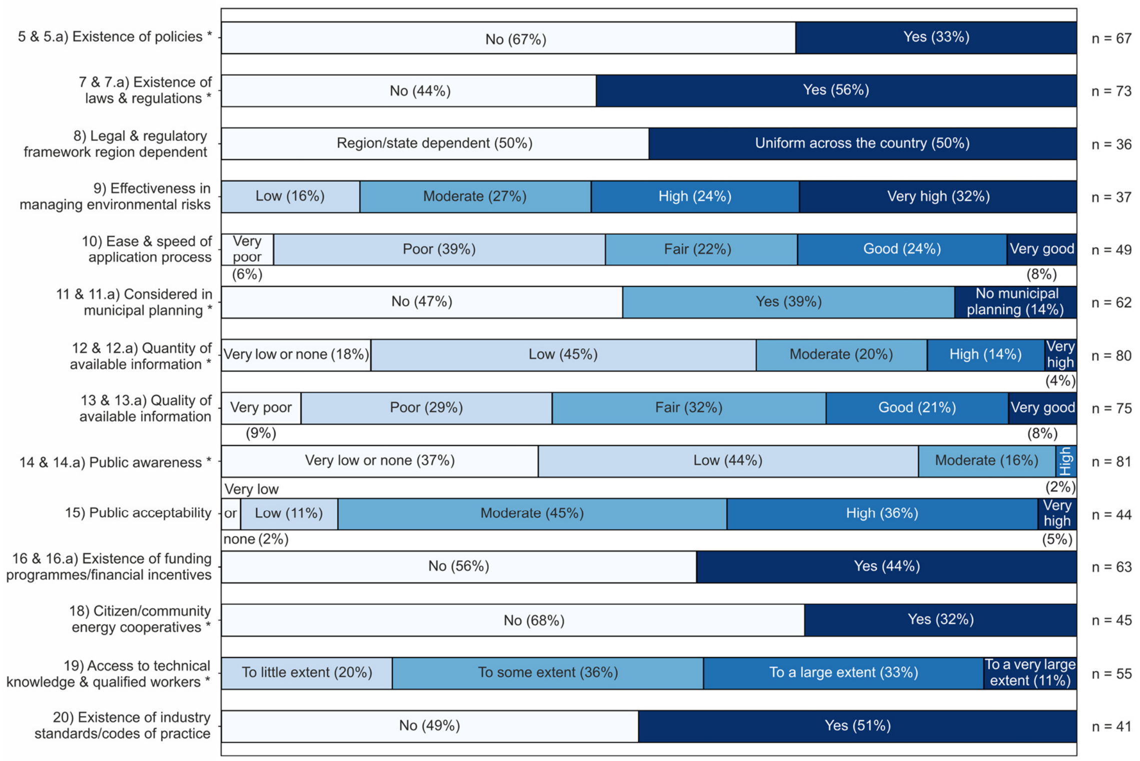


Figure 5.4: Survey responses to further questions and their shares of the total number of responses (n) per question. Response numbers differ between questions due to the survey design and the disregard of 'don't know' responses. Questions marked with an asterisk suggest a statistically significant dependence between ATES market development level (Table 5.1) and the question's topic when using a significance level of 0.05. Chapters 5.3.1.2 to 5.3.1.8. describe the results of some questions in more detail.

5.3.1.3 Existence of ATES laws and regulations

Survey questions 7 & 7.a: *"Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?"*

Overall, 56 % of respondents reported active laws and regulations for ATES in their countries (Figure 5.4). Survey results suggest that the ATES market development level significantly affects the existence of laws or regulations for ATES. In *mature & growing markets* most answers confirm existing governance of ATES systems. Most respondents from *emerging markets* also stated 'yes'. Conversely, 80 % from *countries without ATES* indicated no legal and regulatory basis for ATES.

5.3.1.4 Ease and speed of ATES application process

Survey question 10: *"In your country, how do you rate the ease or difficulty and speed of the application process to gain planning permission for new ATES installations?" (for* mature & growing markets *and* emerging markets *only)*

Respondents from *mature & growing markets* and *emerging markets* rated their country's ATES planning application process frequently (39 %) as 'poor', compared to 32 % rating the application process as 'good' or 'very good' (Figure 5.4). Statistically significant differences between the two groups were not evident. This suggests there is scope even in *mature & growing markets* to reduce barriers for ATES resulting from lengthy and difficult permitting processes.

5.3.1.5 Quantity of available information on ATES

Survey questions 12 & 12.a: *"How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?"*

Limited availability of ATES information can hinder deployment. 63 % of responses rated the information quantity as 'poor' or 'very poor' (Figure 5.4), with a significant influence of ATES market development level on the ratings. As countries progress from *without ATES* towards *mature & growing markets*, the rating of available information improves. The Netherlands stands out with the highest amount of information available, with 86 % of all Dutch responses being 'high' or 'very high'.

5.3.1.6 Public awareness of ATES

Survey questions 14 & 14.a: *"How do you rate the level of public awareness of ATES in your country?"*

81 % of responses rated public awareness of ATES as 'very low or none' or 'low' (Figure 5.4). However, ATES public awareness was also rated the second least important factor for its uptake (Chapter 5.3.1.1), suggesting that high public awareness may not be a priority for increased adoption. This is supported by 86 % of Dutch responses rating public awareness of ATES as low or moderate, despite it being an established technology (Fleuchaus et al., 2018).

5.3.1.7 Existence of funding programmes for ATES

Survey questions 16 & 16.a: *"Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?"*

Around 56 % of respondents said their country lacks funding programmes or incentives for ATES (Figure 5.4). This rises to 82 % in countries with no installed ATES systems, compared to 46 % in countries with ATES. Notably, 37 % of respondents in *countries without ATES* don't know if financial incentives exist.

5.3.1.8 Access to technical knowledge and qualified workers for ATES installation

Survey question 19: *"To what extent does your country have access to enough technical knowledge and qualified workers for the installation of ATES systems?" (for* mature & growing markets *and* emerging markets *only)*

Around 69 % of respondents state that there is access to sufficient technical knowledge and qualified workers ‘to some extent’ or ‘to a large extent’ (Figure 5.4). ATES market development level has a significant influence on the responses reflected in more ratings ‘to a large extent’ from *mature & growing markets*.

5.3.1.9 Country comparison

This section provides a condensed comparison of the survey results from the only mature (the Netherlands, 7 responses), a growing (Denmark, 7 responses) and an emerging market (Germany, 15 responses). The sophisticated Dutch ATES policy and accompanying beneficial conditions are acknowledged by the Dutch respondents leading to overall most favourable and affirming responses (Table 5.3). Furthermore, only in the Netherlands legally binding technical regulations regarding drilling work and installation of the subsurface and surface parts of ATES exist.

Conversely, despite being a growing market, no distinct ATES policy, funding and industry standards exist in Denmark. Increasing Danish ATES numbers therefore may result from economic and environmental benefits compared to conventional types of heating and cooling (Schüppler et al., 2019; Stemmle et al., 2021; Vanhoudt et al., 2011). It might also be related to Denmark’s historically progressive heat planning strategies, which led to an internationally outstandingly high share of district heating supply (Johansen and Werner, 2022; Werner, 2017). This contrasts with the Netherlands with a stronger focus on individual heat and cold supply fostering the high adoption of decentralised ATES systems. However, the Danish district heating systems can also benefit from ATES on the ambitious way to full decarbonisation by 2030 through integration of large-scale thermal storage into the heat grids and utilization of unused industrial waste heat (Johansen and Werner, 2022). Thus, while not specifically tailored towards ATES, the Danish energy and climate protection policy appears to have created a favourable environment for emerging sustainable technologies. This also reflects in a high share of responses stating that citizen or community energy cooperatives play a role in the Danish ATES market (Table 5.3). Cooperative ownership of district heating grids ensured a local heating supply in many Danish municipalities (Johansen and Werner, 2022).

In contrast to policies, laws and regulations for ATES exist in all three countries. The introduction of technology regulation governing the installation and use of ATES thus seems to be of higher priority than establishing a policy stimulating ATES. For Germany, the engineering standard on underground thermal energy storage (UTES) VDI 4640 Part 3 was mentioned repeatedly. Other than the Dutch industry protocols, this technical standard is voluntary and recommended only. A legally binding framework for authorisation of planning, installing and operating ATES in Germany is provided by the German Water Resources Act (German: *Wasserhaushaltsgesetz*, WHG). It is, however, embedded in a much broader context and aims at protecting water as basis for life, ecosystem and usable asset (Hähnlein et al., 2011; Neidig, 2022). According to several respondents, an opportunity to stimulate ATES in Germany is the existence of funding programmes supporting the installation of energy-efficient buildings and district heating networks with a high share of renewable energies. These programmes consider technologies for large-scale heat storage including ATES. Nevertheless, the lower half of Table 5.3 shows that Germany has the least favourable environment for growing ATES diffusion in this comparison. For Denmark and the Netherlands progressively improving conditions for ATES are indicated.

Table 5.3: Comparison of survey results for the Netherlands (mature ATES market), Denmark (growing ATES market) and Germany (emerging ATES market). Percentages indicate the shares of corresponding responses with regard to total response number for the respective question and country. The lower half of the table shows results from the average ratings of all responses from the respective country (Y yes; N no; + high; o moderate; - low).

	Netherlands	**Denmark**	**Germany**
Existence of policies	Y (100 %)	N (100 %)	Y (50 %) N (50 %)
Existence of laws & regulations	Y (100 %)	Y (100 %)	Y (71 %) N (29 %)
Legal & regulatory framework region dependent	Region/state dependent (50 %) Uniform across the country (50 %)	Uniform across the country (100 %)	Region/state dependent (100 %)
Considered in municipal planning	Y (83 %) N (17 %)	Y (50 %) N (50 %)	Y (60 %) N (40 %)
Existence of funding programmes/financial incentives	Y (50 %) N (50 %)	N (100 %)	Y (75 %) N (25 %)
Citizen/community energy cooperatives	Y (60 %) N (30 %)	Y (80 %) N (20 %)	Y (17 %) N (83 %)
Existence of industry standards/codes of practice	Y (100 %)	N (100 %)	Y (60 %) N (40 %)
Effectiveness in managing environmental risks	+	+	o
Ease & speed application process	o	o	-
Quantity of available information	+	o	-
Quality of available information	+	o	o
Public awareness	-	-	-
Public acceptability	+	o	o
Access to technical knowledge & qualified workers	+	o	o

5.3.2 Results of expert interviews

16 interviews were conducted with select experts or practitioners who had participated in the survey, to gather more detailed information on ATES policies and regulations and current obstructive and beneficial factors for ATES deployment (Table 5.4). The expert interviews were limited to countries with existing ATES, since the survey finds that laws, regulations and policies for ATES are mainly absent in countries without installations. The interview results are synthesized in the following sections.

Table 5.4: Expert interviews: Participants, countries and organisation types.

Interview participant(s)	Country	Organisation name	Organisation type
David Simpson	Belgium	AGT - Advanced Groundwater Techniques	Private company: Hydrogeological consultancy
Xiaobo Wu	China	CEEC Geothermal Co., LTD (China Energy Engineering Corporation)	State-owned enterprise: Geothermal energy engineering
Rasmus Aaen & Anders Juhl Kallesøe	Denmark	NIRAS A/S	Private company: Engineering consultancy
Teppo Arola	Finland	Geological Survey of Finland	National geological survey
Guillaume Attard	France	Ageoce Solutions	Private company: Geoscience consultancy
Christian Boissavy	France	Cabinet Boissavy	Private company: Geothermal energy consultancy
Paul Fleuchaus	Germany	tewag GmbH	Private company: Geoscience consultancy
Frank Agterberg	Netherlands	Brancheveneniging Bodemenergie Nederland (Dutch shallow geothermal energy association)	Industry/trade association
Martin Bloemendal	Netherlands	Delft University of Technology	University/academia
Bas Godschalk	Netherlands	IF Technology	Private company: Geothermal energy engineering
Bjørn Frengstad	Norway	NTNU Norwegian University of Science and Technology	University/academia
Horia Ban	Romania	Termoline	Private company: Renewable heating and cooling
Vincent Badoux	Switzerland	GEOTEST Ltd	Private company: Geoscience consultancy
Edward Hough	United Kingdom	British Geological Survey	National geological survey
Anonymous	United Kingdom	N/A	Public sector organisation
Erick Burns	USA	N/A	Public sector organisation

5.3.2.1 Current factors benefiting ATES deployment

Once again, Dutch interviewees confirmed the sophisticated Dutch policy described in the introduction. Besides this purposeful ATES policy, there are further factors benefiting ATES in the Netherlands and partially in countries with *growing markets* as well. They include the pre-existing expertise regarding the use of groundwater for other purposes, such as drinking water production, which has served as a technological driver for ATES implementation as stated during interviews with Dutch and Danish experts. This led to a mostly high quality of early ATES systems resulting in good reputation and growing awareness amongst the professional field (e.g. policy makers, municipalities, heating and cooling sectors).

Policy drivers indirectly promoting ATES in *mature & growing markets* are strict building energy efficiency requirements, mandatory local heat planning and a general focus on heat pumps and district heating. A sufficient workforce and an overall open-minded or even favourable attitude towards ATES among local authorities were also stressed as benefiting factors. Increasing interest in ATES was also attributed to rising gas prices and the desire for primary energy savings.

For countries with *emerging markets*, several interviewees acknowledged the presence of suitable aquifers for ATES and further beneficial factors (Table 5.5). Interviews with French and Finnish experts revealed existing water and environmental acts already largely suitable for handling ATES. For some *emerging markets*, such as Germany, available funding options for individual systems and ATES research were reported as means to initiate a phase of growing ATES utilization.

5.3.2.2 Current barriers to ATES deployment

Obstructing factors to an increasing use of ATES are found to be more numerous in *emerging ATES markets* than in *mature & growing markets* (Table 5.5). For example, interviewees from Norway and France described insufficient installation quality of early ATES systems causing technical problems and bad publicity. The few systems in *emerging markets* typically face lengthy permit procedures, sometimes more than a year, which reduces the appeal of ATES. Lacking availability of information on ATES, low awareness among practitioners, such as heat pump sellers and heating engineers, as well as missing financial incentives were further highlighted as barriers which effective ATES policies should address. Some structural problems pointed out during interviews include lacking capacity and expertise within local authorities and insufficient planning and installation workforce. The greater policy focus on other renewable technologies, such as wind and solar power, also contributes to low ATES uptake in *emerging markets*.

An exemplary barrier mentioned by experts from the Netherlands and Belgium reflecting the already more widespread ATES application in these *mature & growing markets* is the prevailing individual approach of ATES planning and permission. Especially in dense urban areas, this might lead to inefficient subsurface utilisation in the future compared to a coordinated district-level approach. Despite growing numbers of ATES installations in Denmark and Belgium, interviewees from these countries criticised the slow permitting process and missing industry-wide installation and operation standards. The much faster growth of air source heat pumps (ASHP) as a competing option for meeting building energy requirements was also pointed out as an impeding factor in these markets.

Table 5.5: Some beneficial and obstructing factors for increased ATES deployment reported during expert interviews.

Mature & growing markets		**Emerging markets**	
Beneficial factors	**Obstructive factors**	**Beneficial factors**	**Obstructing factors**
Suitable aquifers	No coordinated planning (Netherlands, Belgium)	Suitable aquifers	Region-dependent legislation in some countries
Suitable laws and regulations	Slow permit process (Denmark, Belgium)	Suitable laws and regulations in some countries	Slow permit process
Uniform legislation (Netherlands, Denmark)	No industry standards (Denmark, Belgium)	Some existing demonstration systems	Technical problems with early systems
Fast permit processes (Netherlands)	ASHP as a strong competitor	Funding available (some countries)	No funding available (some countries)
Abundance of available information		Pre-existing expertise in groundwater utilisation	Lack of available information
High awareness in professional field			Low awareness in professional field
High quality of systems			Lacking workforce
Industry standards (Netherlands)			Lacking capacity and expertise within local authorities
Sufficient workforce			Focus on other types of renewable energy
Favourable attitude and expertise in local authorities			
High building efficiency requirements			
Pre-existing expertise in groundwater utilisation			
Focus on related technologies			

5.3.3 Policy recommendations

Based on the online survey results and the insights from the expert interviews and complemented by relevant literature, this subsection develops policy recommendations on how to overcome legislative, regulatory and socio-economic barriers to a wider international ATES deployment. The following sections cover a variety of important elements constituting a sophisticated ATES policy (Figure 5.5). For each of these elements, recommendations as well as key actions to achieve them are presented. If available, relevant quotes from the interviews introduce new aspects.

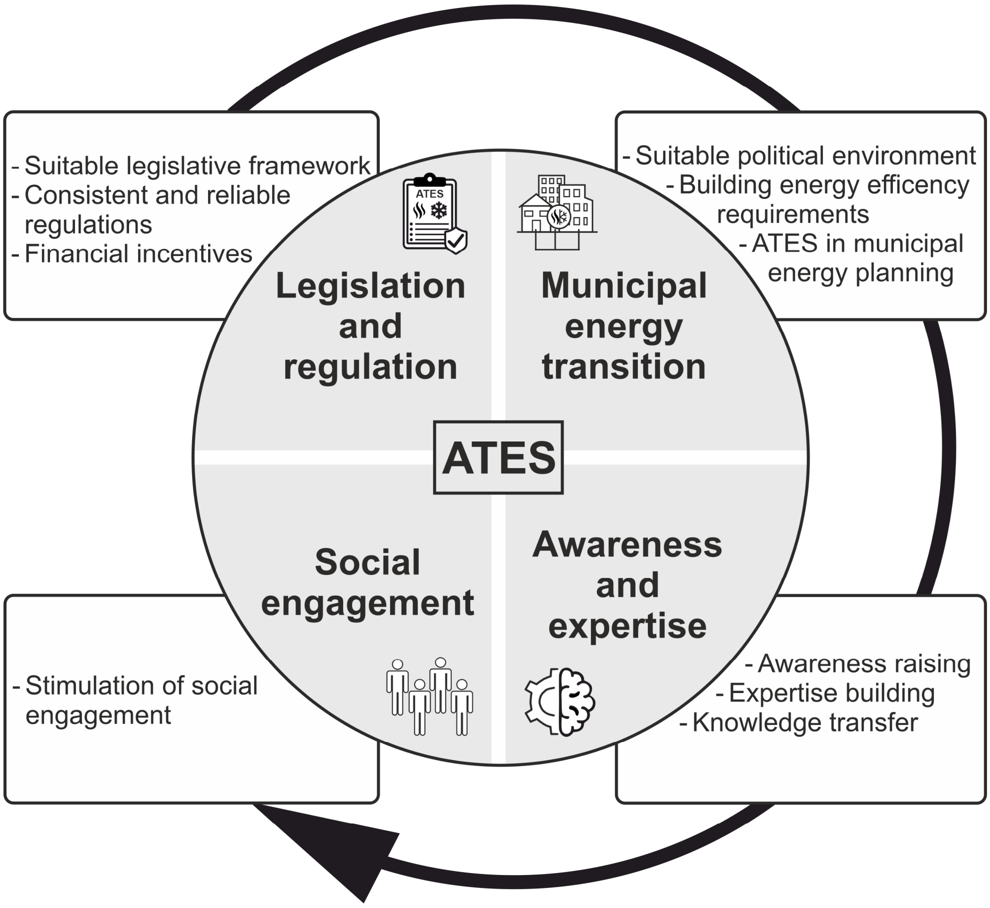


Figure 5.5: Recommendations for a sophisticated ATES policy consisting of different policy elements. Detailed key actions for each element are described in the text. The arrow indicates a coarse practical order of actions, which provides the structure to the following subchapters.

5.3.3.1 Legislation and regulation of ATES

The online survey revealed suitable legislation for and regulation of ATES as one of the most important market factors (Figure 5.3). A lack of a reliable legislative framework and suitable regulations has previously been described as a threat to technology introduction, increasing diffusion and widespread economic application in the context of ATES and SGE in general (Drijver and Godschalk, 2018; García-Gil et al., 2020; Neidig, 2022).

Recommendation 1: Creation of a suitable legislative framework for ATES

In many countries, ATES is legally governed by national water acts and environmental protection acts, accompanied by various regional or local laws and directives. Being not specifically designed for ATES, these laws commonly cover all types of groundwater actions which have varying requirements for a suitable legislation. In a first step, it is therefore necessary to check, if existing water and environmental protection acts sufficiently address specific requirements of ATES, such as handling re-injection of heated and cooled groundwater. With only few installed systems, Finland represents an exemplary country where ATES is considered a niche technology and no specific legislative framework is in effect. Nevertheless, existing Finnish water and environmental acts proved suitable in providing necessary tools governing the first ATES applications. In countries where this is not the case, a legislative reform of existing laws or the purposeful creation of a specific ATES legal framework are necessary. The latter happened in the Netherlands in 2013 when existing acts were combined and improved upon creating a single Geo Energy Systems Amendment which governs the thermal use of groundwater.

“The harmonisation [...] made it much easier to get the permits.” – Martin Bloemendal, Delft University of Technology, Netherlands

A suitable ATES legislation should allow for an easy and rapid permitting. This was repeatedly highlighted as a critical point during the interviews. Half of all survey respondents pointed out regional or federal differences in the legal framework including permit procedure variations. A unified procedure across an entire country holds great potential to reduce permit duration and complexity. Harmonising scattered permitting rules directly affects potential system adopters and benefits consultancies and public authorities in decision making and thus can contribute to a favourable perception of ATES among all relevant stakeholders.

Recommendation 2: Creation of consistent and reliable ATES regulations

A successful set of ATES regulations must ensure a high ATES installation quality and operational performance as well as addressing environmental risks. Detrimental impacts of ATES on the environment can result from mixing of groundwater with different physical-chemical composition (Bonte et al., 2011; McClean and Pedersen, 2023; Possemiers et al., 2014; Regnier et al., 2023). Changes in groundwater temperature can further alter physical-chemical properties and geochemical equilibria with adverse implications for drinking water quality (Hähnlein et al., 2013). Temperature changes can also affect the ecological conditions and biological processes of groundwater ecosystems and their respective ecosystem services (Blum et al., 2021; Griebler and Avramov, 2015; Koch et al., 2021; Ni et al., 2016).

Risk management should therefore include preliminary evaluations of the expected extent of thermal impact. A regulatory framework for ATES should also address inefficiencies in the permission procedure due to approval of excessively large capacities often not fully used and thus hindering future installations (Bloemendal et al., 2014; García-Gil et al., 2020; Perego et al., 2022). While based on a countrywide harmonised set of regulations, permission procedures should ideally contain some reasonable flexibility and public authority discretion in approving storage temperatures in already thermally influenced urban aquifers (i.e. subsurface heat islands, SUHI) (Hähnlein et al., 2013; Menberg et al., 2013a). System operation monitoring and reporting should be made mandatory in any ATES regulatory framework to control operational compliance with permitted temperature limits, extraction volumes and energy balance requirements.

"It took us a couple of years to get to the point where we are." – Martin Bloemendal, Delft University of Technology, Netherlands

At the same time, it became clear from the interviews that the regulatory regime should not be too restrictive and burdensome. Overly complex and lengthy permit procedures could otherwise hinder an increasing ATES deployment. This was realised in the Netherlands, where regulatory maintenance and monitoring requirements were originally introduced for environmental protection purposes. Over time, Dutch ATES regulations were expanded and complemented by legally binding industry standards aiming for high system installation and operation standards. Despite the extensive regulations, rapid permission times of eight weeks are common and lightweight permit procedures for smaller systems ($< 50\ m^3/h$) lower bureaucratic barriers for potential system owners (Drijver and Godschalk, 2018). This way, the reasonable and reliable Dutch regulatory framework supports decisions and actions among planners, installation companies and local authorities alike.

ATES regulations should account for the country-specific ATES market development level (Table 5.1) and include space for dynamic adjustments. Past changes in Dutch regulations due to an increasing number of ATES installations serve as a good illustration. Currently, newly created systems must adhere to strict rules stating that extraction temperatures of already existing neighbouring systems cannot be affected by more than ±0.5 K. Especially in dense urban areas this might hinder further ATES deployment in the long term. A Dutch interviewee accordingly hoped for further adjustments introducing a more flexible approach towards system spacings and a coordinated planning of multiple systems which can achieve an overall higher system performance in dense urban settings (Bloemendal et al., 2018; Sommer et al., 2015).

Recommendation 3: Provision of financial incentives for ATES

Space heating and cooling with ATES is commonly subject to higher upfront capital costs than other types of heating and cooling such as ASHPs, gas boilers or compression chillers (Schüppler et al., 2019). The high importance of economic feasibility as an ATES market factor was underlined in the online survey responses (Figure 5.3). The availability of funding schemes tailored towards ATES can significantly reduce financial risks and can constitute a crucial part of ATES policies to attract financial interest of potential system owners. Besides decentralized ATES systems for single building complexes, centralized ATES feeding into district grids can profit from funding, too.

"If you lower the costs, that will remove one of the main barriers." – Rasmus Aaen, NIRAS A/S, Denmark

Funding schemes for individual installations might cover different ATES deployment stages. Besides subsidising system installation, funding for site-specific feasibility studies, hydrogeological exploration and thermo-hydraulic simulations can lower financial barriers during system planning. Other financial allocation mechanisms such as low-interest loans and reduced electricity prices for heat pump operation are also conceivable. Funding of ATES research projects and demonstration sites can further help in stimulating a broad ATES market uptake.

The specific design of financial incentives for ATES provided through national funding programmes or tax deduction schemes is subject to the country-specific fiscal policy and institutional environment. It can also be adapted over time as happened in the Netherlands where financial support during the start-up phase of market implementation in the 1990s was granted for early ATES systems through a market uptake programme by the Dutch Ministry of Economic Affairs (now the Ministry of Economic Affairs and Climate Policy). Today, however, in the context of a mature and fully commercialised ATES market, no financial incentives specific to ATES are available or required any more.

Besides ATES specific funding, more general funding schemes and financial incentives supporting building energy efficiency, high-efficiency heat pumps, seasonal thermal storage or storage systems feeding into heating grids can indirectly foster a higher ATES deployment rate. In this case, ATES should specifically be included in a technology portfolio eligible for funding.

5.3.3.2 Role of ATES in the municipal energy transition

Municipalities are key actors for a successful heat transition in the built environment (Beauchampet and Walsh, 2021). Municipal engagement with energy includes holistic municipal energy planning, building energy retrofitting and the uptake of sustainable technologies such as low-carbon district heating grids and high-efficiency heat pumps, all of which can facilitate increased ATES deployment (Coy et al., 2021; Herreras Martínez et al., 2022).

Recommendation 1: Establishing a suitable political environment

National governments are responsible to create the right policy framework for the heat transition and, in this course, establish political drivers encouraging an increased ATES implementation. This starts with clearly communicating climate protection targets, the heat transition's urgency and suitable transformation strategies for the built environment (Herreras Martínez et al., 2022;

Sillak, 2023). Reliable and consistent governmental strategies and information on suitable technological solutions are crucial for long-term planning security of municipal, business and private stakeholders.

Mandatory municipal heat planning is an important example for legally binding instruments supporting the leading role of local authorities in the heat transition (Herreras Martínez et al., 2022). Local empowerment facilitated by central governments can further encourage this leading role (Coy et al., 2022; Coy et al., 2021; Vringer et al., 2021). This way, municipalities can substantially engage in the transformation of the heating and cooling infrastructure reflected by their own transformation from solely consumers of heat and cold to active prosumers, i.e., a combined role of producers and consumers. A supporting central governance should clearly outline the energy planning role of municipalities and increase municipal competences in finding the best technological solutions accounting for local opportunities and barriers. The unique Danish energy policy granting far-reaching autonomy to municipalities in making long-term decisions on their supply of thermal energy could potentially serve as an exemplary practice model for other countries (Bulkeley, 2010; Chittum and Østergaard, 2014; Johansen and Werner, 2022; Sperling et al., 2011).

Recommendation 2: Establishing building energy efficiency requirements

Increasingly strict building energy efficiency requirements are considered an integral part of an overarching policy framework for sustainable space heating and cooling concerning building energy retrofitting as well as the construction of new buildings.

"That [building energy efficiency] policy worked out quite well to increase market demand." – Martin Bloemendal, Delft University of Technology, Netherlands

As pointed out by several interviewees in the Netherlands and Belgium, strict efficiency standards of newly constructed buildings can effectively foster a widespread ATES deployment since ATES is a well-suited technology to substantially reduce the primary energy consumption for space heating and cooling. ATES and its energetic and cost benefits should therefore be promoted within the portfolio of efficient technological solutions.

Recommendation 3: Integrating ATES into municipal energy planning

Municipal energy planning accounts for local chances and barriers in advancing the energy transition at a local level. Accompanying the increasingly decentralised and climate friendly generation and supply of electricity and thermal energy, municipal energy plans aim to find the right technological solutions district by district (Brandoni and Polonara, 2012; Sperling et al., 2011). Seasonal thermal storage can be an important component of municipal energy plans (Kauko et al., 2022; Paiho et al., 2017) which therefore might stipulate increased ATES deployment including the integration of ATES into DHC grids.

National or regional governments can assist municipalities in considering ATES in municipal energy planning by providing information services, energy planning guides and tools. These could include government-operated online map applications that show suitable regions for ATES across the country including some preliminary statements on site-specific feasibility and existing installations including operational information such as permitted extraction volumes. This can also benefit early design considerations of individual systems. The freely accessible services in Belgium (www.dov.vlaanderen.be/portaal/?module=verkenner) and the Netherlands (www.wkotool.nl) can serve as inspirations for similar services in other countries. Free and easy online access to hydrogeological subsurface data can also facilitate consideration of ATES in municipal energy plans.

"The municipalities can make a kind of [ATES] master plan." – Bas Godschalk, IF Technology, Netherlands

Accompanying the legal obligation for municipalities to prepare energy plans, a holistic and coordinated approach of managing ATES and other shallow geothermal systems is to be encouraged as it can prevent thermal interferences between installations early on or even intentionally allow them to achieve overall higher system performance on the district level (Bloemendal et al., 2018; Sommer et al., 2015). Especially in countries with higher installation densities such as Belgium and the Netherlands, interviewees stressed the advantages of such a coordinated planning over individual system planning. Structural expertise building in local authorities might be necessary to adequately address this level of urban energy planning potentially involving heat transport modelling and other sophisticated management measures.

5.3.3.3 ATES awareness and expertise

While not being rated as important market factors for an increased ATES uptake in the online survey (Figure 5.3), the low level of public ATES awareness and lacking hydrogeological and technological expertise regarding ATES were repeatedly stressed during several interviews as severe barriers to a broader ATES development. This is in line with past experience with other renewable energy technologies, such as photovoltaics, solar thermal energy, ASHPs and ground source heat pumps (GSHPs) (Briggs et al., 2022; Karytsas and Theodoropoulou, 2014; Peñaloza et al., 2022; Seetharaman et al., 2016).

Recommendation 1: Raising awareness of ATES

A sophisticated and thorough ATES policy in a given country should make a wide variety of stakeholders aware of ATES, such as potential consumers, energy planners, installation companies, the national heating, ventilation and air conditioning (HVAC) and heat pump industry as well as regional and local authorities. Indeed, relevant policy makers have to be aware of ATES for this to happen in the first place, which is often lacking. As some interviewees pointed out, initial awareness raising initiatives could therefore come from governmental energy agencies, national heat pump associations or national geothermal associations. These organisations can take a crucial role in increasing awareness in the responsible governmental bodies.

"You need to talk about ATES and [...] improve awareness." – Anonymous interviewee, public sector organisation, UK

Awareness building measures raised by interviewees include workshops, conferences and online courses organised by governmental energy and environmental agencies in cooperation with industry associations or universities. Aiming at different target audiences, these events can explain ATES operation principles and suitable use cases as well as stressing its benefits. Informing the public can help reducing adverse impressions of an overly high technological complexity of ATES linked to the widely unfamiliar term 'aquifer'.

"Go and advertise it." – Teppo Arola, Geological Survey of Finland, Finland

Another great leverage effect in raising public awareness can be attributed to existing ATES installations, both demonstration projects and pioneering commercial systems, the existence and benefits of which should be communicated to all stakeholders (Fleuchaus et al., 2021). National or regional geological surveys and energy agencies can provide information about existing systems via web pages and similar distribution channels. The unique example of façade plaques for Dutch buildings highlighting space heating and cooling with ATES could also set a precedent in illustrating a subsurface technology that is otherwise not visible.

"Energetically, ATES is the best source of a heat pump, including [...] passive cooling." – Frank Agterberg, Branchevereniging Bodemenergie Nederland, Netherlands

In recent years, heat pumps have been a central part of many energy transition strategies in the building sector and corresponding supportive national and international policies (Grubler and Wilson, 2014; IEA, 2022). Besides presenting ATES as a distinct new technology, ATES policies could use this ongoing political and societal focus on heat pumps as a starting point to promote heat stored in the underground as the ideal heat source for heat pump operation. Communicating the environmental and economic benefits due to primary energy savings compared to other heat sources, such as the outside air, could help increasing ATES popularity. This includes stressing its capability of passive cooling during summer, i.e. without running the heat pump's compressor (Fleuchaus et al., 2018; Schüppler et al., 2019). Benefits of centralized ATES application as storage components of district heating grids should be emphasized as well.

Recommendation 2: Building up ATES expertise

The online survey results presented in Figure 5.3 illustrate the high importance of knowledge and expertise among relevant stakeholders in industry and government authorities. Especially in emerging ATES markets, skill shortages and insufficient training and qualifications were often pointed out as significant barriers to a wider ATES deployment. This problem is not unique to

ATES and can be observed for other related areas as well, such as building energy retrofits, photovoltaic and heat pump installation (Branford and Roberts, 2022; Briggs et al., 2022; Jagger et al., 2013; Zekira and Chitchyan, 2019).

"There are courses and trainings for people to get into this business." – Bas Godschalk, IF Technology, Netherlands

Policies fostering a coordinated approach of government and industry to build up sufficient education and training capacities are needed for a rapid workforce upskilling (Briggs et al., 2022). Governmental education programmes and training infrastructure can take the form of information campaigns and skills boot camps focusing on various groups of workforces along the supply chain of ATES deployment.

"They don't see the opportunity, even if they are situated on top of it." – Teppo Arola, Geological Survey of Finland, Finland

Government-controlled capacity building initiatives should also address knowledge on subsurface utilization opportunities and basic hydrogeological processes that is often lacking amongst energy planners, building architects and heat pump sellers since these groups arguably have the highest impact on promoting ATES commercialization.

"A lot of those [...] who do similar things could be re-trained." – Erick Burns, USA

Additionally, a higher number of qualified personnel could potentially be generated by a systematic skill shift in technologically related sectors. Especially in countries with a high share of groundwater resources in drinking water production, such as Germany and Denmark, ATES education and training could benefit from already existing expertise and high-quality standards in the water industry. This skill shift might also be conceivable for pre-existing expertise in hydrocarbon exploration in some countries. Speeding up permission procedures for ATES requires capacity development in government authorities as well since a robust knowledge on reasonable system spacing and temperature limits is necessary including special considerations in already thermally affected urban aquifers.

"Hopefully you plant some seeds [in the universities] and it starts to grow in five or ten years." – Bjørn Frengstad, Norwegian University of Science and Technology, Norway

Besides upskilling amongst practitioners and public authorities, adjusted education in relevant disciplines at universities can also build up ATES expertise in the long term.

"The market follows the successful projects." – Teppo Arola, Geological Survey of Finland, Finland

Especially in emerging markets, the importance of successful ATES systems early on was stressed during several interviews due to the pioneering role of early lighthouse projects. Industry standards and codes of practice in the form of guidelines on ATES design, installation and operation can ensure system quality. Ideally policy makers should implement such standards as legally binding protocols as enforced in the Netherlands in 2013. These protocols are designed to dynamically incorporate new research findings to further improve ATES quality. The Netherlands can also serve as a best practice model in establishing mandatory national certifications for specialist companies active in ATES consultation, design and construction. Such certifications can pose an integral element of a sophisticated ATES policy leading to higher system quality, decreasing installation costs, increasing reputation and ultimately fully commercialising the ATES market.

Recommendation 3: Establishing ATES knowledge transfer

Policy-initiated expertise development for ATES as described above could be supplemented by establishing different platforms for knowledge exchange, both on national and an international level.

"Owners of ATES systems have unified themselves in the user platform." – Martin Bloemendal, Delft University of Technology, Netherlands

Again, the Netherlands provides an example for a successful knowledge exchange platform among individual ATES users. This platform (gebruikersplatform.bodemenergie.nl) by the Dutch industry association for geothermal systems consists of an online member forum and a knowledge platform offering consultation for end users and webinars on a regular basis providing valuable information on optimal system operation.

"We are open for [international] collaboration." – Bas Godschalk, IF Technology, Netherlands

ATES knowledge transfer on the international level is currently mostly limited to academic research projects. Technical assistance or collaboration programmes could address a more systematic transfer of ATES expertise and knowledge on a broader level. Such transfer could take place in the frame of existing structures, such as the Technology Collaboration Programme on Heat Pump Technologies (HPT TCP) by the International Energy Agency (IEA). As pointed out during some interviews, national geological surveys could also significantly contribute to ATES knowledge transfer between different countries generating important shared expertise especially between neighbouring countries with similar hydrogeological subsurface characteristics. Examples of this already happening are the Nordic countries Norway, Sweden and Finland. However, this exchange was described as being limited and rather unstructured indicating potential for a more systematic exchange between geological surveys. This is also true for collaborations and research projects between national heat pump associations organised under the auspices of the European Heat Pump Association (EHPA), which could be expanded for topics more specific to ATES.

"It's easy to copy and paste this legislation." – Horia Ban, TermoLine, Romania

Besides addressing technical challenges and research findings on ATES, insights into suitable and practically proven ATES legislation and regulation could also be part of international knowledge transfer. Especially countries with emerging ATES markets and countries that have yet to see first ATES installations could benefit from already implemented and successful legislative and regulatory ATES frameworks from other countries. In the long-term, this might also encourage a harmonized ATES legislation across national borders, for example, in the context of the European Union.

5.3.3.4 Social engagement with ATES

Active participation of citizens in transforming the energy system is often described as a meaningful part of the energy transition and a way to increase acceptance of renewable energies. Such social engagement allows meaningful citizen interactions with the energy system and thereby empowers formerly marginalised actors (Beauchampet and Walsh, 2021; Hartmann and Palm, 2023; Wüstenhagen et al., 2007). In some countries, citizen-led community initiatives have already contributed to a wider acceptance and larger share of renewable energies in electricity supply (Fouladvand et al., 2022; Hartmann and Palm, 2023). This can serve as a model for social engagement with sustainable heating and cooling solutions as well. It should be noted, however, that the research participants provided very little information about social engagement with ATES during the online survey and the interviews.

Recommendation: Stimulation of social engagement with ATES

A common form of collective social engagement is a citizen energy cooperative which describes local communities with joint investments in technologies to generate and consume or sell renewable energy (Dóci et al., 2015; Fouladvand et al., 2022). Since ATES is not commonly applied for individual residential buildings, especially large-scale ATES applications feeding into heating and cooling grids are conceivable for energy cooperatives. Integrating ATES into these grids allows for a flexible use of locally generated renewable energy and available waste heat increasing local value added (Todorov et al., 2020). The sense of ownership provoked by such an energy system collectively owned by the consumers themselves might serve as a key motivation for social engagement with ATES.

A sophisticated ATES policy should encourage local authorities to explicitly create space for citizen engagement in their urban heat planning. Creating awareness of the citizen energy business model in municipalities and local governments contributes to a supportive mindset and promotes the involvement of the local community early on (Hartmann and Palm, 2023). Some other policy measures mentioned above are also relevant for increasing social engagement coordinated in citizen energy cooperatives. The importance of public awareness raising and provision of necessary information on ATES to different groups of stakeholders must be reiterated here since a proper information basis allows citizens to make informed decisions. Citizen workshops, information campaigns and community energy roadshows can bring citizen energy cooperatives and ATES to the public attention (Coy et al., 2022). In addition, financial incentives specifically designed for collective community engagement such as citizen energy cooperatives can reduce financial barriers.

5.4 Conclusions

This study presents an international comparison of ATES policies regarding their existence and suitability to overcome legislative, regulatory and socio-economic barriers to a wider international ATES deployment. For this, we conducted an online survey among experts and practitioners in relevant sectors, such as universities, private companies and government authorities from a total of 30 countries. Additional information was collected through 16 semi-structured expert interviews. For the survey evaluation, countries were aggregated to three distinct groups to identify similarities and differences between different ATES market development levels.

Across all market development levels, geological feasibility of ATES as well as suitable laws and regulations were rated as the most important market factors. The existence of laws and regulations governing ATES was confirmed by 56 % of all survey respondents. In contrast, a mere 33 % of all respondents stated that there are policies designed to support increased ATES deployment in their respective countries. Especially survey participants from countries with a mature or growing ATES market predominantly confirmed distinct ATES policies and a legislative and regulatory framework. A dependence on the ATES market development level could also be inferred for other aspects such as public awareness and access to sufficient technical knowledge and qualified workers.

The expert interviews confirmed the overall favourable conditions for an increased use of ATES in mature or growing markets. This applies to both ATES policy elements as well as indirect drivers benefiting ATES deployment including existing widespread utilization of groundwater technologies for other purposes and strict building energy efficiency requirements. In contrast, interviewees from emerging ATES markets pointed out many obstructing factors, such as lengthy ATES permit procedures, low awareness among relevant stakeholders and a general lack of expertise and skilled workers for planning and installing ATES systems. Overall, the online survey and expert interviews revealed significant shortcomings in many countries regarding the existence and suitability of policies and regulations for reducing market barriers and promoting benefits of ATES.

Based on our findings from the online survey and expert interviews, we developed policy recommendations which can reduce identified barriers and advance ATES market development. The recommendations cover legislative and regulatory topics on the governance of ATES and highlight ways of raising awareness of the technology, its application cases and benefits. A sophisticated ATES policy should furthermore acknowledge the potentially substantial role of ATES in the municipal energy transition and therefore include measures to promote ATES in local urban and energy planning as well as encourage social engagement with ATES. We hope that our proposed ATES policy can contribute to establishing suitable legislative, regulatory and socio-economic conditions for a wider international ATES deployment.

Acknowledgements

All survey participants were asked if they wished to be acknowledged for their contribution to the study and, if so, to provide their name and/or organisation. The authors would like to thank Mohammad Abuasbeh (KTH Royal Institute of Technology), Olof Andersson (Geostrata HB), Quentin Barral (Accenta), Asal Bidarmaghz, Jessica Maria Chicco (Interuniversity Department of Regional, Urban Studies, and Planning, University of Turin), Michael B. Clennell (CSIRO), Alain Dassargues (University of Liège), Anabela Duarte Carvalho (Polytechnic Institute of Coimbra, Coimbra Institute of Engineering), Joao de Sousa Figueira (TPF Consultores/CERIS, University of Lisbon), Steffen Große (EcoVisio GmbH), Carsten Hansen (Consulaqua Hamburg), Ignasi Herms (Institut Cartogràfic i Geològic de Catalunya), Jan Holeček (Czech Geological Survey), Cameron Huddlestone-Holmes (CSIRO), Lars Hjortshøj Jacobsen (ATES A/S), Rita Kobler (BFE), Andreas Koch (Project Management Juelich - Forschungszentrum Juelich GmbH), Nevton Kodhelaj (Energy Resources Department, Faculty of Geology and mining, Polytechnic University of Tirana), Jakob Kulich (GeoSphere Austria), Youngmin Lee (Korea Institute of Geoscience and Mineral Resources), Ingo Leusbrock (AEE INTEC), Peter Malík (Štátny geologický ústav Dionýza Štúra - Geological Survey of Slovak Republic), Anne Medema (TU Delft), Tamás Medgyes, Kirsti Midttømme (NORCE Norwegian Research Centre), Anders Møller (Ramboll Danmark), Lars Boye Mortensen (Aalborg Forsyning), Rodolfo Perego (SUPSI - University of applied sciences and arts of southern Switzerland), Alberto Previati (University of Milano-Bicocca), Paul Ramsak (Netherlands Enterprise Agency/RVO), Nina Rman (Geological Survey of Slovenia), Grzegorz Ryżyński (Polish Geologial Institute - National Research Institute), Martin Sabel (BWP e.V.), Sami Vallin (Geological Survey of Finland), Simon Schüppler (KPC - Kommunalkredit Public Consulting), Sandeep Bandarwadkar (Kaunas University of Technology - Civil engineering and architecture department), Vincent Vandeweijer (TNO), G.P. Vasilyev, Anna Volkova (Tallinn University of Technology), Henning Wienkenjohann (Technical University of Denmark - Department of Environmental and Resource Engineering), Andy Wilkins (CSIRO), Henk Witte (Groenholland Geoenergiesystemen BV), Kai Zosseder (Technical University of Munich, Chair of Hydrogeology, Geothermal Energy Group) and 23 anonymous respondents for their willingness to participate at the online survey.

The authors would further like to thank Rasmus Aaen (NIRAS A/S), Frank Agterberg (Branchevereniging Bodemenergie Nederland), Teppo Arola (Geological Survey of Finland), Guillaume Attard (Ageoce Solutions), Vincent Badoux (GEOTEST Ltd), Horia Ban (Termoline), Martin Bloemendal (Delft University of Technology), Christian Boissavy (Cabinet Boissavy), Paul Fleuchaus (tewag GmbH), Bjørn Frengstad (Norwegian University of Science and Technology), Bas Godschalk (IF Technology), Edward Hough (British Geological Survey), Anders Juhl Kallesøe (NIRAS A/S), David Simpson (AGT - Advanced Groundwater Techniques), Xiaobo Wu (CEEC Geothermal Co., LTD.) and two anonymous contacts for their willingness to provide valuable information during the online survey as well as the expert interviews.

This work was supported by the Scholarship Program of the German Federal Environmental Foundation (DBU) for Ruben Stemmle, the funding of Kathrin Menberg via the Margarete von Wrangell program of the Ministry of Science, Research and the Arts (MWK) of the State of Baden-Württemberg, the SpeicherCity project funded by the German Federal Ministry of Education and Research (BMBF), grant number 03G0911A. Richard Hanna, Matthew Jackson and Iain Staffell were funded by the ‘Aquifer thermal energy storage for decarbonisation of heating and cooling: Overcoming technical, economic and societal barriers to UK deployment (ATESHAC)’ project, with funding provided by the UK Engineering and Physical Sciences Research Council (grant number EP/V041878/1).

Finally, the research stay of Ruben Stemmle at Aalborg University, Denmark was funded by Karlsruhe House of Young Scientist (KHYS).

The survey results for this paper were generated using Qualtrics software, Version March 2023 of Qualtrics. Copyright © 2023 Qualtrics. Qualtrics and all other Qualtrics product or service names are registered trademarks or trademarks of Qualtrics, Provo, UT, USA. https://www.qualtrics.com

Appendices

Appendix A Online survey questionnaire

All online survey questions and possible answers are listed below:

1. Before receiving this survey, were you aware of Aquifer Thermal Energy Storage (ATES)?
    - Yes
    - No
2. Have Aquifer Thermal Energy Storage (ATES) systems been installed in your country?
    - Yes
    - No
    - Don’t know
3. Do you think that ATES is a promising technology that could be widely deployed in your

country?
  - Yes
  - No
  - ATES is already widely employed in my country
  - Don’t know

4. At the present time and in your view, how important are the following market factors in influencing the uptake of ATES in your country?
   - Technical (engineering) feasibility
   - Geological feasibility including presence of suitable aquifers
   - Lack of (limited) subsurface space due to other subsurface uses
   - Economic feasibility including investment and operational costs
   - Policy support
   - Laws and regulations
   - Industry knowledge and skills
   - Public awareness
   - Public trust and acceptability
     - Five-point scale from ‘not important’ to ‘very important’
     - Don’t know
5. Are there any policies being applied currently in your country to increase the installation and use of ATES?
   - Yes
   - No
   - Don’t know
6. If known, please provide brief details about any policies being applied currently in your country to increase the installation and use of ATES.
7. Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?
   - Yes
   - No
   - Don’t know
8. Is the legal and regulatory framework concerning ATES uniform across the country or are there differences between regions?
   - Uniform across the country
   - Region/state dependent
   - Don’t know
9. In your country, how do you rate the effectiveness of planning laws and regulations to manage environmental risks (e.g. groundwater quality impacts or subsurface temperature changes) associated with ATES installation and use?
   - Five-point scale from ‘very low or none’ to ‘very high’
   - Don’t know
10. In your country, how do you rate the ease or difficulty and speed of the application process to gain planning permission for new ATES installations?
    - Five-point scale from ‘very poor’ to ‘very good’
    - Don’t know
    - Not applicable
11. Is ATES considered as part of municipal or local authority heat (energy) plans in your country?
    - Yes
    - No

- My country does not have municipal or local authority heat (energy) plans
- Don't know

12. How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?
    - Five-point scale from 'very low or none' to 'very high'
    - Don't know
13. How do you rate the quality of information about ATES available to the public and system or energy planners in your country?
    - Five-point scale from 'very poor' to 'very good'
    - Don't know
14. How do you rate the level of public awareness of ATES in your country?
    - Five-point scale from 'very low or none' to 'very high'
    - Don't know
15. How do you rate the level of public acceptability of ATES in your country?
    - Five-point scale from 'very low or none' to 'very high'
    - Don't know
16. Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?
    - Yes
    - No
    - Don't know
17. If known, please provide brief details about any currently active funding programmes or financial incentives for ATES in your country, particularly on what is funded or incentivised.
18. Do citizen or community energy cooperatives play a role in your country's ATES market?
    - Yes
    - No
    - Don't know
19. To what extent does your country have access to enough technical knowledge and qualified workers for the installation and operation of ATES systems?
    - Five-point scale from 'Not at all' to 'To a very large extent'
    - Don't know
20. Are there any industry standards or codes of practice to manage the quality of ATES installations and operation in your country?
    - Yes
    - No
    - Don't know
21. If known, please provide brief details about any industry standards or codes of practice to manage the quality of ATES installations and operation in your country.
22. Optional: If known, please state the/an approximate number of ATES installations in your country.

If respondents answered 'no' or 'don't know' to question 2, they were presented a smaller number of partially slightly modified questions:

3.a Do you think that ATES is a promising technology that could be adopted in your country?
- Yes
- No
- Don't know

4.a At the present time and in your view, how important are the following market factors in influencing the potential adoption of ATES in your country?
- Technical (engineering) feasibility
- Geological feasibility including presence of suitable aquifers
- Lack of (limited) subsurface space due to other subsurface uses
- Economic feasibility including investment and operational costs
- Policy support
- Laws and regulations
- Industry knowledge and skills
- Public awareness
- Public trust and acceptability
  - Five-point scale from ‘not important’ to ‘very important’
  - Don’t know

5.a Are there any policies being applied currently in your country to encourage the adoption and use of ATES?
- Yes
- No
- Don’t know

6.a If known, please provide brief details about any policies being applied currently in your country to encourage the adoption and use of ATES.

7.a Are there any laws or regulations currently in effect or active in your country to govern the installation and use of ATES systems?
- Yes
- No
- Don’t know

9.a To what extent do you think that planning laws and regulations in your country are adequate to support the adoption of ATES systems?
- Five-point scale from ‘Not at all’ to ‘To a very large extent’
- Don’t know

11.a Is ATES considered as part of municipal or local authority heat (energy) plans in your country?
- Yes
- No
- My country does not have municipal or local authority heat (energy) plans
- Don’t know

12.a How do you rate the quantity (amount) of information about ATES available to the public and system or energy planners in your country?
- Five-point scale from ‘very low or none’ to ‘very high’
- Don’t know

13.a How do you rate the quality of information about ATES available to the public and system or energy planners in your country?
- Five-point scale from ‘very poor’ to ‘very good’
- Don’t know

14.a How do you rate the level of public awareness of ATES in your country?
- Five-point scale from ‘very low or none’ to ‘very high’
- Don’t know

16.a Are there any currently active funding programmes or financial incentives which provide support for ATES systems in your country?
- Yes

- No
- Don’t know

17.a If known, please provide brief details about active currently active funding programmes or financial incentives for ATES in your country, particularly on what is funded or incentivised.

Appendix B Expert interviews guide

Questions used as an interview guide for the semi-structured expert interviews are listed below:

I. How would you describe the current situation and history with respect to the deployment and installation of ATES in your country?

II. To what extent do you think ATES has potential to be more widely deployed in your country?

III. In the survey you indicated that […] and […] are the most important market factors influencing whether ATES could be more widely deployed in your country. Could you explain your reasons for this?

IV. In the survey you indicated that […] and […] are the least important market factors influencing whether ATES could be more widely deployed in your country. Could you explain your reasons for this?

V.a *[If relevant policies exist]* How effective have any policies been in increasing the installation and use of ATES in your country?

V.b *[If relevant policies do not exist]* Which types of policies could be effective for encouraging wider deployment and use of ATES in your country?

VI.a *[If funding programmes or financial incentives exist]* How effective are any funding programmes or financial incentives in supporting the installation of ATES systems in your country?

VI.b *[If funding programmes or financial incentives do not exist]* How do you think funding programmes or financial incentives could be designed to effectively support the installation of ATES in your country?

VII.a [*If relevant laws or regulations exist]* How effective are any laws or regulations in governing the installation and use of ATES systems in your country? To what extent could this legal and regulatory framework be improved?

VII.b *[If relevant laws or regulations do not exist]* How could laws or regulations be designed to effectively govern the installation and use of ATES systems in your country? What could an effective legal and regulatory framework for ATES look like?

VIII. *[If legal and regulatory framework is region or state dependent]* How do regional or state differences in laws and regulations relevant to ATES affect the ease or difficulty of installing it?

IX. *[If applicable]* In the survey you indicated that ATES is considered as part of municipal or local authority heat (energy) plans in your country. Can you explain more about how ATES is considered in these plans?

X. Can you explain more about the quantity, quality and types of information available to the public and system planners about ATES in your country?

XI. *[If survey response to question 14 or 14.a was ‘very low’ to ‘moderate’]* How could the level of public awareness of ATES in your country be improved?

XII. Are there any strategies in your country to maximise public trust and acceptance of ATES?

XIII. *[If citizen or community energy cooperatives play a role]* What role do citizen or community energy cooperatives have in ATES deployment in your country?

XIV.a *[If survey response to question 19 was ‘to little extent’ or ‘to some extent’]* How could jobs, skills and technical knowledge for ATES design, installation and use be further developed in your country?

XIV.b *[If survey response to question 19 was 'to a large extent' or 'to a very large extent']* In the survey, you indicated that your country has a high level of access to technical knowledge and qualified workers for ATES installation. To what extent is this a result of particular initiatives to develop skills, knowledge and labour for ATES, or inherited from other industries already existing in your country?

XV.a *[For emerging markets only]* Have you or others in your country benefited from knowledge transfer from countries with greater experience in ATES, and if so from which countries?

XV.b *[For mature & growing markets only]* Do you or other ATES specialists in your country provide knowledge transfer to other countries, and if so which ones?

XVI.a *[If industry standards or codes of practice exist]* How effective are any industry standards or codes of practice in managing the quality of ATES installations and operation in your country?

XVI.b *[If industry standards or codes of practice do not exist]* How do you think industry standards or codes of practice could be designed to effectively manage the quality of ATES installations and operation in your country?

XVII. Is there any requirement for the performance of ATES systems to be monitored after installation?

Appendix C Response rates of online survey

Country	Invitations	Responses	Response rate [%]
Albania	2	1	50
Australia	5	5	100
Austria	12	5	42
Belarus	1	0	0
Belgium	11	3	27
Bosnia and Herzegovina	4	0	0
Bulgaria	5	0	0
Canada	7	0	0
China	3	1	33
Croatia	8	0	0
Cyprus	1	0	0
Czech Republic	4	1	25
Denmark	26	7	27
Estonia	5	1	20
Finland	8	2	25
France	15	3	20
Germany	32	15	47
Greece	4	1	25
Hungary	7	2	29
Iceland	7	0	0
Ireland	6	0	0
Italy	9	2	22
Japan	2	0	0
Kazakhstan	1	0	0

Kosovo	2	0	0
Latvia	2	0	0
Lithuania	5	1	20
Moldova	1	0	0
Montenegro	1	0	0
Netherlands	17	7	41
North Macedonia	2	0	0
Norway	10	2	20
Poland	7	1	14
Portugal	5	2	40
Romania	2	1	50
Russia	5	1	20
Serbia	3	1	33
Slovakia	3	1	33
Slovenia	5	1	20
South Korea	4	2	50
Spain	10	1	10
Sweden	19	2	11
Switzerland	15	5	33
Turkey	4	0	0
Ukraine	3	0	0
United Kingdom	16	4	25
USA	7	1	14

6 Synthesis

6.1 Summary and conclusions

Heating and cooling currently account for more than 50 % of Germany's final energy consumption (AEE, 2023), illustrating the importance of decarbonizing this sector for a successful energy transition in Germany. A possibility in this regard is the increased utilization of environmental heat, i.e. summer heat and winter cold, as well as industrial waste heat or excess renewable energies. To make use of these energy sources more extensively, Aquifer Thermal Energy Storage (ATES) can reduce the temporal offset between their availability and the demand for heating and cooling. Although ATES has achieved a high technical readiness (Fleuchaus et al., 2018), the very limited utilization of ATES systems in most countries including Germany requires the comprehensive evaluation of a potential large-scale use of the technology.

To answer this thesis's overarching research question, how ATES can contribute to the German energy transition, possible environmental and energetic benefits, application opportunities as well as ways to overcome legislative, regulatory, and socio-economic barriers of ATES are evaluated. To address these points, the main findings of Studies I to IV presented in Chapters 2 to 5 and their respective methodological novelties are summarized below answering the research questions formulated in Chapter 1.3. In addition, the studies' objectives, methods, and results are summarized in Figure 6.1.

Research question I: *To what extent can LT-ATES systems contribute to reducing greenhouse gas emissions compared to other types of space heating and cooling?*

The ambitious goal of achieving carbon neutrality by 2045 set by the German federal government requires the extensive application of sustainable heating and cooling technologies with low specific greenhouse gas (GHG) emissions. Only few studies, however, quantify the specific GHG emissions of ATES systems and compare them with other types of heating and cooling. Hence, Study I (Chapter 2) presents a novel life cycle assessment (LCA) regression model to estimate GHG emissions of Low-Temperature ATES (LT-ATES) systems across their entire life cycle. In contrast to conventional LCAs, the regression model requires only the ten most important system-characterizing parameters as input, such as the number of wells and annual operation times. Thus, it provides a quick-to-use, low-threshold yet robust tool that is applicable for a wide range of different ATES configurations and serves a dual purpose. First, it can be used during the planning of individual ATES systems. Possible site-specific GHG emission savings estimated with the LCA regression model could convince builder-owners to actively consider ATES for heating and cooling their building.

Second, taking advantage of its straightforward parametric design, the LCA regression model is implemented within a Monte Carlo simulation framework to determine GHG emissions of a large variety of different ATES configurations. The resulting range of GHG emissions is presented in Chapter 2.3.2. With the median of the Monte Carlo distribution representing a typical ATES system with specific GHG emissions of 83.2 $gCO_2eq\ kWh_{th}^{-1}$, substantial GHG emission savings are shown with regard to other technologies. Compared to electrically powered compression chillers, GHG emissions can be reduced by up to 59 %. The savings amount to up to 74 % when compared to heating based on heating oil or natural gas. These numbers illustrate that ATES is a meaningful technological option for the energy transition. The findings of Study I further show that GHG emission savings in heating mode are expected to increase in the future with growing shares of green electricity used for ATES operation. The high reductions in GHG emissions could encourage political decision-makers to consider ATES in climate protection policies and energy transition strategies alongside other types of sustainable energy supply.

Research question II: *Where are suitable regions for LT-ATES located in Germany?*

Scaling up GHG emission savings possible with ATES to a meaningful national scope in the German energy transition requires sufficiently large areas suitable for ATES across the country. For this reason, Study II (Chapter 3) combines spatial hydrogeological and climatic data to identify regions with high suitability for the application of LT-ATES systems. The considered data include the productivity of groundwater resources, iron and manganese contents in groundwater, the groundwater flow velocity, and a climate-based estimation of heating and cooling demands. The resulting ATES potential map presented in Chapter 3.3.3 is the most detailed one of its kind and includes additional and more detailed information compared to earlier supra-regional maps. This allows better identification of suitable regions and preliminary assessments when planning systems.

The map shows that 54 % of Germany's area is well or very well suitable, excluding hard rock areas. This number is expected to rise in the future due to an increasing cooling demand. Most of the well or very well suitable areas are located in the North German Basin, the Upper Rhine Graben, and the South German Molasse Basin. These regions are characterized by often highly productive porous aquifers with comparatively low groundwater flow velocities and thus fulfill basic requirements for an efficient ATES operation. The high share of well or very well suitable areas demonstrates the substantial potential for the application of ATES in Germany. Especially in the three aforementioned regions, ATES could play a significant role in transforming the heating and cooling supply on the way to a successful energy transition in Germany.

Research question III: *To what extent can LT-ATES supply existing energy demands for space heating and cooling in an urban setting?*

Further quantitative assessment of the heating and cooling supply possible with ATES is necessary for the consideration of ATES in urban energy planning. Especially in dense inner-city areas, consideration of the subsurface space requirements of individual ATES systems is crucial. Study III (Chapter 4) therefore presents a novel methodology to determine the technical potential of LT-ATES on the city scale that is universally applicable to a wide range of regions. It is based on 3D numerical subsurface heat transport models of simple geometry, which account for local hydrogeological subsurface conditions and technical specifications of ATES operation, such as different well layouts. The methodology allows the determination of heating and cooling power densities of ATES as well as heating and cooling supply rates, that can be achieved with ATES. Compared to conventional purpose-built and region-specific subsurface models, the presented universal modeling approach is much faster to use regarding model creation, meshing, and simulation runtimes.

Applying the modeling framework to the city of Freiburg im Breisgau as an exemplary study area reveals spatially resolved ATES heating and cooling supply rates as presented in Chapter 4.3.3. For about 50 % of all considered buildings, ATES could supply more than 60 % of the heating demand. Cooling demand could even be completely supplied for 92 % of the buildings. These high supply rates show that ATES can contribute substantially to meeting urban energy demands in a sustainable way. It should be noted, however, that the stated supply rates are specific to the Freiburg study area. Building density, thermal energy demands, and hydrogeological subsurface conditions, such as the groundwater flow velocity, have a major influence on the supply rates in other cities or regions. Nevertheless, the presented modeling framework can be considered a practice-oriented tool for urban energy planning to rapidly quantify the potential energetic contribution of ATES in many other regions of Germany as well.

Research question IV: *What is the current international status of ATES policies and which aspects should a sophisticated ATES policy include that can contribute to increasing ATES deployment?*

Studies I to III presented above address hydrogeological-technical research topics on the contribution of ATES to the energy transition. Beyond hydrogeological and technical feasibility, appropriate national policies for ATES are crucial in driving ATES deployment. Hence, Study IV (Chapter 5) provides an international comparison of ATES policies. By means of an online survey and semi-structured interviews with ATES experts, an extensive data set on national ATES policies, important market barriers, and related aspects is collected. The paramount importance of these aspects is underlined by the fact, that the participating experts rated suitable laws and regulations as the second most important market factor for ATES after geological feasibility. The results also show significant differences among countries regarding legislative and regulatory frameworks governing ATES. The overall most supportive policy environments can be reported for mature and growing markets, with the purposefully created Dutch ATES policy standing out internationally. In many more countries, indirect beneficial drivers exist, such as the pre-existing use of groundwater technologies and increasingly strict building efficiency requirements. Nevertheless, supportive measures promoting a wider ATES deployment are often missing, especially in emerging markets and countries without ATES. Hence, political decision-makers are called upon to change this issue.

For this reason, Chapter 5.3.3 presents recommendations for a sophisticated ATES policy derived from the key findings of the online survey and expert interviews. These recommendations aim to support the above-mentioned favorable factors and remove identified ATES market barriers. They address legislative and regulatory issues, such as problematic permit procedures, which are often lengthy and subject to regional or federal differences in Germany and many other countries. Other recommendations include financial incentives to reduce economic risks associated with ATES as an emerging technology. Promoting ATES within the technology portfolio to fulfill increasingly strict building energy efficiency requirements could also serve as an effective lever to increase ATES market interest and deployment. Furthermore, practice-oriented planning tools for municipalities could drive the application of ATES as a component of municipal energy transitions. To tackle low awareness and expertise across all stages of ATES planning, permission, and installation, a variety of policy measures are possible. They include the clear communication of successful demonstration projects and the establishment of binding industry standards. Overall, the presented ATES policy design could guide policymakers to better make use of the environmental benefits and application opportunities of ATES that are shown in Studies I to III.

Overarching research question: *How can ATES contribute to the energy transition in Germany?*

To conclude this thesis' overarching research question, the following points summarize how ATES can contribute to the energy transition in Germany:

- Typical LT-ATES systems can reduce GHG emissions by up to 74 % compared to other types of heating and cooling, with further reductions to be expected in the future. The developed low-threshold LCA tool can be used during the planning of individual systems.
- About 54 % of Germany, excluding hard rock areas, are well or very well suitable for shallow LT-ATES as shown in a countrywide potential map that identifies suitable regions. The used methodology can easily be adapted to other countries and regions or to include additional data.
- For the exemplary urban study area of Freiburg im Breisgau, substantial heating and cooling supply rates are shown, which could be achieved with LT-ATES. The proposed modeling approach can be used for urban energy planning in other regions suitable for ATES as well.
- Recommendations for a sophisticated ATES policy can contribute to overcoming crucial legislative, regulatory, and socio-economic barriers to a wider ATES deployment. The suggested policy framework could serve as a reference for policymakers.

The environmental benefits and substantial application opportunities of ATES systems at national and city scales shown in this thesis demonstrate the great transformative potential of

ATES for a successful energy transition in Germany. The recommendations for action developed for a sophisticated ATES policy can help to bring this potential closer to realization.

While this thesis focuses on the role of ATES within the energy transition in Germany, it should be noted, that the developed methods and some of the presented findings are also applicable and highly relevant to other parts of the world.

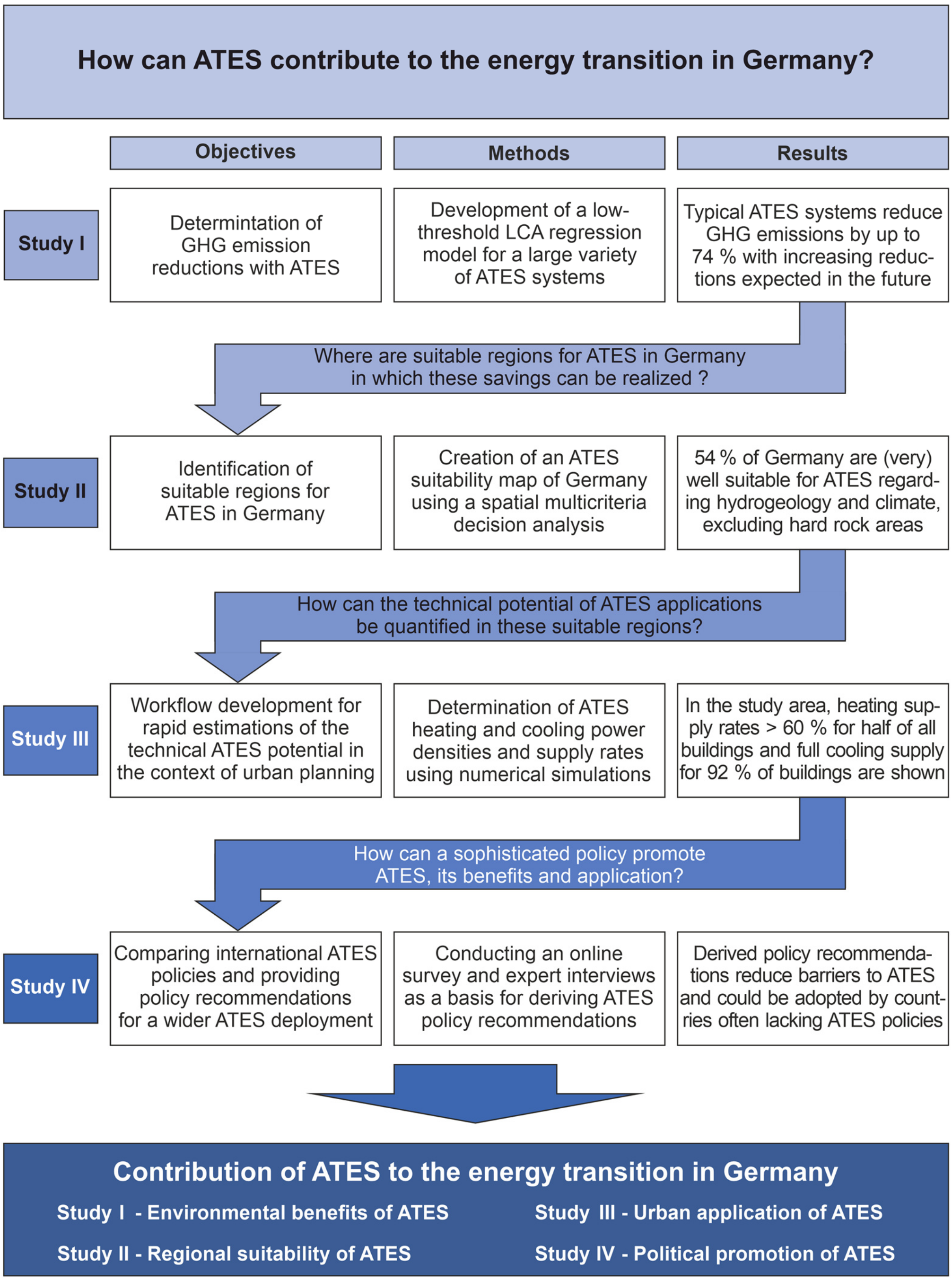


Figure 6.1: Objectives, methods, and results of the four studies collected in this thesis to answer the overarching research question how ATES can contribute to the German energy transition.

6.2 Perspectives and outlook

Since the 1990s, the German energy transition has for a long time focused primarily on the generation of renewable electricity (Biehl et al., 2023; Renn and Marshall, 2020). This is even though the importance of the building sector for a 100 % renewable energy system has long been acknowledged (Ürge-Vorsatz et al., 2007; Wiel et al., 1998). In recent years, however, this realization has increasingly brought the building sector and sustainable heating and cooling to the political attention. In Germany, this is evident from the federal government's increasing focus on energetic building refurbishment, heat pumps, and heat planning. This takes legislative form in the German Buildings Energy Act (*Gebäudeenergiegesetz*, GEG, amended in 2023) and Heat Planning Act (*Wärmeplanungsgesetz*, WPG, enacted in 2023, in force since 2024). The findings of this thesis fit in well with this ongoing political momentum and, in this course, may promote ATES in the German energy transition.

To this end and expanding on the findings from Chapters 2 to 5, further research on the following topics is required:

- **Additional environmental impacts of ATES:** Besides reductions in GHG emissions, ATES might offer other environmental benefits. Thus, additional research should compare further environmental impacts of ATES and other types of heating and cooling. This should include savings in primary energy consumption that can be achieved with ATES. Another environmental impact of ATES, which is the focus of current research, is the influence of changes in groundwater temperature on vulnerable groundwater ecosystems and their ecosystem services (Griebler et al., 2016; Koch et al., 2021). A reliable state of knowledge and scientific consensus on this issue are necessary to conclusively evaluate the environmental benefits and potential risks of ATES. Further research in this regard therefore should also serve as a basis for robust and justified regulations, which, for example, are crucial for governing potential conflicts of use between drinking water production from groundwater resources on the one hand and large-scale application of ATES on the other hand (Blum et al., 2021).
- **Economic evaluation of ATES in the energy transition context:** A more sophisticated evaluation of the economic viability of ATES could provide additional insights into the potential role of the ATES technology in the context of the German energy transition. Transparent and detailed studies on ATES economics are scarce (Schüppler et al., 2019). They typically address specific capital costs in relation to the storage capacity or payback times with respect to a reference heating and cooling system (Ghaebi et al., 2017; Schüppler et al., 2019; Vanhoudt et al., 2011). Life cycle cost analyses (LCCA) could combine these aspects as well as facilitate the determination of GHG abatement costs. Such cost comparisons between ATES and fossil-based technologies as well as other types of renewable heating and cooling (RHC) could ultimately also benefit the design of effective financial incentives for

promising sustainable technologies including ATES. In addition, more up-to-date economic analyses of ATES systems should reflect the volatility of fossil fuels in price and availability resulting in an increased prioritization of energy security and a decentralized energy supply in recent years.

- **Contribution of HT-ATES to the energy transition:** This thesis focuses primarily on LT-ATES (cf. Figure 1.3). However, High-Temperature ATES (HT-ATES) systems should be studied as well regarding their potential role in the German energy transition. Due to their intended use for storing excess thermal energy, such as industrial waste heat, at higher temperatures and often at greater depths, these systems can be more challenging compared to LT-ATES systems. Besides the potentially much greater hydrogeochemical impact of elevated storage temperatures during system operation, the availability of relevant heat sources is a critical point of HT-ATES (Fleuchaus et al., 2020a). Only a few studies quantify the potential of industrial waste heat sources in Germany or other countries (Brückner, 2016; Miró et al., 2015). Moreover, combined utilization of such heat sources with ATES applications requires the existence of aquifers suitable for high temperature storage. Hence, the creation of a countrywide and depth-resolved map analogous to Figure 3.5 seems promising to identify potential locations for HT-ATES systems. Such a map should integrate subsurface requirements of high temperature storage as well as the location of heat sources and heat consumers. Industrial waste heat sources and the spatial potential for excess solar thermal energy could also be compiled in a geodatabase specifically tailored towards HT-ATES applications.

Insights from the above-proposed research topics could further contribute to demonstrating the transformative potential of ATES for sustainable heating and cooling and the decarbonization of the building sector as crucial key elements to the successful energy transition in Germany and other countries.

References

Ablain, M., Legeais, J.F., Prandi, P., Marcos, M., Fenoglio-Marc, L., Dieng, H.B., Benveniste, J., Cazenave, A., 2017. Satellite Altimetry-Based Sea Level at Global and Regional Scales. Surv Geophys 38, 7–31. https://doi.org/10.1007/s10712-016-9389-8.

Abuasbeh, M., Acuña, J., Lazzarotto, A., Palm, B., 2021. Long term performance monitoring and KPIs' evaluation of Aquifer Thermal Energy Storage system in Esker formation: Case study in Stockholm. Geothermics 96, 102166. https://doi.org/10.1016/j.geothermics.2021.102166.

AEE, 2023. Endenergieverbrauch nach Strom, Wärme und Verkehr: Energieverbrauch in Deutschland im Jahr 2022 nach Strom, Wärme und Verkehr. https://www.unendlich-viel-energie.de/mediathek/grafiken/endenergieverbrauch-strom-waerme-verkehr (accessed 21 November 2023).

AGEB, 2021. Endenergieverbrauch in Deutschland: Nach Sektoren - Anteile in Prozent 2020. https://ag-energiebilanzen.de/21-0-Infografik.html (accessed 4 October 2021).

Alva, G., Lin, Y., Fang, G., 2018. An overview of thermal energy storage systems. Energy 144, 341–378. https://doi.org/10.1016/j.energy.2017.12.037.

Anibas, C., Kukral, J., Possemiers, M., Huysmans, M., 2016. Assessment of Seasonal Aquifer Thermal Energy Storage as a Groundwater Ecosystem Service for the Brussels-Capital Region: Combining Groundwater Flow, and Heat and Reactive Transport Modeling. Energy Procedia 97, 179–185. https://doi.org/10.1016/j.egypro.2016.10.048.

Baden-Württemberg, 2009. Arbeitshilfe zum Leitfaden zur Nutzung von Erdwärme mit Grundwasserwärmepumpen. Stuttgart, 48 pp.

Bakr, M., van Oostrom, N., Sommer, W., 2013. Efficiency of and interference among multiple Aquifer Thermal Energy Storage systems; A Dutch case study. Renewable Energy 60, 53–62. https://doi.org/10.1016/j.renene.2013.04.004.

Banks, D., 2009. Thermogeological assessment of open-loop well-doublet schemes: a review and synthesis of analytical approaches. Hydrogeol J 17, 1149–1155. https://doi.org/10.1007/s10040-008-0427-6.

Bannick, C., Engelmann, B., Fendler, R., Frauenstein, J., Ginzky, H., Hornemann, C., Ilvonen, O., Kirschbaum, B., Penn-Bressel, G., Rechenberg, J., Richter, S., Roy, L., Wolter, R., 2008. Grundwasser in Deutschland. Reihe Umweltpolitik (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU)).

Barns, D.G., Taylor, P.G., E Bale, C.S., Owen, A., 2021. Important social and technical factors shaping the prospects for thermal energy storage. Journal of Energy Storage 41, 102877. https://doi.org/10.1016/j.est.2021.102877.

Barrios, M., 2015. Evaluation of an Aquifer Thermal Energy Storage (ATES) for the City Hospital in Karlsruhe (Germany). Master thesis. Karlsruhe, 74 pp.

Bayer, P., Attard, G., Blum, P., Menberg, K., 2019. The geothermal potential of cities. Renewable and Sustainable Energy Reviews 106, 17–30. https://doi.org/10.1016/j.rser.2019.02.019.

Bayer, P., Saner, D., Bolay, S., Rybach, L., Blum, P., 2012. Greenhouse gas emission savings of ground source heat pump systems in Europe: A review. Renewable and Sustainable Energy Reviews 16, 1256–1267. https://doi.org/10.1016/j.rser.2011.09.027.

Beauchampet, I., Walsh, B., 2021. Energy citizenship in the Netherlands: The complexities of public engagement in a large-scale energy transition. Energy Research & Social Science 76, 102056. https://doi.org/10.1016/j.erss.2021.102056.

Beck, M., Sperlich, A., Blank, R., Meyer, E., Binz, R., Ernst, M., 2018. Increasing Energy Efficiency in Water Collection Systems by Submersible PMSM Well Pumps. Water 10, 1310. https://doi.org/10.3390/w10101310.

Beernink, S., Bloemendal, M., Kleinlugtenbelt, R., Hartog, N., 2022. Maximizing the use of aquifer thermal energy storage systems in urban areas: effects on individual system primary energy use and overall GHG emissions. Applied Energy 311, 118587. https://doi.org/10.1016/j.apenergy.2022.118587.

Beims, U., 1983. Planung, Durchführung und Auswertung von Gütepumpversuchen. Zeitschrift für angewandte Geologie 29, 482-490.

Benz, S.A., Bayer, P., Menberg, K., Jung, S., Blum, P., 2015. Spatial resolution of anthropogenic heat fluxes into urban aquifers. The Science of the total environment 524-525, 427–439. https://doi.org/10.1016/j.scitotenv.2015.04.003.

Best, R., Burke, P.J., 2018. Adoption of solar and wind energy: The roles of carbon pricing and aggregate policy support. Energy Policy 118, 404–417. https://doi.org/10.1016/j.enpol.2018.03.050.

Bettgenhäuser, K., Boermans, T., 2011. Umweltwirkung von Heizungssystemen in Deutschland. Umweltbundesamt (Ed.), 91 pp.

BfG, 2021. Wasserschutzgebiete-DE. https://geoportal.bafg.de/ggina-portal/ (accessed 18 February 2022).

BGR, 2019a. Ergiebigkeit der Grundwasservorkommen von Deutschland 1:1.000.000 (ERGW1000) - Groundwater Yields of Germany 1:1,000,000 (ERGW1000): Digital map data v1. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

BGR, 2019b. Geogene Grundwasserbeschaffenheit von Deutschland 1:1.000.000 (GEOGW1000) - Geogenic Groundwater Quality of Germany 1:1,000,000 (GEOGW1000): Digital map data v1. Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover.

BGR, UNESCO, 2019. International Hydrogeological Map of Europe 1:1,500,000 (IHME1500): Version IHME1500 v1.2. Bundesanstalt für Geowissenschaften und Rohstoffe, UNESCO, Hannover/Paris.

Bidarmaghz, A., Choudhary, R., Soga, K., Kessler, H., Terrington, R., Thorpe, S., 2019. Influence of geology and hydrogeology on heat rejection from residential basements in urban areas.

Biehl, J., Missbach, L., Riedel, F., Stemmle, R., Jüchter, J., Weber, J., Kucknat, J., Odenweller, A., Nauck, C., Lukassen, L.J., Zech, M., Grimm, M., 2023. Wicked facets of the German energy transition – examples from the electricity, heating, transport, and industry sectors. International Journal of Sustainable Energy 42, 1128–1181. https://doi.org/10.1080/14786451.2023.2244602.

Birhanu, Z.K., Kitterød, N.-O., Krogstad, H.E., Kværnø, A., 2015. Numerical modeling of aquifer thermal energy efficiency under regional groundwater flow: a case study at Oslo Airport. Hydrology Research 46, 721–734. https://doi.org/10.2166/nh.2015.119.

BKG, 2021. Digitales Geländemodell Gitterweite 1000 m: DGM1000. Bundesamt für Kartographie und Geodäsie, Leipzig.

Bloemendal, M., Hartog, N., 2018. Analysis of the impact of storage conditions on the thermal recovery efficiency of low-temperature ATES systems. Geothermics 71, 306–319. https://doi.org/10.1016/j.geothermics.2017.10.009.

Bloemendal, M., Hoekstra, N., Slenders, H.L.A., van de Mark Bart, van de Ven, F., Andreu, A., Simmons, N., Sani, D., 2016. Europe-wide Use of Sustainable Energy from aquifers: E-USE(aq) Complete Deliverable Report. https://doi.org/10.13140/RG.2.1.3548.8883.

Bloemendal, M., Jaxa-Rozen, M., Olsthoorn, T., 2018. Methods for planning of ATES systems. Applied Energy 216, 534–557. https://doi.org/10.1016/j.apenergy.2018.02.068.

Bloemendal, M., Olsthoorn, T., 2018. ATES systems in aquifers with high ambient groundwater flow velocity. Geothermics 75, 81–92. https://doi.org/10.1016/j.geothermics.2018.04.005.

Bloemendal, M., Olsthoorn, T., Boons, F., 2014. How to achieve optimal and sustainable use of the subsurface for Aquifer Thermal Energy Storage. Energy Policy 66, 104–114. https://doi.org/10.1016/j.enpol.2013.11.034.

Bloemendal, M., Olsthoorn, T., van de Ven, F., 2015. Combining climatic and geo-hydrological preconditions as a method to determine world potential for aquifer thermal energy storage. The Science of the total environment 538, 621–633. https://doi.org/10.1016/j.scitotenv.2015.07.084.

Bloemendal, M., van der Schans, M., Beernink, S., Hartog, N., Vardon, P.J., 2023. Drivers to allow widespread adoption of ATES systems: a reflection on 40 years experience in The Netherlands. Symposium on Energy Geotechnics, 3-5 October 2023, Delft, the Netherlands.

Blum, P., Campillo, G., Münch, W., Kölbel, T., 2010. CO2 savings of ground source heat pump systems – A regional analysis. Renewable Energy 35, 122–127. https://doi.org/10.1016/j.renene.2009.03.034.

Blum, P., Menberg, K., Koch, F., Benz, S.A., Tissen, C., Hemmerle, H., Bayer, P., 2021. Is thermal use of groundwater a pollution? Journal of contaminant hydrology 239, 103791. https://doi.org/10.1016/j.jconhyd.2021.103791.

Bonamente, E., Aquino, A., 2017. Life-Cycle Assessment of an Innovative Ground-Source Heat Pump System with Upstream Thermal Storage. Energies 10, 1854. https://doi.org/10.3390/en10111854.

Bonte, M., Stuyfzand, P.J., van den Berg, G.A., Hijnen, W.A.M., 2011. Effects of aquifer thermal energy storage on groundwater quality and the consequences for drinking water production: a case study from The Netherlands. Water science and technology : a journal of the International Association on Water Pollution Research 63, 1922–1931. https://doi.org/10.2166/wst.2011.189.

Bonte, M., van Breukelen, B.M., Stuyfzand, P.J., 2013. Environmental impacts of aquifer thermal energy storage investigated by field and laboratory experiments. Journal of Water and Climate Change 4, 77–89. https://doi.org/10.2166/wcc.2013.061.

Born, H., Bracke, Rolf, Eicker, Timm, Rath, M. Roadmap Oberflächennahe Geothermie: Erdwärmepumpen für die Energiewende - Potenziale, Hemmnisse und Handlungsempfehlungen. Fraunhofer IEG, Bochum, 18 pp.

Bott, C., Dressel, I., Bayer, P., 2019. State-of-technology review of water-based closed seasonal thermal energy storage systems. Renewable and Sustainable Energy Reviews 113, 109241. https://doi.org/10.1016/j.rser.2019.06.048.

Böttcher, F., Casasso, A., Götzl, G., Zosseder, K., 2019. TAP - Thermal aquifer Potential: A quantitative method to assess the spatial potential for the thermal use of groundwater. Renewable Energy 142, 85–95. https://doi.org/10.1016/j.renene.2019.04.086.

Bozkaya, B., Li, R., Zeiler, W., 2018. A dynamic building and aquifer co-simulation method for thermal imbalance investigation. Applied Thermal Engineering 144, 681–694. https://doi.org/10.1016/j.applthermaleng.2018.08.095.

Bozkaya, B., Zeiler, W., 2019. The effectiveness of night ventilation for the thermal balance of an aquifer thermal energy storage. Applied Thermal Engineering 146, 190–202. https://doi.org/10.1016/j.applthermaleng.2018.09.106.

Brandoni, C., Polonara, F., 2012. The role of municipal energy planning in the regional energy-planning process. Energy 48, 323–338. https://doi.org/10.1016/j.energy.2012.06.061.

Branford, Z., Roberts, J., 2022. The installer skills gap in the UK heat pump sector and the impacts on a just transition to net-zeo. Research Brief University of Strathclyde Engineering 2022.

Braungardt, S., Bürger, V., Zieger, J., Kenkmann, T., 2018. Contribution of Renewable Cooling to the Renewable Energy Target of the EU. Öko-Institut e. V. (Ed.), Freiburg i. Br.

Bridger, D.W., Allen, D.M., 2014. Influence of geologic layering on heat transport and storage in an aquifer thermal energy storage system. Hydrogeol J 22, 233–250. https://doi.org/10.1007/s10040-013-1049-1.

Briggs, C., Atherton, A., Gill, J., Langdon, R., Rutovitz, J., Nagrath, K., 2022. Building a ‘Fair and Fast’ energy transition? Renewable energy employment, skill shortages and social licence in regional areas. Renewable and Sustainable Energy Transition 2, 100039. https://doi.org/10.1016/j.rset.2022.100039.

Brückner, S., 2016. Industrielle Abwärme in Deutschland: Die Bestimmung von gesichertem Aufkommen und technischer bzw. wirtschafltlicher Nutzbarkeit. Doctoral thesis. Munich, 119 pp.

Bulkeley, H., 2010. Cities and the Governing of Climate Change. Annu. Rev. Environ. Resour. 35, 229–253. https://doi.org/10.1146/annurev-environ-072809-101747.

Bundesministerium der Justiz und für Verbraucherschutz, 2021. Bundes-Klimaschutzgesetz: KSG.

Bundesregierung, 2021. Klimaschutzgesetz 2021: Generationenvertrag für das Klima. https://www.bundesregierung.de/breg-de/themen/klimaschutz/klimaschutzgesetz-2021-1913672 (accessed 6 July 2021).

Bunruamkaew, K., 2012. How to do AHP analysis in Excel. University of Tsukuba. http://giswin.geo.tsukuba.ac.jp/sis/gis_seminar/How%20to%20do%20AHP%20analysis%20in%20Excel.pdf (accessed 20 August 2021).

Burnett, R.D., Frind, E.O., 1987. Simulation of contaminant transport in three dimensions 2. Dimensionality effects. Water Resour. Res. 23, 695–705. https://doi.org/10.1029/WR023i004p00695.

Cabeza, L.F., Palomba, V., 2022. The Role of Thermal Energy Storage in the Energy System. Encyclopedia of Energy Storage, 338–350. https://doi.org/10.1016/B978-0-12-819723-3.00017-2.

Chen, Y., Yu, J., Khan, S., 2010. Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation. Environmental Modelling & Software 25, 1582–1591. https://doi.org/10.1016/j.envsoft.2010.06.001.

Chittum, A., Østergaard, P.A., 2014. How Danish communal heat planning empowers municipalities and benefits individual consumers. Energy Policy 74, 465–474. https://doi.org/10.1016/j.enpol.2014.08.001.

Christenson, M., Manz, H., Gyalistras, D., 2006. Climate warming impact on degree-days and building energy demand in Switzerland. Energy Conversion and Management 47, 671–686. https://doi.org/10.1016/j.enconman.2005.06.009.

Clark, T., Foster, L., Sloan, L., 2021. Bryman's social research methods. Oxford University Press, Oxford, 670 pp.

Collignon, M., Klemetsdal, Ø.S., Møyner, O., Alcanié, M., Rinaldi, A.P., Nilsen, H., Lupi, M., 2020. Evaluating thermal losses and storage capacity in high-temperature aquifer thermal energy storage (HT-ATES) systems with well operating limits: insights from a study-case in the Greater Geneva Basin, Switzerland. Geothermics 85, 101773. https://doi.org/10.1016/j.geothermics.2019.101773.

COMSOL, 2020a. Heat Transfer Module User's Guide. https://doc.comsol.com/5.6/doc/com.comsol.help.heat/HeatTransferModuleUsersGuide.pdf (accessed 20 January 2022), 822 pp.

COMSOL, 2020b. Porous Media Flow Module User's Guide. https://doc.comsol.com/5.6/doc/com.comsol.help.porous/PorousMediaFlowModuleUsersGuide.pdf (accessed 20 January 2022), 290 pp.

COP26, 2021. COP26: The Glasgow Climate Pact. UN Climate Change Conference UK 2021 (Ed.). UN Climate Change Conference UK 2021, 28 pp.

Coy, D., Malekpour, S., Saeri, A.K., 2022. From little things, big things grow: Facilitating community empowerment in the energy transformation. Energy Research & Social Science 84, 102353. https://doi.org/10.1016/j.erss.2021.102353.

Coy, D., Malekpour, S., Saeri, A.K., Dargaville, R., 2021. Rethinking community empowerment in the energy transformation: A critical review of the definitions, drivers and outcomes. Energy Research & Social Science 72, 101871. https://doi.org/10.1016/j.erss.2020.101871.

Daikeler, J., Bošnjak, M., Lozar Manfreda, K., 2020. Web Versus Other Survey Modes: An Updated and Extended Meta-Analysis Comparing Response Rates. Journal of Survey Statistics and Methodology 8, 513–539. https://doi.org/10.1093/jssam/smz008.

Di Dato, M., D'Angelo, C., Casasso, A., Zarlenga, A., 2022. The impact of porous medium heterogeneity on the thermal feedback of open-loop shallow geothermal systems. Journal of Hydrology, 127205. https://doi.org/10.1016/j.jhydrol.2021.127205.

Dickinson, J.S., Buik, N., Matthews, M.C., Snijders, A., 2009. Aquifer thermal energy storage: theoretical and operational analysis. Géotechnique 59, 249–260. https://doi.org/10.1680/geot.2009.59.3.249.

Dillman, D.A., Smyth, J.D., Christian, L.M., 2015. Internet, phone, mail, and mixed-mode surveys: The tailored design method, 4th ed. Wiley, Hoboken, New Jersey.

DIN EN ISO 14040, 2009. DIN EN ISO 14040:2009-11: Umweltmanagement - Ökobilanz - Grundsätze und Rahmenbedingungen.

DIN EN ISO 14044, 2018. DIN EN ISO 14044:2018-05: Umweltmanagement - Ökobilanz - Anforderungen und Anleitungen.

Dóci, G., Vasileiadou, E., Petersen, A.C., 2015. Exploring the transition potential of renewable energy communities. Futures 66, 85–95. https://doi.org/10.1016/j.futures.2015.01.002.

Doughty, C., Hellström, G., Tsang, C.F., Claesson, J., 1982. A dimensionless parameter approach to the thermal behavior of an aquifer thermal energy storage system. Water Resour. Res. 18, 571–587. https://doi.org/10.1029/WR018i003p00571.

Drijver, B., Bakea, G., Oerlemans, P., 2019. State of the art of HT-ATES in The Netherlands, in: European Geothermal Congress 2019, Den Haag, The Netherlands. 11-14 June 2019.

Drijver, B., Godschalk, B., 2018. Important criteria for ATES legislation. EnerSTOCK 2018, 14th International Conference on Energy Storage, Adana, Turkey 2018.

Drijver, B., van Aarssen, M., Zwart, B. de, 2012. High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable. Presented at the 12th International Conference on Energy Storage, 2012, Lleida, Spanien.

Drijver, B.C., Henssen, M., Dinkla, I., Gehrels, H., van Nieuwkerk, E., Grotenhuis, J., 2010. National research program on the effects of UTES – Use of the subsoil in a sustainable way. Proceedings Consoil, Salzburg, Austria 2010 2010.

Drobne, S., Lisec, A., 2009. Multi-attribute Decision Analysis in GIS: Weighted Linear Combination and Ordered Weigthed Averaging. Informatica 33, 459–747.

Duijff, R., Bloemendal, M., Bakker, M., 2021. Interaction Effects Between Aquifer Thermal Energy Storage Systems. Ground water. https://doi.org/10.1111/gwat.13163.

Dutch ATES, 2016. Dutch Policy on ATES Systems, 13 pp. https://dutch-ates.com/wp-content/uploads/2016/09/DutchPolicyOnATESSystems092016.pdf (accessed 9 March 2023).

Eicker, U., 2006. Entwicklungstendenzen und Wirtschaftlichkeit solarthermischer Kühlung. Tagungsband 4. Symposium Solares Kühlen in der Praxis, Veröffentlichungen der Hochschule für Technik Stuttgart.

Enerdata, 2023. Anteil der erneuerbaren Energien an der Stromerzeugung. https://energiestatistik.enerdata.net/erneuerbare-energien/erneuerbare-anteil-in-strom-produktion.html (accessed 17 October 2023).

Epting, J., Böttcher, F., Mueller, M.H., García-Gil, A., Zosseder, K., Huggenberger, P., 2020. City-scale solutions for the energy use of shallow urban subsurface resources – Bridging the gap between theoretical and technical potentials. Renewable Energy 147, 751–763. https://doi.org/10.1016/j.renene.2019.09.021.

Epting, J., Müller, M.H., Genske, D., Huggenberger, P., 2018. Relating groundwater heat-potential to city-scale heat-demand: A theoretical consideration for urban groundwater resource management. Applied Energy 228, 1499–1505. https://doi.org/10.1016/j.apenergy.2018.06.154.

Esen, H., Inalli, M., Esen, M., 2007. A techno-economic comparison of ground-coupled and air-coupled heat pump system for space cooling. Building and Environment 42, 1955–1965. https://doi.org/10.1016/j.buildenv.2006.04.007.

Fastenrath, S., Braun, B., 2018. Sustainability transition pathways in the building sector: Energy-efficient building in Freiburg (Germany). Applied Geography 90, 339–349. https://doi.org/10.1016/j.apgeog.2016.09.004.

Fleuchaus, P., Godschalk, B., Stober, I., Blum, P., 2018. Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876. https://doi.org/10.1016/j.rser.2018.06.057.

Fleuchaus, P., Schüppler, S., Bloemendal, M., Guglielmetti, L., Opel, O., Blum, P., 2020a. Risk analysis of High-Temperature Aquifer Thermal Energy Storage (HT-ATES). Renewable and Sustainable Energy Reviews.

Fleuchaus, P., Schüppler, S., Godschalk, B., Bakema, G., Blum, P., 2020b. Performance analysis of Aquifer Thermal Energy Storage (ATES). Renewable Energy 146, 1536–1548. https://doi.org/10.1016/j.renene.2019.07.030.

Fleuchaus, P., Schüppler, S., Stemmle, R., Menberg, K., Blum, P., 2021. Aquiferspeicher in Deutschland. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie 26, 123–134. https://doi.org/10.1007/s00767-021-00478-y.

Fouladvand, J., Ghorbani, A., Mouter, N., Herder, P., 2022. Analysing community-based initiatives for heating and cooling: A systematic and critical review. Energy Research & Social Science 88, 102507. https://doi.org/10.1016/j.erss.2022.102507.

Frandell, A., Feeney, M.K., Johnson, T.P., Welch, E.W., Michalegko, L., Jung, H., 2021. The effects of electronic alert letters for internet surveys of academic scientists. Scientometrics 126, 7167–7181. https://doi.org/10.1007/s11192-021-04029-3.

Fraunhofer IWES/IBP, 2017. Heat transition 2030: Key technologies for reaching the intermediate and long-term climate targets in the building sector. Summary, 22 pp.

Frick, C., Steiner, H., Mazurkiewicz, A., Riediger, U., Rauthe, M., Reich, T., Gratzki, A., 2014. Central European high-resolution gridded daily data sets (HYRAS): Mean temperature and relative humidity. metz 23, 15–32. https://doi.org/10.1127/0941-2948/2014/0560.

Frick, S., Kaltschmitt, M., Schröder, G., 2010. Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. Energy 35, 2281–2294. https://doi.org/10.1016/j.energy.2010.02.016.

Gao, B., Zhu, X., Yang, X., Yuan, Y., Yu, N., Ni, J., 2021. Operation performance test and energy efficiency analysis of ground-source heat pump systems. Journal of Building Engineering 41, 102446. https://doi.org/10.1016/j.jobe.2021.102446.

Gao, L., Zhao, J., An, Q., Liu, X., Du, Y., 2019. Thermal performance of medium-to-high-temperature aquifer thermal energy storage systems. Applied Thermal Engineering 146, 898–909. https://doi.org/10.1016/j.applthermaleng.2018.09.104.

Gao, L., Zhao, J., An, Q., Wang, J., Liu, X., 2017. A review on system performance studies of aquifer thermal energy storage. Energy Procedia 142, 3537–3545. https://doi.org/10.1016/j.egypro.2017.12.242.

García-Gil, A., Goetzl, G., Kłonowski, M.R., Borovic, S., Boon, D.P., Abesser, C., Janza, M., Herms, I., Petitclerc, E., Erlström, M., Holecek, J., Hunter, T., Vandeweijer, V.P., Cernak, R., Mejías Moreno, M., Epting, J., 2020. Governance of shallow geothermal energy resources. Energy Policy 138, 111283. https://doi.org/10.1016/j.enpol.2020.111283.

GDI-BW, 2015. Stadtteile der Stadt Freiburg i. Br.: Spatial data set. Landesamt für Geoinformation und Landentwicklung Baden-Württemberg.

GEF Ingenieur AG, ifeu - Institut für Energie- und Umweltforschung gGmbH, badenova-Gruppe, 2021. Masterplan Wärme Freiburg 2030.

GEG, 2023. Buildings Energy Act of August 8, 2020 (Federal Law Gazette I p. 1728), which was amended by Article 1 of the Act of October 16, 2023 (Federal Law Gazette 2023 I No. 280).

Geofabrik, 2022. Regierungsbezirk Freiburg: OpenStreetMap spatial data set.

Geyer, O.F., Gwinner, M.P., 2011. Geologie von Baden-Württemberg, 5th ed. Schweizerbart, Stuttgart, 627 pp.

Ghaebi, H., Bahadori, M.N., Saidi, M.H., 2017. Economic and environmental evaluation of different operation alternatives to aquifer thermal energy storage in Tehran, Iran. Scientia Iranica 24, 610–623.

Giraldo, R., Herrera, L., Leiva, V., 2020. Cokriging Prediction Using as Secondary Variable a Functional Random Field with Application in Environmental Pollution. Mathematics 8, 1305. https://doi.org/10.3390/math8081305.

Gizzi, M., Taddia, G., Abdin, E.C., Lo Russo, S., 2020. Thermally Affected Zone (TAZ) Assessment in Open-Loop Low-Enthalpy Groundwater Heat Pump Systems (GWHPs): Potential of Analytical Solutions. Geofluids 2020, 1–13. https://doi.org/10.1155/2020/2640917.

Griebler, C., Avramov, M., 2015. Groundwater ecosystem services: a review. Freshwater Science 34, 355–367. https://doi.org/10.1086/679903.

Griebler, C., Brielmann, H., Haberer, C.M., Kaschuba, S., Kellermann, C., Stumpp, C., Hegler, F., Kuntz, D., Walker-Hertkorn, S., Lueders, T., 2016. Potential impacts of geothermal energy use and storage of heat on groundwater quality, biodiversity, and ecosystem processes. Environ Earth Sci 75. https://doi.org/10.1007/s12665-016-6207-z.

Grossmann, K., 2019. Using conflicts to uncover injustices in energy transitions: The case of social impacts of energy efficiency policies in the housing sector in Germany. Global Transitions 1, 148–156. https://doi.org/10.1016/j.glt.2019.10.003.

Grubler, A., Wilson, C., 2014. Energy technology innovation: Learning from historical successes and failures. Cambridge University Press, Cambridge, 387 pp.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life cycle assessment: past, present, and future. Environmental science & technology 45, 90–96. https://doi.org/10.1021/es101316v.

Habibullah, M.S., Din, B.H., Tan, S.-H., Zahid, H., 2022. Impact of climate change on biodiversity loss: global evidence. Environmental science and pollution research international 29, 1073–1086. https://doi.org/10.1007/s11356-021-15702-8.

Hähnlein, S., Bayer, P., Blum, P., 2010. International legal status of the use of shallow geothermal energy. Renewable and Sustainable Energy Reviews 14, 2611–2625. https://doi.org/10.1016/j.rser.2010.07.069.

Hähnlein, S., Bayer, P., Ferguson, G., Blum, P., 2013. Sustainability and policy for the thermal use of shallow geothermal energy. Energy Policy 59, 914–925. https://doi.org/10.1016/j.enpol.2013.04.040.

Hähnlein, S., Blum, P., Bayer, P., 2011. Oberflächennahe Geothermie – aktuelle rechtliche Situation in Deutschland. Grundwasser 16, 69–75. https://doi.org/10.1007/s00767-011-0162-0.

Haque, M.E., Islam, M.R., Islam, M.S., Haniu, H., Akhter, M.S., 2017. Life Cycle Cost and Energy Consumption Behavior of Submersible Pumps Using in the Barind Area of Bangladesh. Energy Procedia 110, 479–485. https://doi.org/10.1016/j.egypro.2017.03.172.

Härdtlein, M., Reith, S., Notheis, M., Kirch, F., Eltrop, L., 2018. Datengrundlagen und Konzeption für den Online-Wärmekostenrechner für Wohn- und Nichtwohngebäude: Teilprojekt im Rahmen des Vorhabens „Maßnahmenpaket Bioenergie-Wärme“ der AEE, 2018, Stuttgart.

Hartmann, K., Palm, J., 2023. The role of thermal energy communities in Germany's heating transition. Front. Sustain. Cities 4, 1027148. https://doi.org/10.3389/frsc.2022.1027148.

Hecking, H., Hintermayer, M., Lencz, D., Wagner, J., 2018. The energy market in 2030 and 2050: The contribution of gas and heat infrastructure to efficient carbon emission reductions. ewi Energy Resarch & Scenarios gGmbH (Ed.), 110 pp.

Heier, J., Bales, C., Martin, V., 2015. Combining thermal energy storage with buildings – a review. Renewable and Sustainable Energy Reviews 42, 1305–1325. https://doi.org/10.1016/j.rser.2014.11.031.

Heldt, S., Wang, B., Bauer, S., 2023. Parameter identification and range restriction through sensitivity analysis for a high-temperature heat injection test. Geotherm Energy 11. https://doi.org/10.1186/s40517-023-00255-5.

Hellriegel, U., Cañas Kurz, E.E., Luong, T.V., Bundschuh, J., Hoinkis, J., 2020. Modular treatment of arsenic-laden brackish groundwater using solar-powered subsurface arsenic removal (SAR) and membrane capacitive deionization (MCDI) in Vietnam. Journal of Water Reuse and Desalination 10, 513–526. https://doi.org/10.2166/wrd.2020.031.

Herreras Martínez, S., Harmsen, R., Menkveld, M., Faaij, A., Kramer, G.J., 2022. Municipalities as key actors in the heat transition to decarbonise buildings: Experiences from local planning and implementation in a learning context. Energy Policy 169, 113169. https://doi.org/10.1016/j.enpol.2022.113169.

HLNUG, 2022. Wasserschutzgebiete - Heilquellenschutzgebiete. https://www.elwasweb.nrw.de/elwas-web/index.xhtml (accessed 21 February 2022).

IEA, 2022. The Future of Heat Pumps. International Energy Agency. https://doi.org/pumps.

IRENA, 2020. Innovation outlook: Thermal energy storage. International Renewable Energy Agency (Ed.), 144 pp.

IRENA, OECD/IEA, REN21, 2020. Renewable Energy Policies in a Time of Transition: Heating and cooling, 150 pp.

Jagger, N., Foxon, T., Gouldson, A., 2013. Skills constraints and the low carbon transition. Climate Policy 13, 43–57. https://doi.org/10.1080/14693062.2012.709079.

Jakubcionis, M., Carlsson, J., 2017. Estimation of European Union residential sector space cooling potential. Energy Policy 101, 225–235. https://doi.org/10.1016/j.enpol.2016.11.047.

Jaxa-Rozen, M., 2019. Methods for simulation, planning, and operation of Aquifer Thermal Energy Storage under deep uncertainty. Dissertation. Delft, The Netherlands, 263 pp.

Johansen, K., Werner, S., 2022. Something is sustainable in the state of Denmark: A review of the Danish district heating sector. Renewable and Sustainable Energy Reviews 158, 112117. https://doi.org/10.1016/j.rser.2022.112117.

Jolliet, O., Margini, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R., 2003. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. The International Journal of Life Cycle Assessment 8, 324–330.

Kammen, D.M., Sunter, D.A., 2016. City-integrated renewable energy for urban sustainability. Science (New York, N.Y.) 352, 922–928. https://doi.org/10.1126/science.aad9302.

Kangas, M.T., Lund, P.D., 1994. Modeling and simulation of aquifer storage energy systems. Solar Energy 53, 237–247. https://doi.org/10.1016/0038-092X(94)90630-0.

Kappas, M., Menz, G., Richter, M., Treter, U. (Eds.), 2003. Nationalatlas Bundesrepublik Deutschland: Band 3 - Natur und Umwelt II: Klima, Pflanzen- und Tierwelt, 176 pp.

Karytsas, S., Theodoropoulou, H., 2014. Public awareness and willingness to adopt ground source heat pumps for domestic heating and cooling. Renewable and Sustainable Energy Reviews 34, 49–57. https://doi.org/10.1016/j.rser.2014.02.008.

Kauko, H., Pinel, D., Graabak, I., Wolfgang, O., 2022. Assessing the potential of seasonal thermal storage for local energy systems: Case study for a neighborhood in Norway. Smart Energy 6, 100075. https://doi.org/10.1016/j.segy.2022.100075.

Kiavarz, M., Jelokhani-Niaraki, M., 2017. Geothermal prospectivity mapping using GIS-based Ordered Weighted Averaging approach: A case study in Japan's Akita and Iwate provinces. Geothermics 70, 295–304. https://doi.org/10.1016/j.geothermics.2017.06.015.

Koch, F., Menberg, K., Schweikert, S., Spengler, C., Hahn, H.J., Blum, P., 2021. Groundwater fauna in an urban area – natural or affected? Hydrol. Earth Syst. Sci. 25, 3053–3070. https://doi.org/10.5194/hess-25-3053-2021.

Kreienkamp, F., Enke, W., Spektat, A., 2010. WR2010_EH5_1_A1B: UBA-WETTREG ECHAM5/OM 20C + A1B Lauf 1 realization run 1961-2100. World Data Center for Climate (WDCC) at DKRZ, Hamburg.

Kreienkamp, F., Spekat, A., Enke, W., 2011. Ergebnisse regionaler Szenarienläufe für Deutschland mit der statistischen Methode WETTREG auf der Basis der SRES Szenarios A2 und B1 modelliert mit ECHAM5/MPI-OM: Bericht. Climate and Environment Consulting Potsdam GmbH (Ed.), 106 pp.

Kunkel, C., Agemar, T., Stober, I., 2019. Geothermisches Nutzungspotenzial der Buntsandstein- und Keuperaquifere im Nordosten Bayerns mit Fokus auf tiefe Aquiferspeicher. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie 24, 251–267. https://doi.org/10.1007/s00767-019-00430-1.

Lacirignola, M., Meany, B.H., Padey, P., Blanc, I., 2014. A simplified model for the estimation of life-cycle greenhouse gas emissions of enhanced geothermal systems. Geotherm Energy 2, 200. https://doi.org/10.1186/s40517-014-0008-y.

Lee, H., Calvin, K., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P.W., Trisos, C., Romero, J., Aldunce, P., Barrett, K., Blanco, G., Cheung, W.W., Connors, S., Denton, F., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, Y.-Y., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F.E., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H.-O., Revi, A., Roberts, D.C., Roy, J., Ruane, A.C., Skea, J., Shukla, P.R., Slade, R., Slangen, A., Sokona, Y., Sörensson, A.A., Tignor, M., van Vuuren, D., Wei, Y.-M., Winkler, H., Zhai, P., Zommers, Z., Hourcade, J.-C., Johnson, F.X., Pachauri, S., Simpson, N.P., Singh, C., Thomas, A., Totin, E., Arias, P., Bustamante, M., Elgizouli, I., Flato, G., Howden, M., Méndez-Vallejo, C., Pereira, J.J., Pichs-Madruga, R., Rose, S.K., Saheb, Y., Sánchez Rodríguez, R., Ürge-Vorsatz, D., Xiao, C., Yassaa, N., Alegría, A., Armour, K., Bednar-Friedl, B., Blok, K., Cissé, G., Dentener, F., Eriksen, S., Fischer, E., Garner, G., Guivarch, C., Haasnoot, M., Hansen, G., Hauser, M., Hawkins, E., Hermans, T., Kopp, R., Leprince-Ringuet, N., Lewis, J., Ley, D., Ludden, C., Niamir, L., Nicholls, Z., Some, S., Szopa, S., Trewin, B., van der Wijst, K.-I., Winter, G., Witting, M., Birt, A., Ha, M., Kim, J., Haites, E.F., Jung, Y., Stavins, R., Orendain, D.J.A., Ignon, L., Park, S., Park, Y., Reisinger, A., Cammaramo, D., Fischlin, A., Fuglestvedt, J.S., Matthews, J.R., Péan, C., 2023. Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC (Ed.), Geneva, Switzerland, 186 pp.

LfU, 2021. Wasserschutzgebiete Rheinland-Pfalz. Personal communication 22.02.2022.

Lim, Y., Edelenbos, J., Gianoli, A., 2019. Smart Energy Transition: An Evaluation of Cities in South Korea. Informatics 6, 50. https://doi.org/10.3390/informatics6040050.

Lo Russo, S., Taddia, G., Verda, V., 2012. Development of the thermally affected zone (TAZ) around a groundwater heat pump (GWHP) system: A sensitivity analysis. Geothermics 43, 66–74. https://doi.org/10.1016/j.geothermics.2012.02.001.

Lu, H., Tian, P., Guan, Y., Yu, S., 2019a. Integrated suitability, vulnerability and sustainability indicators for assessing the global potential of aquifer thermal energy storage. Applied Energy 239, 747–756. https://doi.org/10.1016/j.apenergy.2019.01.144.

Lu, H., Tian, P., He, L., 2019b. Evaluating the global potential of aquifer thermal energy storage and determining the potential worldwide hotspots driven by socio-economic, geo-hydrologic and climatic conditions. Renewable and Sustainable Energy Reviews 112, 788–796. https://doi.org/10.1016/j.rser.2019.06.013.

LUBW, 2006. Hydrogeologischer Bau und hydraulische Eigenschaften: INTERREG III A-Projekt MoNit Modellierung der Grundwasserbelastung durch Nitrat im Oberrheingraben, 162 pp.

LUBW, 2017. Energieatlas – Wärmebedarfsdichte von Wohngebäuden. Landesanstalt für Umwelt Baden-Württemberg, Karlsruhe.

LUBW, 2022a. Quellenschutzgebiet. https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/uis/metadaten/beschreibung.aspx?typ=0&uuid=6cdd2a01-d2fe-4f5b-9309-dca7e8273702 (accessed 21 February 2022).

LUBW, 2022b. Wasserschutzgebietszone. https://rips-dienste.lubw.baden-wuerttemberg.de/rips/ripsservices/apps/uis/metadaten/beschreibung.aspx?typ=0&uuid=19db48dd-576f-498c-bafa-083b200baad5 (accessed 21 February 2022).

Malczewski, J., 2000. On the Use of Weighted Linear Combination Method in GIS: Common and Best Practice Approaches. Trans in GIS 4, 5–22. https://doi.org/10.1111/1467-9671.00035.

Mands, E., Sanner, B., Sauer, M., Grundmann, E., Brehm, D., 2010. Grundwassergekoppelte Wärmepumpenanlage am Bonner Bogen. bbr (Sonderheft 2010), 74–80.

Matthes, F.C., Emele, L., Hermann, H., Loreck, C., Peter, F., Ziegenhagen, I., Cook, V., 2017. Germany's electric future: Coal phase-out 2035. WWF Germany (Ed.), 130 pp.

McClean, A., Pedersen, O.W., 2023. The role of regulation in geothermal energy in the UK. Energy Policy 173, 113378. https://doi.org/10.1016/j.enpol.2022.113378.

Medearis, D., Daseking, W., 2012. Freiburg, Germany: Germany’s Eco-Capital, in: Beatley, T. (Ed.), Green Cities of Europe: Global Lessons on Green Urbanism. Island Press/Center for Resource Economics, Washington, DC, pp. 65–82.

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., Blum, P., 2013a. Subsurface urban heat islands in German cities. The Science of the total environment 442, 123–133. https://doi.org/10.1016/j.scitotenv.2012.10.043.

Menberg, K., Heo, Y., Choudhary, R., 2016a. Sensitivity analysis methods for building energy models: Comparing computational costs and extractable information. Energy and Buildings 133, 433–445. https://doi.org/10.1016/j.enbuild.2016.10.005.

Menberg, K., Pfister, S., Blum, P., Bayer, P., 2016b. A matter of meters: state of the art in the life cycle assessment of enhanced geothermal systems. Energy Environ. Sci. 9, 2720–2743. https://doi.org/10.1039/C6EE01043A.

Menberg, K., Steger, H., Zorn, R., Reuß, M., Pröll, M., Bayer, P., Blum, P., 2013b. Bestimmung der Wärmeleitfähigkeit im Untergrund durch Labor- und Feldversuche und anhand theoretischer Modelle. Grundwasser 18, 103–116. https://doi.org/10.1007/s00767-012-0217-x.

Meng, B., Vienken, T., Kolditz, O., Shao, H., 2018. Modeling the groundwater temperature response to extensive operation of ground source heat pump systems: A case study in Germany. Energy Procedia 152, 971–977. https://doi.org/10.1016/j.egypro.2018.09.102.

Miocic, J.M., Krecher, M., 2022. Estimation of shallow geothermal potential to meet building heating demand on a regional scale. Renewable Energy 185, 629–640. https://doi.org/10.1016/j.renene.2021.12.095.

Miró, L., Brückner, S., Cabeza, L.F., 2015. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. Renewable and Sustainable Energy Reviews 51, 847–855. https://doi.org/10.1016/j.rser.2015.06.035.

Montgomery, Douglas C., Peck, Elizabeth A., Vining, G. Geoffrey, 2012. Introduction to Linear Regression Analysis: Fifth edition. Wiley, Hoboken, New Jersey, 679 pp.

Moulopoulos, A., 2014. Life Cycle Assessment of an Aquifer Thermal Energy Storage system: Exploring the environmental performance of shallow subsurface space development. Master Thesis. Utrecht, 89 pp.

Mourshed, M., 2012. Relationship between annual mean temperature and degree-days. Energy and Buildings 54, 418–425. https://doi.org/10.1016/j.enbuild.2012.07.024.

Mueller, A., 2019. Space cooling needs density map of buildings in eu28 + switzerland, norway and iceland for the year 2015. Zenodo. https://doi.org/10.5281/ZENODO.4687109.

Mueller, A., Fallahnejad, M., 2020. Heat density map (final energy demand for heating and dhw) of buildings in eu28 + switzerland, norway and iceland for the year 2015. Zenodo. https://doi.org/10.5281/ZENODO.4687129.

MULNV NRW, 2022. Wasserschutzgebiete - Heilquelle. https://www.elwasweb.nrw.de/elwas-web/index.xhtml (accessed 21 February 2022).

Nakićenović, N., 2000. Special report on emissions scenarios: A special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, 599 pp.

Narula, K., Oliveira Filho, F. de, Chambers, J., Romano, E., Hollmuller, P., Patel, M.K., 2020. Assessment of techno-economic feasibility of centralised seasonal thermal energy storage for decarbonising the Swiss residential heating sector. Renewable Energy 161, 1209–1225. https://doi.org/10.1016/j.renene.2020.06.099.

Neidig, P., 2022. Rechtsfragen saisonaler Aquifer-Wärmespeicher: Hemmnisse und Lösungsmöglichkeiten aus Sicht des Berg- und Umweltrechts, 1st ed. Erich Schmidt Verlag GmbH & Co, Berlin, 455 pp.

Nerem, R.S., Beckley, B.D., Fasullo, J.T., Hamlington, B.D., Masters, D., Mitchum, G.T., 2018. Climate-change-driven accelerated sea-level rise detected in the altimeter era. Proceedings of the National Academy of Sciences of the United States of America 115, 2022–2025. https://doi.org/10.1073/pnas.1717312115.

Ni, Z., van Gaans, P., Smit, M., Rijnaarts, H., Grotenhuis, T., 2016. Combination of aquifer thermal energy storage and enhanced bioremediation: resilience of reductive dechlorination to redox changes. Applied microbiology and biotechnology 100, 3767–3780. https://doi.org/10.1007/s00253-015-7241-6.

Ni, Z., Wang, Y., Wang, Y., Chen, S., Xie, M., Grotenhuis, T., Qiu, R., 2020. Comparative Life-Cycle Assessment of Aquifer Thermal Energy Storage Integrated with in Situ Bioremediation of Chlorinated Volatile Organic Compounds. Environmental science & technology 54, 3039–3049. https://doi.org/10.1021/acs.est.9b07020.

NLWKN, 2021. Heilquellenschutzgebiete. https://www.nlwkn.niedersachsen.de/startseite/wasserwirtschaft/daten_karten/wasserbuch/downloadseite_wsg/downloadseite-schutz-und-gewinnungsgebiete-fuer-trink-und-grundwasser-sggw-46101.html (accessed 21 February 2022).

Ohmer, M., Klester, A., Kissinger, A., Mirbach, S., Class, H., Schneider, M., Lindenlaub, M., Bauer, M., Liesch, T., Menberg, K., Blum, P., 2022. Berechnung von Temperaturfahnen im Grundwasser mit analytsichen und numerischen Modellen. Grundwasser, 113-129. https://doi.org/10.1007/s00767-022-00509-2.

Padey, P., Girard, R., Le Boulch, D., Blanc, I., 2013. From LCAs to simplified models: a generic methodology applied to wind power electricity. Environmental science & technology 47, 1231–1238. https://doi.org/10.1021/es303435e.

Paiho, S., Hoang, H., Hukkalainen, M., 2017. Energy and emission analyses of solar assisted local energy solutions with seasonal heat storage in a Finnish case district. Renewable Energy 107, 147–155. https://doi.org/10.1016/j.renene.2017.02.003.

Park, B.-H., Lee, K.-K., 2021. Evaluating anisotropy ratio of thermal dispersivity affecting geometry of plumes generated by aquifer thermal use. Journal of Hydrology 602, 126740. https://doi.org/10.1016/j.jhydrol.2021.126740.

Paulus, C., Mangold, D., Desmedt, J., Fransson, L., Pini, N., Schmidt, R.-R., van Helden, W., Birk, W., 2021. Strategic Research Innovation Agenda for District Heating & Cooling and Thermal Energy Storage Technologies. RHC Renewable Heating and Cooling - European Technology and Innovation Platform (Ed.), 40 pp.

Pavlov, Georgi K., Olesen, B.W., 2012. Thermal energy storage - A review of concepts and systems for heating and cooling applications in buildings: Part 1 - Seasonal storage in the ground. HVAC&R Research 18, 515–538. https://doi.org/10.1080/10789669.2012.667039.

Pellegrini, M., Bloemendal, M., Hoekstra, N., Spaak, G., Andreu Gallego, A., Rodriguez Comins, J., Grotenhuis, T., Picone, S., Murrell, A.J., Steeman, H.J., 2019. Low carbon heating and cooling by combining various technologies with Aquifer Thermal Energy Storage. The Science of the total environment 665, 1–10. https://doi.org/10.1016/j.scitotenv.2019.01.135.

Peñaloza, D., Mata, É., Fransson, N., Fridén, H., Samperio, Á., Quijano, A., Cuneo, A., 2022. Social and market acceptance of photovoltaic panels and heat pumps in Europe: A literature review and survey. Renewable and Sustainable Energy Reviews 155, 111867. https://doi.org/10.1016/j.rser.2021.111867.

Perego, R., Dalla Santa, G., Galgaro, A., Pera, S., 2022. Intensive thermal exploitation from closed and open shallow geothermal systems at urban scale: unmanaged conflicts and potential synergies. Geothermics 103, 102417. https://doi.org/10.1016/j.geothermics.2022.102417.

Piga, B., Casasso, A., Pace, F., Godio, A., Sethi, R., 2017. Thermal Impact Assessment of Groundwater Heat Pumps (GWHPs): Rigorous vs. Simplified Models. Energies 10, 1385. https://doi.org/10.3390/en10091385.

Pinel, P., Cruickshank, C.A., Beausoleil-Morrison, I., Wills, A., 2011. A review of available methods for seasonal storage of solar thermal energy in residential applications. Renewable and Sustainable Energy Reviews 15, 3341–3359. https://doi.org/10.1016/j.rser.2011.04.013.

Pophillat, W., Attard, G., Bayer, P., Hecht-Méndez, J., Blum, P., 2020a. Analytical solutions for predicting thermal plumes of groundwater heat pump systems. Renewable Energy 147, 2696–2707. https://doi.org/10.1016/j.renene.2018.07.148.

Pophillat, W., Bayer, P., Teyssier, E., Blum, P., Attard, G., 2020b. Impact of groundwater heat pump systems on subsurface temperature under variable advection, conduction and dispersion. Geothermics 83, 101721. https://doi.org/10.1016/j.geothermics.2019.101721.

Possemiers, M., Huysmans, M., Batelaan, O., 2014. Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium. Journal of Hydrology: Regional Studies 2, 20–34. https://doi.org/10.1016/j.ejrh.2014.08.001.

Pulselli, R.M., Broersma, S., Martin, C.L., Keeffe, G., Bastianoni, S., van den Dobbelsteen, A., 2021. Future city visions. The energy transition towards carbon-neutrality: lessons learned from the case of Roeselare, Belgium. Renewable and Sustainable Energy Reviews 137, 110612. https://doi.org/10.1016/j.rser.2020.110612.

Ramos-Escudero, A., Bloemendal, M., 2022. Assessment of potential for Aquifer Thermal Energy Storage Systems for Spain. Sustainable Cities and Society, 103849. https://doi.org/10.1016/j.scs.2022.103849.

Ramos-Escudero, A., García-Cascales, M.S., Cuevas, J.M., Sanner, B., Urchueguía, J.F., 2021. Spatial analysis of indicators affecting the exploitation of shallow geothermal energy at European scale. Renewable Energy 167, 266–281. https://doi.org/10.1016/j.renene.2020.11.081.

Regnier, G., Salinas, P., Jackson, M.D., 2023. Predicting the risk of saltwater contamination of freshwater aquifers during aquifer thermal energy storage. Hydrogeol J 31, 1067–1082. https://doi.org/10.1007/s10040-023-02630-9.

Regnier, G., Salinas, P., Jacquemyn, C., Jackson, M.D., 2022. Numerical simulation of aquifer thermal energy storage using surface-based geologic modelling and dynamic mesh optimisation. Hydrogeol J. https://doi.org/10.1007/s10040-022-02481-w.

Renn, O., Marshall, J.P., 2020. History of the energy transition in Germany: from the 1950s to 2019, in: Renn, O., Ulmer, F., Deckert, A. (Eds.), The Role of Public Participation in Energy Transitions. Elsevier, pp. 9–38.

Rhodes, C.J., 2016. The 2015 Paris Climate Change Conference: COP21. Science progress 99, 97–104. https://doi.org/10.3184/003685016X14528569315192.

Rivoirard, J., 2001. Which Models for Collocated Cokriging? Mathematical Geology 33, 117–131. https://doi.org/10.1023/A:1007530600152.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodin, A., Schlese, U., Schulzweida, U., Tompkins, A., 2003. The atmospheric general circulation model ECHAM5 - Part I: Model description.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., Schulzweida, U., 2004. The atmospheric general circulation model ECHAM5 Part II: Sensitivity of simulated climate to horizontal and vertical resolution. https://doi.org/10.17617/2.995221.

Rohracher, H., Späth, P., 2014. The Interplay of Urban Energy Policy and Socio-technical Transitions: The Eco-cities of Graz and Freiburg in Retrospect. Urban Studies 51, 1415–1431. https://doi.org/10.1177/0042098013500360.

Román-Palacios, C., Wiens, J.J., 2020. Recent responses to climate change reveal the drivers of species extinction and survival. Proceedings of the National Academy of Sciences of the United States of America 117, 4211–4217. https://doi.org/10.1073/pnas.1913007117.

Rosa, M. de, Bianco, V., Scarpa, F., Tagliafico, L.A., 2014. Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach. Applied Energy 128, 217–229. https://doi.org/10.1016/j.apenergy.2014.04.067.

Rosen, M.A., Koohi-Fayegh, S., 2017. Geothermal energy: Sustainable heating and cooling using the ground. John Wiley & Sons Inc, Chichester, West Sussex, United Kingdom, 277 pp.

Rubel, F., Kottek, M., 2010. Observed and projected climate shifts 1901-2100 depicted by world maps of the Köppen-Geiger climate classification. metz 19, 135–141. https://doi.org/10.1127/0941-2948/2010/0430.

Rundel, P., Meyer, B., Meiller, M., Meyer, I., Daschner, R., Jakuttis, M., Franke, M., Binder, S., Hornung, A., 2013. Speicher für die Energiewende. Fraunhofer-Institut für Umwelt-, Sicherheits- und Energietechnick UMSICHT (Ed.), 117 pp.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. Journal of Mathematical Psychology 15, 234–281. https://doi.org/10.1016/0022-2496(77)90033-5.

Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, New York, 287 pp.

Saidur, R., Islam, M.R., Rahim, N.A., Solangi, K.H., 2010. A review on global wind energy policy. Renewable and Sustainable Energy Reviews 14, 1744–1762. https://doi.org/10.1016/j.rser.2010.03.007.

Saltelli, A., Annoni, P., Azzini, I., Campolongo, F., Ratto, M., Tarantola, S., 2010. Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. Computer Physics Communications 181, 259–270. https://doi.org/10.1016/j.cpc.2009.09.018.

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisane, M., Tarantola, S., 2008. Global sensitivity analysis: The primer. John Wiley & Sons Ltd, Chichester, England, x, 292.

Saner, D., Juraske, R., Kübert, M., Blum, P., Hellweg, S., Bayer, P., 2010. Is it only CO2 that matters? A life cycle perspective on shallow geothermal systems. Renewable and Sustainable Energy Reviews 14, 1798–1813. https://doi.org/10.1016/j.rser.2010.04.002.

Sarbu, I., Sebarchievici, C., 2014. General review of ground-source heat pump systems for heating and cooling of buildings. Energy and Buildings 70, 441–454. https://doi.org/10.1016/j.enbuild.2013.11.068.

Schiel, K., Baume, O., Caruso, G., Leopold, U., 2016. GIS-based modelling of shallow geothermal energy potential for CO2 emission mitigation in urban areas. Renewable Energy 86, 1023–1036. https://doi.org/10.1016/j.renene.2015.09.017.

Schmidt, T., Pauschinger, T., Sørensen, P.A., Snijders, A., Djebbar, R., Boulter, R., Thornton, J., 2018. Design Aspects for Large-scale Pit and Aquifer Thermal Energy Storage for District Heating and Cooling. Energy Procedia 149, 585–594. https://doi.org/10.1016/j.egypro.2018.08.223.

Schubert, T. (Ed.), 2016. Regionale Hydrogeologie von Deutschland: Die Grundwasserleiter: Verbreitung, Gesteine, Lagerungsverhältnisse, Schutz und Bedeutung. Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Stuttgart, 452 pp.

Schüppler, S., Fleuchaus, P., Blum, P., 2019. Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany. Geotherm Energy 7, 669. https://doi.org/10.1186/s40517-019-0127-6.

Seetharaman, A., Sandanaraj, L.L., Moorthy, M.K., Saravanan, A.S., 2016. Enterprise framework for renewable energy. Renewable and Sustainable Energy Reviews 54, 1368–1381. https://doi.org/10.1016/j.rser.2015.10.127.

Short, A., Guthrie, P., Soulti, E., Macmillan, S., 2015. Health Technical Memorandum 07-02: EnCO2de 2015 – making energy work in healthcare: Environment and sustainability. Part A: Policy and management. https://www.england.nhs.uk/wp-content/uploads/2021/05/HTM_07-02_Part_A_FINAL.pdf (accessed 17 February 2022).

Sillak, S., 2023. All talk, and (no) action? Collaborative implementation of the renewable energy transition in two frontrunner municipalities in Denmark. Energy Strategy Reviews 45, 101051. https://doi.org/10.1016/j.esr.2023.101051.

Smil, V., 2015. Power density: A key to understanding energy sources and uses. The MIT Press, Cambridge, Massachusetts, London, England, 306 pp.

Sobol, I., 2001. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Mathematics and Computers in Simulation 55, 271–280. https://doi.org/10.1016/S0378-4754(00)00270-6.

Sommer, W., 2015. Modelling and monitoring of Aquifer Thermal Energy Storage: Impacts of heterogeneity, thermal interference and bioremediation. Dissertation. Wageningen, Niederlande, 206 pp.

Sommer, W., Valstar, J., Leusbrock, I., Grotenhuis, T., Rijnaarts, H., 2015. Optimization and spatial pattern of large-scale aquifer thermal energy storage. Applied Energy 137, 322–337. https://doi.org/10.1016/j.apenergy.2014.10.019.

Sommer, W., Valstar, J., van Gaans, P., Grotenhuis, T., Rijnaarts, H., 2013. The impact of aquifer heterogeneity on the performance of aquifer thermal energy storage. Water Resour. Res. 49, 8128–8138. https://doi.org/10.1002/2013WR013677.

Sommer, W.T., Doornenbal, P.J., Drijver, B.C., van Gaans, P.F.M., Leusbrock, I., Grotenhuis, J.T.C., Rijnaarts, H.H.M., 2014. Thermal performance and heat transport in aquifer thermal energy storage. Hydrogeol J 22, 263–279. https://doi.org/10.1007/s10040-013-1066-0.

Somogyi, V., Sebestyén, V., Nagy, G., 2017. Scientific achievements and regulation of shallow geothermal systems in six European countries – A review. Renewable and Sustainable Energy Reviews 68, 934–952. https://doi.org/10.1016/j.rser.2016.02.014.

Sperling, K., Hvelplund, F., Mathiesen, B.V., 2011. Centralisation and decentralisation in strategic municipal energy planning in Denmark. Energy Policy 39, 1338–1351. https://doi.org/10.1016/j.enpol.2010.12.006.

Spinoni, J., Vogt, J., Barbosa, P., 2015. European degree-day climatologies and trends for the period 1951-2011. Int. J. Climatol. 35, 25–36. https://doi.org/10.1002/joc.3959.

Spinoni, J., Vogt, J.V., Barbosa, P., Dosio, A., McCormick, N., Bigano, A., Füssel, H.-M., 2018. Changes of heating and cooling degree-days in Europe from 1981 to 2100. Int. J. Climatol 38, e191-e208. https://doi.org/10.1002/joc.5362.

Statistisches Bundesamt, 2020. Energieverbrauch der privaten Haushalte für Wohnen. https://www.destatis.de/DE/Themen/Gesellschaft-Umwelt/Umwelt/UGR/private-haushalte/Tabellen/energieverbrauch-haushalte.html (accessed 8 July 2021).

Stauffer, F., Bayer, P., Blum, P., Molina-Giraldo, N., Kinzelbach, W., 2014. Thermal Use of Shallow Groundwater. CRC Press, Boca Raton, Florida, 1290 pp.

Stemmle, R., Blum, P., Schüppler, S., Fleuchaus, P., Limoges, M., Bayer, P., Menberg, K., 2021. Environmental impacts of aquifer thermal energy storage (ATES). Renewable and Sustainable Energy Reviews 151, 111560. https://doi.org/10.1016/j.rser.2021.111560.

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geotherm Energy 10, 24. https://doi.org/10.1186/s40517-022-00234-2.

Steubing, B., Wernet, G., Reinhard, J., Bauer, C., Moreno-Ruiz, E., 2016. The ecoinvent database version 3 (part II): analyzing LCA results and comparison to version 2. Int J Life Cycle Assess 21, 1269–1281. https://doi.org/10.1007/s11367-016-1109-6.

Stott, P., 2016. How climate change affects extreme weather events. Science (New York, N.Y.) 352, 1517–1518. https://doi.org/10.1126/science.aaf7271.

Timilsina, G.R., Kurdgelashvili, L., Narbel, P.A., 2012. Solar energy: Markets, economics and policies. Renewable and Sustainable Energy Reviews 16, 449–465. https://doi.org/10.1016/j.rser.2011.08.009.

Tissen, C., Menberg, K., Bayer, P., Blum, P., 2019. Meeting the demand: geothermal heat supply rates for an urban quarter in Germany. Geotherm Energy 7, 9. https://doi.org/10.1186/s40517-019-0125-8.

Tissen, C., Menberg, K., Benz, S.A., Bayer, P., Steiner, C., Götzl, G., Blum, P., 2021. Identifying key locations for shallow geothermal use in Vienna. Renewable Energy 167, 1–19. https://doi.org/10.1016/j.renene.2020.11.024.

Todorov, O., Alanne, K., Virtanen, M., Kosonen, R., 2020. A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: A case study in Finland. Sustainable Cities and Society 53, 101977. https://doi.org/10.1016/j.scs.2019.101977.

Tomasetta, C., 2013. Life Cycle Assessment of Underground Thermal Energy Storage Systems: Aquifer Thermal Energy Storage versus Borehole Thermal Energy Storage. Tesi di Laurea. Venice, 79 pp.

Tomasetta, C., van Ree, C.C.D.F., Griffioen, J., 2015. Life Cycle Analysis of Underground Thermal Energy Storage, in: Lollino, G., Manconi, A., Guzzetti, F., Culshaw, M., Bobrowsky, P., Luino, F. (Eds.), Engineering Geology for Society and Territory - Volume 5. Springer International Publishing, Cham, pp. 1213–1217.

Tsagarakis, K.P., Efthymiou, L., Michopoulos, A., Mavragani, A., Anđelković, A.S., Antolini, F., Bacic, M., Bajare, D., Baralis, M., Bogusz, W., Burlon, S., Figueira, J., Genç, M.S., Javed, S., Jurelionis, A., Koca, K., Ryżyński, G., Urchueguia, J.F., Žlender, B., 2020. A review of the legal framework in shallow geothermal energy in selected European countries: Need for guidelines. Renewable Energy 147, 2556–2571. https://doi.org/10.1016/j.renene.2018.10.007.

Umweltbundesamt, 2020. Energiebedingte Emissionen. https://www.umweltbundesamt.de/daten/energie/energiebedingte-emissionen#energiebedingte-treibhausgas-emissionen (accessed 23 April 2020).

Umweltbundesamt, 2023. Erneuerbare Energien in Zahlen. https://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen (accessed 25 November 2023).

Ürge-Vorsatz, D., Danny Harvey, L.D., Mirasgedis, S., Levine, M.D., 2007. Mitigating CO 2 emissions from energy use in the world's buildings. Building Research & Information 35, 379–398. https://doi.org/10.1080/09613210701325883.

USGS, 2017. Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global. Earth Resources Observation And Science (EROS) Center, U.S. Geological Survey.

van Zalk, J., Behrens, P., 2018. The spatial extent of renewable and non-renewable power generation: A review and meta-analysis of power densities and their application in the U.S. Energy Policy 123, 83–91. https://doi.org/10.1016/j.enpol.2018.08.023.

Vanhoudt, D., Desmedt, J., van Bael, J., Robeyn, N., Hoes, H., 2011. An aquifer thermal storage system in a Belgian hospital: Long-term experimental evaluation of energy and cost savings. Energy and Buildings 43, 3657–3665. https://doi.org/10.1016/j.enbuild.2011.09.040.

Vidal, R., Olivella, S., Saaltink, M.W., Diaz-Maurin, F., 2022. Heat storage efficiency, ground surface uplift and thermo-hydro-mechanical phenomena for high-temperature aquifer thermal energy storage. Geotherm Energy 10. https://doi.org/10.1186/s40517-022-00233-3.

Villinger, E., 1999. Freiburg im Breisgau - Geologie und Stadtgeschichte. Landesamt für Geologie, Rohstoffe und Bergbau Baden-Württemberg, Freiburg i. Br.

Vringer, K., Vries, R. de, Visser, H., 2021. Measuring governing capacity for the energy transition of Dutch municipalities. Energy Policy 149, 112002. https://doi.org/10.1016/j.enpol.2020.112002.

Walch, A., Li, X., Chambers, J., Mohajeri, N., 2021. Shallow geothermal energy potential for heating and cooling of buildings with regeneration under climate change scenarios.

Watson, S.D., Lomas, K.J., Buswell, R.A., 2019. Decarbonising domestic heating: What is the peak GB demand? Energy Policy 126, 533–544. https://doi.org/10.1016/j.enpol.2018.11.001.

Wendland, F., Albert, H., Bach, M., Schmidt, R. (Eds.), 1993. Atlas zum Nitratstrom in der Bundesrepublik Deutschland: Rasterkarten zu geowissenschaftlichen Grundlagen, Stickstoffbilanzgrößen und Modellergebnissen. Springer Berlin Heidelberg, Berlin, Heidelberg, 96 pp.

Werner, S., 2016. European space cooling demands. Energy 110, 148–156. https://doi.org/10.1016/j.energy.2015.11.028.

Werner, S., 2017. International review of district heating and cooling. Energy 137, 617–631. https://doi.org/10.1016/j.energy.2017.04.045.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Wesselink, M., Liu, W., Koornneef, J., van den Broek, M., 2018. Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands. Energy 147, 477–489. https://doi.org/10.1016/j.energy.2018.01.072.

Wibig, J., 2003. Heating degree days and cooling degree days variability in Lodz in the period 1931-2000. Fifth International Conference on Urban Climate 2003.

Wiel, S., Martin, N., Levine, M., Price, L., Sathaye, J., 1998. The role of building energy efficiency in managing atmospheric carbon dioxide. Environmental Science & policy 1, 27–38. https://doi.org/10.1016/S1462-9011(98)00004-5.

Wirsing, G., Luz, A., 2005. Hydrogeologischer Bau und Aquifereigenschaften der Lockergesteine im Oberrheingraben (Baden-Württemberg). Regierungspräsidium Freiburg, Abteilung 9 Landesamt für Geologie, Rohstoffe und Bergbau (LGRB), Freiburg i. Br.

WPG, 2023. Heat Planning Act of December 20, 2023 (Federal Law Gazette 2023 I No. 394).

Wüstenhagen, R., Wolsink, M., Bürer, M.J., 2007. Social acceptance of renewable energy innovation: An introduction to the concept. Energy Policy 35, 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001.

Xu, J., Wang, R.Z., Li, Y., 2014. A review of available technologies for seasonal thermal energy storage. Solar Energy 103, 610–638. https://doi.org/10.1016/j.solener.2013.06.006.

Younes, A., Fahs, M., Ataie-Ashtiani, B., Simmons, C.T., 2020. Effect of distance-dependent dispersivity on density-driven flow in porous media. Journal of Hydrology 589, 125204. https://doi.org/10.1016/j.jhydrol.2020.125204.

Zekira, Y., Chitchyan, R., 2019. Exploring Future Skills Shortage in the Transition to Localised and Low-Carbon Energy Systems. Paper presented at 6th International Conference on ICT for Suistainability, ICT4S, Lappeenranta, Finland 2019.

Zhang, H., Baeyens, J., Cáceres, G., Degrève, J., Lv, Y., 2016. Thermal energy storage: Recent developments and practical aspects. Progress in Energy and Combustion Science 53, 1–40. https://doi.org/10.1016/j.pecs.2015.10.003.

Zhu, K., Blum, P., Ferguson, G., Balke, K.-D., Bayer, P., 2010. The geothermal potential of urban heat islands. Environ. Res. Lett. 5, 44002. https://doi.org/10.1088/1748-9326/5/4/044002.

Acknowledgements

The help and support that I have continuously received from many people is greatly appreciated. This thesis would not have been possible without them. At this point, I would like to thank…

… PD Dr. Kathrin Menberg for her excellent supervision at all times and her uncomplicated way of dealing with every question I had. Our countless discussions on ongoing and planned research have always proved to be of great value. I will remember these conversations as encouraging and motivating. Over the last few years, I have truly enjoyed working with her.

… Prof. Dr. Philipp Blum for providing me the opportunity to do a PhD in a fantastic work environment. In many conversations I have learned a lot from him, both directly and indirectly related to my research topic. Not least, I thank him for co-supervising me and encouraging an independent way of working.

… Prof. Dr. Jasper Griffioen for his willingness to be my co-examiner.

… Prof. Dr. Nico Goldscheider and Prof. Dr. Peter Bayer for being part of my doctoral committee.

… Prof. Dr. Poul Alberg Østergaard for hosting me during my research stay at Aalborg University.

… Marco Fuchs and Matthias Herrmann for the productive yet sociable atmosphere in our office.

… Nicole Suteu for her valuable support in administrative matters.

… all other colleagues and friends from the Engineering Geology and Hydrogeology groups for a wonderful time on and off campus.

… the German Federal Environmental Foundation (DBU) for the financial support.

… the Karlsruhe House of Young Scientists (KHYS) for funding my research stay in Aalborg.

… my family and friends who have always supported me and accompanied me on this journey.

Declaration of authorship

Study 1 (Chapter 2)

Stemmle, R., Blum, P., Schüppler, S., Fleuchaus, P., Limoges, M., Bayer, P., Menberg, K., 2021. Environmental impacts of aquifer thermal energy storage (ATES). Renewable and Sustainable Energy Reviews 151, 111560. https://doi.org/10.1016/j.rser.2021.111560.

Ruben Stemmle: Writing – original draft, conceptualization, methodology, visualization. Philipp Blum: Supervision. Simon Schüppler: Writing – review & editing. Paul Fleuchaus: Supervision, investigation. Melissa Limoges: investigation. Peter Bayer: Writing – review & editing. Kathrin Menberg: Supervision, conceptualization, writing – review & editing.

Study 2 (Chapter 3)

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geothermal Energy 10, 24. https://doi.org/10.1186/s40517-022-00234-2.

Ruben Stemmle: Conceptualization, methodology, data collection, visualization, writing – original draft. Vanessa Hammer: Methodology, data collection, visualization. Philipp Blum: Conceptualization, supervision, writing – review and editing. Kathrin Menberg: Conceptualization, supervision, writing – review and editing. All authors read and approved the final manuscript.

Study 3 (Chapter 4)

Stemmle, R., Lee, H., Blum, P., Menberg, K., 2024. City-scale heating and cooling with aquifer thermal energy storage (ATES). Geothermal Energy 12, 2. https://doi.org/10.1186/s40517-023-00279-x.

Ruben Stemmle: Conceptualization, methodology, results evaluation and analysis, visualization, writing – original draft. Haegyeong Lee: Methodology. Philipp Blum: Conceptualization, writing – review & editing, supervision. Kathrin Menberg: Conceptualization, writing – review & editing, supervision.

Study 4 (Chapter 5)

Stemmle, R., Hanna, R., Menberg, K., Østergaard, P.A., Jackson, M., Staffell, I., Blum, P. Policies for Aquifer Thermal Energy Storage: International comparison, barriers and recommendations. Clean Technologies and Environmental Policy (submitted).

Ruben Stemmle: Conceptualization, investigation, methodology, visualization, writing – original draft. Richard Hanna: Conceptualization, investigation, methodology, software, writing – review & editing. Kathrin Menberg: Conceptualization, supervision, writing – review & editing. Poul Alberg Østergaard: Writing – review & editing. Matthew Jackson: Writing – review & editing. Iain Staffell: Writing – review & editing. Philipp Blum: Conceptualization, supervision, writing – review & editing.

Publications and contributions

Peer-reviewed journal articles

Stemmle, R., Hanna, R., Menberg, K., Østergaard, P.A., Jackson, M., Staffell, I., Blum, P. Policies for Aquifer Thermal Energy Storage: International comparison, barriers and recommendations. Clean Technologies and Environmental Policy *(submitted)*.

Stemmle, R., Lee, H., Blum, P., Menberg, K., 2024. City-scale heating and cooling with aquifer thermal energy storage (ATES). Geothermal Energy 12, 2. https://doi.org/10.1186/s40517-023-00279-x.

Biehl, J., Missbach, L., Riedel, F., **Stemmle, R.**, Jüchter, J., Weber, J., Kucknat, J., Odenweller, A., Nauck, C., Lukassen, L.J., Zech, M., Grimm, M., 2023. Wicked facets of the German energy transition – examples from the electricity, heating, transport, and industry sectors. International Journal of Sustainable Energy 42, 1128–1181. https://doi.org/10.1080/14786451.2023.2244602.

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Potential of low-temperature aquifer thermal energy storage (LT-ATES) in Germany. Geothermal Energy 10, 24. https://doi.org/10.1186/s40517-022-00234-2.

Stemmle, R., Menberg, K., Rybach, L., Blum, P., 2022. Tunnel geothermics – A review. Geomechanics and Tunnelling 15, 104–111. https://doi.org/10.1002/geot.202100084.

Stemmle, R., Blum, P., Schüppler, S., Fleuchaus, P., Limoges, M., Bayer, P., Menberg, K., 2021. Environmental impacts of aquifer thermal energy storage (ATES). Renewable and Sustainable Energy Reviews 151, 111560. https://doi.org/10.1016/j.rser.2021.111560.

Fleuchaus, P., Schüppler, S., **Stemmle, R.**, Menberg, K., Blum, P., 2021. Aquiferspeicher in Deutschland. Grundwasser – Zeitschrift der Fachsektion Hydrogeologie 26, 123–134. https://doi.org/10.1007/s00767-021-00478-y.

Conference proceedings

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2023. Potential von Niedrig-Temperatur-Aquiferspeichern (NT-ATES) in Deutschland. Fachsektionstage Geotechnik – Interdisziplinäres Forum, Würzburg, Germany, 6pp.

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Subsurface and Climatic Suitability of Shallow Aquifer Thermal Energy Storage (ATES) in Germany. European Geothermal Congress, Berlin, Germany, 8pp.

Conference contributions (as first author)

Stemmle, R., Menberg, K., Herrmann, M., Barth, F., Blum, P., 2024. Thermische Aquiferspeicher – Potentiale und Barrieren in Deutschland. GeoTHERM expo & congress, Offenburg, Germany, 29 Feb - 1 Mar 2024 (presentation).

Stemmle, R., Lee, H., Blum, P., Menberg, K., 2023. City-scale heating and cooling with Aquifer Thermal Energy Storage (ATES). GeoBerlin, Berlin, Germany, 3-7 Sept 2023 (presentation).

Stemmle, R., Lee, H., Blum, P., Menberg, K., 2023. Residential heating and cooling with Aquifer Thermal Energy Storage (ATES) on city scale. EGU General Assembly, Vienna, Austria, 23-28 Apr 2023. https://doi.org/10.5194/egusphere-egu23-1030 (poster).

Stemmle, R., Hammer, V., Blum, P., Menberg, K., 2022. Potential of Shallow Aquifer Thermal Energy Storage (ATES) in Germany. European Geothermal Congress, Berlin, Germany, 17-21 Oct 2022 (presentation).

Stemmle, R., Blum, P., Schüppler, S., Fleuchaus, P., Limoges, M., Bayer, P., Menberg, K., 2021. Greenhouse gas emissions of aquifer thermal energy storage (ATES). EGU General Assembly, online, 19-30 Apr 2021. https://doi.org/10.5194/egusphere-egu21-5052 (vPICO presentation).