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# D1.1.4 Proof-of-concept study on reuse of abandoned wells for Aquifer Thermal Energy Storage (ATES) development

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# Executive Summary

Aquifer Thermal Energy Storage (ATES) is a potential solution for seasonal heat storage, though it is currently uneconomical compared to hydrothermal energy. The process involves assessing existing wells and potentially modifying them (e.g. side-tracking, deepening or perforating) to facilitate the storage of excess heat, typically in the form of hot water collected in summer, for retrieval and use during winter heating seasons. Successful implementation hinges on specific geological conditions: high-permeability reservoirs with suitable temperatures and minimal groundwater flow are crucial. While shallow ATES systems (less than 400 metres deep) offer lower drilling costs, accessing target aquifers from deep wells can be difficult. Currently, high-temperature (>90°C) systems in deeper wells (>400 m) are the most viable option. However, practical, full-scale ATES reuse projects are non-existent and only exist as pilot tests. These projects are susceptible to scaling and corrosion risks. Further research and development are needed to overcome economic and technical challenges before ATES can be adopted more widely.

*The TRANSGEO project (https://www.interreg-central.eu/projects/transgeo/) is co-funded by the European Regional Development Fund through the Interreg Central Europe program. The overall objective of TRANSGEO is to investigate the potential to transform abandoned hydrocarbon wells into new sources of green geothermal energy. To reach this goal, the TRANSGEO team is providing new tools and knowledge to support communities and industries in the energy transition and to break down economic and technical barriers to well reuse.*

# A. Description of technology

In Aquifer Thermal Energy Storage (ATES) systems excess heat or chill is stored in the subsurface in a suitable aquifer via wellbores. The stored heat or chill is produced back when needed. This technology provides an environmentally friendly alternative to conventional greenhouse gas emitting fossil fuel supplied systems for building heating and cooling (Lerm et al., 2011) and is one of the few technologies to store large amounts of energy. ATES systems are considered as open systems where the naturally occurring groundwater is used as heat storage and transfer medium. The high (or low) temperature water is stored in a water-saturated confined aquifer that lies between two aquitards. This system typically has hot and cold wells that have both production and injection functions at each location, typically known as doublet systems. The energy stored in the aquifer and pumped back to the surface is then transferred through a heat exchanger at the surface to a secondary working fluid to allow direct use for both heating and cooling of a surface facility as shown in Figure A.1 (Lee, 2013).

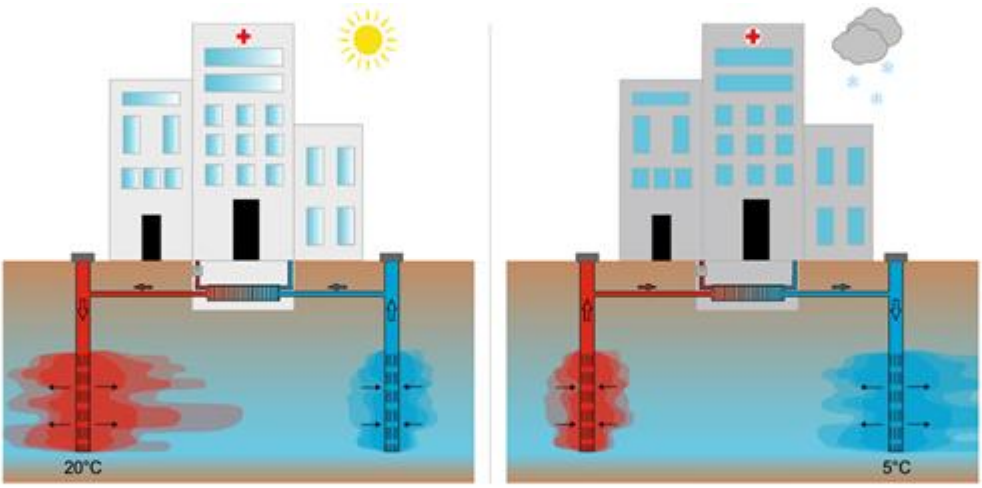


**Figure A.1: Operational principle of an ATES system in summer (left) and winter (right) including the current temperature threshold for low temperature (LT) ATES in Germany (modified from Schüppler, 2019).**

ATES works on a seasonal basis. In the summer, cold water is extracted from an aquifer through the cold well(s), for example to cool down buildings. This process heats up the fluid, which is then re-injected into the same or another aquifer through the warm well(s). In the winter, the process is reversed and warm water is withdrawn through the warm well(s) for heating, which cools down the fluid, which is then reinjected through the cold well (Duijff, 2021; Lu et al., 2019; Sommer, 2015). Thus, ATES requires drilling at least two wells into an aquifer to circulate water between storage areas, or reusing and modifying existing wells that access an aquifer. The wells are separated by a critical distance to ensure that the warm and cold storage remain separate and that thermal breakthrough does not occur within one season (Lee, 2010). Multi-well configurations have been employed where large volumes of water are required and where individual well yields are too low to meet the demand. One of the largest ATES systems in Europe, located at Eindhoven University of Technology in the Netherlands, consists of more than 30 groundwater wells ranging in depth from 20 to 80 meters (Sommer, 2015). Single-well applications referred to as mono-well systems have also been employed using vertical separation of hot and cold groundwater where multiple aquifers exist. In this case, both hot and cold water are injected through the same well, but into different aquifers (Blöcher et al., 2024).

# B. Lessons learned

## B.1 Result of generic modelling of reference site Berlin-Spandau site, Germany

As studied by Liu (2025), by conducting a numerical simulation and the sensitivity analysis using a data set from the Berlin-Spandau project, where the suitability of (re)use of existing wells of a former gas storage site for future ATES use was investigated (Blöcher et al., 2023), the key finding and implication are as follows:

### B.1.1 Permeability as the dominant hydrogeological parameter

The sensitivity analysis confirmed that aquifer permeability exerts the strongest influence on the productivity and injectivity of ATES systems. In the investigated Muschelkalk formation, the anisotropic permeability distribution – characteristic of carbonate rocks – directly impacts fluid flow efficiency. The high permeability of the upper and lower porous layers (500 mD in the base case) is essential for ensuring sufficient groundwater circulation rates, which are critical for balancing seasonal energy storage and extraction. However, the heterogeneous nature of carbonate matrices, with interbedded low-permeability micritic layers, introduces risks of preferential flow paths and thermal dispersion. This heterogeneity necessitates detailed site-specific characterization to avoid underperformance, particularly in long-term operations.

The dominance of permeability also underscores the importance of repurposing existing wells with proven hydraulic access to high-permeability zones. For instance, at the Berlin-Spandau site wells BH2 and BH3, despite their age, demonstrated adequate productivity (0.5–1.2 L/s/bar), validating their potential for reuse. However, the limited thickness of perforated intervals (7–17 m) in these wells suggests that future ATES designs in similar settings should prioritize maximizing contact with porous layers through strategic well completion or multi-well configurations.

### B.1.2 Temperature management and system efficiency

Injection temperature emerged as the most significant operational parameter affecting heat recovery efficiency. The base case simulation, with 60°C hot water injection and 16°C cold water injection, achieved a heat recovery factor (HRF) of 80% over 20 years. This aligns with efficiencies reported in Dutch LT-ATES systems but falls short of HT-ATES benchmarks (85–90%). This difference stems from higher thermal losses in deeper, fractured carbonate aquifers compared to unconsolidated sand/gravel systems. The sensitivity of the heat recovery factor to injection temperature highlights a critical trade-off: while higher temperatures improve energy density, they also raise risks of geochemical reactions (e.g., mineral dissolution/precipitation) and buoyancy-driven thermal plumes. In the Muschelkalk, where brine salinity exceeds 100 g/L, elevated temperatures could accelerate scaling or corrosion in wellbores, as observed in Germany's Rostock HT-ATES system (Fleuchaus et al., 2021). Thus, operational strategies must balance temperature thresholds with material durability and system efficiency.

### B.1.3 Long-term viability in carbonate aquifers

The 20-year simulation demonstrated stable thermal performance, with no significant decline in productivity or recovery rates. This suggests that carbonate aquifers, despite their complexity, can support long-term ATES operations if managed appropriately. However, the model's assumption of a single-porosity system underestimates the impact of fractures and karst features on heat dispersion. Field data from the Spandau site indicated minor fracture influence, but regions with higher fracturing (e.g., the Schaumkalk facies) may require dual-permeability models to capture short-circuiting risks.

Furthermore, the cyclic thermal loading imposed minimal mechanical stress on the reservoir in simulations. Yet, real-world applications must account for thermo-hydro-mechanical-chemical (THMC) coupling, particularly in evaporite-rich Middle Muschelkalk layers, where thermal expansion could reactivate faults or compromise well integrity (Liu, 2025).

## B.2 Strategic recommendations for ATES deployment based on reference site Spandau

For further recommendation on the ATES deployment, based on Liu (2025), the following conditions are required for a successful ATES system deployment.

### B.2.1 Site selection and well design optimization

- Prioritise high-permeability zones: targeting the upper and lower porous layers of the Muschelkalk (UPL/LPL) preferentially can enhance flow rates. Geophysical surveys combined with hydraulic testing should guide the additional well companion to the intended well for reuse.
- Adaptive well completions: Mono-well systems may be sufficient for small-scale applications, but multi-well layouts are advisable for urban areas. Extending perforation intervals and using corrosion-resistant materials can improve longevity.
- Monitoring Protocols: Standardized real-time monitoring of temperature, pressure, and water quality (e.g., iron/manganese levels) is essential to detect clogging or leakage early. The Fasanenstraße site's DTS (distributed temperature sensing) system offers a replicable model for this.

### B.2.3 Mitigating technical risks

- Geochemical Stability: Pre-injection water treatment (e.g., deaeration, pH adjustment) can minimize scaling and microbial activity. For HT-ATES, silica scaling risks necessitate periodic well stimulation or chemical inhibitors.
- Thermal Breakthrough Prevention: Maintaining well spacing >200 m, as modeled in the base case, effectively delays thermal interference. However, dynamic simulation tools should inform adaptive management in denser urban layouts.
- Climate Resilience: Berlin's climate provides balanced heating/cooling demand, but rising ambient temperatures may compromise balanced seasonal cycles. Incorporating climate projections into system design ensures adaptability.

## B.3 Conclusion on the workflow validation based on feasibility study at the reference region Lausitz

### B.3.1 Well reuse potential for ATES

Initial efforts focused on repurposing existing infrastructure for Aquifer Thermal Energy Storage (ATES). ATES requires well locations near both the district heating network and a heat source - such as excess heat, waste heat, or district heating return flow – as well as wells with a minimum 7-inch diameter and demonstrated integrity. The TRANSGEO well selection tool (Figure B.1, accessible at https://transgeo.eu ) was used to identify potentially suitable existing wells apart from the manual selection based on the well data owned by LBGR. Table B.1 details the potential of well reuse for ATES technology (green color wells) within the Lausitz area in Brandenburg. **Figure B.1** shows that there are no suitable ATES wells, specifically the wells that are younger than 30 years (from today). Most of the wells are older than 30 years as listed in Table B.1. Based on the availability of data from the TRANSGEO database and manual assessment, we concluded that the wells drilled between 1879 and 1986 are not viable for reuse. Therefore, developing ATES in this region necessitates drilling new wells, informed by existing subsurface data from these legacy wells.

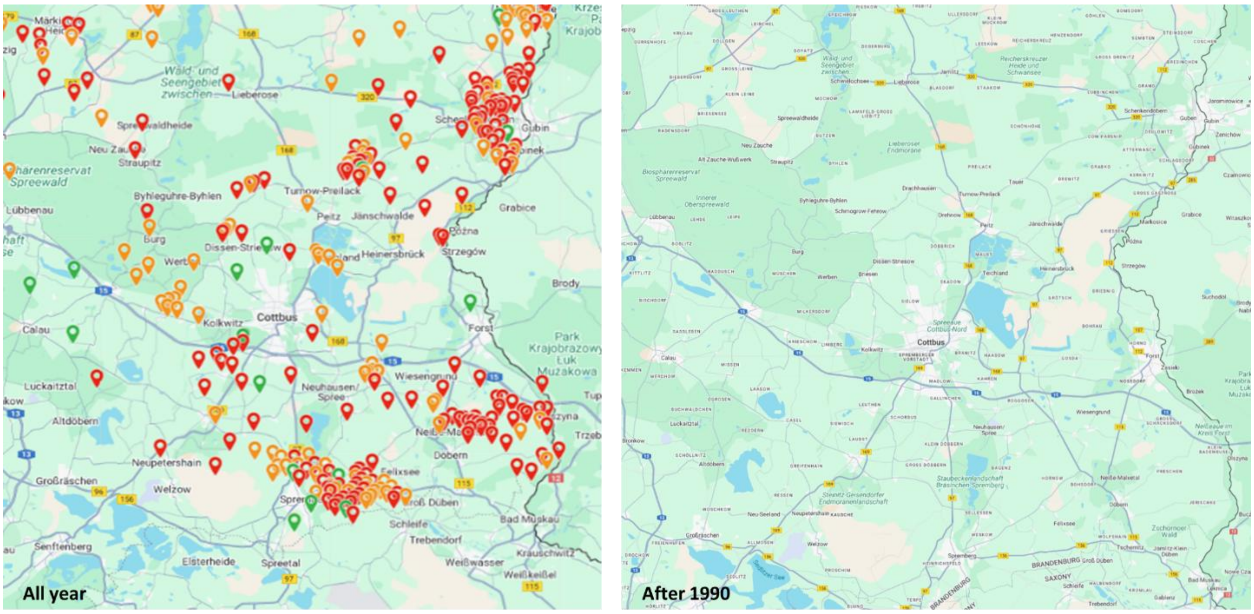


**Figure B.1: Advance existing well assessment for the ATES technology using the well selection tool developed in the TRANSGEO project. (https://transgeo.eu).**

**Table B.1 ATES potential wells determined from the well selection tool (https://transgeo.eu).**

| **Well name** | Drilling year | Type of the well | Depth (m) |
|---|---|---|---|
| Brk Klba 1986/67 | 1986 | coal exploration well | 851 |
| Kb Hä/17 | 1979 | exploration well | 851 |
| E Laz 103E/62 | 1962 | hydrocarbon well | 780 |
| Kb Forst 1/61 | 1961 | exploration well | 501 |
| Kb Werben 1/61 | 1961 | exploration well | 494 |
| Kb Guben 1/61 | 1960 | exploration well | 501 |
| Cu Sp 73/60 | 1960 | mining well | 957 |
| Cu Sp 64E/59 | 1959 | mining well | 890 |
| Brk Hä 3/1879 | 1879 | coal exploration well | 851 |

A field survey was carried out in early 2024 to assess the condition of surface infrastructure under the responsibility of the State Office for Mining, Geology and Raw Materials (LBGR). The primary objective was to compile a comprehensive inventory of existing wells in Brandenburg and specifically in the Lausitz region, with a focus on identifying which—if any—remain structurally suitable for potential repurposing. However, as observed during the survey, many of the wells are still open and not legally plugged and abandoned, with surface conditions such as those illustrated in Figures B.2 (a) and (b). But reusing the well is still not possible. All other wells are not visible on the surface anymore. These findings highlight the challenges of reusing legacy infrastructure and underscore the need for targeted new development in areas with favorable geological and logistical conditions by means as close as possible to the existing district heating or heat source location. Figure B.3, by contrast, presents an example of a well that was recently abandoned and that is owned by a private oil and gas company, illustrating the continued presence of subsurface infrastructure that remains subject to commercial control. This example serves as a counterpart to the publicly managed infrastructure assessed in the field survey and reflects the varying degrees of accessibility and regulatory oversight across different well types in the region.


**Figure B.2: Rests of (a) old copper well and hydrocarbon well (b) in the Lausitz region. Source: LBGR field survey, 2025.**

**Figure B.3: A recently abandoned hydrocarbon well, located in the north of the Lausitz region, remains under the ownership of a private sector entity. Source: LBGR field survey, 2025.**

# C. Requirements to reuse hydrocarbon wells as Aquifer Thermal Energy Storage (ATES)

Any ATES application requires a sound knowledge of target-aquifer properties (Andersson (2007)), including geometry (areal extent, thickness), stratigraphy, static head, natural groundwater gradient, hydraulic conductivity, transmissivity, storage coefficient, leakage factor, and boundary conditions. The first group is typically derived from topographic, geological and hydrogeological maps, existing wells and prior site investigations; the latter from geophysics, pumping tests and related field data. Groundwater chemistry and natural groundwater temperature are also essential inputs (Bridger and Allen, 2005). This report examines the essential parameters necessary for ATES systems, organized into key categories that influence system performance and viability.

## C.1 Reservoir depth and temperature

Table C.1 presents the classification of ATES systems in the Netherlands according to temperature range and aquifer depth. The categorization is based on Van Helden (2024), which provides an overview of thermal energy storage technologies.

**Table C.1. Classification of ATES systems in the Netherlands according to temperature range (Van Helden, 2024).**

| Type | Temperature range | Depth (from source) | Notes |
|---|---|---|---|
| LT-ATES (WKO) | ~5 - 30 °C | Not specified | Most widely applied system in NL (low-temperature storage, heating/cooling of buildings). |
| MT-ATES | Up to ~60 °C | Not specified | Newer development; already applied on the market. |
| HT-ATES | Up to ~90 °C | ≥ 300 m (deeper aquifers) | Full-scale demonstrations in recent years; higher storage temp = deeper aquifers. |

## C.2 Aquifer type and lithology

The physical makeup of the aquifer (e.g., aquifer rocks and depth, aerial extent, fracture developing degree, and watery thickness of permeability) are significant factors in the application of ATES. Most ATES systems use unconsolidated aquifers as storage media. Nonetheless, highly fractured and unfractured aquifers can also be used for ATES. However, layering, fissures, fractures, heterogeneity, and faults negatively affect the thermal efficiency of ATES systems. As an example, preferential flow paths with extreme lateral loss of thermal energy easily arise through exchange with the aquifer blocks in-between fissures, fractures, and faults. These aspects result in potentially poorer performance of ATES in complex hydrological structures. Nonetheless, major groundwater basins (e.g., sand and inter-granular aquifers) and gravel aquifers are suitable for ATES application (Lu et al., 2019).

## C.3 Hydraulic properties

### C.3.1 Hydraulic conductivity and transmissivity

The most important properties for ATES application include hydraulic conductivity (permeability), transmissivity (permeability × thickness), storage coefficient (yield as a function of volume), and leakage factor (vertical leakage to the aquifer). These may contain geophysical data as well as pumping tests and so forth.

ATES requires hydraulic conductivity > **$10^{-5}$ m/s** to ensure water exchange between the aquifer and the well (Schmidt et al., 2003). The sensitivity of LCOH to transmissivity is considerable because of the wide range (i.e., many orders of magnitude) over which transmissivity varies in nature. Therefore, transmissivity is a key property in determining the economic success of HT-ATES. The minimum economically viable transmissivity (MEVT) can be approximated as $5{\cdot}10^{-13}$ $m^3$. This approximation is possible because the MEVT is relatively insensitive to depth, reservoir thickness, and faulting regime. The MEVT is perhaps the most useful result for HT-ATES pre-assessment and can facilitate global estimates of HT-ATES potential (Birdsell et al., 2015).

Heat transfer within an aquifer is primarily controlled by its thermal properties, namely the volumetric heat capacity and effective thermal conductivity. The heat capacity defines the temperature change resulting from energy absorption or release, while thermal conductivity reflects the ability of the aquifer medium to transmit heat. Because water possesses a higher heat capacity but a lower thermal conductivity than rock, aquifers with high porosity are most suitable for thermal energy storage, as they reduce conductive heat losses and enhance storage efficiency (Lee, 2013).

### C.3.2 Groundwater flow effects

Ghaebi et al. (2015) conducted a parametric study on pressure distribution in confined aquifers used for seasonal thermal energy storage. The research examined the influence of natural groundwater flow, porosity, permeability, injection and withdrawal rates, as well as the number and spatial arrangement of wells (linear, triangular, rectangular). The main findings can be summarized as follows:

- By increasing the natural flow of ground water, pressure in the aquifer increases
- An increase of porosity leads to lowering of the pressure loss
- As permeability increases, the pressure loss in the aquifer decreases
- As injection/withdraw rates increase, the pressure loss increases
- When the number of wells increases, while the total injection/withdraw rates remain unchanged, the pressure loss increases
- The pressure losses in the linear three-well and five-well arrangements are higher than when the arrangements are triangular and rectangular

The lower the reservoir pressure, the deeper the static/pumping water level, which necessitates the use of electric submersible pumps (ESPs) to achieve higher production rates (Hörbrand et al., 2023).

## C.4 Reservoir thickness and geometry

Doughty et al. (1981) claim that the shape of the heated volume should be as compact as possible to minimize the heat loss. The recovery factor has a rather flat maximum when the radius of the heated volume is about 2/3 of the aquifer thickness.

According to Beernink et al. (2024), both analytical and numerical results indicate that storage performance in ATES systems is strongly influenced by the geometry of the storage volume. In particular, the ratio of well screen length to the thermal radius (L/Rth) and the ratio of storage surface area to storage volume (A/V) were identified as key parameters for evaluating and improving storage design. Results show that heat losses (10–80% after five years) arise from a combination of conduction, dispersion, and buoyancy-driven flow, with their relative contribution depending on aquifer properties and storage geometry. For conduction-dominated systems, an intermediate geometry (L/Rth ≈ 2) minimizes the A/V ratio and thus heat losses, providing a stable design compromise. In contrast, when buoyancy effects are significant (e.g., ground water flux (q0) > 0.05 m/d), lower ratios (L/Rth < 1) help reduce tilting losses. Conversely, higher ratios (L/Rth ≈ 4) can be favorable only if buoyancy risks are well controlled (Figure C.1 and Table C.2).

**Table C.2. Classification of ATES systems in the Netherlands according to temperature range (Van Helden, 2024)**

| L/Rth ratio | Geometry | Conduction | Dispersion | Buoyancy-driven flow | Design implication |
|---|---|---|---|---|---|
| < 1 | Thin aquifer relative to thermal radius | ↑ High (A/V too large) | Low | Reduced (thermal front far from well) | Not optimal - conduction dominates and losses increase |
| ≈ 2 | Intermediate geometry | ↓ Lowest (optimal A/V) | Low | Moderate | **Best compromise** - minimizes conduction, stable design |
| ≈ 4 | Thick aquifer relative to thermal radius | Moderate | Low | Can increase (if T high, K high) | Good if buoyancy risk is controlled, but not always optimal |

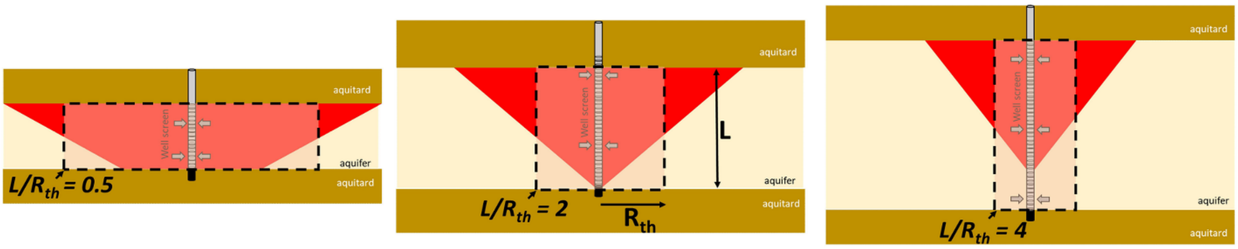


**Figure C.1: Schematic representation of different storage geometries for ATES systems at L/Rth (ratio of well screen length to the thermal radius) of 0.5, 2, and 4, illustrating the relation between aquifer thickness and thermal radius and the corresponding implications for conduction, dispersion, and buoyancy-driven flow (after Beernink et al., 2024).**

## C.5 Well configuration and spacing

**According to Birdsell et al. (2021),** the optimal spacing between hot and cold wells for HT-ATES is L/Rth ≈ 1.8 . This value lies within the commonly recommended LT-ATES range (about one to > three thermal radii) but toward its lower end, and is expected to maintain high thermal efficiency with limited thermal breakthrough, pending confirmation with coupled hydro-thermal modelling. Birdsell et al. argue that tighter spacing is plausible for HT-ATES because breakthrough at the cold well primarily degrades LT cooling performance, whereas HT-ATES is used solely for heating. They also note the contrast with the ~3.5 $R_{th}$ spacing reported **by** Gao et al. (2018) (as cited therein), **which** likely reflects different modelling assumptions (Birdsell et al., 2021) neglect advective heat loss (appropriate for low-permeability reservoirs), while Gao et al. (2018) explore higher permeabilities and place the hot well downstream of the cold well under ambient flow, which accelerates breakthrough.

Kowalczyk and Havinga (1991) showed that optimal well spacing depends on the storage type (heat, cold, or combined) and injection temperatures. If injection occurs on both sides of the natural groundwater temperature, the thermal radii of warm and cold wells should not overlap, requiring spacing larger than three times Rth. In other cases, a spacing of about 1–2 Rth is sufficient. Thermal breakthrough also depends on regional groundwater flow, its direction relative to the wells and possible preferential flow paths.

Two analytical approaches can be applied to estimate well spacing and thermal interactions in aquifer systems: Davis and DeWeist (1966) and Gringarten and Sauty (1975). Their main characteristics are summarized in Table C.3.

**Table C.3. Analytical solutions to estimate well spacing and thermal interactions in aquifer systems (after Merce et al., 1981).**

| Reference | Problem | Major Assumptions | Usage |
|---|---|---|---|
| Davis and DeWeist (1966) | Steady groundwater flow among wells | Uniform hydrologic properties; porous medium | Evaluating well spacing and patterns; determining groundwater flow fields for heat transport |
| Gringarten and Sauty (1975) | Heat flow between well doublet | Convection in receiving formation; conductive heat loss to confining units; two wells | Estimating well spacing; predicting production temperatures after breakthrough |

## C.6 Water chemistry

According to Jenne et al. (1992), most hydro-chemical related clogging and corrosion issues in ATES systems can be anticipated and mitigated through proper design, construction, and operation if a thorough pre-investigation is performed. Table C.4 summarizes the main clogging mechanisms, their conditions, effects, and corresponding preventive or remedial measures.

**Table C.4. Overview of clogging types in ATES wells, including their main causes, effects on well performance, and common mitigation measures (after Jenne et al. (1992)).**

| Type | Conditions / Parameters | Effects | Solutions / Measures |
|---|---|---|---|
| Physical clogging | Fine particles < 0.002 mm (clay/silt); high pumping rates → mobilization; insufficient gravel pack | Reduced yield, higher drawdown | Proper gravel pack sizing, step-drawdown tests, regular redevelopment (air-lift, surging) |
| Biological clogging | Growth of Fe/Mn bacteria; organic matter;<br>Temp: 10-25 °C ideal for bacteria; stagnant zones; nutrients (C, N, P) | Biofilm growth, slimy deposits in filter and gravel pack | Chlorination (50-200 mg/L), biocides, periodic shock treatment, brushing, air-lift |
| Chemical clogging (Scaling) | Fe > 0.2-0.3 mg/L (oxidizes → $Fe(OH)_3$ precipitate)<br>Mn > 0.05 mg/L<br>$CaCO_3$ precipitation at pH > 7.5 and T > 20 °C<br>Sulfate-rich water (gypsum precipitation) | Precipitates clog pores and filter slots | Acidization (HCl 5-10%), mechanical + chemical cleaning, oxygen control, inhibitors |

| | | | |
|---|---|---|---|
| Corrosion-related clogging | Oxygen entry in wells with steel casing; Fe/Mn bacteria accelerate; electrochemical corrosion | Rust products and oxides clog filter and pipes | Corrosion-resistant materials (PVC, stainless steel), cathodic protection, protective coatings |
| Colmatage of gravel pack | Hydraulic gradients cause fine particles to enter gravel pack; improper grain-size selection | Entrance resistance increases | Correct filter/gravel size ratio (d15/d85), sufficient well development after drilling |

## C.7 Conclusions

Defining an ideal aquifer for ATES is challenging because numerous physical factors must be considered. For instance, while a thinner aquifer may help reduce tilting of the thermal front, it is also likely to experience greater heat losses. Table C.5 summarizes key characteristics of ATES-suitable sites, highlighting both favorable and unfavorable conditions. Regardless of other factors, a low natural groundwater gradient is generally advantageous (Mercer et al. 1981).

In addition to general site characteristics, practical design and operational ranges for ATES systems have also been reported. The EU Commission SAVE Programme and Nordic Energy Research (2004) provide a comprehensive overview of typical system parameters (Table C.6), including flow rates, borehole dimensions, aquifer transmissivity, and storage costs. These values serve as reference points for system planning and performance evaluation.

Furthermore, site-specific prerequisites vary depending on the project scale. As summarized in Table C.7, small projects generally require shallower aquifers with moderate transmissivity, whereas large-scale systems necessitate deeper aquifers, thicker confining layers, and stricter monitoring of natural groundwater flow. This highlights that ATES feasibility is not defined by a single parameter but by a balance of geological, hydrological, and technical conditions.

**Table C.5. Desirable Characteristics of an ATES Project and Corresponding Favorable and Unfavorable Aquifer Conditions (after Mercer et al. 1981)**

| Desired Character | Favorable Condition | Unfavorable Condition |
|---|---|---|
| Lack of thermal tilting | Thin aquifer; low vertical permeability; moderate horizontal permeability | Thick aquifer; high vertical permeability |
| Low heat loss to confining beds | Thick aquifer | Thin aquifer |
| Low pumping and injection costs | High horizontal permeability | Low horizontal permeability |
| Rapid heat exchange between fluid/rock | High porosity; fine grains; homogeneous conditions | Heterogeneous conditions |
| Low heat loss to surface | Deep confined aquifer | Shallow water-table aquifer |
| Minimum thermal dispersion | Homogeneous aquifer | Highly heterogeneous aquifer |
| Lack of regional flow | Low regional hydraulic head gradient (i.e., low pore water velocity) | High regional hydraulic head gradient (i.e., high pore water velocity) |

**Table C.6. Typical values of ATES system for heat storage application (from EU Commission SAVE Programme and Nordic Energy Research 2004).**

| Parameter | Typical value / range |
|---|---|
| Flow pumped per well ($m^3/h$) | 10-100 |
| Capacity per well at 25 $m^3/h$ and $\Delta T$ = 30 K (kW) | 870 |
| Flow re-infiltration per well ($m^3/h$) | 10-75 |
| Min./max. re-infiltration temperature (°C) | 3/80 |
| Borehole diameter (mm) | 200-600 |
| Transmissivity of aquifer ($m^2/s$) | $10^{-3}$ to $10^{-4}$ |
| Borehole depth (m) | 10-300 |
| Typical total cost of ATES storage (€/kW) | 100-200 |

Table C.7. Site-specific prerequisites for ATES systems (from EU Commission SAVE Programme and Nordic Energy Research 2004).

| Parameter | Small project (25 $m^3/h$) | Big project (500 $m^3/h$) |
|---|---|---|
| Thickness of confining layer | d > 5 m | d > 20 m |
| Thickness of aquifer | D > 10 m | D = 50-100 m |
| Transmissivity | $T > 5 \times 10^{-4}$ $m^2/s$ | $T = 1 \times 10^{-2}$ to $3 \times 10^{-2}$ $m^2/s$ |
| Natural groundwater flow | v < 3 cm/d | v < 11 cm/d |
| Danger of ground depression | Not relevant | Prefer deep aquifer |

# D. Workflow to reuse hydrocarbon wells for Aquifer Thermal Energy Storage

The workflow of ATES from the reuse case as described in this study is mainly adopted from the Spandau project (Blöcher et al., 2023) and best practice of ATES well development from the literature review. Considering the location of hydrocarbon wells are already within the radius of the district heating and potential geothermal gradients are known, the workflow is summarised as follows.

## D.1. Well investigation

The objective is to provide optimum access to the depth of the target reservoir for storage. This includes the investigation of well integrity including the condition of the casing. The hydraulic access as well as the hydrogeological characteristics of the target reservoir are then tested with appropriate hydraulics as part of the evaluation of the suitability of the reservoir for ATES implementation. The well investigation is also typically by logging such as pressure, temperature and calliper tests.

## D.2. Well workover operation

Permits are required for any workover operation. As in the case of the Spandau project, permits are required to perforate at the interval depth of the target reservoir and to conduct hydraulic testing in the reservoir section. In the case of Germany, at least 4 permits are required for well completion and hydraulic testing:

- Special operating plan for the recompletion of wells
- General operating plan and hydraulic test
- Application for a commercial geothermal exploration permit
- Water law permit to conduct hydraulic tests

Perforation is particularly necessary if the potential reservoir is completely or partially backfilled with cement. This workover operation also includes the installation of downhole instruments such as DTS (Distributed Temperature Sensing) at the reservoir depth in preparation of the hydraulic tests. For this purpose, a fiber optic (FO) sensor cable can temporarily be installed using a winch. The temperature distribution along the borehole is then recorded using DTS technology. The sensor cable can also be used to insert a UGS depth gauge into the borehole to record pressure and temperature at the reservoir level. Distributed Acoustic Sensing (DAS) measurements can also be taken using the sensor cable. The DTS and DAS measurements were taken continuously over a period of the nitrogen lift test at the Berlin-Spandau site.

## D.3. Performing hydraulic tests and downhole sampling

The following hydraulic tests can be carried out to evaluate the reservoir and well parameters. Depending on the availability of well data and the additional information required to conduct a feasibility study, it is recommended that these series of tests be performed:

- **A nitrogen lift test (NLT) or short-term production test** with subsequent shut-in to determine the transmissivity and skin factor of the well, with DTS measurement and hydro-chemical and microbiological monitoring program. For this test, a surface facility as pump and surface tank were needed in the surface to accommodate the test and produced reservoir fluid. Simultaneously, temperature distribution along the borehole is then recorded using DTS technology. The sensor cable can also be used to insert a downhole gauge into the borehole to record pressure and temperature trends. Distributed Acoustic Sensing (DAS) measurements are also taken using the sensor cable. The DTS and DAS measurements were taken continuously over a period of the nitrogen lift test and after the list test to observe the pressure recovery after conducting the nitrogen lift test.

- **Step Rate Test (SRT)/ Slug Withdrawal test**. The purpose is to determine a reliable productivity index, steady state conditions. The transmissivity and storativity can be derived from the SRT tests. Both SRT and SWT can be used to determine the change in aquifer properties caused by hot water injection and change in storativity by conducting the same test procedure.
- **Push-Pull Tests (PPT) with tracers**: The purpose of this test is to analyse the longitudinal dispersion, natural groundwater velocity, and to obtain the attenuation factor caused by cross-flow. Injecting the tracers together with hot water and monitoring the temperature with **Distributed temperature sensing** (DTS) can improve the performance of Push-pull tests (PPT).
- **Injection test (IT)** of the previously extracted thermal water to determine the injectivity index. During the short-term production tests temperature and conductivity measurements on surrounding groundwater measurement points are recommended to be performed. As ATES is an open system, the monitoring is important to assess any impact of production-injection operation to the surrounding formation.
- **Downhole sampling** to determine gas concentration for gas wells or oil content for oil wells. Downhole sampling can be carried out after removing the downhole instruments used during short-term production testing and performing the necessary logging to obtain a fluid sample from the target reservoir. The fluid sample can be subjected to chemical and microbiological characterization and contaminant analysis.
- The short-term test is designed to evaluate the reservoir behavior over a given period of time. Long-term production tests or long historical production-injection data are therefore recommended to gain an understanding of reservoir properties such as permeability, which is the most important parameter for ATES feasibility assessment. The lesson learned from Spandau is that 16 hours of hydraulic testing is not enough to provide subsurface information. History matching is difficult to achieve in a short period of flow testing. A minimum of 2 weeks to 1 month of continuous production testing is required to justify the feasibility of reservoir performance.

## D.4 Perform analytical and numerical modelling as a part of feasibility study

This step is important to evaluate the performance of the reservoir calibrated with the field measurement. The purpose is to evaluate an ideal operation parameter of the ATES system based on the given condition as observed during the short-term production test. This step will be followed by a feasibility study to plan the development of the ATES system. From this study, further well rehabilitation and modification can be designed to meet the required energy output required from the reservoir by implementing the ATES technology.

## D.5. Perform well modification and well completion or drilling a new ATES well as decided from the feasibility study

In ATES wells, depending on the size of the well, two strings can be installed in the same well to act as production and injection tubing. A single string can also be used in two different wells at different locations. ESP (Electric Submersible Pump), fiber optic/sensor cable for DTS and DAS measurement are the main elements for well completion. The completion of the ATES well, typically employ filters at the targeted reservoir depth interval. The bottom of the well, which is not exposed to the reservoir section, is usually filled with gravel or even cemented. For reference, the design of the ATES research well at Berlin Fasanenstrasse project is shown in Figure D.1 (Blöcher et al., 2024).

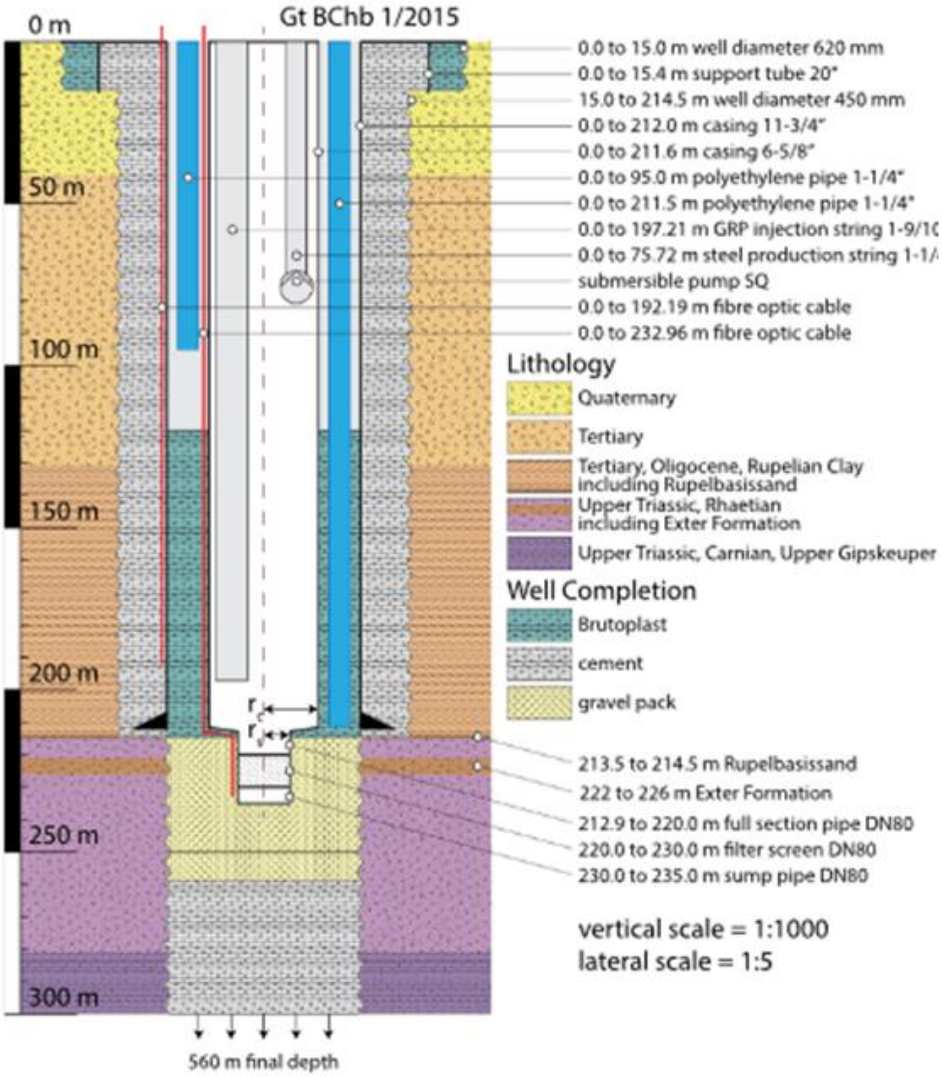


**Figure D.1: Typical ATES well completion as implemented in well Gt BChb 1/2015 (Blöcher et al., 2024).**

# E. Feasibility analysis

## E.1 Technical and economic feasibility

Based on the pre-feasibility analysis for the Lausitz region, opportunities to repurpose abandoned or existing wells for Aquifer Thermal Energy Storage (ATES) are limited. Field surveys conducted by the Landesamt für Bergbau, Geologie und Rohstoffe (LBGR) revealed that many abandoned wells are either not visible at the surface or are in poor condition, and private ownership adds complexity to access. Literature reviews for deliverables D 1.1.6 indicate that no ATES projects in the Brandenburg area have successfully converted hydrocarbon wells for ATES. While Berlin-Spandau served as a reference site demonstrating the potential for ATES well reuse, a significant challenge for ATES projects remains connecting the heat source (surface excess steam) to the district heating system and locating suitable areas for both warm and cold wells, often requiring new drilling. Although the Lausitz region, specifically the cities of Cottbus and Guben, boasts an established district heating network and proximity to potential heat sources and renewable energy grids, subsurface uncertainty remains a hurdle.

Despite this challenge, our feasibility analysis shifted focus to identifying potential locations for ATES, leveraging the Lausitz region's strategic advantages. Crucially, the proposed site benefits from its proximity to the Jänschwalde power plant and the Heating Power Plant Cottbus (HKW GmbH site) – significant heat sources for potential ATES integration. This proximity minimizes thermal losses during heat transfer, reducing system costs and maximizing efficiency. The existing district heating network in Cottbus (HKW GmbH site) provides a readily available thermal distribution infrastructure, eliminating the need for extensive and costly pipeline development, and initial assessments suggest sufficient capacity to accommodate the anticipated thermal output.

Supporting this infrastructural advantage is comprehensive analogue well data, including profiles from wells E Bres 3/89, E Gu 12h/64, E Tau 101/65, and E Lka 6/79. This data confirms the presence of economically viable aquifer formations – specifically the Rhaetian/Lias sandstone and Middle Buntsandstein – at depths suitable for efficient ATES operation. Regional analysis indicates favorable permeability and porosity characteristics, essential for high storage capacity and recovery rates, though site-specific evaluations are crucial as reservoir characteristics are not universally transferable. The proposed location falls within the LEAG master plan area, ensuring alignment with regional energy strategy and potential synergies with existing infrastructure.

Drilling the necessary doublet wells for ATES, in proximity to heating infrastructure and with sufficient storage volume, presents inherent uncertainties. Further exploration is required to reduce risk and build confidence. Recognizing this need, the Brandenburg Ministry of Economic Affairs has commissioned the Landesamt für Bergbau, Geologie und Rohstoffe (LBGR) to conduct an initial seismic survey of Lower Lusatia. The resulting data will provide a strong basis for planning for local authorities, industry, and project developers, ultimately reducing investment risks and paving the way for the feasible deployment of ATES. At this exploration stage, a definitive assessment of ATES economic viability remains premature.

## E.2 Legal feasibility

The shallow reservoir depths typically utilized by ATES systems are subject to stringent groundwater protection regulations. This overlap between energy storage and water protection interests can lead to rigid permitting processes and limited flexibility. Furthermore, securing permits for both land acquisition and drilling operations will likely be complex and present a significant challenge.

# F. References

Andersson, O. (2007). *Aquifer thermal energy storage*. In H. Ö. Paksoy (Ed.), *Thermal energy storage for sustainable energy consumption*. Springer, Dordrecht.

Beernink, S., Hartog, N., Vardon, P. J., & Bloemendal, M. (2024). Heat losses in ATES systems: The impact of processes, storage geometry and temperature. *Geothermics, 117,* 102889. https://doi.org/10.1016/j.geothermics.2023.102889.

Birdsell, D. T., Adams, B. M., & Saar, M. O. (2021). Minimum transmissivity and optimal well spacing and flow rate for high-temperature aquifer thermal energy storage. *Applied Energy, 289,* 116658.

Blöcher, G., Regenspurg, S., Kranz, S., Lipus, M., Pei, L., Norden, B., Reinsch, T., Henninges, J., Siemon, R., Orenczuk, D., Zeilfelder, S., Scheytt, T., Saadat, A. (2024) Best practices for characterization of High Temperature-Aquifer Thermal Energy Storage (HT-ATES) potential using well tests in Berlin (Germany) as an example. Geothermics 116, 102830.

Blöcher, G., Deon, F., Wenzlaff, C., Winterleiter, G., Regenspurg. S, Virchow, L. (2023) Abschlussbericht des Vorhabens Geothermische Nutzung der Karbonatgesteine im Norddeutschen Becken ATES iQ. Scientific Technical Report.

Bridger, D. W., & Allen, D. M. (2005). Designing aquifer thermal energy storage systems. *ASHRAE Journal, 47*(9), S32–S37.

Christi, L.F., Sieron, K., Weinert, S., Vogel, F., Höding, T., Kurevija, T., Macenić, M., Marojević, K., Frick, M.: Feasibility study for the pilot region Lausitz (North German Basin). Technical Report, Interreg-Central Europe, (2025c). URL: https://www.interreg-central.eu/wp-content/uploads/2026/01/2-3-7-Feasibility-study-Lausitz.pdf.

Doughty, C., Hellström, G., Tsang, C. F., & Claesson, J. (1981). *A study of ATES thermal behavior using a steady flow model* (Report No. LBL-11029; PNL-3924). Lawrence Berkeley Laboratory, University of California; Lund Institute of Technology.

Duijff, R., Bloemendal, M., Bakker, M. Interaction effects between Aquifer Thermal Energy Storage Systems. https://doi.org/ 10.1111/gwat.13163.

EU Commission SAVE Programme and Nordic Energy Research. (2004). *Pre-design guide for ground source cooling systems with thermal energy storage*. COWI A/S, Denmark.

Fleuchaus, P., Schüppler, S., Stemmle, R., Menberg, K., Blum, P. (2021) Aquiferspeicher in Deutschland. Grundwasser - Zeitschrift der Fachsektion Hydrogeologie (2021) 26:123-134.

Gao, L., hao, J., An, Q., Liu, X., & Du, Y. (2018). Thermal performance of medium-to high-temperature aquifer thermal energy storage systems. *Applied Thermal Engineering, 146,* 898-909. http://dx.doi.org/10.1016/j.applthermaleng.2018.09.104.

Ghaebi, H., Bahadori, M. N., & Saidi, M. H. (2015). Parametric study of the pressure distribution in a confined aquifer employed for seasonal thermal energy storage. *Scientia Iranica, 22*(1), 235-244.

Hofmann, H., Hölzel, M., Hoyer, S., Werkl, P., Brives, J., Christi, L.F., Liu, Y., Blöcher, G., Petrova, E., Kurevija, T., Perković, L., Macenić, M., Sedlar, D.K., Prkič, I.S.M., Sieron, K., Fedor, F., Castro, C.C., Szanyi, J., Kovács, J., Svetina, M. Engineering workflows for retrofitting abandoned wells. Technical Report (2025). Interreg-Central Europe. URL: https://www.interreg-central.eu/wp-content/uploads/2025/02/TRANSGEO-D1.1.6-Engineering-Workflows-FINAL-December 2024.pdf

Hörbrand, T., Mayr, M., Beichel, K., Lex, W., & Jahrfeld, T. (2023). VESTA Malm – high temperature ATES in the Malm reservoir of the greater Munich region. In *Der Geothermiekongress DGK 2023*, 17.-19.10.2023, Essen.

Jenne, E. A., Andersson, O., & Willemsen, A. (1992). Well, hydrology, and geochemistry problems encountered in ATES systems and their solutions (No. 929153). *SAE Technical Paper*.

Lee, K. S. (2010). A review on concepts, applications, and models of aquifer thermal energy storage systems. *Energies*, *3*(6), 1320-1334.

Lee, K. S. (2013). Heating and cooling of buildings with aquifer thermal energy storage: Design and applications. Springer, London. https://doi.org/10.1007/978-1-4471-4273-7.

Lerm, S., Alawi, M., Miethling-Graff, R., Wolfgramm, M. (2011) Influence of microbial process on the operation of a cold store in shallow aquifer: impact on well injectivity and filter lifetime, Grundwasser-Zeitschrift der Fachsektion Hydrogeologie, 16:93–104, http://doi.org/10.1007/s00767-011-0165-x.

Liu, Y. (2025). Evaluating the Potential Performance of Reusing Old Wells for Aquifer Thermal Energy Storage (ATES): A Numerical Simulation and Sensitivity Analysis Study, Master Thesis, Technische Universität Berlin, Germany.

Lu, H., Tian, P., He, Li. (2019) 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 (2019) 788–796.

Mathey, B. (1977). Development and resorption of a thermal disturbance in a phreatic aquifer with natural convection. *Journal of Hydrology, 34,* 315–333.

Mercer, J. W., Faust, C. R., Miller, W. J., & Pearson, F. J., Jr. (1981). *Review of simulation techniques for aquifer thermal energy storage (ATES)* (PNL-3924). Pacific Northwest Laboratory.

Molz, F. J., Parr, A. D., Andersen, P. F., Lucido, V. D., & Warman, J. C. (1979). Thermal energy storage in a confined aquifer: Experimental results. *Water Resources Research, 15*(6), 1509–1514.

Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2003, June). Seasonal thermal energy storage in Germany. In *ISES Solar World Congress* (Vol. 14, No. 19.06, p. 2003).

Schüppler, S., Fleuchaus, P., Blum, P. (2019) Techno-economic and environmental analysis of an Aquifer Thermal Energy Storage (ATES) in Germany. Geothermal Energy (2019) 7:11.

Sommer, Wijbrand. (2015) Modelling and monitoring of Aquifer Thermal Energy Storage- Impacts of heterogeneity, thermal interference and bioremediation. Dissertation.

Tsang, C. F., & Hopkins, D. L. (1982). Aquifer thermal energy storage: A survey. In T. N. Narasimhan (Ed.), *Recent trends in hydrogeology*.

van Helden, W. (2024, June 30). *Internationale assessment warmteopslag onderzoek en ontwikkeling: Toepassing in de gebouwde omgeving* [in Dutch] (Report No. TSE6230007). Renewable Heat B.V.

Werner, D., & Kley, W. (1977). Problems of heat storage in aquifers. *Journal of Hydrology, 34,* 35-43.

# G. APPENDIX

Table G.1 Reservoir and wellbore parameters required for ATES Technology

| Parameters | Unit | Max | Median | Min | Reference Site | Required parameters to reuse hydrocarbon well for ATES |
|---|---|---|---|---|---|---|
| **Reservoir Depth** | m | 1250 | 620 | 15 | **[Max]** Neubrandenburg, Germany<br>**[Median]** Spandau, Germany<br>**[Min]** Rostock, Germany | < 1000 |
| **Max** [Würdemann et al., 2014; Holstenkamp et al.,2017]<br>**Median** [Blöcher et al., 2023]<br>**Min** [Schmidt and Müller-Steinhagen, 2004] | | | | | | |
| **Reservoir Thickness** | m | > 170 | 30 | 4 | **[Max]** Reichstag-Berlin, Germany<br>**[Median]** Spandau, Germany<br>**[Min]** TU Berlin, Germany | > 5 |
| **Max** [Kabus and Seibt, 2000; Sanner and Knoblich, 2004]<br>**Median** [Blöcher et al., 2023]<br>**Min** [Saadat et al., 2016] | | | | | | |
| **Natural Fluid Velocity** | m/year | 25 | - | 3.65 | **[Max]** Minimum fluid velocity range in Netherlands<br>**[Min]** Reichstag-Berlin, Germany | < 3.65 |
| **Max** [Bloemendal, 2018]<br>**Min** [Kranz und Frick, 2013] | | | | | | |
| **Reservoir Temperature** | °C | 140 | 54 | 13.2 | **[Max]** Deepstore-KIT, Germany<br>**[Median]** Neubrandenburg, Germany<br>**[Min]** Adlershof-Berlin, Germany | < 100 |
| **Max** [Deepstore description, 2020]<br>**Median** [Würdemann et al.,2014]<br>**Min** [ Blöcher et al., 2018] | | | | | | |
| **Porosity** | % | 0.38 | 0.24 | 0.06 | **[Max]** Reichstag-Berlin, Germany<br>**[Median]** Spandau, Germany<br>**[Min]** Adlershof, Germany | > 0.1 |
| **Max** [Kabus et al.,2005]<br>**Median** [Blöcher et al., 2023]<br>**Min** [Blöcher et al., 2018] | | | | | | |
| **In-situ Permeability** | $m^2$ | $1 \times 10^{-10}$ | $1 \times 10^{-12}$ | $1 \times 10^{-13}$ | **[Max, Min]** Adlershof, Germany<br>**[Median]** TU Berlin, Germany | $> 1 \times 10^{-13}$ |
| **Max, Min** [Blöcher et al., 2023]<br>**Median** [Saadat et al., 2016] | | | | | | |
| **Flow rate** | L/s | 135 | 60 | 5 | **[Max]** Spandau, Germany<br>**[Median]** Reichstag-Berlin, Germany<br>**[Min]** TU Berlin | > 50 |
| **Max** [Blöcher et al., 2023]<br>**Median** [Kabus and Seibt, 2000]<br>**Min** [Saadat et al., 2016] | | | | | | |
| **Bottom-hole diameter** | inch | 13 3/8 | 9 5/8 | 2 | **[Max, Median]** Spandau, Germany<br>**[Min]** Kieh University Project, Germany | > 7 |
| **Max, Median** [Blöcher et al., 2023]<br>**Min** [Heldt et al., 2021] | | | | | | |
| **Productivity Index/ Injectivity Index** | L/s/MPa | 24.86 | 15 | 5 | **[Max]** Reichstag, Germany<br>**[Median]** Spandau, Germany<br>**[Min]** Spandau, Germany | > 10 |
| **Max** [Kabus et al., 2005]<br>**Median, Min** [Blöcher et al., 2023] | | | | | | |

Table G.2 Summary of literature review of ATES operating parameters (Hofmann et a., 2024).

| Parameters | Unit | Max | Median | Min | Reference Site |
|---|---|---|---|---|---|
| **Recovery Rate** | % | 93 | 89 | 72 | **[Max]** Reichstag-Berlin, Germany<br>**[Median]** Westland, Neatherland<br>**[Min]** Neubrandenburg |
| ATES Factsheet [Kleyböcker & Bloemendal., 2020] | | | | | |
| **Temperature (in)**<br>**Warm Borehole** | Celcius | 90 | 50 | 16 | **[Max]** TU Berlin, Germany<br>**[Median]** Rostock, Germany<br>**[Min]** Adlershof, Germany |
| **Max** [Holstenkamp et al., 2017]<br>**Median** [Schmidt et al., 2004]<br>**Min** [ Blöcher et al., 2018] | | | | | |
| **Temperature (out)**<br>**Warm Borehole** | Celcius | 90 | 50 | 25 | **[Max]** Spandau, Germany<br>**[Median]** Rostock, Germany<br>**[Min]** Lüneburg, Germany |
| **Max** [Blöcher et al., 2023]<br>**Median** [Schmidt et al.,2004]<br>**Min** [Holstenkamp et al., 2017] | | | | | |
| **Temperature (in)**<br>**Chill Borehole** | Celcius | 130 | 85 | 5 | **[Max]** BMW-Dingoflingen, Germany<br>**[Median]** Lüneburg, Germany<br>**[Min]** Reichstag-Berlin, Germany |
| **Max** [Ueckert et al. (2019), Holstenkamp et al., 2017]<br>**Median** [Holstenkamp et al., 2017]<br>**Min** [Kranz and Frick, 2013] | | | | | |
| **Temperature (out)**<br>**Chill Borehole** | Celcius | 25 | 10 | 5 | **[Max]** Lüneburg, Germany<br>**[Median]** Reichstag-Berlin, Germany<br>**[Min]** Spandau, Germany |
| **Max** [Holstenkamp et al., 2017]<br>**Median** [Kranz and Frick, 2013]<br>**Min** [Blöcher et al., 2022] | | | | | |