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Review

Insights into Aquifer and Borehole Thermal Energy Storage Systems for Slovenia's Energy Transition

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Abstract: Since the heating and cooling sectors consume most of the energy in Europe through fossil fuels, the transition to a low-carbon and sustainable energy system is crucial. Underground Thermal Energy Storage (UTES) systems, such as aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES), offer promising solutions by enabling seasonal storage of renewable thermal energy, balancing the mismatch between supply and demand. ATES and BTES systems store excess heat or cold for later use, making them suitable for large-scale applications like residual heat storage from industrial or power generation processes by offering flexibility in heating and cooling. This review explores the geological and hydrogeological requirements for ATES and BTES systems, pointing out the importance of basic geological knowledge, laboratory and field investigations, and operational monitoring to optimize their performance. The study highlights the need for Slovenia to use the experiences of other European nations to overcome initial challenges, develop effective site evaluation methods, and integrate these systems into existing energy infrastructure.

Keywords: underground thermal energy storage; seasonal heat storage; pilot BTES site; geothermal parameters; Slovenia

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1. Introduction

The heating and cooling sector presents an important part of the low-carbon and sustainable energy system transition. Heating and cooling consume half of all energy in Europe, and most of the demand (85%) is fulfilled with fossil fuels. Low-carbon heat sources, such as geothermal, biomass, solar, and waste heat, show alternatives to conventional heat sources. Heat storage is pivotal in this development, providing flexibility between supply and demand. Underground Thermal Energy Storage (UTES) represents a specter of techniques for seasonal storage of thermal energy in subsurface geological formations. This is a space-saving technique since it uses a geological medium beneath the built environment [1]. The selection of the optimal storage method depends on factors such as storage capacity, storage duration, and supply and demand temperatures. UTES is the preferred choice for long-term thermal energy storage because it is characterized by high storage efficiencies and capacities. Therefore, UTES systems should be developed and become an integral component of future energy system infrastructure.

Renewable thermal energy is usually available when the energy demand is low. Geothermal energy provides a base load, while solar and wind are changeable and depend on weather conditions. This mismatch can be balanced by seasonal energy storage in

Underground Thermal Energy Storage (UTES) systems. In this type of technology, heat is either injected for later use (heat storage) or extracted from the ground (cold storage), which is later used for cooling. There are various such technologies summarized by the acronym UTES: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), cavern thermal energy storage (CTES) [2], pit thermal energy storage (PTES) [3], mine thermal energy storage (MTES) [3], reservoir thermal energy storage (RTES) [4], and similar.

This paper focuses on ATES and BTES technologies as it was estimated that they are the most applicable types of UTES in Slovenia. ATES works as an open-loop system, where heat and cold are temporarily stored in the subsurface through injection and withdrawal of groundwater, while BTES is a closed-loop, which is more or less independent of the subsurface permeability [5]. Depending on storing temperature, both can be subdivided into low-temperature (LT < 30 °C), medium-temperature (MT 30–60 °C), and high-temperature (HT 60–90 °C) systems [5]. They can be used both for heating and cooling. ATES and BTES should be applied where there is a large need for short-term thermal storage, peak shifting, or seasonal storage. This requires a larger storage place, which underground structures can mainly provide. It is expected to be used as large-scale storage of residual heat from industry, waste incineration plants, power plants, or combined heat and power (CHP) plants. But to establish their profitable nature, it is necessary to have this residual heat or cold available for free or almost free. It can also be used in combination with district heating networks.

The main properties defining the suitability of ATES and BTES are thermal conductivity, heat capacity and hydraulic conductivity, and can be estimated by using geological maps and rock samples. In contrast, laboratory tests on samples like drill cuttings or cores yield more accurate values [6], as they account for local mineral composition, porosity, and other in situ conditions. The most valuable data can be obtained by field measurements such as the thermal response test (TRT) and distributed temperature sensing (DTS).

In this review paper, the geological requirements and technological settings of ATES and BTES are discussed. Their recovery efficiency, recommendations on monitoring systems, and several examples of each type are presented. As this is a novel and still poorly known technology in Slovenia, this paper also aims to provide a baseline and ideas for new investments, supporting the implementation of such technologies within the energy transition of the heating and cooling sector.

2. Aquifer Thermal Energy Storage (ATES)

Aquifer thermal energy storage (ATES) uses subsurface volumes to balance the availability and demand for thermal energy. The aquifer thermal energy system works on the principle of extracting water from the aquifer, which is heated or cooled before re-injecting it back into the same aquifer. Groundwater and sediment in which it is found serve as heat storage with much larger volumes than surface tanks or pits. The system usually requires a minimum of two wells, extracting and injecting one. They are preferably separated to avoid mixing warm and cold water [7].

The system can work in two ways: extracting from a warm well, then injecting into a cold well, and extracting from a cold well, and then injecting into a warm well (Figure 1). In winter, warm water is extracted from an aquifer through a warm well. Heat is being used, and therefore, water in a heat exchanger becomes cooled down and re-injected back into the aquifer through a cold well. This way, water and sediment around the cold well become colder. That low-temperature water is then used during summer for cooling. In that process, water becomes warmer and is re-injected into a warm well, heating the surroundings of the well. By continuously extracting and injecting warm/cold water, water in warm/cold wells becomes warmer/colder. Since the direction of water flow reverses twice a year, each well is equipped with an injection string and a production pump. ATES's bi-directional manner is an economical technology that uses summer heat in the winter and winter heat in the summer.

While HT-ATES (high-temperature aquifer thermal energy storage) systems require greater depths for storing heat as they work with higher temperatures and need to eliminate heat losses due to surface influence, LT-ATES (low-temperature aquifer thermal energy storage) can work in shallower aquifers. This makes it more cost-effective compared to HT-ATES because of lower drilling costs and larger storage capacity due to the greater temperature difference between groundwater and the reinjected water [8].

The ATES system can be applied in both fresh and saline groundwater, but saline waters require saline-resistant equipment to prevent corrosion. That is why the system is cheaper and less sensitive to fresh water. Still, ATES has significant opportunities in coastal areas where groundwater can be brackish or even saline, so it is not useful for agriculture or domestic use [9,10].

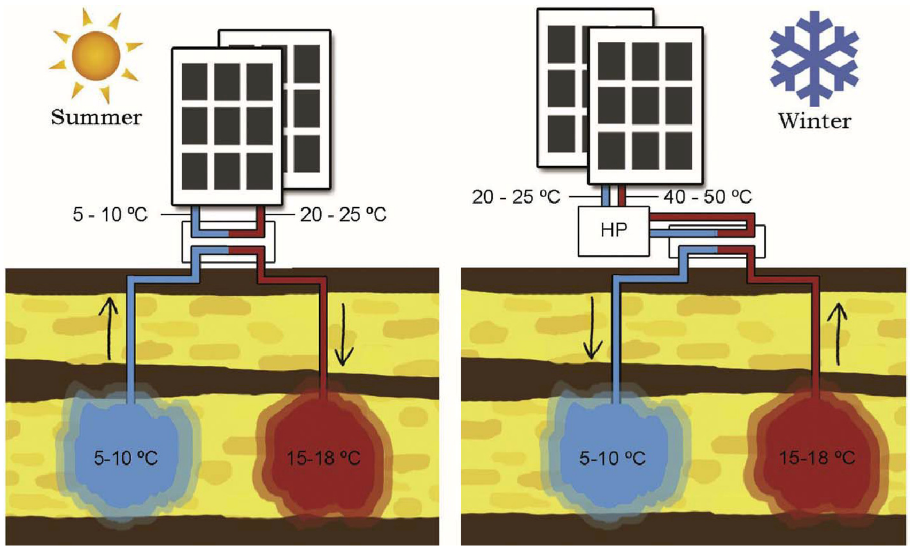


Figure 1. Illustration of the basic working principle of a low-temperature seasonal ATES system in cooling and heating mode [11].

2.1. Geological Conditions

Knowledge of geological conditions is crucial. They are a key precondition for establishing the ATES system. A suitable aquifer with favorable properties and dimensions must be available [3].

Geological settings applicable to ATES systems can be found in sedimentary basins. Unconsolidated aquifers have shown themselves as the best storage media, but highly fractured and unfractured aquifers can also be used for ATES [12]. Ideally, aquifers are made of medium- to fine-grained sand, gravel, and other porous rocks and sediments. The depth of an aquifer is also important (especially for HT-ATES) since too shallow an aquifer can negatively influence thermal effects on the surface, shallow subsurface, and drinking water resources, and heat losses are larger for shallow systems [10]. Also, when there is a short distance between the surface and the storage layer, the thermal gradient is high, which makes heat losses larger. However, aquifers must not be too deep because drilling costs are higher with depth. Also, hydraulic conductivity decreases with depth, which causes decreased thermal storage capacity [13]. To accumulate sufficient quantities of groundwater, an aquifer needs to be thick enough; according to [10], aquifer thickness for ATES should be at least 15 m. It is hard to expect the aquifer to be homogeneous, but it should be as least heterogeneous as it can be [3] since heterogeneity implies zones with higher and lower groundwater velocities, which can cause lateral loss of heat. Fissures, fractures, and faults harm the thermal efficiency of ATES systems as they can cause leakage [10] and likely cause preferential flow paths with extreme lateral loss of thermal energy [9]. Heterogeneity in aquifers affects storage volume shape and thermal efficiency [11]. An aquifer should have a confining layer, both on the top and at the bottom, because it limits the impact of buoyancy flow on the recovery efficiency and temperature and associated geochemical effects in the shallower layer [10].

2.2. Hydrogeological Conditions

For the ATES system to work, the presence of groundwater is necessary. According to [12], areas with small groundwater storage are less suitable for ATES systems as liquid yield from a single well is usually required to reach about 70 m^3/h.

Larger ATES systems are less affected by ambient groundwater flow than smaller ones, but losses may be substantial. Aquifers with higher groundwater flow rates are less suited to store thermal energy [9]. Velocities less than 25 m/y can still impact ATES system efficiency due to the advection of thermal energy stored within it [9]. Therefore, it is crucial to know and restrict groundwater flow velocity in the storage aquifer to prevent the drift of warm stored water and minimize advection losses [10,13]. High ambient groundwater flow significantly affects the recovery efficiency of ATES systems [11]. This property is directly proportional to permeability, which must have values between 3.5 and 8 Darcy, and hydraulic conductivity with optional values between 3.5×10^{-5} and 8.1×10^{-5} m/s, as experienced for Dutch aquifers [3]. Another important property to look at is transmissivity, which affects the peak loads that can be covered by the system, as high transmissivity leads to high loads that can be covered [10].

Maximum production flow rates for ATES wells are defined based on hydraulic conductivity and thickness of the aquifer (Equation (1)):

$$Q_w = 4\pi r \times KH \tag{1}$$

where Q_w is the maximum well capacity [m^3/h], r is the radius of the borehole at well screen depth [m], K is the hydraulic conductivity of the aquifer [m/d], and H is the length of the well screen [m].

2.3. Hydrogeochemical Conditions

Although adding cold water to the aquifer (lower temperature than in situ temperature) does not have significant impacts, adding warm water may cause changes in some element's concentrations (As, P, K, Si, As, Mo ...), pH, and dissolved organic carbon (DOC). Consequently, these elements should be monitored for the water quality of ATES projects [14]. Groundwater quality also determines the life expectancy of ATES wells and their required maintenance.

2.4. Well Configuration

The design of an ATES well field should minimize interference between production and injection wells as it will have a negative influence on production temperature. Also, the design should prevent unwanted hydraulic and thermal impacts in surrounding areas. According to Bakema and Drijver [15], if the need for capacity of an HT-ATES system is larger than a doublet can provide, a star-shaped configuration is preferable (Figure 2). In a star-shaped configuration, warm wells should be placed in the middle, surrounded by cold wells. That way, cold wells will insulate the heat around warm wells. Also, the ATES system can be achieved by grouping warm wells on one side of the aquifer and cold wells on the other side.

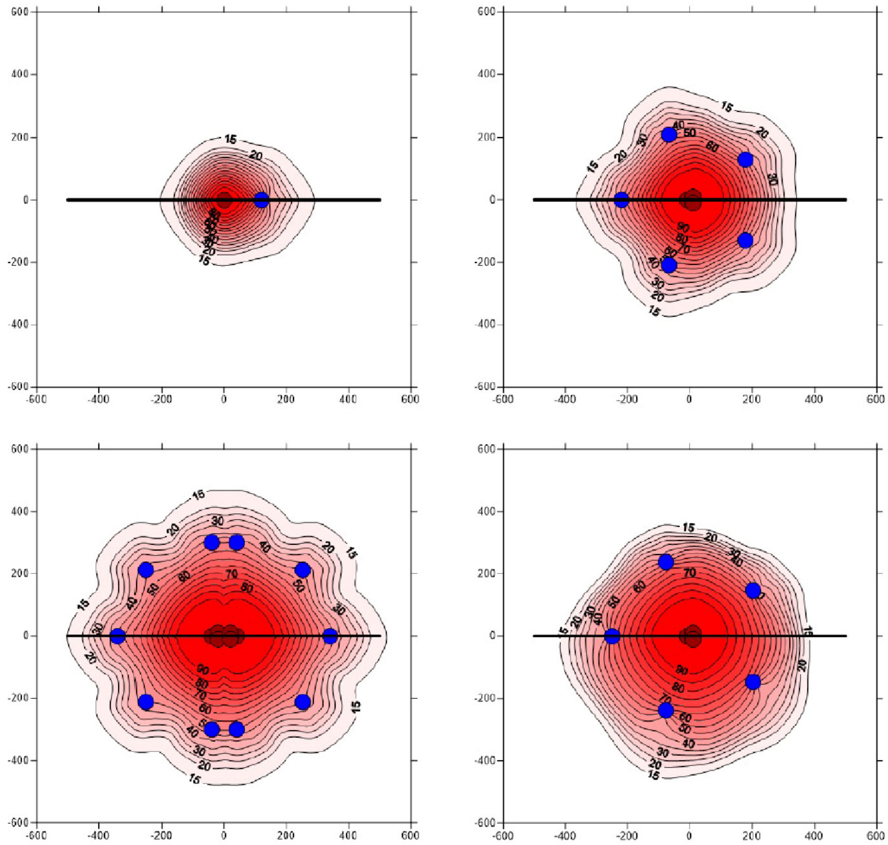


Figure 2. Simple doublet (upper left) and modeled star-shaped well configurations. Cold wells—blue, warm wells—red. Temperature contours are in degrees Celsius [16].

2.5. Monitoring

Monitoring the ATES system is important for understanding the operational issues and its sustainability. Monitoring data are the source for diagnosing issues, optimizing the system, preventing possible problems, and scheduling maintenance operations. Energy flow, supply and return temperatures, and electricity consumption are parameters that are usually monitored at five- or ten-minute intervals [17].

Besides physical parameters (temperature, flow rate, . . .), the chemical properties of water should also be monitored. Negligible effects on groundwater chemistry are expected when storing cold water; however, the rising temperature often causes exponential changes in (bio)hydrogeochemical processes. Biological processes usually prevail when temperatures are below 30 °C, while chemical processes are accelerated when ground(water) temperature exceeds 55 °C. Both may severely impact the quality of groundwater.

That increased temperature may mobilize chlorinated pollutants due to their increased solubility and reduced sorption, increase pollutant toxicity, or affect biodegradation if microbes are active. Heat storage is reported to cause, for example, an increase in concentrations of dissolved organic carbon, P, K, Si, As, Mo, V, B, and F, changes in Ca, Fe, methane (if present), and similar. These parameters, preferably, should therefore be regularly monitored for water quality [14]. However, sometimes storage can help to remediate polluted sites as it may speed up bio-decomposition of pollutants.

2.6. Recovery Efficiency

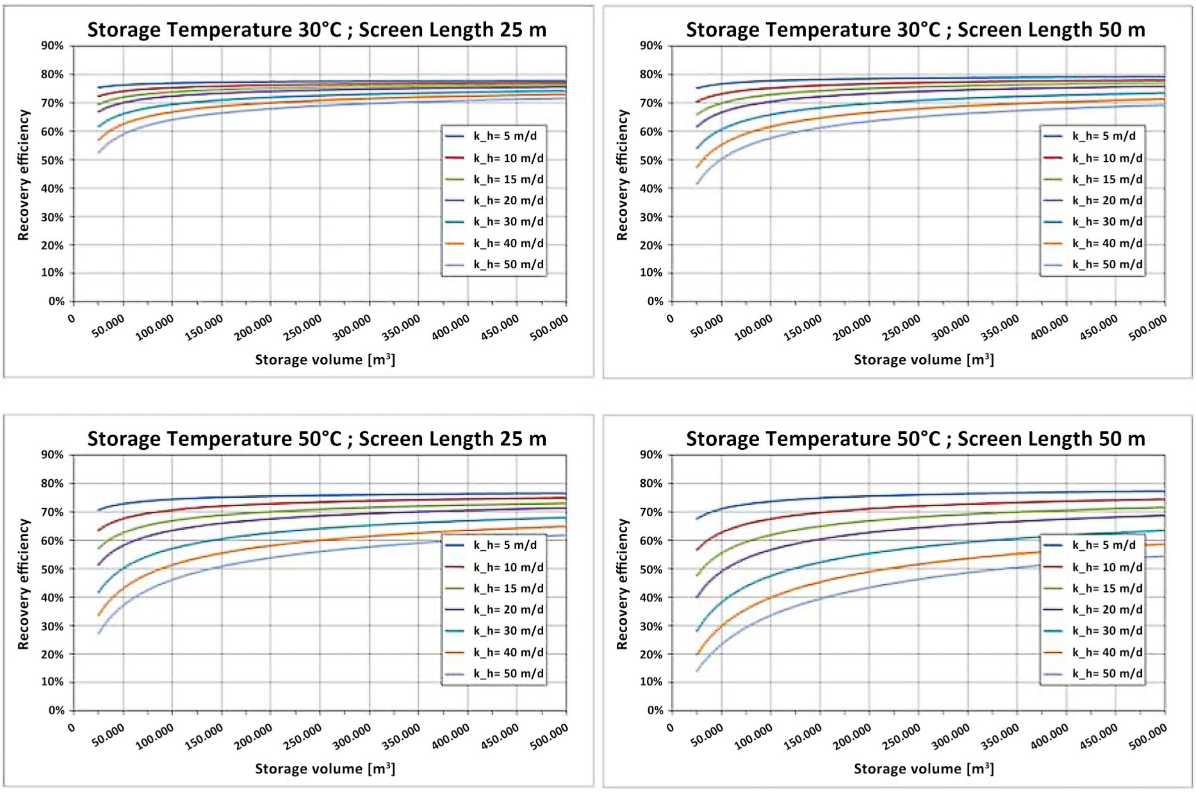
The thermal recovery efficiency (η_{th}, Equation (2)) is defined as a ratio between extracted thermal energy in one extraction period and injected thermal energy in the previous injection period [18].

$$\eta_{th} = \frac{E_{ex}}{E_{in}} = \frac{\int_0^t Q_{ex} c_w \Delta T dt}{\int_0^t Q_{in} c_w \Delta T dt} \tag{2}$$

where E_{ex} and E_{in} (J) are the extracted and injected energy, respectively, Q_{ex} and Q_{in} (m^3/d) are the well discharges during extraction and injection, ΔT (°C) is the absolute temperature difference between the injected or extracted water and the in situ temperature of the aquifer, c_w is the volumetric heat capacity of the groundwater (J/m^3K), and t is time (d).

The recovery efficiency of the storage is determined by heat losses in the subsurface and the minimum usable temperature extracted from the warm well. That temperature is referred to as the cut-off temperature. The lower the cut-off temperature, the more stored heat can be recovered, which improves recovery efficiency [15].

The recovery efficiency is one of the most important parameters that describe the overall energy savings of an ATES system. It is affected by storage and hydrogeological conditions that may lead to heat losses and changes in the cut-off temperature. Existing systems often show significant differences between the predicted and actual recovery efficiency. Actual recovery efficiency is usually lower than predicted due to heat losses, which can be ascribed to parameters that were not considered when planning the ATES system. This is explained by ATES' sensitivity to variations in the storage volume, the storage temperatures, the cut-off temperature, the permeability of the aquifer, and the screen length (Figure 3) [15].



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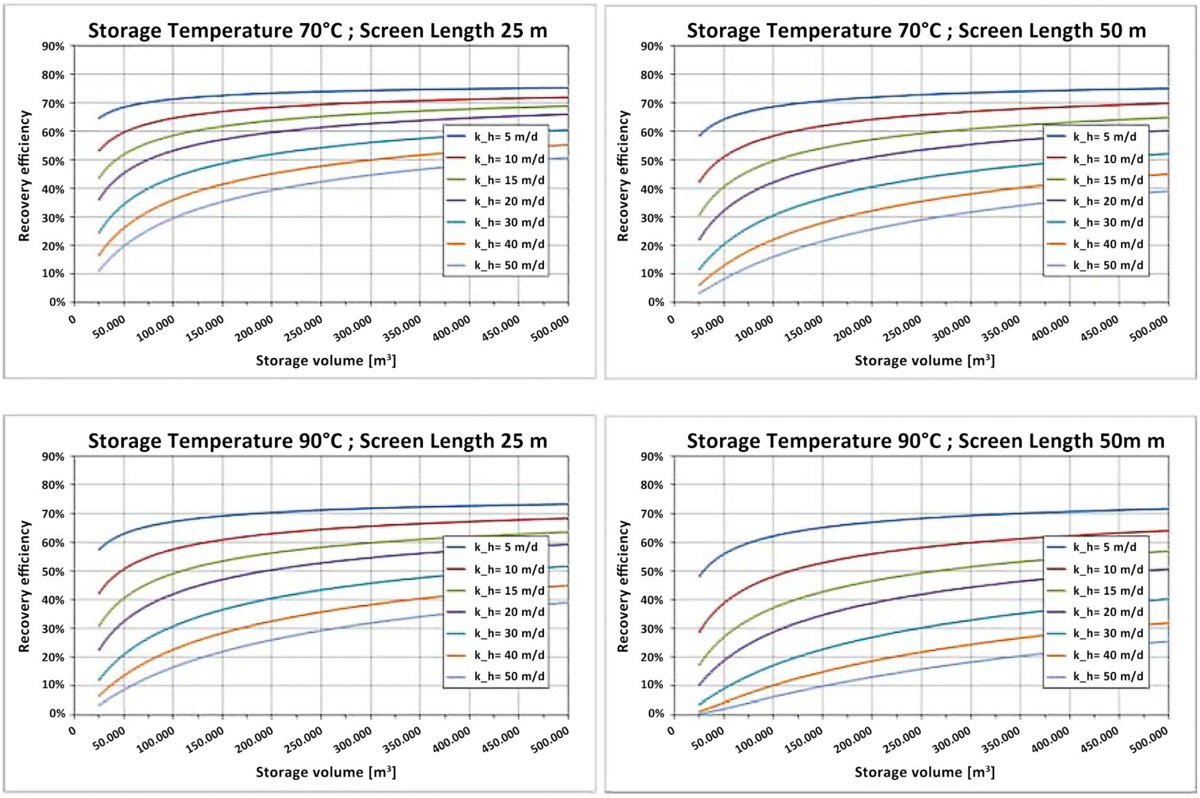

Figure 3. Recovery efficiency for different storage temperatures and aquifer thickness values [15].

One ATES cycle consists of four periods: injection period, storage period, extraction period, and rest period (Figure 4). Each period lasts a different amount of time, depending on system properties, climate conditions, demand, and others [19].

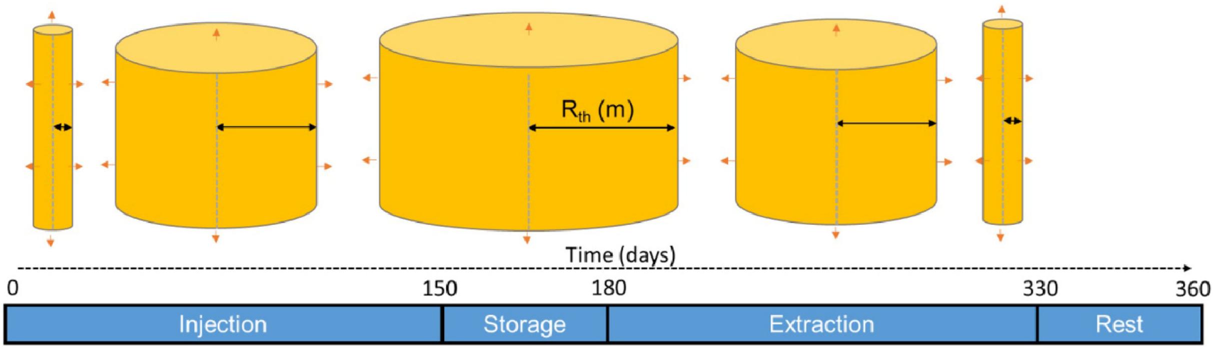

Figure 4. Schematic storage geometry variation of the thermal volume stored around an ATES well during one ATES cycle. In this study, the time of injection/extraction is 150 days, and the time of storage and rest is 30 days. In practice, charging, storage, and discharge periods may vary greatly due to variations in demand and availability of thermal energy [19].

Thermal recovery efficiency increases for each successive cycle (Figure 5), but the rate of increase decreases over time so that thermal recovery efficiency for the fifth cycle can be considered representative of the long-term behavior of the system [20].

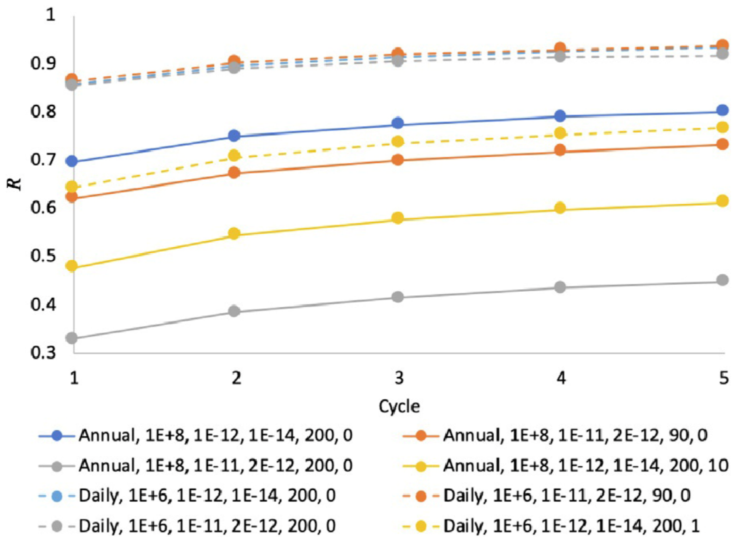

Figure 5. Evolution of thermal recovery efficiency (R) over time in selected scenarios at 400 m depth with a thickness of 20 m. Legend indicates cycle length, fluid mass injected (M_i) [kg], permeability—horizontal (k_{ah}) [m^2], permeability—vertical (k_{av}) [m^2], temperature of injected water (T_i) [°C], and longitudinal dispersion lengths ($d_{||}$) [m] [20].

2.7. Case Examples

In 2023, the European Geothermal Energy Council identified as much as 19 ATES systems in six countries in Europe [21]. Despite many, publications on their implementation are still rather sparse. Furthermore, several examples are given.

2.7.1. LT-ATES at Rosenborg (Sweden)

The site is in the northern part of Stockholm, on the property called Rosenborg 3. The aquifer is made of glaciofluvial sediments (sand, gravel, and cobbles). Bedrock is made of acidic intrusive rock as well as metamorphic rock of sedimentary origin. The depth from the surface to the bedrock ranges from 12 to 20 m, and aquifer thickness ranges between 8 and 15 m. The hydraulic conductivity of the aquifer ranges between 2.5 and 2.9×10^{-3} m/s.

The ATES system consists of three warm wells in the northern part of the site and two cold wells in the southern part. Warm wells are positioned 7–11 m below the groundwater level, while cold wells are 14–15 m below the groundwater level. The cold side stores water at temperatures of 6–12 °C, while the warm side stores water at temperatures of 9–16 °C [22].

2.7.2. MT-ATES at Neubrandenburg (Germany)

The geothermal heat storage is in Neubrandenburg, North German Basin. The aquifer thermal energy storage is based on the technical equipment of an existing geothermal heat plant. A geothermal doublet is placed in a water-bearing sandstone at 1228–1268 m depth. The distance between warm and cold wells is 1300 m. The gas- and steam-turbine-driven cogeneration plant (GSCP) serves as the heat source. Fluid temperatures around the warm well range between 54 °C and 87 °C, while temperatures around the cold well are around 47 °C. Charging during summer provides a capacity of up to 4 MW, while a low-temperature district heat supply system forms a 12 MW heat sink for discharging heat in the winter [23,24].

2.7.3. HT-ATES at Plaisir Thiverval-Gringon (France)

The site is located 30 km west of Paris. ATES was built in 1985–87 to store excess heat from municipal waste incineration plants, which provided heat at 200 °C for the district heating network. Inlet temperatures were up to 150 °C, and outlet temperatures were between 60 and 70 °C. The intended storage temperature was 180 °C, and the calculated energy efficiency was 60%, which could be reached if the heat was unloaded at 80 °C. The expected heat storage capacity was 20 GWh [25].

ATES consisted of four wells at approximately 500 m depth, one central injection (storage) well, and three wells for warm water unloading. The targeted aquifer was 16 m thick and made of quite homogeneous unconsolidated sand, with hydraulic conductivity ranging from 4 to 6.3×10^{-5} m/s. The cap rock is clay. The system worked fine for about two years until particle inflow damaged the pumps.

2.7.4. HT-ATES at Delft (The Netherlands)

High-Temperature ATES is planned to be integrated into a wider heating system on and around the Technical University Delft campus. It is estimated to produce heat from a geothermal doublet at around 75–80 °C with a flow rate of approximately 350 m^3/h. Return temperatures are estimated at 50–55 °C. The system will store excess heat from geothermal wells during summer.

The HT-ATES system will contain seven wells, three hot wells (80 °C), and four warm wells (50 °C), approximately 200 m deep. Warm wells will work as cold ones. Storage is in an unconsolidated sedimentary aquifer at 160–200 m depth. The targeted storage capacity is 25–50 TJ since the storage volume is 400,000–800,000 m^3.

The system is still in development. Pilot drilling is ongoing for detailed well design, subsurface screening, and monitoring. Final well location selection and integration in the energy system is ongoing, such as the preliminary design phase for HT-ATES wells [26].

3. Borehole Thermal Energy Storage (BTES)

Borehole thermal energy storage is a system that utilizes boreholes and fluid within a closed loop (often referred to as borehole heat exchangers (BHEs)) for transferring heat or cold to the surrounding ground material since thermal energy can be seasonally stored in that material [27]. BTES systems are becoming very popular for seasonal storage of thermal energy, thanks to their slow thermal response and large storage capacities [28].

BHEs are widely used when sufficient heat exchange capacity in the underground is needed. Relatively constant temperatures and known thermal gradients below a certain depth below the surface make this possible [29].

While charging, the rock is heated and cooled during discharging. Vertical boreholes are heat exchangers between the storage volume and the working fluid carrying the heat. Heat is transferred to rock by conduction when working fluid circulates during the charging period [6]. Heat carriers circulate inside plastic pipes of various designs. The most common ones are U-tube, double U-tube, and coaxial, which are placed in closely spaced boreholes.

In the beginnings of BTES technology, storages were designed "open" without grouting (Figure 6). In these cases, working fluid was in direct contact with rocks in the underground. To be fair, this was mostly used in Scandinavia, where igneous rocks are placed near the surface, and underground water flow is limited. However, these systems showed significant heat losses due to precipitation, working fluid losses, and the appearance of air and gases [6].

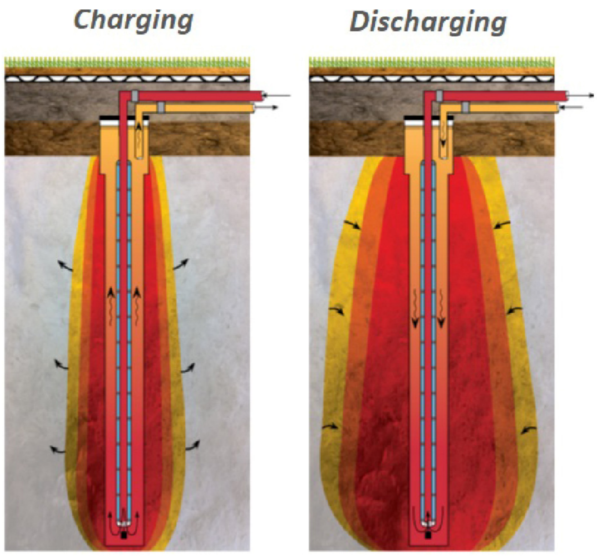

Figure 6. A system with open coaxial borehole heat exchanger with dual flow function (arrows). The flow is reversed when discharged compared to charging [30].

3.1. Geology

Preferred geological conditions for BTES include drillable ground with high heat capacity and low natural groundwater flow. A preliminary screening of local geology is essential, typically based on existing well records, to assess depth, lithostratigraphic information, groundwater flow, and water table depth. This information guides the selection of drilling and grouting techniques. Based on this screening, estimates of the thermal properties of encountered geological layers can be made. However, regional geological variations may affect these values, requiring careful evaluation and consideration of uncertainty [3].

BTES function is based on the geological matrix's ability to store and conduct heat. Therefore, thermal properties enable efficient heat storage with minimal losses. These properties are affected by factors such as mineral composition, temperature at the storage depth and of the heat carrier, fluid content (saturated or unsaturated zone), and groundwater flow around the boreholes.

The required properties are high heat capacity and reasonable thermal conductivity. Higher heat capacity allows more heat to be stored in the BTES. While high thermal conductivity aids in charging heat into the storage volume, it also increases heat conduction away from storage, leading to lower temperatures at the storage during discharge. In other words, the high thermal conductivity of rock and soil increases heat losses [31].

Studies have shown that BTES efficiency increases with decreasing soil thermal conductivity, as lower conductivity leads to higher efficiency in heat extraction. However, low thermal conductivity may still decrease the ability to charge the storage efficiently. Therefore, thermal conductivity values should be restricted to be considered desirable for thermal energy storage systems depending on other thermal properties like heat capacity. Performing a (Geo-) Thermal Response Test ((G)TRT) at the BTES site provides essential data for design calculations, including thermal conductivity and borehole thermal resistance. This test involves heating fluid in the borehole and monitoring heat transfer into the surrounding ground as the fluid circulates in the tubes filled with grout [3]. Low thermal resistance is desirable as poor heat transfer in the collectors will affect the storage efficiency both at injection and production.

TRT works by injecting (or extracting) heat with constant power and recording the temperature of thermal vector fluid. It allows for calculating the equivalent thermal conductivity of the volume of the materials affected by the heat exchanger during the test [32].

Besides the thermal response test (TRT), where heating is supplied by circulating heating fluid inside the pipes and continuous temperature measurement at the pipe inlet and outlet during the heating phase, there are other variations of this test.

At enhanced TRT (ETRT), the heat is supplied by a copper wire, which is placed along the BHE and connected to a power source. The heat energy emitted to the ground can be calculated from the supplied voltage and electric current flow. Optical fibers and copper wires are often combined into hybrid cables, so the heating and temperature detection takes place at the same location anywhere inside the BHE. ETRT is assumed to supply equal heat along the BHE, which is not necessarily given by conventional TRT due to heat loss from the fluid on its way through the pipe [33].

According to Table 1, for optimal performance of the BTES system, the thermal conductivity of the underground should be a bit smaller than the average value for respective lithology. The thermal conductivities of rocks found in Slovenia can be seen in Table 2.

Table 1. Thermal conductivity of different sediment and rock types. Data from [34].

Sediment/Rock	Thermal Conductivity [W/mK]	Recommended Values [W/mK]
Clay and silt (dry)	0.4–1.0	0.5
Water-saturated clay and silt	1.1–3.1	1.8
Sand (dry)	0.3–0.9	0.4
Water-saturated sand	2.0–3.0	2.4
Water-saturated gravel	1.6–2.5	1.8
Till/loam	1.1–2.9	2.4

Table 2. Values of arithmetic mean thermal conductivity (TC) with standard deviation (s.d.) and median (Me) TC of a total of 606 rock and sediment samples from Slovenia, grouped by lithology and main groups of rocks (bold text) [35].

Lithology	No. of Samples	Mean TC [W/mK]	s.d. TC [W/mK]	Me TC [W/mK]
Igneous rocks	**34**	**2.43**	**0.66**	**2.27**
Plutonic rocks	**5**	**2.45**	**0.46**	**2.56**
Quartz diorite (tonalite)	3	2.41	0.54	2.56
Cezlakite	1	2.86	/	2.86
Peridotite	1	2.18	/	2.18
Volcanic rocks	**29**	**2.43**	**0.69**	**2.25**
Keratophyre	2	2.69	0.04	2.69
Andesite, andesite lava	4	2.80	0.62	2.87
Andesitic tuff, andesitic breccia	9	1.94	0.22	1.89
Tuff, tuffite, tuffaceous breccia	12	2.64	0.83	2.52
Dacite	1	1.72	/	1.72
Diabase	1	2.95	/	2.95
Metamorphic rocks	**23**	**3.14**	**0.58**	**3.05**
Schist (green, amphibolitic, chloritic, etc.)	6	2.67	0.30	2.74
Phyllonite	1	3.88	/	3.88
Eclogite	4	3.17	0.56	3.36
Quartz phyllite	1	3.62	/	3.62

Table 2. *Cont.*

Lithology	No. of Samples	Mean TC [W/mK]	s.d. TC [W/mK]	Me TC [W/mK]
Amphibolite	1	2.64	/	2.64
Gneiss	9	3.41	0.59	3.31
Mica schist tuff	1	2.77	/	2.77
Sedimentary rocks	**549**	**2.57**	**0.49**	**2.53**
Clay, clay with impurities	46	1.57	0.38	1.57
Lignite, lignite with clay	9	1.04	0.37	0.97
Marl, marlstone with impurities	56	1.92	0.43	1.90
Claystone and shale, with impurities	36	2.13	0.74	1.89
Mudstone	5	2.12	0.26	2.15
Sand, sand with impurities	16	1.51	0.48	1.39
Silt, silt with impurities	5	1.65	0.48	1.68
Siltstone, siltstone with impurities	65	2.39	0.50	2.27
Sandstone (calcareous, marly, silty...)	78	2.36	0.45	2.38
Quartz sandstone	28	3.56	0.56	3.46
Conglomerate (dolomitic, quartz)	14	3.59	0.88	3.59
Breccia (dolomitic, limestone)	12	3.21	0.70	3.21
Dolomite	60	4.20	0.60	4.11
Dolomitized limestone, Limestone grading into dolomite	13	3.25	0.54	3.21
Limestone	106	2.70	0.39	2.68

3.2. Hydrogeology

A good knowledge of local hydrogeological conditions regarding groundwater level and flow is crucial. Water flow through or around the storage volume can cause heat loss by advection, which should be minimized. Ideally, a BTES should be placed above the groundwater table or in geological conditions with low hydraulic conductivity, such as tight clay, till, non-karstified limestones, sediments with low permeability, or un-fractured crystalline rocks. For zones with unavoidable high groundwater flow, insulation with thermally reducing grout can minimize heat loss. Thermally enhanced grout is typically used in other zones to increase heat transfer from the borehole to storage volume. If BTES is partially below the groundwater table, it may be necessary to lower the groundwater table during construction, depending on drilling, U-tube installation, and grouting techniques [3].

Groundwater flow is not desirable as convective heat transport with groundwater flow may reduce heat storage performance (Figure 7). Highly permeable grounds and large hydraulic gradients may cause moving bodies of heat outside of the storage [27].

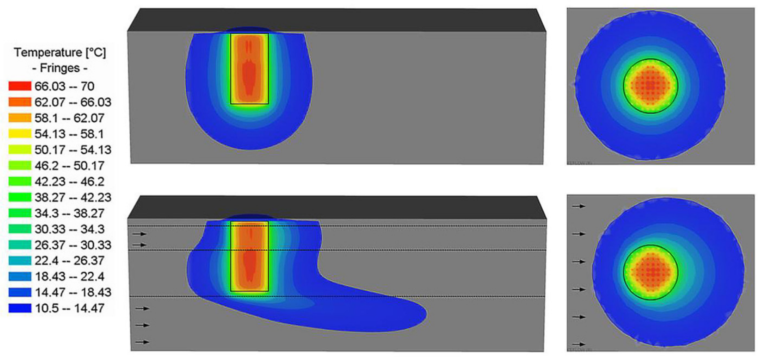

Figure 7. Simulated temperature profile of a BTES with (arrows) and without moving groundwater. The horizontal cuts on the right show the temperature 15 m below the ground surface (~middle of the upper aquifer) (Taken from [36]).

3.3. Borehole Installations

Ground source heat exchangers (GSHE) for BTES are drilled to a certain depth, typically from 20 to 200 m. They are usually grouted as grout stabilizes and seals boreholes, enables good thermal contact between the geological formation and the collector pipes, and reduces thermal resistance [29].

Boreholes can be equipped with various heat exchangers, making all BHEs in storage work as one large BHE. The most used types of collectors are single and double U-tube pipes (Figure 8) since they are reliable, simple to install, and have the lowest cost. There are also various types of coaxial collectors with hard and soft shells; they are more expensive, more complicated to install, and have a high risk of leakage [27].

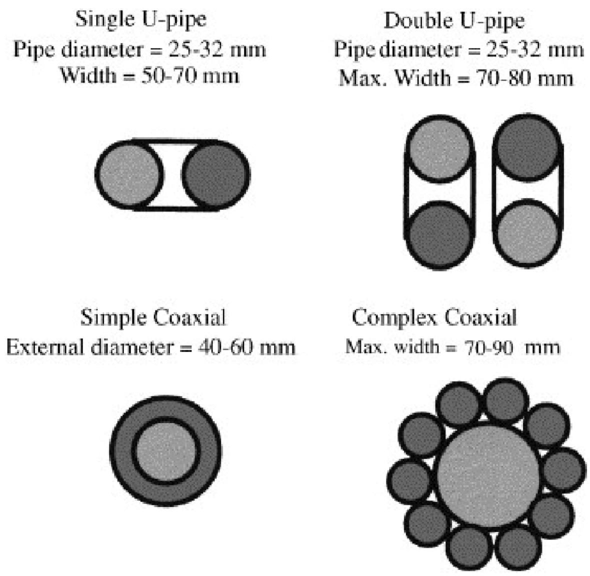

Figure 8. Common vertical ground heat exchanger designs [29].

U-tubes are often connected in series to form circuits for working fluid flow, with flow direction designed to maximize efficiency and minimize heat loss. Field tests have shown that double U-tubes are more efficient than single ones, although coaxial collectors should be most effective [3].

High-density polyethylene (PEX) is normally used for tubing the boreholes because it is strong, chemically resistant, and able to withstand pressures and temperatures during long periods of operation [37].

3.4. Storage Geometry

Storage geometry is an important parameter to prevent heat loss. Storage capacity is proportional to storage volume, while heat losses are proportional to surface area. Therefore, a design with a small surface-to-volume ratio is desirable. Also, storages are usually insulated on top to minimize heat losses to the surface [27]. In Sibbitt and McClenahan [37], it is recommended to cover the top part of interconnected U-tubes and headers with a 0.5 m thick layer of insulating material, which is then covered with a membrane. Then, another 0.5 m thick layer of insulating material should be followed by a geotextile cloth and 1 m of native topsoil. The insulation layer should generally extend beyond the outer ring or row of boreholes.

The BTES system is made of boreholes drilled in certain arrays. Borehole spacing is usually uniform. The array may be either quadratic or hexagonal (Figure 9), where hexagonal shows better energy transmission and heat losses in the rock mass, while the square array is simpler to drill and enables easier borehole connecting [38].

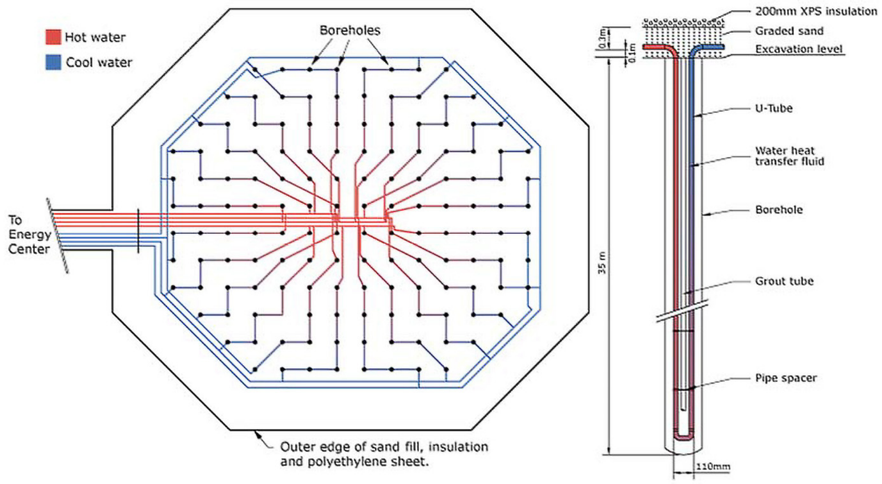

Figure 9. The layout of a borehole thermal energy storage and cross-section of a single borehole and U-tube [37].

Compact shapes of the storage reduce heat losses. To minimize land usage and heat losses due to the surface, boreholes are occasionally drilled obliquely, giving the store a broom-like shape. Depth, spacing, and configuration must be optimized for each project [6]. The distance between boreholes is crucial for efficiency [3]. The distance between boreholes depends, among other factors, on the thermal properties of the rock [38]. Spacing between boreholes depends on the local conditions, but boreholes are typically 2–5 m apart, 20–200 m deep, and sealed with grout. Thermal losses depend on subsurface properties, borehole layout, local groundwater flow, and surface heat losses.

The amount of stored heat, extracted heat, and storage efficiency increases with an increased number of borehole heat exchangers and their length [39]. However, for increased specific heat extraction rates, a larger number of borehole heat exchangers is more relevant than their length.

Boreholes can be connected in a serial or parallel configuration or a combination of those two, depending on the planned thermal loading and unloading [40]. The pattern and depth of the boreholes determine the outer shape of the BTES storage [3].

3.5. Monitoring

Most BTES systems include additional monitoring boreholes inside and outside the storage volume. In these boreholes, temperature monitoring equipment is installed to evaluate the performance.

For monitoring, temperature and volume flow sensors in BTES connections of inlet and outlet pipes, such as ground temperature sensors inside and outside the storage volume, are used. There are also heat flux sensors and two assigned temperature sensors in the cover insulation, one under the insulation and the other on top of it.

Novel technologies, such as optical fibersused fordistributed temperature sensing (DTS), are often used for temperature monitoring in BHEs. These systems offer real-time data collection, capturing spatio-temporal temperature dynamics within the boreholes, which improves understanding of the thermal properties of reservoir rock and fluid movements in and around the borehole. This type of technology is based on Raman scattering of light, where the ratio of Stokes and Anti-Stokes intensity is proportional to temperature [41].

For example, the first DTS measurements in Sweden were executed in 2019 on BTES in Emmaboda. Fiber optical cables were installed in the observation boreholes UB1 and UB46 (GT-1/2 and GT-3 in Figure 10). The fiber optical cable was led into the “technical room” close to the storage and was connected to a data logger. The temperature profile was measured every five minutes for every half a meter. The fiber cables were hung freely from the borehole's middle to the borehole's wall [42].

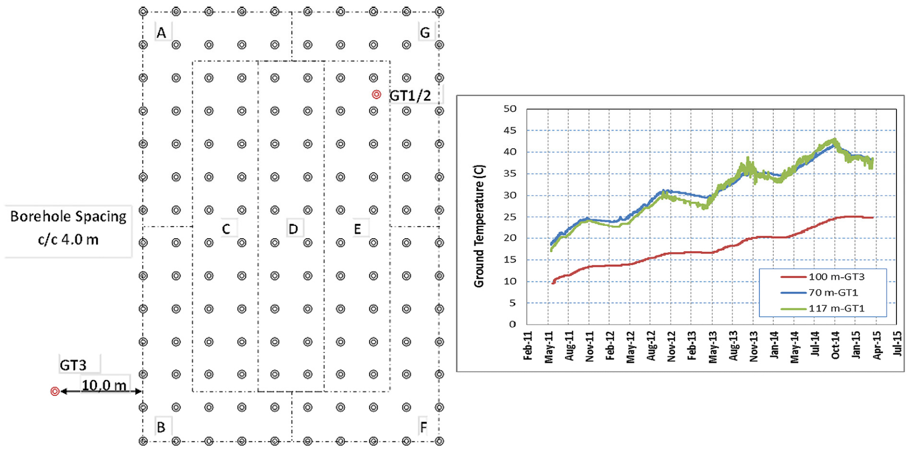

Figure 10. Rectangular plan of the Emmaboda BTES boreholes (gray circles) and monitoring boreholes (GT; red circles) and measured storage temperatures at different depths [43].

3.6. Recovery Efficiency

Recovery efficiency for most BTES systems ranges between 45% and 60% and is often lower than expected. That is the case because observed heat losses are higher than planned/modeled. This can be affected by poor construction methods, poor knowledge of groundwater flow, inadequate storage design, or simply choosing the wrong parameters for modeling.

According to [44], a start-up period is needed to reach steady-state behavior in the BTES when heating up storage volume and surroundings. In this example, Malmberg et al. [40] simulated HT-BTES operation without discharging during the first year of operation. That means the system was charged for two periods before being discharged. Furthermore, in this case, more heat is lost during transmission than anticipated, leading to inefficiency. Also, the demand is often higher and requires more heat than expected, which impacts system performance. Without a short-term buffer, the system cannot fully benefit from the coupling between solar panels and the BTES, which is further reducing efficiency.

3.7. Case Examples

3.7.1. MT-BTES at Neckarsulm (Germany)

Borehole thermal energy storage in Neckarsulm consists of 528 boreholes, 30 m deep, arranged in rectangular geometry. Storage is insulated on top with a 20 cm thick XPS insulation to minimize top losses due to surface. Double U-tubes were chosen as the collector type. The heat source is the solar collector field [45].

Boreholes are drilled into a 30–35 m thick layer of clay. Its low hydraulic conductivity, favorable volumetric heat capacity, and thermal conductivity proved ideal for BTES. Because of the presence of highly permeable dolomites under the clay layer, boreholes were limited to a maximum depth of 30 m [28].

The highest measured temperature, 57 °C, was injected at a depth of 20 m in 2000. Return temperature of the working fluid decreased from 47.6 °C in 1999 to 43.4 °C in 2002 due to decreasing distribution net supply temperatures.

About 50% of the total solar heat delivery (1667 MWh) was used to charge the BTES during the charging period. During the discharge period, 187 MWh were discharged from the BTES, the rest of the heating demand was fulfilled by direct solar heat and gas boilers. A significant increase in the storage efficiency was expected in the later years [46]

3.7.2. HT-BTES at Mol (Belgium)

This project was established in 2002 and aimed at demonstrating and evaluating BTES in a water-saturated sand layer. During summertime, waste heat from a CHP power plant is stored at 90 °C. During winter, the stored heat is discharged and used for heating.

BTES consists of 144 boreholes to a depth of 30 m in a hexagonal shape. The spacing between boreholes is 2 m, and the storage diameter is 26 m. Each borehole is installed with a single U-tube and 20 cm thick top insulation. Temperature sensors are placed in 66 different locations and depths to be able to monitor the 3D temperature development.

During the first year of operation, the maximum temperature in the storage was 70 °C during charging and 30 °C during discharging. However, overall efficiency was very low (30% in the second year) and expected to increase when steady state heat flow is reached [47].

4. Possibilities in Slovenia

Little research has been performed on this aspect in Slovenia up to now. Stritih et al. [48] have performed a preliminary evaluation of the Slovenian potential for ATES (Table 3). They emphasized that ATES might be an issue because almost all drinking water in Slovenia is gained from groundwater which is protected by water protection areas. They covered 17.4% of the territory in 2021 [49], so the ATES location should be carefully selected to avoid potential land use conflicts.

Table 3. Estimated parameters of some aquifers in Slovenia that are suitable for ATES [48].

Location	Composition	Depth to (m)	Thickness (m)	Hydraulic Conductivity (m/s)	Gradient	Porosity	Flow Rate
Velenje Valley	Pliocene sands	100	10	10^{-6}	$<1 \times 10^{-3}$	0.2	4.3×10^{-4}
Krško–Brežice Plain	Plio-quaternary clayey gravels	50	5	10^{-6}	$0.5–1 \times 10^{-3}$	0.15	2.8×10^{-4}
Prekmurje	Pliocene sands	8–55	50–200	10^{-6}	1×10^{-3}	0.2	4.3×10^{-4}
Ljubljansko Barje	Quaternary gravels and sands	50	15	10^{-4}	$<1 \times 10^{-3}$	0.2	4.3×10^{-4}

They emphasized the importance of using aquifers with slow groundwater flow, which is essential for efficient heat storage, and proximity to larger centers, which is important for cost-effective energy transportation. Based on this, they delineated several potentially suitable areas in Slovenia as follows:

- Velenje Valley—a Pleistocene tectonic depression with medium porosity sands and low groundwater gradient;
- Krško-Brežice Plain—an extensive basin with high permeability in the upper zone and reduced permeability in the lower Pliocene part, which slows groundwater flow, making it suitable for heat storage;
- Prekmurje and Mura Plain—an extensive quaternary aquifer with fast groundwater flow in the Quaternary part and slower in the deeper Pliocene part where the aquifer is suitable for heat storage;
- Ljubljansko Barje—a young tectonic depression with alternating layers of high and low porosity.

Consequently, if one would design ATES in these areas, a detailed investigation of possible impacts on the quality and quantity of groundwater needs to be performed.

In recent years, geological reinterpretation of Plio-Quaternary clastic sediments, Pliocene Ptuj-Grad, and Miocene Mura Formations took place. Šram et al. [50] pointed out the possibility of thick-enough sequences of rather permeable poorly lithified sandstone in the central to eastern part of Pomurje. They can be a favorable target for LT-ATES or

MT-ATES as the depths between 200 and 700 m are not exploited for drinking or technological water, or thermal water production. However, groundwater properties should be studied carefully in a test well before developing the site as it is reported that the water is often enriched in iron, manganese, or arsenic [51]; similar is also reported for the Ljubljana Basin [52].

There are possibilities of using geothermal heat pump technologies in Slovenia with registered sites of geothermal heat pump types based on official data of the Ekosklad and Water Agency in the period 2016–2024 on water permits, special use of water, and grants for drillings, and on voluntarily reported data on large heat pumps in the period 1994 to 2024 [53].

On the other hand, BTES systems are not so restricted by geology as they mostly need areas with no or low groundwater flow. They could be designed in areas with low permeability rocks, where groundwater exploitation potential is limited. According to Figure 11, potential areas could be as follows:

- Flysch rocks in the western part of Slovenia and the coast;
- Low permeable clastic rocks in the Sava Fold area in central Slovenia and in the hilly areas of Haloze, Slovenske gorice, and Goričko in eastern Slovenia;
- Metamorphic rocks at and around Pohorje.

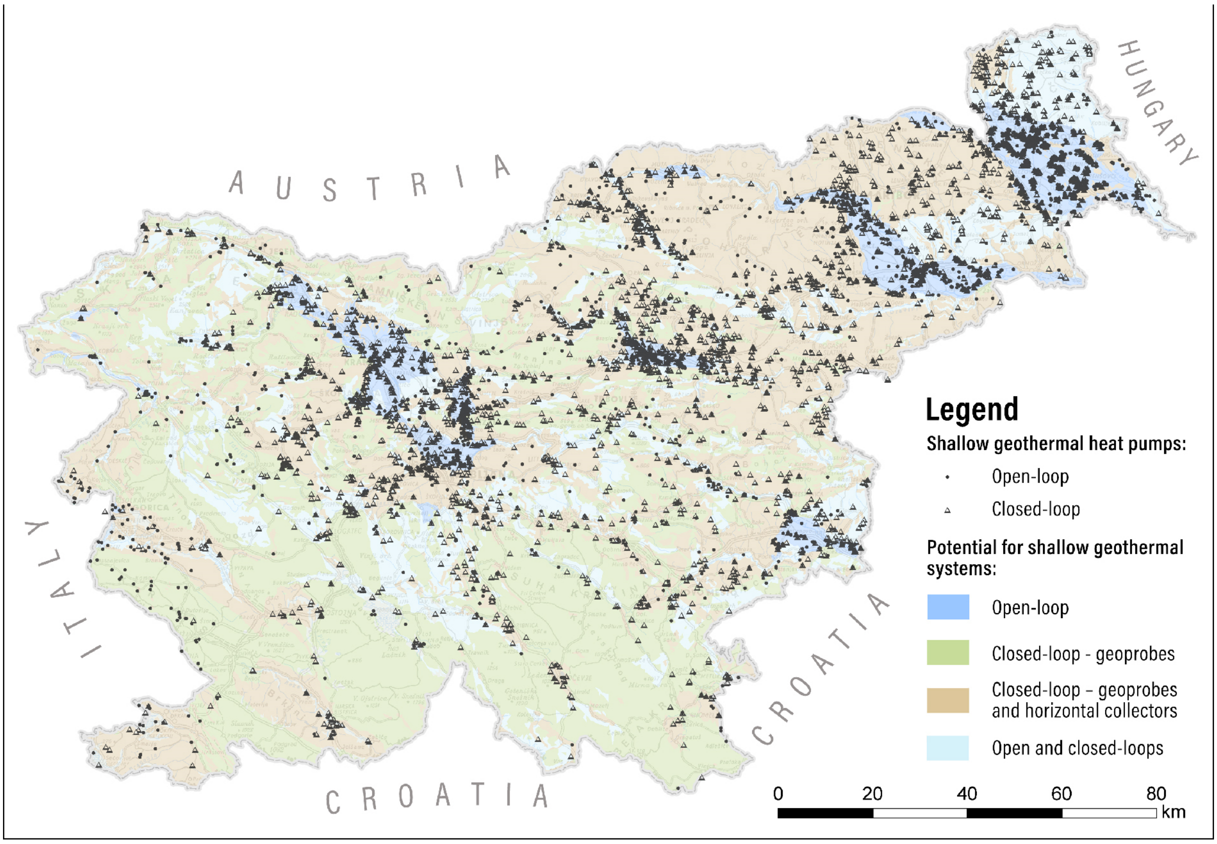

Figure 11. Existing open- and closed-loop systems in Slovenia, with highlighted potential for each type of shallow geothermal system.

In an attempt to harmonize and assure the quality of drilling works for shallow geothermal energy for both geoprobes (BHE) and water wells, guidelines for shallow geothermal drillings up to a depth of 300 m are published on the website of the Ministry of Environment, Climate, and Energy [54]. Unfortunately, we see that they are not applied as much as planned, and control is lacking. The noticeable barrier to faster ATES/BTES development in Slovenia is also the poor findability of geothermal information [55], which should be used for planning. Web portals eGeologija and Geotermija/Geothermal contain freely accessible geothermal maps and measurement results, but most of them are available only on a regional or national scale.

A First Example of UTES in Slovenia

In 2024, the first BTES system was developed in Slovenia to provide heating and cooling for the industrial premises of DEWESoft Co. They invested in 1500 m of boreholes altogether to provide storage facilities in Trbovlje town. There are 55 boreholes with a U-tube design positioned 2.7 m apart and in a hexagonal array (Figure 12). Boreholes are drilled 27 m deep into the clay. Three additional boreholes of 1″ in diameter are used for observation, and flow and temperatures are continuously measured at all wellheads. The diameter of the storage facility is approximately 20 m.

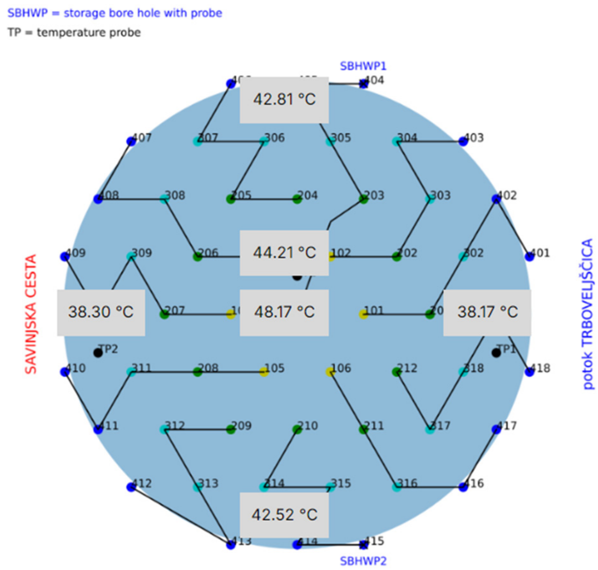

Figure 12. An array of 55 geoprobes of the first BTES site in Trbovlje, Slovenia. Charging temperatures are shown as of mid-December 2024. TP1–TP3 are observation boreholes, and TP-3 is closest to the center. SBHWP are active U-tube boreholes with an additional observation tube installed wherein sensors are positioned at depths of 10 and 18 m.

The charging heat is provided by 400 m^2 of solar panels used for climate control, and a sum of 100 MWh of its waste heat plus 60 MWh of waste heat from technological processes is used to fill the storage. The estimated heating demand is 80 MWh (40–50% recovery) with a produced target temperature of 55 °C in autumn, which is planned to decrease to the cut-off temperature of 30 °C at the end of the heating season (Figure 13). Floor heating and circulation pumps will be used to harvest stored heat from BTES. The rest of the 600 m^2 of solar panels are used to provide electricity for technological processes.

The system has several large water tanks to balance the heating and cooling process. The charging and, if needed, backup heating sources are two 100 kW heat pumps, an air-water heat pump, and a geothermal open-loop heat pump.

The investment is estimated to be EUR 210,000, where BTES accounts for 62%, solar panels for 14%, and monitoring systems for 24%. The amortization period is estimated to be five to seven years based purely on energy savings.

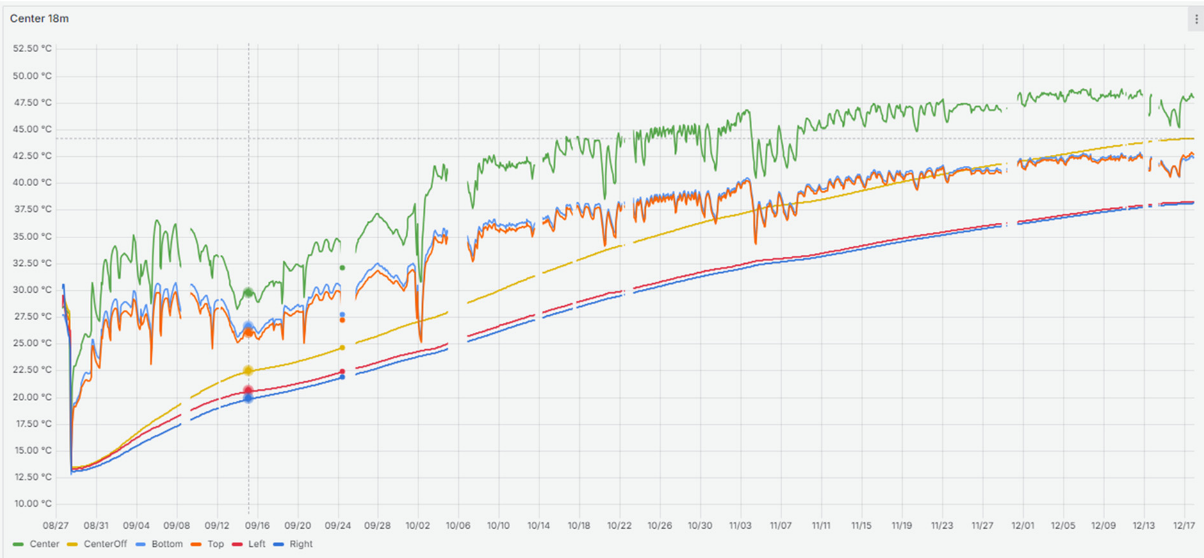

Figure 13. The Dewesoft BTES has been charging since August 28th, 2024. The increase in charging temperature at active U-tubes SBHHWP is shown by the top three curves marked as Center, Bottom, and Top. The steady heating of the BTES area is measured in observation boreholes TP and shown by the lower three curves (Center Off, Left, Right).

5. Conclusions

Most papers focus either on UTES design simulations or site examples at a specific location. Therefore, this paper tries to overcome this issue by highlighting the basic concepts of the two main UTES technologies, ATES and BTES.

It provides criteria for assessing site suitability, such as aquifer characteristics, thermal conductivity of the rocks, and groundwater flow. These criteria enable quick evaluation of potential sites and help to avoid unsuitable ones for thermal storage. It additionally helps to identify common risks associated with ATES and BTES technologies, such as thermal imbalances, groundwater contamination, or operational inefficiencies, and provides strategies for mitigating risks, including monitoring systems.

Despite 19 systems being listed in Europe in 2023 [21], it was especially challenging to find geological and technological information on either ATES or BTES sites, which exemplifies that these technologies are still in the development phase. We tried to find an example per type and temperature range (low-, medium-, and high-temperature).

This article demonstrates the geological and hydrogeological potential for ATES and BTES systems in Slovenia in a pre-feasibility phase, as no new analysis or field work has yet been performed.

As shown, a thorough geological understanding is essential for ensuring the efficiency of ATES and BTES sites. Key information includes geological settings, groundwater occurrence, gradient, velocity, and flow rates. Anisotropy and heterogeneity are relevant and should already be accounted for when dimensioning the system and its capacity. This should be followed by laboratory (core) and field (TRT) investigation of site properties enabling the optimization of utilization protocols. During the project's lifetime, operational monitoring is essential to predict, identify, and mitigate potential operational issues. For ATES, this means regular tracking of groundwater and thermal plume behavior, while for BTES, this involves monitoring subsurface temperature distribution.

Several European countries, such as the Netherlands and Germany, have successfully developed LT-ATES and LT-BTES systems and face no major technological challenges. Today, new advancements are emerging in the field of medium- and especially high- to ultra-high temperature storage systems, requiring innovative insulation techniques, improved heat exchanger materials, and enhanced modeling tools to optimize performance. This is not the case in Slovenia, where, to our knowledge, the first BTES was installed only in 2024. To accelerate adoption, Slovenia should prioritize pilot projects, interdisciplinary collaboration between research institutions and industry, and policy incentives to attract investment in UTES technologies.

The successful implementation of ATES and BTES systems requires not only a sound geological foundation but also careful integration with existing energy infrastructure, access to cheap or free excess heat or cold, and regulatory frameworks. This study recommends that Slovenia establish transparent permitting guidelines for such systems, develop financial support mechanisms, and create a freely available database of thermal storage potential based on geological and hydrogeological assessments. In Slovenia, where the deployment of these technologies is still in its beginning, there is a unique opportunity to learn from the experiences of other European countries. By incorporating best practices in site evaluation, system design, and operational monitoring, Slovenia can overcome initial barriers and accelerate the deployment of more advanced thermal storage solutions, just enough to meet its national energy goals.

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