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ÜBERSICHTSBEITRAG

Current research on aquifer thermal energy storage (ATES) in Germany

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Abstract
This paper reviews the current research on aquifer thermal energy storage (ATES) and mine thermal energy storage (MTES) in Germany providing descriptions of 3 low-temperature ATES (LT-ATES), 8 high-temperature ATES (HT-ATES), and 2 MTES research sites. While the overview reveals a diverse field of investigations spanning various spatial scales, research objectives, and methodologies, the predominant focus is limited to early-stage research with low technology readiness levels (TRL). The high number of HT-ATES research sites suggests greater research interest compared to LT-ATES. The integration of ATES into district heating (DH) grids in particular is a prominent research focus, yet almost none of the projects are specifically intended for practical implementation. Future research should therefore prioritize real-world demonstration projects and identify key locations, which is crucial for showcasing the benefits of ATES. The need for a streamlined regulatory framework that addresses environmental risks and ensures installation quality and efficient permit procedures is also discussed.

Keywords Aquifer thermal energy storage · Research projects · Heating and cooling · Review paper · Technology readiness level · Germany

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Aktuelle Forschung zu thermischen Aquiferspeichern in Deutschland

Zusammenfassung

Die vorliegende Arbeit stellt die aktuelle Forschung in Deutschland zu thermischen Aquiferspeichern (ATES, engl.: aquifer thermal energy storage) und thermischen Bergwerksspeichern (MTES, engl.: mine thermal energy storage) vor. Es werden drei Forschungsstandorte zu Niedertemperatur-ATES (NT-ATES), acht zu Hochtemperatur-ATES (HT-ATES) sowie zwei zu MTES beschrieben. Trotz einer breit gefächerten Forschungslandschaft mit unterschiedlichen räumlichen Untersuchungsskalen, Forschungszielen und -methoden zeichnet sich der Großteil der Forschungsvorhaben durch einen niedrigen Technologie-Reifegrad (TRL, engl: technology readiness level) aus. Die große Anzahl an HT-ATES-Forschungsstandorten weist auf ein erhöhtes Forschungsinteresse im Vergleich zu LT-ATES hin. Einen aktuellen Forschungsschwerpunkt stellt insbesondere die ATES-Integration in Wärmenetze dar, wobei jedoch fast keines der Projekte konkret auf eine praktische Umsetzung abzielt. Im Rahmen künftiger Forschungsarbeiten sollten daher prioritär praxisnahe Demonstrationsanlagen errichtet sowie Schlüsselstandorte identifiziert werden. Abschließend wird in dieser Arbeit die Notwendigkeit optimierter regulatorischer Rahmenbedingungen diskutiert, welche Umweltrisiken adressieren sowie eine hohe Anlagenqualität und effiziente Genehmigungsverfahren sicherstellen.

Schlüsselwörter Thermische Aquiferspeicher · Forschungsprojekte · Heizen und Kühlen · Übersichtsartikel · Technologie-Reifegrad · Deutschland

Abbreviations

ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CTES	Cavern Thermal Energy Storage
DH	District Heating
DHC	District Heating and Cooling
GCW	Groundwater Circulation Well
GHG	Greenhouse Gas
HT-ATES	High-Temperature ATES
HTHP	High-Temperature Heat Pump
LT-ATES	Low-Temperature ATES
MNA	Monitored Natural Attenuation
MTES	Mine Thermal Energy Storage
RHC	Renewable Heating and Cooling
ROM	Reduced Order Model
TES	Thermal Energy Storage
THC	Thermal-Hydraulic-Chemical
TRL	Technology readiness level
URG	Upper Rhine Graben
UTES	Underground Thermal Energy Storage
VOC	Volatile Organic Compounds

Introduction

Until now, the decarbonization of the heating and cooling sector in Germany has made slow progress with a share of renewable energies in this sector of only about 19% (Umweltbundesamt 2024), although space heating and cooling alone is responsible for more than 30% of Germany's final energy consumption (AGEB 2021). In total, the German heating and cooling sector including industrial process heat accounts for around 50% of the country's final energy consumption (AEE 2024), which demonstrates the sector's importance for a successful energy transition. One option to fully make use of available sources of heating and cooling is the utilization of thermal energy storage (TES) systems. Various types of TES can tackle seasonal discrepancies between periods of highest thermal energy demand and times of available energy sources such as renewable heating and cooling (RHC) and waste heat. Decoupling demand and availability is considered one of the main challenges to progressing decarbonization of the heating and cooling sector (e.g. Bott et al. 2019; Heier et al. 2015; Narula et al. 2020; Pavlov and Olesen 2012). In this regard, long-term seasonal underground thermal energy storage (UTES) systems seem especially promising. Various types of UTES include aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), cavern thermal energy storage (CTES), and mine thermal energy storage (MTES).

While having specific requirements in the subsurface, ATES using groundwater as the main heat storage medium is characterized by large storage volumes and low space requirements at the surface. Depending on the storage temperatures, ATES is typically classified into low-temperature ATES (LT-ATES) and high-temperature ATES (HT-ATES). LT-ATES systems are typically charged with waste heat and waste cold from space cooling and space heating, respectively. LT-ATES systems are thus commonly charged during warmer seasons by transferring excess heat into an aquifer at temperatures of up to 25 °C (Fleuchaus et al. 2018, 2020) and discharged for space heating in colder seasons by extracting thermal energy, typically supported by a heat pump. The thermally depleted groundwater is reinjected into the cold storage area (Fig. 1a) and extracted again during the following cooling period. The waste heat from this space

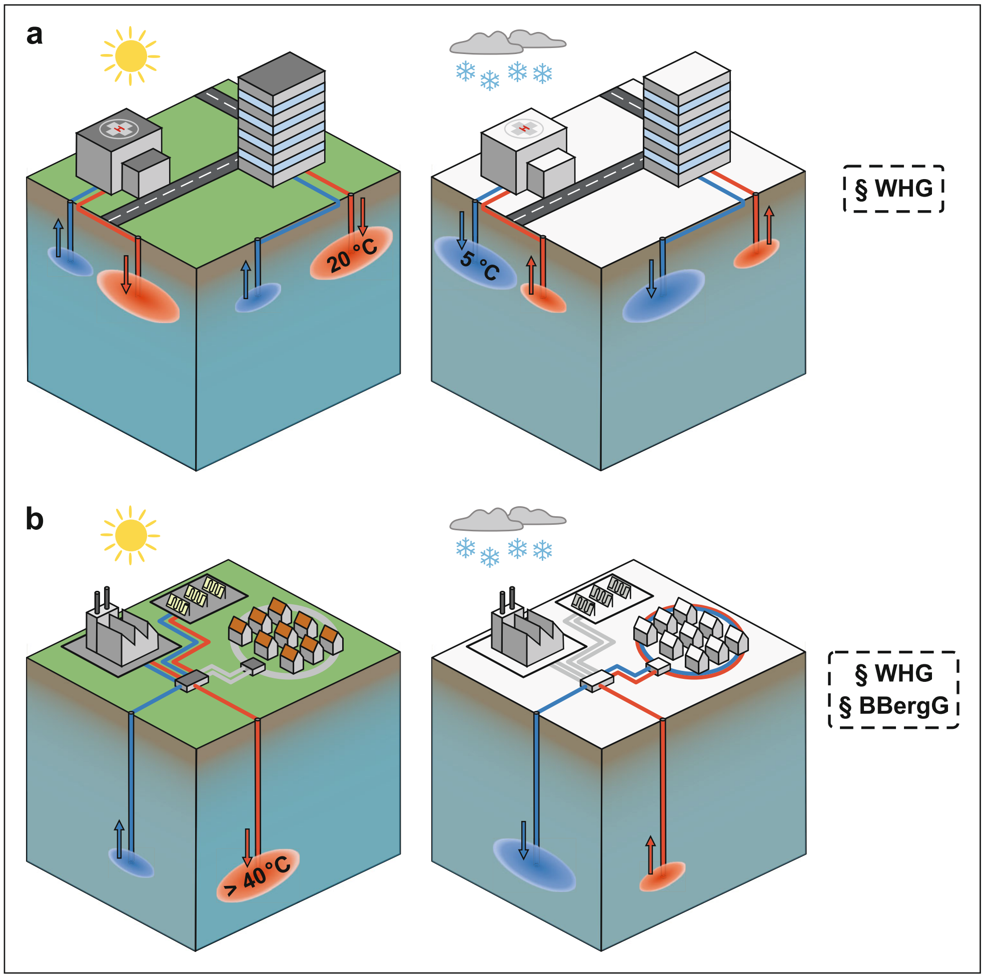

Fig. 1 Schematic operation principles of LT-ATES (**a**) and HT-ATES (**b**) during periods of surplus heat (e.g. in summer; left) and during periods of surplus cold (e.g. winter; right). (The included temperatures are common storage temperatures of LT-ATES and HT-ATES systems)

Abb. 1 Schematische Funktionsweisen von LT-ATES (**a**) und HT-ATES (**b**) während Zeiten überschüssiger Wärme (z. B. im Sommer; links) und während Zeiten überschüssiger Kälte (z. B. im Winter; rechts). (Die angegebenen Temperaturen sind übliche Speichertemperaturen von LT-ATES- und HT-ATES-Systemen)

cooling process, i.e. the heated groundwater, is injected into the aquifer to complete a storage cycle. HT-ATES systems work according to the same seasonal operation scheme of heat storage by reversing the groundwater pumping direction, with the major difference that storage temperatures typically exceed 40 °C (e.g. Drijver et al. 2019; Fleuchaus et al. 2020; Heldt et al. 2023). HT-ATES systems typically store thermal energy of external sources, i.e. generated independently from the consumer. Possible sources are industrial waste heat or renewable sources of thermal energy, such as excess solar thermal or geothermal energy (Fig. 1b) (Fleuchaus et al. 2020; Wesselink et al. 2018). Typical application cases of ATES include space heating and cooling of large building complexes and the integration into district heating (DH) or district heating and cooling (DHC) grids. Depending on the depth of the ATES installation, the German Water Resources Act (*Wasserhaushaltsgesetz*, WHG) and the German Federal Mining Act (*Bundesberggesetz*, BBergG) are the two most relevant laws providing the legal framework for planning, installing, and operating ATES systems.

The first deployment of ATES systems started in the 1960s in China and was followed by ATES utilization in other countries in the following decades (Fleuchaus et al. 2018). Today, around 3500 ATES systems are installed worldwide with around 85% of them located in the Netherlands (Jackson et al. 2024; Stemmle et al. 2024a). This is due to the Netherlands favorable subsurface conditions as well as regulatory and legislative frameworks (Bloemendal et al. 2015; Drijver and Godschalk 2018; Stemmle et al. 2024a). Internationally, however, adoption of ATES remains limited to this day despite a number of ecological and economic benefits.

For instance, previous studies on ATES systems showed that the technology can reduce greenhouse gas emissions (GHG) by up to 74% compared to conventional technologies, such as gas-fired boilers and compression chillers (Stemmle et al. 2021), while also being economically competitive (Ghaebi et al. 2017; Schüppler et al. 2019; Vanhoudt et al. 2011). Moreover, Stemmle et al. (2022) showed that more than 50% of the German territory with shallow porous aquifers is suitable for ATES utilization. Nevertheless, only very few ATES systems have been installed in Germany so far with only two ATES systems being currently in full operation (Fleuchaus et al. 2021). This is partly due to an insufficient regulatory framework. While the aforementioned WHG and BBergG provide a legally binding framework, the specific details of the permit procedures are subject to the responsible authorities and are highly region-dependent (Neidig 2022; Stemmle et al. 2024a). In recent years, however, research interest in the technology has increased in Germany and other countries (Fleuchaus et al. 2021, 2018; Gao et al. 2017; Holstenkamp et al. 2017). This work provides an overview of ongoing research on ATES in Germany, focusing on site-specific research. Current research on the related MTES technology, which uses mines for thermal energy storage, is also included.

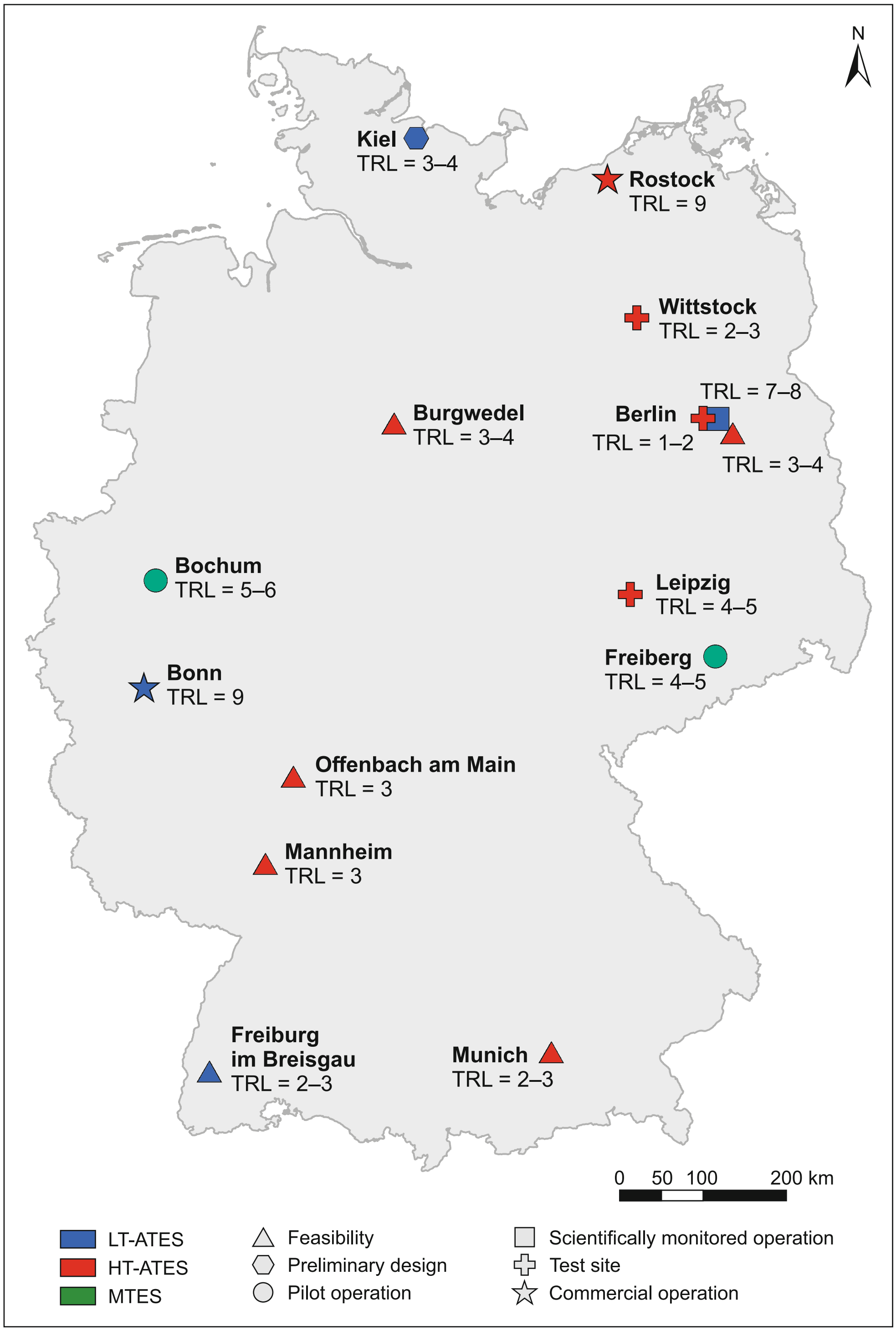

Fig. 2 Current ATES and MTES research sites in Germany, their respective status, and technology readiness level (*TRL*). (The two commercial ATES systems currently in operation are also included)

Abb. 2 Aktuelle ATES- und MTES-Forschungsstandorte in Deutschland, ihr jeweiliger Status und Technology Readiness Level (*TRL*). (Die beiden derzeit in Betrieb befindlichen kommerziellen ATES-Systeme sind ebenfalls dargestellt)

Table 1 Overview of LT-ATES, HT-ATES, and MTES research sites in Germany. The two commercial ATES systems currently in operation are also included
Tab. 1 Übersicht über die LT-ATES-, HT-ATES- und MTES-Forschungsstandorte in Deutschland. Die beiden derzeit in Betrieb befindlichen kommerziellen ATES-Systeme sind ebenfalls dargestellt

Site	Research project	TES type	Status	TRL[1]	Well depth [m]	Aquifer type	Number of wells	Flow rate [l/s]	Temperature—cold storage [°C]	Temperature—warm storage [°C]	Thermal capacity [MW]	Modeling software
Berlin—Mitte	DemoSpeicher	LT-ATES	In operation	7–8	27	Sands and gravels	1	0.4–1.7	10	16	0.025	Leapfrog, FEFLOW
Bonn—Bonner Bogen	Commercial system	LT-ATES	Commercial operation	9	22–28	Sands and gravels	6	83	13	20	–	–
Freiburg[2]	SpeicherCity	LT-ATES	Feasibility	2–3	20–140	Sands and gravels	Not known yet	7	6	18	~0.3	Leapfrog Geo, COMSOL, Multiphysics, FEFLOW
Kiel—Bremerskamp[3]	SpeicherCity	LT-ATES	Preliminary design	3–4	60–100	Sands	Not known yet	~56–97	~5	~20	Max. ~2	OpenGeoSys
Berlin—Adlershof	GEOFERN, SpeicherCity, GeoSpeicher Berlin, PUSH-IT	HT-ATES	Feasibility	3–4	410	Fine sands	1	~27–42	~20	95	~10	GOLEM/MOOSE, PHREEQC, FEFLOW
Berlin—Spandau	ATES iQ, SpeicherCity, TRANSGEO	HT-ATES	Test site	1–2	535	Fractured limestone	3	15–38	~32	–	–	FEFLOW, PHREEQ, CMG
Burgwedel[2]	GeoTES	HT-ATES	Feasibility	3–4	~1200	Sands	≥ 2	50	–	~90	–	Petrel, DuMux, COMSOL Multiphysics, Python

Table 1 (Continued)
Tab. 1 (Fortsetzung)

Site	Research project	TES type	Status	TRL[1]	Well depth [m]	Aquifer type	Number of wells	Flow rate [l/s]	Temperature—cold storage [°C]	Temperature—warm storage [°C]	Thermal capacity [MW]	Modeling software
Leipzig—Wissenschaftspark	KONATES, SpeicherCity	HT-ATES	Test site	4–5	10–15	Sands and gravels	2	0.2	10	70	–	OpenGeoSys
Mannheim[2]	PotAMMO	HT-ATES	Feasibility	3	150	Quaternary, Upper Tertiary; porous aquifers possibly confined with consolidated and unconsolidated sediments	≥2	~55	~40	~90	~15	Petrel, FEFLOW, MOOSE, Dymola
Munich—greater area (German Molasse Basin)	SpeicherCity	HT-ATES	Feasibility	2–3	2300–2800	Carbonate rocks	2	~100	95	140	~19.5	GOLEM/MOOSE
Offenbach[2]	PotAMMO	HT-ATES	Feasibility	3	Up to 1000	Tertiary, Rotliegend; porous aquifers possibly confined with consolidated and unconsolidated sediments	≥2	~28	~40	80–120	~10	Dymola, FEFLOW, MOOSE, Petrel
Rostock	Commercial system	HT-ATES	Commercial operation	9	20	Sands	2	4	–	50	–	–
Wittstock—test field	TestUM Aquifer, TestUM II Aquifer	HT-ATES	Test site	2–3	6–15	Sands	2	~0.3	–	80	~0.075	OpenGeoSys
Bochum—research campus	HEATSTORE, SpeicherCity	MTES	Pilot operation	5–6	64	Mining drift within the Ruhr Carboniferous	3	0.8	10	60	0.17	SPRING
Freiberg—Himmelfahrt Fundgrube/Reiche Zeche	MineATES	MTES	Pilot operation	4–5	150	Fractured rocks in the vadose zone	0 (underground mine)	Not applicable	5	50	0,006 (pilot test)	OpenGeoSys, PHREEQC, TOUGHREACT

[1]TRL: Technology readiness level
[2]City-scale
[3]University campus

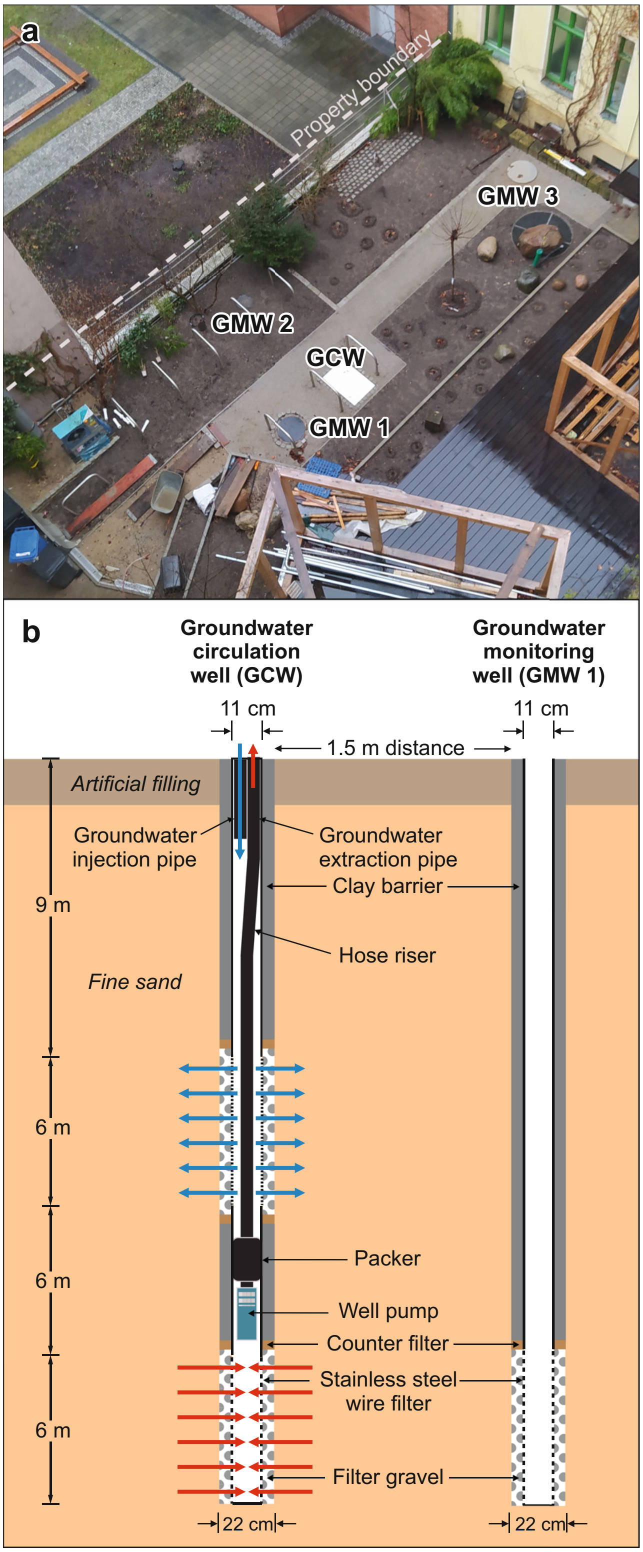

Fig. 3 **a** The *DemoSpeicher* site in Berlin-Mitte, **b** Sketch of the groundwater circulation well (GCW) and groundwater monitoring well 1 (GMW 1) construction

Abb. 3 **a** Der *DemoSpeicher*-Standort in Berlin-Mitte, **b** Schema des Grundwasserzirkulationsbrunnens (GCW) und der Grundwassermessstelle 1 (GWM 1)

ATES and MTES research sites in Germany

The following sections provide descriptions of 3 LT-ATES, 8 HT-ATES, and 2 MTES research sites or areas throughout Germany (Fig. 2). For each of them, information on the respective reservoir, research goals and methods, operation schemes as well as the current status and planned future steps are presented, if available. Additional information is compiled in Table 1.

Low-temperature aquifer thermal energy storage (LT-ATES)

Berlin—Mitte

The Berlin-Mitte site is part of the *DemoSpeicher* project which aims to demonstrate the implementation of LT-ATES systems in urban areas motivated by the increasing demand for cooling in summer. Hence, the backyard of an office building complex in Berlin-Mitte was chosen as the first test site. In Berlin, the aquifers generally provide favorable conditions for LT-ATES with low groundwater flow velocities, sufficiently thick aquifers, and high hydraulic conductivities (Stemmle et al. 2022). The favorable underground conditions also led to the implementation of the first German ATES system, which was installed in Berlin in 1999 to supply the Reichstag building with heating and cooling (Fleuchaus et al. 2021; Sanner et al. 2005). However, the actual implementation of larger doublet systems is hampered by site-specific constraints such as small properties with different owners, surface space restrictions in densely built-up areas, and drilling depth restrictions.

Under these conditions, groundwater circulation wells (GCW) can be a compromise with lower space requirements than classic doublet solutions. Such a system was implemented at a demonstration site in Berlin-Mitte (Fig. 3). The groundwater circulation well (GCW) and three groundwater monitoring wells (GMWs) were installed in a backyard, while the adjacent office buildings were energetically renovated. The 27 m deep GCW located in unconsolidated fine and gravelly sands within the Berlin glacial valley. In a GCW, groundwater is drawn from the lower end of the well system (24 m depth at the Berlin-Mitte site) and fed to the heat pump via an inner pipe. After thermal energy extraction, the groundwater is re-injected via an outer pipe within the same borehole into a shallower layer (13 m depth at the site). The injection of cooled or heated groundwater in winter and summer, respectively, results in vertical circulation of the groundwater within the aquifer.

The heating and cooling load of the renovated ~3000 m^2 building complex at the site is 150 and 40 kW, respectively. To cover the base load, the GCW will operate with a pump rate of 1.7 l/s. Due to the limited access to the backyard, the drilling rig was brought into the backyard using a mobile crane, whose limited load capacity restricted the drilling depth to 30 m. At the site, the allowed temperature spread in the aquifer is limited to 3 K. With reference to the local ambient groundwater temperature of around 13 °C, the thermal loading of the aquifer therefore can only vary between 10 and 16 °C. The plant went into operation in June 2024.

Within the scope of the project, the entire construction and operating cycle is considered, ranging from project planning to grid integration, commissioning, and thermal energy supply. The project includes extensive monitoring of the thermal-hydraulic, geochemical, and ecological impacts on the aquifer. As the depth to water table is only around 4 m at the site, basement waterlogging due to pump operation has to be avoided. A circulation test with a pump rate of 8 m^3/h revealed a maximum groundwater level increase of 9 cm, which did not cause any waterlogging. The potential for seasonal heat storage in the aquifer was investigated with preliminary modeling results indicating possible thermal short circuits in the GCW configuration. This raises the question of whether the GCW merely allows a seasonal regeneration of the aquifer to maintain natural groundwater temperature in the long-term rather than actively storing heated and cooled groundwater. Such a disadvantage of GCW can be eliminated if the distance between the filter sections used for pumping and injection is sufficiently large. Consequently, a greater drilling depth would be needed for a suitable configuration. For this site, the heat transport model showed that a short circuit could be avoided with a minimum distance of 20 m between the filter sections. Nevertheless, this concept can represent a solution for the regenerative energy supply of densely built-up urban areas and larger buildings like in Berlin.

Freiburg im Breisgau—city-scale

The research, which is part of the *SpeicherCity* project, aims to quantify the technical potential of LT-ATES on the city scale. The city of Freiburg im Breisgau is located at the eastern boundary of the Upper Rhine Graben (URG) and the western flank of the Black Forest mountain range. The upper graben fill of the URG is characterized by productive porous aquifers consisting of Pliocene and Quaternary sand and gravel deposits which developed as an alluvial fan from the Black Forest mountain range and are highly conductive (hydraulic conductivities in the range 10^{-5} to 10^{-3} m/s). In most parts of the study area, these sediment deposits have a thickness of up to 100 m and therefore are being investigated with respect to their LT-ATES potential. For the quantification of the technical potential, a 3D numerical subsurface heat transport model of the Freiburg study area was developed. In addition, a generalized workflow for the consideration of the quantified technical ATES potential in urban energy planning was developed using a simplified modeling approach. This workflow is exemplarily applied to the Freiburg area and used to determine ATES power densities, which relate the thermal power output of ATES systems to the required horizontal surface area. The workflow considers the simulation of different well layouts with varying distances and numbers of well doublets to achieve the highest storage efficiencies in a regime of elevated regional groundwater flow velocities of up to 13 m/d. Based on the power densities, supply rates were calculated for the existing urban heating and cooling demands that can be covered by LT-ATES systems. As reported by Stemmle et al. (2024b), substantial supply rates for both heating and cooling could be achieved with heating supply rates of 60% or more for about half of all residential buildings in the study area. Cooling demand could be supplied entirely for around 92% of the buildings.

The study shows that ATES can be considered in a quantified way in urban energy planning by taking into account important aspects such as advective heat transport and different well layouts in order to determine possible heating and cooling supply rates. The proposed workflow enables a straightforward adoption to other cities or regions. For the Freiburg study case, the results, and in particular the 3D heat transport model, are planned to be handed over to the municipality's authorities for their consideration in planning.

Kiel—Bremerskamp

In the framework of the *SpeicherCity* project, the Christian-Albrecht-University (CAU) Kiel is currently planning and constructing a significant extension of its Bremerskamp university campus. Within the next 15 to 20 years, the extension comprises the construction of more than 200,000 m^2 of laboratory and office buildings as well as a new computing center. The new campus will require residential and technical heat, mainly during winter, but will also contain a computing center and some cooled laboratories as net heat sources, especially during summer. These individual heat sinks and sources will be integrated into two local heat networks on temperature levels adjusted to the respective heating and cooling needs and will be connected to a subsurface heat storage system, which provides the required seasonal shift of heat from summer to winter. This storage system is currently in the design stage and an ATES system is being considered due to the (hydro-) geological setting. ATES' general suitability to supply university campuses with heating and cooling in an economic and climate-friendly way was previously shown at several Dutch universities (Godschalk et al. 2019). The geological subsurface at the Bremerskamp campus consists of alternating sand and clay layers overlying a confined aquifer of about 40 m thick-

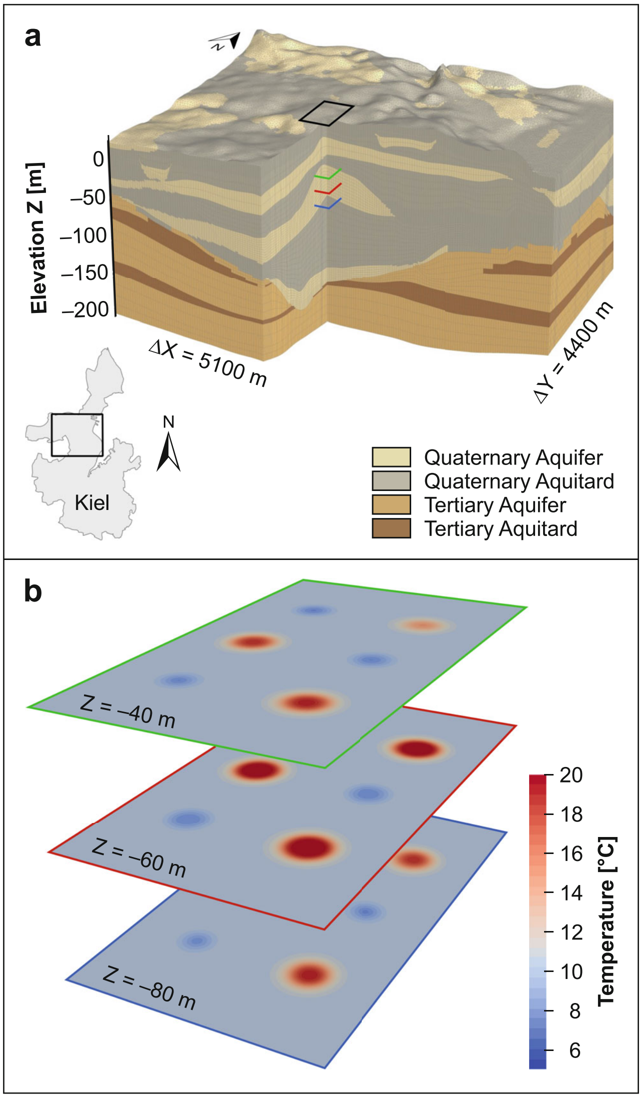

Fig. 4 **a** Three-dimensional view of the geological model of the Kiel Bremerskamp site created with Leapfrog Geo based on data provided by the LfU S-H and its representation as a finite element mesh for the numerical ATES model, **b** Horizontal slices of the simulated temperature distribution at the top, in the center, and at the bottom of the storage aquifer during the operation of a three-doublet ATES system. (The slice locations are indicated in the geological model. The Z-axis in meters above sea level is exaggerated by a factor of 10. The location of the model area within the city of Kiel is marked on the map)

Abb. 4 **a** Dreidimensionale Ansicht des mit Leapfrog Geo auf Basis von Daten des LfU S-H erstellten geologischen Modells des Standortes Kiel Bremerskamp und dessen Darstellung in Form eines Finite-Elemente-Gitters für das numerische ATES-Modell, **b** Horizontale Schnitte der simulierten Temperaturverteilung im oberen, mittleren und unteren Bereich des Speicheraquifers während des Betriebs eines ATES-Systems mit drei Brunnendoubletten. (Die Lage der Schnitte ist im geologischen Modell markiert. Die Z-Achse in Metern über dem Meeresspiegel ist um den Faktor 10 überhöht. Die Lage des Modellgebietes in Kiel ist auf der Karte markiert)

ness. The aquifer consists of medium to fine sand deposits which were identified in boreholes in the depth range of about 60 to 90 m. Sieve analyses indicate a hydraulic conductivity between 10^{-6} and 10^{-4} m/s, while thermal conductivities measured on water-saturated sediment cores yield a range of 2.0 to 3.5 W/(m · K).

As part of the *SpeicherCity* project, the research goal at the university campus is to develop strategies for robust design and operation schemes for the ATES system in the face of changing heating and cooling demands during and after the campus construction phase, influencing both temperature levels and quantity of stored heat. Currently, the ATES system is mainly designed to accommodate the cooling needs of the laboratories and the computational center, which are expected to span a few tens of GWh/a with a peak thermal capacity in the low MW range (Table 1). The specification of an adequate design and operation scheme is tackled by numerical heat transport simulations of the ATES system for a set of scenarios representing varying development stages and geological uncertainties (Fig. 4).

As a first step, the hydrogeological setting was investigated and a geological reservoir model was constructed (Table 1), which allows to estimate the required number of well doublets and pumping rates. In a second step, the robustness of the well field layouts concerning uncertainty in the temporal development of the heating and cooling demands is currently being assessed. The simulated temperature fields of the different ATES scenarios also allow to quantify the expected magnitude of thermal effects of long-term ATES operation in the subsurface.

High-temperature aquifer thermal energy storage (HT-ATES)

Berlin—Adlershof

Among the ongoing projects (Table 1), the research in Berlin-Adlershof seeks to harness excess renewable summer heat generated by the Neukölln wood-fired power plant for subsequent utilization in winter. This initiative anticipates that heat savings of about 25% can be achieved within the DH network by integrating an ATES system. This action is supposed to mitigate approximately 10,000 tons of CO_2 emissions annually. The ATES system is designed to attain a storage capacity of 30 GWh and a thermal capacity of 10 MW, potentially becoming Germany's largest heat storage facility. The plan consists of a well doublet to capture the approximately 40 m thick Hettangian (Jurassic) fine sand aquifer. The previous *GEOFERN* project resulted in the successful drilling of the initial well reaching a depth of 400 m (Blöcher et al. 2023a). Subsequent geophysical well logging assessments, core sample analyses, and preliminary laboratory investigations have corroborated the suitability of the aquifer for ATES applications. Preliminary 3D modeling of the ATES system has revealed that a well doublet with an inter-well spacing between 200 to 300 m could meet the technical requirements and be consistent with an operational cycle of six months. The drilling of a doublet system is an essential part of the following *GeoSpeicher Berlin* project at the Adlershof site.

To understand the aquifer properties at a hundred-meter scale, an extensive array of experimental methodologies, such as push-pull tests with hot water and tracer tests, will be deployed. This experimental work is imperative for the calibration and refinement of the existing 3D heat transport model, which will play a critical role in predicting the long-term operational dynamics of the ATES system.

Berlin—Spandau

The site at the former Berlin natural gas storage facility in Berlin-Spandau captures the shell facies of the naturally fractured Muschelkalk aquifer and was evaluated for geothermal purposes within the *ATES iQ* project (Blöcher et al. 2023b). The exploration of the aquifer revealed a detailed stratigraphic composition comprising two naturally fractured limestone layers, each with an average matrix porosity of 22%. This target formation shows a cumulative thickness of about 30 m with a natural reservoir temperature of 32 °C and is situated at a depth of 535 m below the ground surface. In 2021, slug tests yielded insights into the aquifer productivity, indicating a range between 0.5 and 1.2 l/(s · bar), coupled with a reservoir permeability varying from 250 to 700 mD. Subsequently performed step-rate and injection tests indicated an even higher productivity index between 2.5 and 4.0 l/(s · bar). These findings suggest maximum flow rates ranging from 15 to 38 l/s. Based on geological, hydrogeological as well as comprehensive core and fluid sample analyses, an equivalent porous medium 3D model was set up to simulate thermal-hydraulic processes during geothermal usage. Numerical simulations, incorporating diverse storage volumes ranging from 120,000 m^3 (tailored to a solar heating system) to 295,000 m^3 (suited for a DH system), were performed. The simulations resulted in mean efficiency values between 60 and 90% over a 25-year operational span, which underscores the potential viability and sustained efficiency of the suggested ATES system in Berlin-Spandau, which is numerically evaluated within the *SpeicherCity* project.

Burgwedel—city-scale

The region north of Hanover is well documented regarding the subsurface formations due to the oil and gas exploration activities in the past century (Zhou et al. 2024). Based on extensive analyses of seismic, core and well bore data, sandstone layers at depths of 1100 to 1400 m were identified as target zones for hydrothermal energy not only because of a beneficial temperature anomaly, but also because of appropriate porosities and permeabilities of the respective aquifers. In addition to the conventional hydrothermal doublet concept, seasonal heat storage could significantly enhance the thermal power output during winter and therefore promote the expansion of geothermal energy in this region. Using an example reservoir located in the Burgwedel area, the *GeoTES* project aims to develop a general mathematical model of an optimized surface and subsurface heating system and its integration into heating and electricity grids. The integrated concept considers the extraction of heat from deep aquifers with natural temperatures of up to 60 °C, the thermal and hydrodynamic processes in the borehole, and the inclusion into future heating grids. The aquifers are regenerated by high-capacity heat pumps supplied with renewable energy, including industrial waste heat and solar thermal energy, boosting the subsurface temperature to values beyond 80 °C during the summer season. The overall efficiency of this conceptual approach depends on the thermal capacity of the geological subsurface with year-round availability of high temperatures, heat losses to confining layers and within the borehole, groundwater flow, the behavior of the high-capacity heat pump, and the use of renewable thermal and electrical energy. Based on the project results achieved so far, preliminary economic feasibility studies have been carried out revealing a low best-case payback time of 3 years which serves for a future project implementation at the studied or at an adjacent location (Zhou et al. 2024).

Leipzig—Wissenschaftspark

In the framework of the *KONATES* and *SpeicherCity* research projects, a small-scale HT-ATES pilot project is being carried out at the Science Park in Leipzig (German: *Wissenschaftspark Leipzig*) and test operations started in summer 2024. At the selected site, the 10 to 11 m thick shallow Saale glacial aquifer is underlain by an 8 m thick tillite aquitard and a 5 m thick succession of medium to coarse sands with layers of gravel and silt. This aquifer is affected by a known historical contamination of chlorinated volatile organic compounds (VOC), mainly composed of trichloroethylene and cis-dichloroethylene with a maximum concentration of 6 mg/l. The primary objective of the pilot project is to demonstrate the feasibility of integrating a zeolite absorber, an activated carbon filter, and a stripping module in combination with monitored natural attenuation (MNA) in an ATES operation, in order to establish the practicality of an HT-ATES system in urban or industrial environments with contaminated aquifers. To evaluate the operation, a monitoring network has been established around the operational wells, and up- and downgradient of the test site. The focus of the research is the chemical and microbial impact of the cyclic HT-ATES operation on the contaminated aquifer, with particular emphasis on the behavior of the contaminants and microbial populations associated with the degradation of VOC. The pilot project also serves as a first step in the overall long-term goal of a carbon-neutral Science Park campus. As a small-scale pilot project, it will be operated by an artificial thermal load generated by an electric heater with an injection temperature of 70 °C and artificial heat consumption by cooling the extracted hot water. A cyclical operation is planned with hot and cold seasons of a few weeks and storage periods of a few days to a week, with a planned injection and extraction rate of 0.2 l/s.

Mannheim—city-scale

In the *PotAMMO* project, the geothermal potential of HT-ATES is assessed in order to evaluate its potential contributions to energy efficiency, environmental impacts, and economic benefits within the DH network of the city of Mannheim. The city of Mannheim is located at the transition of the central and the northern URG. Cenozoic sediments in the Mannheim area reach thicknesses of over 3500 m and reflect the complex depositional history of the URG, which led to the deposition of marine, brackish, lacustrine, and terrestrial sediments, with local occurrence of volcanics and evaporites. The sedimentary succession contains sand layers with significant thicknesses as well as increased porosities (10–15%) and permeabilities (10^{-14}–10^{-12} m^2), thus representing potential target horizons for ATES systems. In particular, the unconsolidated Quaternary deposits in the northern URG include potential formations such as the Viernheim and Iffezheim formations, which reach depths of more than 350 m in the Mannheim area. The Iffezheim formation represents the deepest groundwater layer in the Mannheim area and shows high hydraulic conductivities due to its unconsolidated nature, making it a potential target aquifer in the study area (Wirsing and Luz 2007).

The holistic approach takes into account the geological-geothermal ATES potential, local heating infrastructure, potential waste heat sources, usage conflicts, and future heating demand forecasts to allow the identification of technically feasible designs and specific ATES sites. The evaluation of ATES potential is supported by thermo-hydraulic storage simulations and dynamic overall system modeling, to ensure consideration of the thermodynamic system behavior and of the significant impact of system components on the technical potential. A machine learning-based model simplification approach is used to speed up the storage simulations. For the co-simulation of the seasonal ATES operation and the DH network with multiple heat sources and sinks, a modeling environment to couple the individual models was developed (Ohagen et al. 2023). The integrated approach helps to develop ATES deployment strategies for the model area which also consider the long-term environmental and economic benefit of integrating ATES into DH networks over the next 30–40 years. In particular, critical factors and life cycle-based calculations of heat generation costs and greenhouse gas emissions are included in the cost-benefit evaluation (Scholliers et al. 2024). The methodological approaches developed in the project can be transferred to other cities and regions and could make a significant contribution to the broader adoption of the ATES technology.

Munich—greater area

As part of the *SpeicherCity* project, the main objective of current research in the German Molasse Basin is to evaluate the potential for HT-ATES system application using the 500 m thick Malm limestone reservoir. The Upper Jurassic reservoir (Malm aquifer) of the German Molasse Basin, being part of the North Alpine Foreland Basin, represents an extensively investigated resource with 24 currently active geothermal plants. The carbonate reservoir rocks dip southwards below a progressively thicker wedge of Cenozoic and locally Cretaceous sediments. They reach depths of 4000–6000 m at the North Alpine Front (Flechtner et al. 2019), resulting in reservoir temperatures between 40 °C in the north and 160 °C in the south (Weber et al. 2019). The reservoir heterogeneity induces compartmentalization of the fluid migration in different reservoir segments (Birner 2013; Bohnsack et al. 2020; Heine et al. 2021; Homuth et al. 2014; Koch 2000, 1997; Konrad et al. 2021, 2019; Mraz 2019; Przybycin et al. 2017).

In the greater area of Munich, HT-ATES systems can be charged by excess energy, for example, from waste incineration or geothermal plants and can be integrated into the local DH networks to cover peak loads of energy demand. To assess the ATES potential, a physics-based thermal-hydraulic numerical analysis is performed based on field and well log datasets from three operating geothermal systems at depths of about 2000–3000 m TVD, as well as on a wide range of reservoir rock core analyses. Computation results predict promising thermal and hydraulic performance of the HT-ATES system, with an estimated heating capacity of about 19.5 MW (Tzoufka et al. 2024). Subsequently, a machine learning methodology is deployed, enabling the evaluation of the impact of an extensive parameter matrix on the HT-ATES system performance.

Various HT-ATES designs are under consideration. In the present study, the fluid injection and production are implemented by using two vertical wells that intersect the entire reservoir thickness. The well distance is 400 m, i.e.

twice the maximum calculated thermal radius to eliminate any thermal interferences (Doughty et al. 1982). A seasonal storage operation is implemented with semi-annual load cycles over a time span of 10 years. The injected fluid in the warm well has a temperature of 140 °C, whereas the fluid injected in the cold well has a temperature of 95 °C, corresponding to the average reservoir temperature at those depths (Tzoufka et al. 2024). The estimated maximum operational flow rates are in the order of up to 100 l/s, which is typical for the Molasse Basin. Further comprehensive feasibility studies based on numerical simulations are being conducted as preparation and benchmarking for a real HT-ATES demonstrator, which is currently in the planning phase. The feasibility studies will be expanded to cover different reservoir conditions and settings.

Offenbach am Main—city-scale

The city of Offenbach am Main represents the second study area of the *PotAMMO* project besides Mannheim. As for Mannheim, the main research goal is the holistic assessment of the potential integration of HT-ATES into the DH grid of Offenbach. The latter is situated on the so-called Frankfurt Horst which lies east of the URG. Both structures are closely related to the regional tectonic formation history. As in the Mannheim study area, Cenozoic sediments build up the potential target aquifer for HT-ATES. However, in the case of Offenbach, the geological-geothermal potential is evaluated at a greater depth of up to 1000 m.

Wittstock—test field

The test field located near Wittstock on a former military airfield was originally used in 2010 and 2011 for experimental monitoring of hydrogeochemical effects of CO_2 gas leakage in the context of geological CO_2 sequestration (Peter et al. 2012). Since 2017 the site has been used as a hydrogeological test site to analyze the environmental impacts of geological energy storage. Four individual test fields were set up for hydrogen (Löffler et al. 2022) and methane gas injection tests (Hu et al. 2023) as well as for HT-ATES injection tests as part of the projects *TestUM Aquifer* and *TestUM II Aquifer* (Hornbruch et al. 2023).

In the ATES test field, a confined aquifer at a depth of about 6–15 m below ground consisting of sandy glacial deposits of the Saale and Weichsel glacial stages served as the storage formation for a series of HT-ATES experiments. The experiments were conducted on one injection well and one production well with an inter-well distance of 40 m. Approximately 60 monitoring locations can be used for multi-level temperature measurements and groundwater sampling for geophysical, hydraulic, thermal, hydrogeochemical, and microbiological monitoring. In a first short-term heat injection test (May 2019), 86 m^3 of 75 °C hot water was injected for about 5 days at an average injection rate of about 0.3 l/s. A comparison of observed thermal responses with numerical simulations demonstrated the suitability of the monitoring set-up, while the simulation could accurately predict the heat transport mechanisms induced by the hot water injection (Heldt et al. 2021, 2023). Hydrogeochemical analyses of water samples taken at the monitoring wells after injection revealed temperature-induced increases in concentrations of major groundwater constituents and trace elements, as well as the reversibility of concentration changes with declining temperatures (Lüders et al. 2021). In addition, only minor changes occurred in microbial communities (Keller et al. 2021).

In a second experiment performed from 2021 to 2022, a highly transient multi-cyclic heat storage test was performed at an 80 °C injection temperature and a flow rate of about 0.3 l/s. The charging periods of either one or 14 days, corresponding to an injected heat load of about 1.6 or 26 MWh (Nordheim 2023), respectively, were followed by recovery periods of the same durations, while three of the 14-day cycles contained interim standstill periods of 21 days. No hydrogeochemical impacts were observed downstream of the thermally affected area.

Mine thermal energy storage (MTES)

Bochum—research campus

In the framework of the research projects *HEATSTORE* and *SpeicherCity*, a seasonal mine thermal energy storage (MTES) system is being developed as a pilot plant in a former coal mine in Bochum which aims to combine the benefits of mine water, solar energy, and high-temperature heat pump (HTHP) technology to boost the local DH infrastructure. Since 2018, work consisted of planning, designing, procuring, installing, testing, and running specific heat injection and production components of the pilot plant. In summer 2023, the complete storage system setup, including its mine water, solar energy, and HTHP connections, designed as scientific prototypes, was finished. Testing of the MTES system began immediately thereafter.

The first step towards the practical implementation of the project was to apply calculation models for both the subsurface and surface operations. These models showed that initial energy balances could be produced for the design and operation of the plant components. Based on the simulation results, it was possible to derive the location of the boreholes to be drilled into the mine, the size of the solar thermal collectors, the desired operating behavior, and the dimensions of the HTHP. The area targeted by the drilling operation allows to use about 1300 m^3 of water below the natural groundwater level at 22 m depth. The models also show that the surrounding rock potentially acts as an effective heat store, boosting the thermal capacity of the overall storage system.

The MTES system is the result of a research initiative that intends to decarbonize DH networks. The prototype facility will make a real and sustainable contribution to the Bochum South DH grid. Following the initial experience acquired during operational testing of the storage system in 2020 and 2021, tests on the MTES system are now being progressively intensified and expanded. Storage temperatures are being raised to a maximum of 60 °C and the annual flow will be increased to 15,000 m^3 to achieve the maximum thermal output based on the average number of annual hours of sunshine and the performance of the circulation pump. In summer 2023, the HTHP effectively demonstrated that it can supply the DH grid with thermal energy from the MTES. The initial readings are still being analyzed and will eventually provide information on the system efficiency at different storage and DH temperatures.

Freiberg—Himmelfahrt Fundgrube/Reiche Zeche

As part of the *MineATES* research project, the TU Bergakademie Freiberg, in cooperation with the DBI (Gastechnologisches Institut gGmbH Freiberg), is simulating periodic MTES cycles by conducting pilot-scale experiments for both heating and cooling on the 1st level (~150 m below ground) of the former underground silver mine Himmelfahrt Fundgrube/Reiche Zeche. A water-filled reservoir basin of ~21 m^3 volume, located in Freiberg gray gneiss, was selected as a storage facility and is equipped with extensive temperature monitoring (18 boreholes with 5 sensors each; and two separate data-logger systems). The MTES test series started in 2024 and is expected to last at least one year. Heat input and extraction within the temperature limits of 5 and 50 °C is being carried out on-site using a mobile heat pump suitable for use in mines. Heat transfer into the surrounding rock was detected by all sensor levels during the first (active heating and passive cooling) and second (both active heating and cooling) cycles. The heat flux during the heat storage phases was directed into the surrounding mine rock and produced a strong time lag which was observed between the shallowest and deepest sensor levels. Furthermore, the temperature gradient clearly varied over time until a plateau was reached where additional heat input by the heat pump did not contribute to further changes within the monitoring zone. Regardless of passive or active cooling, the temperature gradients were similar to those during the heating phase but in the opposite direction. Conductive and advective heat losses especially via the atmospheric boundary, through fractures and fissures, and through the rock mass itself are strongly dependent on the site hydraulics and rock properties. The pilot-scale experiment confirms that the higher the water flow through the reservoir, the lower the storage process efficiency. To quantify these transient thermal processes, the heat transfer mechanisms around the test reservoir are simulated using a numerical thermal-hydraulic-chemical (THC) model (Chen et al. 2024). In parallel to the temperature monitoring, hydro- and geochemical changes are evaluated at discrete time intervals and at selected points in the reservoir. During heating, precipitation of goethite and gypsum was observed, which is probably caused by an alteration of the thermodynamic equilibrium. Re-dissolution of the precipitated goethite was not observed during cooling. The proper functioning and condition of the installed devices is also continuously monitored to assess the impact of the harsh conditions (e.g. low pH, high humidity, presence of other electrical equipment in the mine) that favor corrosion, signal disturbances and other malfunctions. In addition to the work in the silver mine, detailed investigations are being carried out in the laboratory using temperature-controlled batch and column tests.

Discussion

Variety of research

The research sites presented in this review paper demonstrate extensive ongoing research on ATES in Germany covering a wide variety of spatial scales, research goals, and methods. However, it is apparent that the current research landscape is oriented towards low technology readiness levels (TRL). TRL as a measure for technical maturity has previously been used for ATES. According to Fleuchaus et al. (2018), early theoretical and experimental investigations of the ATES principle can be classified as TRL 2 to 3 reflecting research aimed at proving the principle's feasibility. On an international scale, TRL 8 to 9, i.e. commercial status, have been reached in the early 2010s with widespread ATES deployment in the Netherlands and a revival of the technology in China. Until now, however, most of the German research activities have low TRLs of 3 to 4 (Fig. 5). A noteworthy exception is the GCW installed in Berlin—Mitte. With a TRL of 7 to 8, this system is approaching a commercial status like the ATES systems in operation in Bonn and Rostock (cf. Table 1, Fleuchaus et al. 2021).

Across Germany, most research sites focus on HT-ATES (8 sites, Fig. 2) implying a greater research need compared to LT-ATES (3 sites). The technology maturity is reflected in the vast majority of installed systems worldwide being LT-ATES applications (Fleuchaus et al. 2018). Moreover, a prominent research focus of recent projects is the integration of ATES into DH grids. This focus is an indication of how ATES utilization might shift in the future: Going

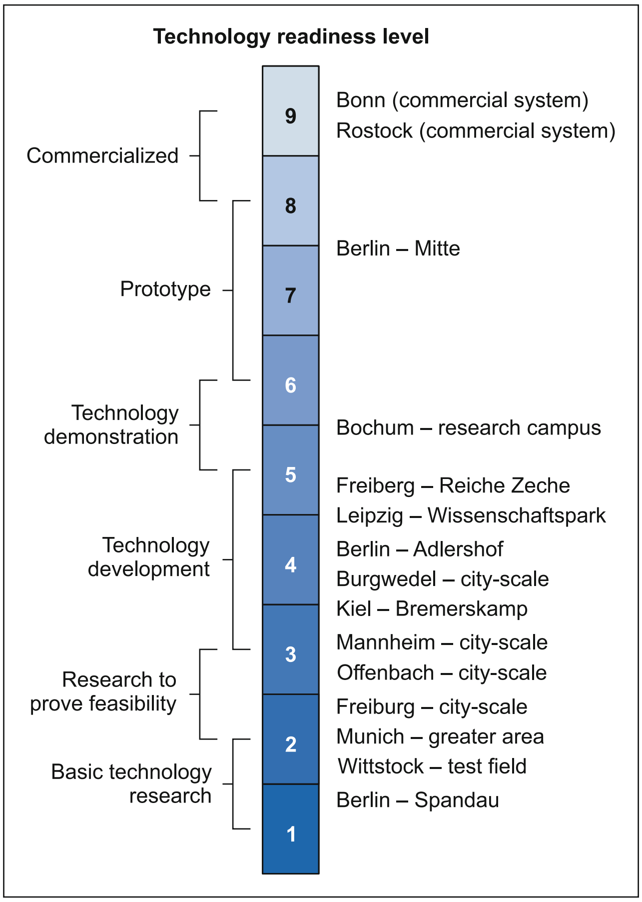

Fig. 5 Technology readiness levels (*TRL*) of the ATES and MTES research sites described in this study. (The two German commercial ATES systems currently in operation are also included)
Abb. 5 Technology Readiness Levels (*TRL*) der ATES- und MTES-Forschungsstandorte, die in dieser Arbeit beschrieben sind. (Die beiden derzeit in Betrieb befindlichen kommerziellen ATES-Systeme sind ebenfalls dargestellt)

beyond the currently most common ATES application case of supplying individual buildings, and ensuring a better coordination of planning on the district level to optimally and sustainably use the subsurface. Eventually, ATES has the potential to integrate an increasing share of renewable and waste heat sources in heating grids (e.g. Beernink et al. 2022; Bloemendal et al. 2014; Bott et al. 2019; Sommer et al. 2015). However, an effective integration of ATES into DH grids raises several challenges, as demonstrated by the current ATES research.

For example, research at the Bremerskamp university campus in Kiel shows that a portfolio of different heat sources and sinks has to be considered regarding the planned campus extension, which requires a flexible interplay between the ATES system and the DH grid. At the same time, long-term uncertainties related to changes in energy demand and availability over time require a robust ATES design and operation scheme. The potential loss of heat sources has previously been identified as a severe risk for the application of HT-ATES systems (Fleuchaus et al. 2020). While the presented research projects tackle these challenges during feasibility studies or early design stages, no project aims for an actual installation and integration of a real ATES system into an existing heating network. This reflects once again the low TRL of current ATES research in Germany.

While ATES is the main focus of current research on UTES technologies in Germany, the reuse of abandoned mines for thermal storage is also investigated here. Early results from the two respective sites suggest that MTES is a promising technology that can benefit from existing geological knowledge of decades to even hundreds of years, well-mapped mine geometries, and a mostly low recovery risk of injected heat. In some parts of Germany with a high density of mines, MTES could be used to transform the so-called “eternal liabilities” of the post-mining era into long-term benefits for heat transition in those regions. However, as with most ATES research sites, MTES research is also conducted at a low TRL level. It remains to be seen whether current research will result in real-world MTES systems that go beyond proof-of-concept studies and small-scale pilot operations and if they can contribute to a significant extent towards regional heat supply.

Another barrier to more widespread deployment of ATES in Germany and other countries is the lengthy, heterogeneous, and complex permit procedures (Fleuchaus et al. 2020; Stemmle et al. 2024a). To a limited extent, the ongoing research in Germany can provide valuable experience regarding the permit procedure. The successful permission of the high-temperature injection test at the Science Park in Leipzig with storage temperatures of 80 °C and shallow storage depths of only around 10 m shows that this kind of ATES operation is generally approvable and could serve as a role model for successful permitting of future commercial ATES systems. At this site, the only restriction imposed by the responsible authority is a maximum groundwater temperature increase of 4 K at the property boundary. The purposeful and synergetic use of a contaminated aquifer for the test operation at the Leipzig site might also serve as a blueprint for ATES systems in urban or industrial areas, which are often characterized by subsurface contaminations (Howard 2015; Kuroda and Fukushi 2008; Zuurbier et al. 2013). Similarly, the commercial HT-ATES system in Rostock has been approved in spite of its location within a highly saline aquifer (Table 1). The system, which is one of the few realized HT-ATES systems worldwide, stores groundwater at relatively high temperatures of 50 °C at shallow depths of about 20 m (Fleuchaus et al. 2021, 2020).

On the other hand, experience at the Berlin—Mitte site shows that despite suitable hydrogeological aquifer conditions, permission for ATES systems can be challenging. This applies especially to densely built-up areas where contamination, limited available space, and restrictive temperature thresholds can hinder ATES permission. At the Berlin—Mitte site, the restrictive set of licensing regulations stipulates a maximum groundwater temperature change of ±3 K. This minor allowable temperature spread considerably limits the thermal performance of the ATES system.

Outlook

The current research on ATES and MTES in Germany consists mostly of early-stage feasibility studies, synthetic simulations, and test sites used for fundamental research. Future research should therefore support the implementation of systems intended for practical use. In particular, the research-driven integration of market-ready ATES systems into existing or newly created DH grids could substantially advance the practical relevance of the research and offer the opportunity to gain valuable experience for future commercial applications. An important role of future ATES research should consist of identifying suitable ATES locations across Germany, where favorable subsurface conditions coincide with the presence of local heating and cooling needs that can be efficiently covered by ATES. Preferential building types at such key locations include, for instance, hospitals, data centers, office buildings, and university campuses (Fleuchaus et al. 2018; Schüppler et al. 2019). A showcase is the Bonner Bogen area in Bonn where office buildings, a data center, a hotel, and a medical center are supplied by a commercial ATES system with heating and cooling (Table 1) (Fleuchaus et al. 2021; Mands et al. 2010; Stemmle et al. 2021). It should be noted, however, that there is no comprehensive scientific monitoring and evaluation of this system. Future research-guided implementation of pioneering lighthouse projects should therefore promote technological readiness and deployment. Such demonstration systems have previously been identified as one of the most effective ways of raising awareness of the ATES technology and its practical benefits beyond the sole research interest (Stemmle et al. 2024a).

ATES expansion requires more R&D funding that is specifically tailored to long-term implementation-oriented research. A set of incentives and a promotional program for commercial systems can also contribute to the more widespread deployment of ATES. The same is true for an appropriate regulatory framework for ATES and related technologies, which is severely lacking in Germany. A favorable set of regulations should address any environmental risks associated with ATES and at the same time ensure a high level of ATES installation quality and operational performance. Furthermore, harmonized and efficient permit procedures embedded in such a regulatory framework could foster ATES deployment (Stemmle et al. 2024a). For this, however, a concerted criteria catalogue that allows feasibility evaluation on a sound scientific basis is required. Thus, future research should further investigate the impacts of groundwater mixing and temperature changes on ecological conditions, drinking water security, and system operational performance. While already being considered to some extent in the current research, ATES operations in thermally altered and chemically contaminated urban areas requires greater research attention.

Another crucial aspect that only a few of the current research projects have investigated so far is the financial viability of ATES and its different application types. Future research therefore should also tackle techno-economic analyses by taking into account competing technologies and country-specific market conditions. Economic analyses are especially lacking for the application case of integrating ATES into DH grids in combination with different types of heat sources.

In general, a shortcoming of the current German ATES research is that there is very limited transfer of research findings and practical experience with ATES from other countries, such as the Netherlands and Belgium. It is therefore highly desirable that future research projects actively engage with numerous contacts existing within the international scientific community and a network of stakeholders to build on the pre-existing knowledge and practical experience from our neighboring countries. A notable exception in this respect is the PUSH-IT project (cf. Table 1), which is being carried out by an international consortium with project partners from the Czech Republic, Germany, the Netherlands and the UK.

Conclusion

This paper presents 13 research sites, comprising ATES (11 sites) and MTES (2 sites) systems. Extensive research in Germany shows a progressively growing awareness of the importance of thermal energy storage applications for a decarbonized heating and cooling sector. The current research landscape reveals a diverse field of investigations spanning various spatial scales, research objectives, and methodologies. Despite these various activities, the predominant focus remains on early-stage research with a low TRL, primarily around 3 to 4. A significant emphasis in research is on HT-ATES and the integration of ATES into DH grids, which can increase the share of renewable and waste heat sources in heating grids. However, challenges remain, particularly in designing robust systems capable of adapting to long-term energy demand and dynamic availability, as highlighted by research activities in Kiel, Berlin, Mannheim, Offenbach, and the greater Munich area.

The findings from this review of current ATES research reveal several critical needs for the future. A decisive step is the shift from feasibility studies and early-stage simulations to the actual implementation of ATES systems, supported by research funding for real and long-term demonstration plants. A criteria catalogue could help to identify key ATES locations across Germany with suitable subsurface conditions and significant energy demand. The demonstration and operation of ATES systems can significantly raise awareness and showcase the benefits of the ATES technology.

Regulatory challenges such as complex and heterogeneous permit procedures hamper the broader deployment of ATES in Germany. Nevertheless, successful cases like the high-temperature injection test at the Science Park in Leipzig demonstrate that HT-ATES is permissible under certain conditions. These experiences underline the need for a streamlined and research-based regulatory framework that addresses environmental risks, ensures installation quality, and promotes efficient permit procedures.

Finally, beyond the importance of ongoing research on ATES and MTES in Germany, a technological progress is required to lead the way from theoretical and early-stage investigations to practical, real-world applications. By addressing regulatory, financial, and technological challenges in such implementation-oriented projects, future research projects can play a decisive role in fostering the spread of ATES and MTES as a contribution contributing to Germany's transition to sustainable energy systems.

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