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Review

High-Temperature Aquifer Thermal Energy Storage (HT-ATES) Projects in Germany and the Netherlands—Review and Lessons Learned †

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Abstract

Aquifer thermal energy storage (ATES) is a concept that can help to address heating and cooling needs through the use of the subsurface as a seasonal thermal energy storage (STES) system. Over 2800 ATES systems have been deployed with storage temperatures typically below 25 °C and only a few with higher temperatures (>40 °C), which would increase the energy density and utility of the stored thermal fluids. Until now, only a few high-temperature aquifer thermal energy storage (HT-ATES) projects have been initiated and are still in operation. These HT-ATES projects have encountered a range of technical and non-technical challenges. This study reviews ten such projects: four in Germany and six in the Netherlands. The non-technical issues include public acceptance, a lack of regulatory framework for these systems, managing overlapping uses of the subsurface, managing changes with the providers and off-takers of thermal energy, and obtaining financing to implement these projects. Common technical issues include geological factors such as incomplete characterization of the subsurface and reservoir heterogeneity; geochemical issues such as mineral scaling, corrosion, and biofouling; lower than expected thermal recovery; and issues with system design and reliability. This review highlights benefits and challenges faced by HT-ATES projects with the goal to use the lessons learned to improve the siting, design, development, and operation of such systems. Recommendations include improved initial subsurface site characterization, use of coupled process models to optimize system design and predict system performance, cascaded uses of stored thermal energy to better utilize the stored heat, monitoring networks to provide feedback on system performance, and expanded system scale to allow for continued operation even when maintenance of some system components is required. Techno-economic modeling and risk analysis could be used to optimize such HT-ATES project design and identify key factors that will affect sustained economic viability. In addition, design flexibility is important for these systems to allow for changing conditions regarding the supply and demand of thermal energy. Adopting these findings should improve the performance and reduce the risks for future HT-ATES projects worldwide.

Keywords: high-temperature aquifer thermal energy storage; case studies; technical issues; characterization; modeling; monitoring; lessons learned

1. Introduction

With the increased diurnal and seasonal mismatches between energy generation and demand, energy storage is one of the key solutions of the clean energy transition [1,2]. This is particularly true for residential and commercial heating and cooling, which is subject to large seasonal fluctuations in demand and supply. Seasonal energy storage systems such as ATES can make surplus energy from the summer months available as needed in the cold seasons (e.g., [3]). Underground geologic reservoirs provide the large volumes and geographic availability required for large-scale deployment of subsurface energy storage (e.g., [4–8]).

There are more than 2800 successful aquifer thermal energy storage (ATES) projects in the world [9], but the vast majority of these are low-temperature ATES systems (LT-ATES) with temperature < 25 °C. While HT-ATES systems (defined by [9] as storing water > 40 °C) provide the potential for higher enthalpy thermal energy storage, very few such projects have been conceived and implemented, and of these, many have been abandoned [10].

This study reviews 10 HT-ATES projects: 4 in Germany and 6 in the Netherlands (Figure 1 and Table 1). These are the two countries where the most HT-ATES projects in the world are located, and the selected projects have ample published information that facilitates a detailed review. Here we examine design concepts and identify issues that arose during development stages as well as during operations, with the objective to identify key lessons from these projects that can be used to inform and improve future efforts. Some of these projects only reached the conceptual phase, some were abandoned after initial field tests, while others are still under development or have achieved operational status. However, by now many of these projects that were put into operation have either been abandoned or suspended. This review therefore intends to identify critical issues that these projects encountered and to suggest potential solutions that could be applied to future HT-ATES projects to reduce the risk of failure, such that systems will be commercially and technically viable. This complements recent and current research efforts (such as the EU Horizon 2020 Geothermica HEATSTORE program, the EU Horizon PUSH-IT project, and the DeepStor project) focused on accelerating the deployment of underground thermal energy storage (UTES) by improving the performance and lowering the risk and cost of these systems (e.g., [11–13]).

Table 1. High-temperature aquifer thermal energy storage (HT-ATES) projects evaluated in this study.

Site	Reservoir Depth (m)	Storage Lithology	Storage Temp (°C)	Fluid TDS (g/L)	# of Wells *	Heated Water Source	Application	Project Status
Germany								
Berlin	320	Sandstone	70	29	2	CH	PBHC	Suspended
Neubrandenburg	1250	Sandstone	80–90	130	2	CH	RHC	Suspended
Rostock	13–27	Sand	50	-	2	SH	RHC	Operational
Dingolfing	500	Limestone	130	0.9	1	CH	IHC	Suspended

Table 1. *Cont.*

Site	Reservoir Depth (m)	Storage Lithology	Storage Temp (°C)	Fluid TDS (g/L)	# of Wells *	Heated Water Source	Application	Project Status
Netherlands								
Monster	160	Sand	<40	11	8	SH, CH	IHC	Operational
Delft	130–190	Sandstone	80	4.7	#	DG	PBHC	Developing
Utrecht	220–260	Sand	90	-	2	CH	PBHC	Abandoned
Zwammerdam	130–150	Sand	90	-	2	CH	PBHC	Abandoned
Waginingen	225–295	Sand	45	-	2	SH	PBHC	Operational
Middenmeer	360–383	Sand	85	17.6	2	DG	IHC	Operational

TDS—total dissolved solids; CH—cogeneration heating; SH—solar heating; DG—deep geothermal; PBHC—public building heating and cooling; RHC—residential heating and cooling; IHC—industrial heating and cooling. * Only refers to injection and production wells in HT-ATES. # HT-ATES wells have not yet been drilled.

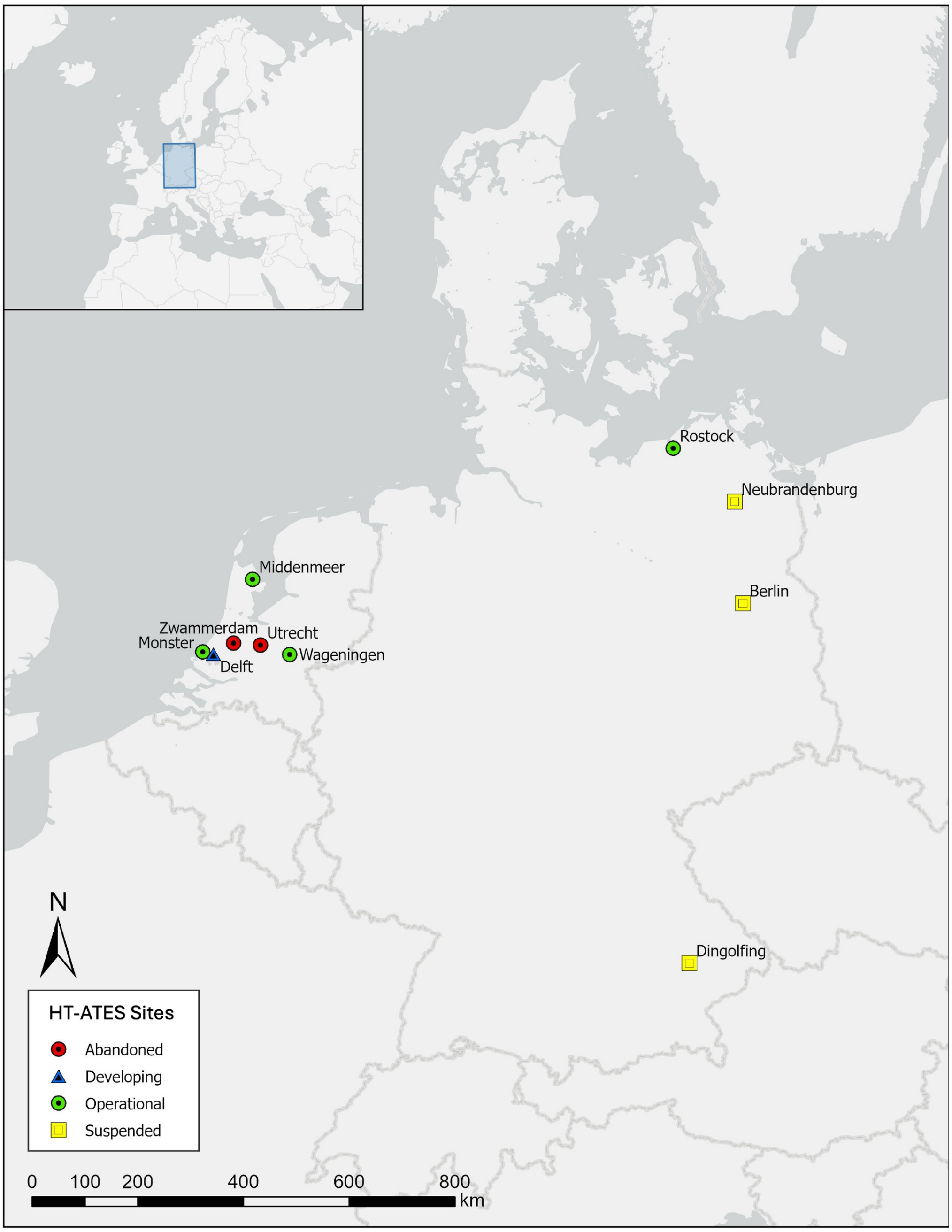


Figure 1. Map depicting locations of HT-ATES projects described in this study.

2. Potential Issues for High-Temperature Aquifer Thermal Energy Storage Projects Identified from Previous Studies

Numerous investigators have previously evaluated some of the challenges faced in the permitting, siting, design, and implementation of ATES projects (e.g., [10,14–18]). These issues fall into the following categories: (1) Non-technical issues, such as public acceptance, regulatory, permitting, and financing; (2) Technical issues, such as system design, availability of low-cost heat for storage, thermal energy recovery efficiency, mineral scaling, corrosion, and system construction and operational problems (Table 2). Fleuchaus et al. [10] performed a risk analysis of HT-ATES systems through an online survey among 38 international experts. They identified risk categories and risk items, which can also be subdivided in non-technical and technical issues. This study focuses on the technical issues encountered with HT-ATES projects.

Table 2. Issues associated with ATES projects.

Non-Technical Issues		
Issues	**Factors**	**References**
Public acceptance	Lack of familiarity; NIMBY (not in my backyard); negative publicity	[19–21]
Regulatory framework	Lack of regulations governing use of the subsurface for energy storage	[22]
Overlapping uses	Competing uses of the subsurface; concerns with contamination of drinking water aquifers	[15,22]
Financing	Lack of previous positive project outcomes hampers obtaining project financing (seen as high risk); budget overruns; project delays	[10,17,23,24]
Technical Issues		
Issues	Factors	References
Geological factors	Inadequate subsurface characterization; reservoir heterogeneity; aquitard cap integrity	[14,16,17]
Geochemical factors	Geochemistry of formation fluids and minerals; degassing caused by pump cavitation leading to scaling; precipitation of mineral phases with retrograde solubility upon heating; entry of oxygen into subsurface—can lead to mineral scaling, biofouling, and corrosion	[14,25–28]
Thermal energy recovery efficiency and system performance	System design vs. operational conditions; availability, quantity, and temperature of hot water for injection, cut-off return temperatures for used hot water	[14,16,17]
System design and construction, maintenance, and operational reliability	Design and completion of hot and cold wells; performance of downhole pumps, filters, water circulation systems, and heat exchanger	[14,16]

2.1. Non-Technical Issues

Although many of the technical components used in high-temperature aquifer thermal energy storage (HT-ATES) systems originate from established deep geothermal technologies and can therefore be considered to have a comparatively high technology-readiness level (TRL), the overall market-readiness level remains low. Only a limited number of full-scale demonstration projects have been realized to date, and the main challenges now lie in achieving long-term storage balance, ensuring reliable integration into district heating networks, and addressing a range of non-technical barriers that currently impede broader market deployment.

There are a variety of non-technical issues that can cause problems relating to siting, deployment, and operation of ATES systems. Many of these issues are highlighted by a review of risk factors associated with HT-ATES projects [10]. Public awareness and acceptance of these projects is a key requirement if large-scale deployment of these systems is to occur (e.g., [19,29]). This requires societal and community acceptance, market acceptance, and political acceptance. There are competing uses of the subsurface, so there may be concerns that an ATES system would interfere with such uses (such as drinking water aquifers), or with existing ATES projects [22]. Currently, there are no clear and specific regulations that govern the use of the subsurface for thermal energy storage, which can contribute to increased risk for project financing. The lack of a regulatory framework could also lead to suboptimal system performance if adjacent systems interfere with each other. An important concern is that improper design and operation of such a system could negatively impact drinking water aquifers by allowing deeper, more saline brines to mix with fresh water present in overlying aquifers, affecting water quality, or that the introduction of thermal energy could lead to unwanted changes in the microbiological communities or could increase the solubility of metals, also impacting water quality [15,30]. A lack of familiarity or negative publicity associated with such systems could lead to public opposition of such projects—unexpected fluid discharges, induced seismicity associated with enhanced geothermal system projects, and subsidence have resulted in negative perception of geothermal projects (e.g., [19–21,31]). Publicized failures of past projects impact the ability to obtain permitting and to secure financing for new projects, as they are deemed as risky ventures [10].

While the issues described above highlight key non-technical barriers to HT-ATES deployment, this manuscript primarily focuses on the technical aspects of system design and operation, as these have not yet been comprehensively summarized in previous work. Detailed evaluations of socio-economic, regulatory, and financial pathways to project success are currently being conducted within several German research initiatives [32,33] under the framework of the Federal Ministry of Education and Research (BMBF, GEO:N—Opportunities and Limitations of Thermal Energy Storage in Aquifers). These projects specifically address questions of legal frameworks, stakeholder acceptance, and the techno-economic integration of HT-ATES into district heating networks, where financial viability and market mechanisms play a decisive role. A comprehensive treatment of these aspects would exceed the scope of this paper; however, forthcoming results from these studies are expected to provide valuable insights into how non-technical and techno-economic challenges can be overcome to enable large-scale implementation of HT-ATES in urban energy systems.

2.2. Technical Issues

There are a number of technical issues that have to be considered and addressed for the successful design, construction, and operation of HT-ATES systems. These include thermal energy recovery efficiency and system performance, system design and construction, maintenance, operational reliability, and geological and geochemical factors. Some of these issues are interdependent. For example, the efficiency of these systems depends on the system design (which has to consider geological and geochemical factors), the operation of the system, as well as market factors such as the availability of inexpensive heated water as well as the demand for the stored energy. For these systems to be economically viable, they need to perform at a minimum threshold system efficiency and meet the projected energy supply and demand [10]. Inadequate site characterization, resulting in a mismatch between expected and actual reservoir properties, can lead to system performance issues [17]. Mineral scaling and corrosion are some of the most commonly experienced operational issues encountered by these systems [10,14]. All of these issues have to be carefully evaluated, assessed, and mitigated based on site-specific conditions and investigations [10].

HT-ATES systems tend to have much more significant issues with mineral scaling than conventional ATES systems because of their elevated temperatures. A wide range of field, experimental, and modeling studies have been conducted to evaluate the potential impacts of water–rock interaction on the feasibility of HT-ATES (e.g., [26–28,34–40]). Because of the retrograde solubility of carbonate and sulfate minerals (i.e., they are less soluble with increasing temperature), heating up a brine already close to saturation with respect to these phases can lead to the precipitation of these minerals (e.g., [41,42]). In addition, degassing of CO_2 caused by system depressurization can also lead to carbonate mineral scaling [28]. Other mineral phases can also precipitate by the mixing of different fluid compositions, or by heating or cooling processes (e.g., [42,43]). Scaling can clog wells and reduce the hydraulic conductivity of the formation by plugging pores in the formation rocks. Chemical dissolution of minerals can lead to formation collapse and subsidence—this is most prevalent with evaporitic formations containing gypsum, halite, or other highly soluble salts. Mineral transformations, such as anhydrite changing to gypsum, can be accompanied by significant volume changes, which can be problematic. For example, drilling operations for a geothermal heat pump project in Staufen, Germany, led to the transformation of anhydrite to gypsum, resulting in a volume increase and surface uplift of up to 15 cm/month that damaged historic buildings [44].

Other laboratory and field studies have evaluated how subsurface microbial communities are affected by, and in turn impact, HT-ATES systems through corrosion and biofouling (e.g., [45–51]). Processes that stimulate the metabolism of different microbial communities (e.g., iron oxidizing *Gallionella*) can lead to biofouling, thus clogging wells and the near-wellbore environment. Two microbial processes can cause low pH fluids that have the potential to corrode metal well casings: (1) the oxidation of reduced sulfur (H_2S) by sulfur-oxidizing bacteria to produce sulfuric acid and (2) the reduction of sulfate by sulfate-reducing bacteria to produce corrosive H_2S (i.e., "souring") (e.g., [35,48,50]).

Reviews of each of the HT-ATES systems examined in this study provide insights as to how these non-technical and technical issues have affected each of the projects. The following section provides details regarding the site geology, system design, system operation, and issues that have impacted these projects.

3. German Case Studies

Previous studies have examined the design, implementation, and performance of HT-ATES projects in Germany (e.g., [52–55]). This review evaluates four of these HT-ATES projects: (1) the German Reichstag Building in Berlin, (2) an energy storage system that is part of a district heating project in Neubrandenburg, (3) a system providing heating for multifamily housing in Rostock, and (4) a proposed (and now suspended) ATES project in the northeastern part of the Bavarian Molasse Basin in Dingolfing. Each of these projects is described in detail below. A review on current research on ATES systems in Germany is provided by Stemmle et al. [56] and includes eight HT-ATES systems.

3.1. Berlin

Both HT- and LT-ATES technologies have been developed to assist in the winter heating and summer cooling energy demands of the Reichstag Building in Berlin, Germany [57,58] (Figure 2). Two aquifer systems located at different depths and separated by a thick sequence of claystone aquitard layers, used as HT-ATES and LT-ATES units, form an integrated space heating and cooling system [59]. The system was designed in the early 1990s along with the refurbishment of the Reichstag Building. The stepwise operation of the system began in 1999 with the storage of thermal energy [57,60–63]. The full operation and utilization of the system commenced in 2003 with the completion of construction of all associated buildings and system integration [64]. Due to changes in systems operations, as described below, use of the HT-ATES system was suspended in 2018 [10].

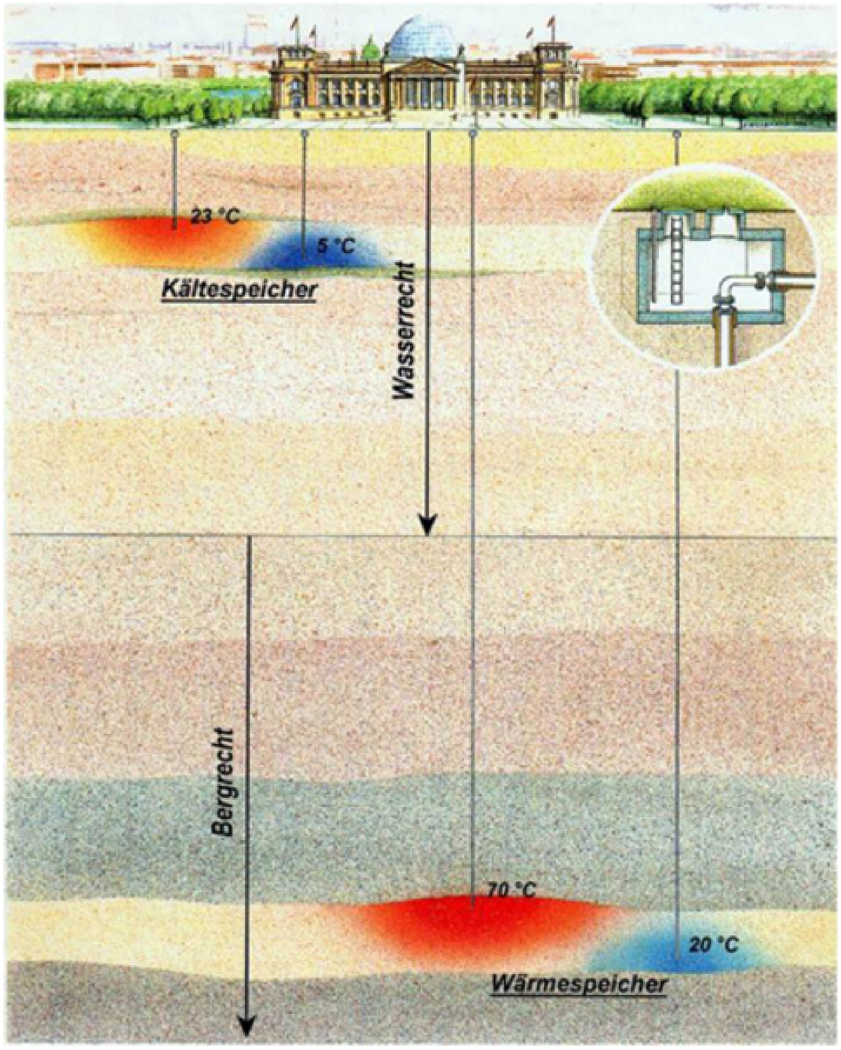


Figure 2. Diagram of the Berlin Reichstag project ATES system (https://www.geothermie.de/bibliothek/lexikon-der-geothermie/e/erdwaermespeicher-aquiferspeicher accessed on 22 October 2025). Reproduced with permission of GTN.

3.1.1. Geology

Figure 3 shows the stratigraphic positions of the aquifers associated with the LT-ATES (cold-storing aquifer) and HT-ATES (heat-storing aquifer) systems. The cold-storing aquifer consists of Quaternary sediments of glacial sands, gravel, and boulder-clay lenses located at 30–60 m depth for storing cold water used for cooling purposes. The porosity of this unit was reported to be about 30%. The deeper heat-storing aquifer consists of lower Jurassic poorly cemented, well-sorted, grayish fine quartz-rich sandstones with weakly rounded grains located between 285 and 315 m depth. The porosity of this unit is reported as 30.4% [59].

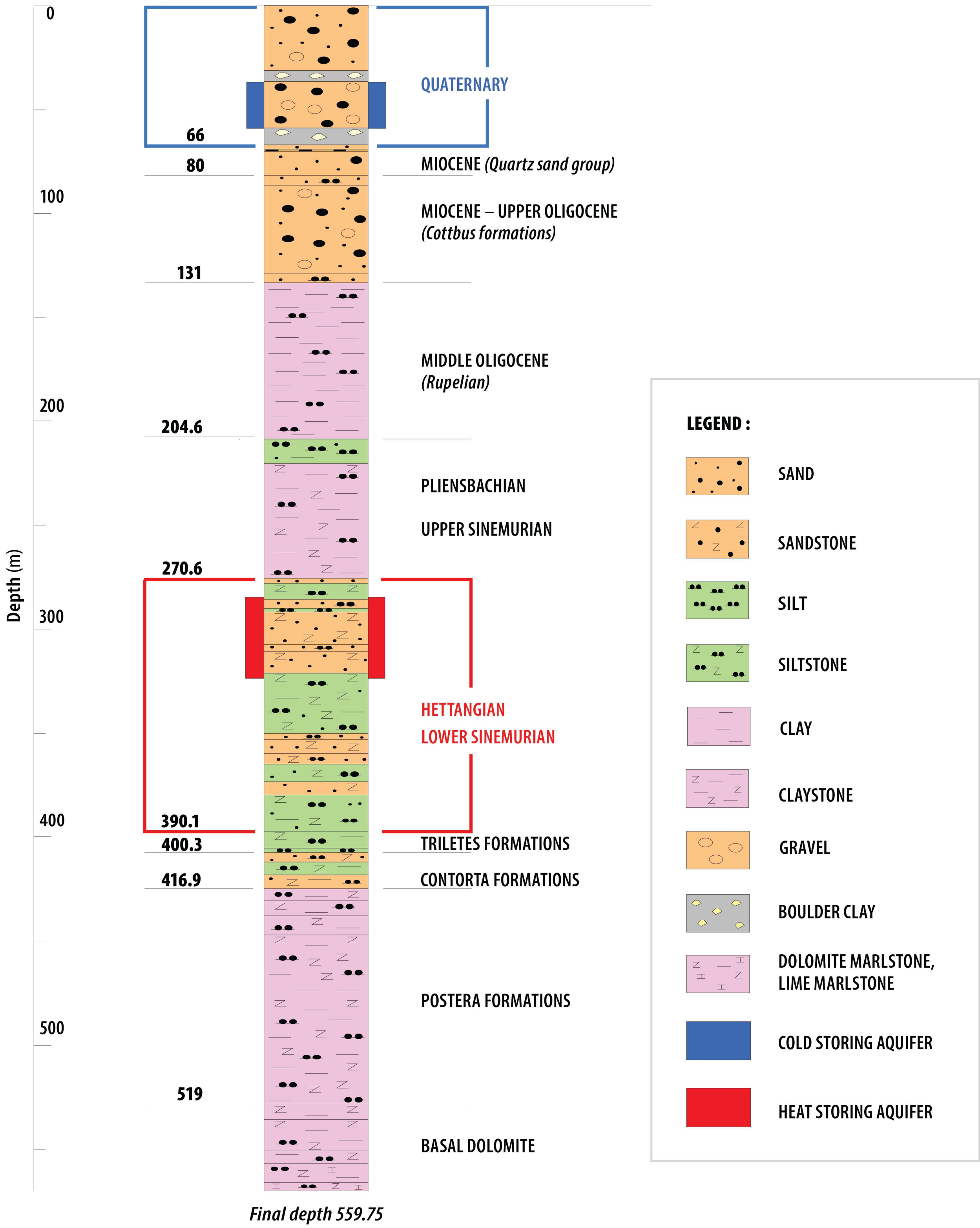


Figure 3. Stratigraphic locations of the LT-ATES and HT-ATES systems associated with the Reichstag Building, Berlin [59]. Reproduced (in redrafted form) with the permission of the International Geothermal Association.

Low-permeability aquitard layers of continuous sequences of peat, loam, and a mixture of sand and gravel occur from the surface down to the cold-storing aquifer, along with discontinuous layers of glacial till. The groundwater within the cold-storing aquifer is confined, and the piezometric water level lies approximately 2 m below ground level. The flow gradient of the groundwater is low with a general flow direction to the north, towards the Spree River. The cold-storing aquifer is underlain by Oligocene Rupel clay that serves as a thermal shield above the heat-storing aquifer as well as an aquitard layer protecting the freshwater ($CaSO_4$-type water with 600 mg/L TDS) in the cold-storing aquifer from the more saline deeper heat-storing NaCl aquifer brine (Table 3).

Table 3. Reported water chemistry for selected HT-ATES aquifer fluids. Concentrations reported in mg/L.

HT-ATES Site	Berlin	Neubrandenburg	Dingolfing	Monster	Middenmeer
Na	11,000	49,000	157	2480	5622
Ca	300	2000	43	605	419.5
Mg	250	630	27	550	526
K	50	210	14	80	95
Sr	20	97	-	7.4	18.7
Fe	1.1	12–15	-	14.9	2.4
Mn	-	0.7	-	0.5	0.2
Cl	17,000	81,000	136	6300	10,681
Br	17	98	-	-	-
SO_4	1	900–1000	16	550	1.4
HCO_3	300	165	485	375	-
TDS	29,000	130,000	880	11,000	17,600
pH	7.2	6	7.07	6.9	-
References	[65]	[47,65]	[38,66]	[67]	[41]

3.1.2. Wells

The HT-ATES system includes two 300 m deep wells (Figure 4), located about 300 m apart. These wells were being interchangeably used as the production and injection wells as dictated by the charging or discharging cycle of the system. The HT wells were installed as twin pipes within a well—one for production (with a submersible pump) and another for injection. Both production and injection strings/pipes are glass fiber-reinforced plastic tubes, with cement-casing (outer) and blocking pipe/casing for internal sheathing. The top section has an annular space (above dynamic water table) pressurized with protective gas/N_2. The bottom section of the well consists of a filter head, a wire-wrapped sand-control screen, and filter gravel [60].

The LT-ATES system consists of 14 wells; each well is 60 m in length. The LT wells are installed in two groups; 7 warm wells are located in the northern well-field, and 7 cold wells are installed in the southern well-field (Figure 4). Two well-fields are nominally located about 300 m apart, and in each well-field, individual wells are separated by about 50 m. Heat exchangers are integrated with the surface pipe system that connects the wells and allows the charging and discharging of the stored thermal energies. The HT system piping is made of glass fiber-reinforced resins (because of higher salinity and temperature) whereas the LT system piping is made of PVC. The piping for both systems is sealed, air-tight and charged with N_2 pressure (0.4 to 0.9 bar) to prevent oxygen from entering the groundwater and avoid clogging [58,64]. In addition, a nitrogen atmosphere is maintained inside the well casing to minimize oxygen entering the reservoir.

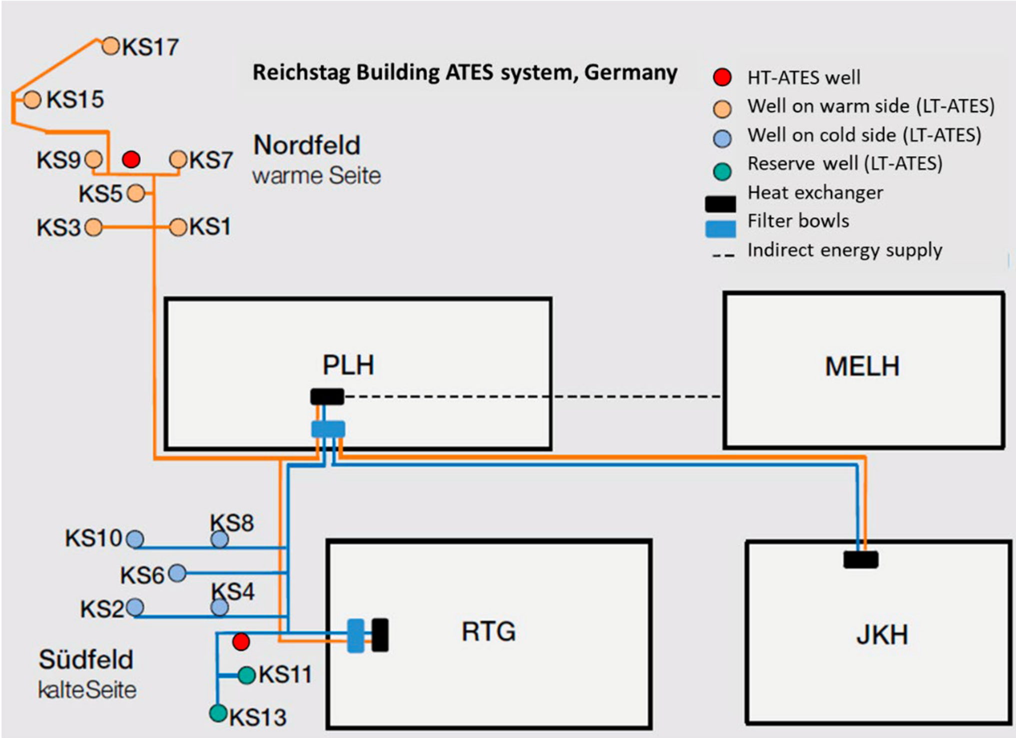


Figure 4. Schematic map showing HT-ATES and LT-ATES wells at the Reichstag Building, Berlin. PLH = Paul Löbe house, RTG = Reichstag Building, JKH = Jakob Kaiser house, MELH = Marie Elisabeth Lüders house. Modified from [64]. Reproduced with permission of DVGW energie | wasser-praxis and GTN.

3.1.3. Charging/Discharging of Thermal Energy

During the summer months, the surplus heat from four cogeneration bio-diesel engines is fed through the warm well into the hotter side of the HT aquifer as a brine heated to 70 °C. Wintertime energy discharge occurs by pumping out brine at 30–65 °C to supply low-temperature heat to buildings. After the heat extraction, the cooler brine is injected back into the HT aquifer at the colder side of the aquifer through the cold well. The production/injection rate of the HT system can be up to 100 m^3/h.

During the design phase, it was assumed that the surplus heat from the cogeneration system and the stored hot water in the HT system could meet 90% of the annual heat demand for the buildings [59]. However, over the years of operation, it became apparent that the surplus heat available during the summer months was not enough to charge the HT aquifer. The poor availability of surplus heat was caused by the higher demand for cooling during summertime as the excess heat from the cogeneration plants was preferentially used to operate the absorption cooling system rather than recharging the HT aquifer, resulting in reduced operational efficiency. The sustained use of low-grade heat during the summer as well as an oversized HT reservoir system did not help maintain the design temperature and the HT-ATES system was shut down in 2018 [10]. However, it is expected that this shutdown would be temporary, and with the addition of other buildings and heat sources the system could be operated again.

During the winter, the LT aquifer is charged with the injection of 5 °C water cooled in cooling towers by ambient cold. Wintertime charging/recharging helps bring the storage temperature down to 6–10 °C. During the summer months, the stored cold water is being produced at 6 to 10 °C, and after heat transfer to cool the buildings, a warmer (15 to 28 °C) water is injected back into the warmer side of the LT aquifer. The production/injection rate of the LT system can be up to 300 m^3/h.

Kranz and Bartels [68] and Kranz and Frick [63] modeled the performance of the Reichstag ATES system. They calculated annual heat recovery factors for the system ranging from 0.53 to 0.76, discounting the 2006–2007 season when the HT system was not operational. Their simulations indicate that for the existing combined (LT-ATES and HT-ATES) storage system, the energy recovery factor could be improved by the following methods:

(a) Increasing the storage temperature for the warm wells;
(b) Lowering the injection temperature for the cold wells;
(c) Increasing the total volume of circulated groundwater;
(d) Increasing the amount of stored thermal energy.

Kranz and Frick [63] determined a coefficient of performance up to eight for the cooling energy provision. Furthermore, they also demonstrated that an efficiency improvement could be achieved by adjusting operating parameters.

3.1.4. Thermal, Geochemical, and Microbiological Modeling and Monitoring

Müller and Regenspurg [36] conducted a series of leaching experiments under reducing and oxidizing conditions using two rock samples obtained from one of the ATES boreholes. One of the samples, from the Hettangian sandstone, represents the rock from the HT-ATES reservoir—it is a quartz arenite (95%) sandstone with 1–2% K-spar, muscovite, and kaolinite, with minor amounts of rutile, ilmenite, pyrite, iron hydroxides, and trace amounts of organic matter. Synthetic brines with compositions similar to those found in this aquifer were used to conduct leaching tests at temperatures ranging from 25 to 90 °C, and under reducing and oxidizing conditions. In these laboratory experiments, pyrite was observed to dissolve under oxidizing conditions, accompanied by a reduction in pH (which accelerated the dissolution of amorphous phases), while iron hydroxide dissolved under anoxic conditions. These dissolution reactions increased with increasing temperature. Filters on the HT-ATES wells were observed to have precipitated iron–copper sulfides, consistent with pyrite dissolution [36,48]. Filter plugging and biofilm development were also observed for the LT-ATES wells, which was in part attributed to microbiological activity [48,64,69,70]. The effect of oxidation has been mitigated by using nitrogen (instead of air) as a headspace gas in the wellbores [64].

3.1.5. Lessons Learned

The original design of the HT-ATES reservoir was oversized relative to the amount of hot water being recharged to the system, so that anticipated system efficiency was never achieved, leading to this portion of the thermal energy storage being shut down in 2018 [10]. As mentioned above, the HT-ATES system became even less efficient over time, because the need for thermal water to power the absorption chiller units for cooling during the summer months meant that water of lower thermal quality was injected into the hot reservoir during this time. There were some operational issues with pumps and pipes; a breakdown of the submersible pump resulted in the HT-ATES not operating during the winter of 2006/2007 [68]. Having a single doublet well system makes the system more vulnerable to failure and required the use of a backup system to provide heating, which added additional cost. The use of nitrogen helped mitigate potential geochemical issues that might have resulted from introducing oxygen into the reducing reservoir environment. The two main issues for the Berlin HT-ATES system were the following: (1) the initial system design led to low system efficiencies, and (2) modifying the operation of the overall system (in response to changes in needs for heating and cooling) affected the efficiency of the HT-ATES system.

3.2. Neubrandenburg

The HT-ATES system in Neubrandenburg was developed from a pre-existing geothermal heating system that was commissioned in 1989, with four wells drilled to depths of 1150 to 1250 m [52,65,71–75]. This system was used to supply a district heating system and was supplemented with a gas and steam turbine cogeneration plant (77 MW_e and 90 MW_{th}) that was commissioned in 1997 [52,76]. The geothermal wells produced water with temperatures of about 50–55 °C and flow rates of up to 100 m^3/h. However, corrosion of pipes from exposure to oxygenated geothermal brines resulted in decreased injectivity, leading to the closure of the system in 1998. A decision was made to convert the geothermal heating system into a HT-ATES system, where excess heat produced by the cogeneration plant during the summer could be stored in the geothermal reservoir, resulting in higher temperature geothermal fluids being produced during the winter months. Two of the existing wells were deepened and recompleted to form a doublet and configured with a heat exchanger for a smaller district heating system (Rostocker Strasse) connected to a thermal load of 12 MW [65,74,76]. A schematic diagram of the system is depicted in Figure 5. The HT-ATES system was operated until 2019, when the public utility moved to an artificial storage tank to balance short-term differences in supply and demand [10].

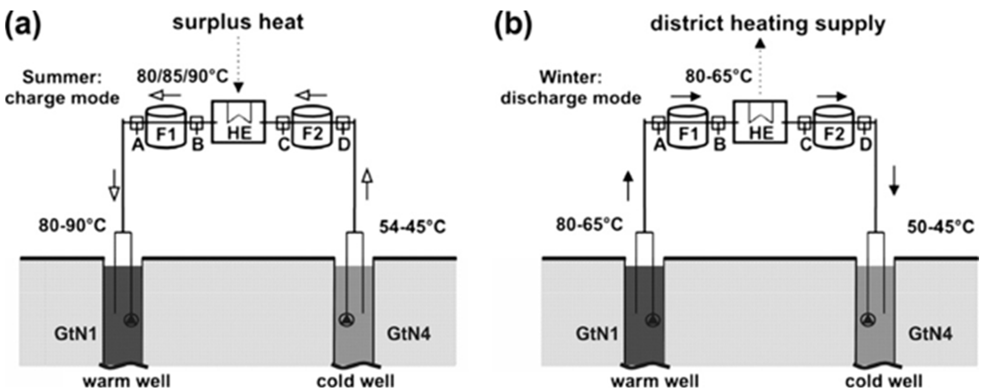


Figure 5. Schematic model of the HT-ATES system at Neubrandenburg, depicting (**a**) summer charging and (**b**) winter discharging modes [49]. Reprinted from Organic Geochemistry, v. 53, Vetter et al., Fluid chemistry and impact of different operating modes on microbial community at Neubrandenburg heat storage (Northeast German Basin), Copyright 2012, with permission from Elsevier.

3.2.1. Geology

Both the Berlin and Neubrandenburg HT-ATES systems are situated within the North German sedimentary basin [77]. The Neubrandenburg wells tap into a reservoir formed by the Triassic upper Postera sandstone, also known as the upper Keuper or Rhaetian reservoir complex. The sandstone is part of a fluvial and deltaic depositional system, and is quartz-dominated, with plagioclase and microcline, and lesser kaolinite, illite, glauconite, chlorite, smectite, muscovite, and some carbonaceous fragments associated with minor pyrite. The sandstone contains diagenetic cement consisting of siderite, calcite, dolomite, and anhydrite. The sandstones are channel-like deltaic deposits, located at a depth of around 1230–1270 m, with porosity values ranging from 20% to 25% and a formation temperature of 54 °C [49,50,52,78]. The formation fluids are reduced Na-Cl brines with ~130,000 mg/L TDS (Table 3).

3.2.2. Wells

The HT-ATES consists of a doublet well system, consisting of two wells (GtN 1/86—hot well and GtN 4/86—cold well) spaced ~1300 m apart, with the warm well having a depth of 1285 m and the cold well having a depth of 1270 m [51,52,73,74]. The original geothermal wells were reconditioned with glass fiber-reinforced casing, new wellheads, new submersible pumps, and completed in the upper Postera using a gravel pack and a 11.43 cm screen. The cold well, which had originally been completed in a slightly shallower sandstone unit (the Hettangian), was deepened, and the previously perforated zone was sealed with a 17.8 cm liner [73,74]. Because flow directions are reversed seasonally, both wells are equipped with pumps, production and injection pipes, and filter systems. A filter system was installed upstream of the heat exchanger to retain solid particles transported from the production well. The wells have a reported average flow rate of 80 m^3/h, with a maximum flow rate of 100 m^3/h; well flow rates were reported to range from 20 to 60 m^3/h upon system restart [50–52].

3.2.3. Charging/Discharging of Thermal Energy

As depicted in Figure 5, excess heat from a public utilities gas/steam cogeneration plant was used to heat water produced from the cold well during the summer months. The temperature of the water injected into the hot well varied over time, ranging from 80 to 90 °C as operational procedures were modified; this heat source could provide up to 4 MW of thermal energy, and could deliver up to 8600 MWh_{th}/year during the winter months [49,52]. During the winter months, the flow direction of the wells was reversed, as hot water was retrieved from the hot well, passed through the heat exchanger, and cooler water (45–54 °C) was injected into the cool well. The wells and the surface facility were maintained under nitrogen pressure (~10 bar) to reduce scaling, degassing, and minimize the possibility for oxygen to enter the system [51].

Several analyses were conducted to evaluate the overall system performance. Seibt and Kabus [52] reported a thermal energy recovery coefficient of 72% for the system based on the early performance results; however, Kabus et al. [76] reported a lower value of 46% using the results from three years of operation from 2005 to 2008, and attribute this decrease to adoption of energy-saving measures adopted by consumers of the stored heat that resulted in a reduction in the energy demand and reduced the effectiveness of the system. By storing excess heat produced by the cogeneration plant in the summer, the HT-ATES nearly eliminated the need for the peaking boiler system (powered by fossil fuel) to provide extra heat to the district heating system during the winter months. The district heating system went from obtaining about 50% of its heating needs from the boiler prior to the installation of the HT-ATES, to relying on it for less than 1% in 2007–2008. Initial estimates suggested that the use of the HT-ATES system could eliminate the emission of 1550 t of CO_2 per year [71].

Fleuchaus et al. [10,55] reported that the HT-ATES system was shut down at the beginning of 2019 after the public utility of Neubrandenburg decided to switch from long-term to short-term thermal energy storage, where excess hot water generated by the combined cycle gas turbine cogeneration plant would be stored during the summer weekdays in an artificial storage tank for use during the weekends. They noted that the idled geothermal wells might be used for direct-use heating rather than for thermal energy storage in the future.

3.2.4. Thermal, Geochemical, and Microbiological Modeling and Monitoring

One key operational question was what maximum operational injection temperature could be achieved without causing scaling issues in the wells and reservoir, as injecting higher temperature water would result in increased thermal energy storage and potentially more efficient operation of the district heating system. Geochemical monitoring was conducted by analyzing the water chemistry for one of the seasonal flow cycles with samples collected monthly to look for possible changes in pH, Eh, conductivity, oxygen content, temperature, alkalinity, Fe, Mn, NH_4, and Si [78]. Only minor changes in concentrations in the primary constituents were observed whereas larger variations were observed in Zn and Fe concentrations. The mineralogy of grains caught in the filters were also routinely studied; these consisted of ~60–70% clay minerals (kaolinite, chlorite, illite), ~10% pyrite, ~10% iron oxide/hydroxide, ~5% quartz and minor feldspar, calcite, anhydrite, and aragonite [78]. Of these phases, the occurrence of carbonates, pyrite, and Fe oxide/hydroxide minerals were attributed to processes related to the thermal storage. Modeling was conducted to predict the geothermal discharge temperature over a four-year period. Geochemical modeling to evaluate the operation of the system at temperatures > 80 °C suggested that silica would dissolve on the hot side and amorphous silica might precipitate after injection in the cold well [76]. However, silica would be mostly mobilized from the dissolution of clay minerals, which are not abundant in the rock (see Section 3.2.1), suggesting that injection temperatures could potentially be increased to 90 °C.

Several microbiological studies were conducted on the Neubrandenburg HT-ATES system to characterize the biota of the cold and hot wells and to evaluate their interactions and impact on the system [47,49–51,70,78,79]. A bypass system was installed to monitor fluid chemistry, physical fluid parameters, pH, redox potential, and conductivity [50]. Samples were collected to monitor microbiology and solids formation, and steel coupons were exposed to brine to evaluate corrosion. The microbial activity led to the generation of iron sulfide scale, and to the formation of biofilm on metal surfaces. The growth of sulfate-reducing bacteria was linked to colder environments, whereas stagnant conditions during system downtime (perhaps allowing some influx of oxygen into the wells through leaking equipment) led to increases in both sulfate-oxidizing bacteria and sulfate-reducing bacteria that appear to be related to increased corrosion [51]. In addition, microbially mediated corrosion processes affected the operational reliability of the plant, resulting in outages due to problems with the submersible pumps [10]. Corrosion damage to the submersible pump caused the system to be out of service from May to July 2006, May to Dec. 2008, and again in 2009 and 2011 [47,51,76].

Several different approaches were used at Neubrandenburg to mitigate scaling and corrosion issues. Decreased injectivity in the cold well was attributed to microbially induced scaling, which was remediated through injection of acid into the well [75]. The use of nitrogen gas to mitigate oxidation seemed to have prevented many of the problems that occurred in the geothermal wells prior to their conversion to the HT-ATES system. Another method proposed to improve systems performance was the "thermal shocking" of biofilm surfaces. Field tests conducted by flowing hot water over metal coupons for a short period detected much less biofilm formation. These observations suggest that intermittent short-term discharge of hot water into the cold well by bypassing the surface heat exchanger may be an effective mitigation strategy [79].

3.2.5. Lessons Learned

While the Neubrandenburg HT-ATES system performed fairly well, changes in the supply and demand of heat ultimately led to its demise [10,55]. These changes included the following: (1) Energy-saving measures reduced the thermal energy demand over time; (2) The baseload power system was augmented by the addition of a sewage gas-powered cogeneration plant, which also impacted the need for geothermal water for heating; (3) Operational issues related to corrosion impacted the submersible pumps and resulted in significant downtime during four different years.

Several design and operational features helped mitigate potential issues. The use of nitrogen reduced the amount of oxygen entering the system impacting subsurface microbial communities and associated corrosion and scaling issues. The use of acid treatments to the wells appears to have improved well injectivity. Field tests also suggested that thermal shocking of the cold well could help reduce biofilm formation. However, the resolution of these operational issues was overshadowed by the changing thermal energy needs of the local utility company.

3.3. Rostock

In 2000, the first ATES system coupled with a central solar heating system began operation in Rostock-Brinckmanshöhe outside of Brinckmansdorf, Germany, as a demonstration project [52,57,80–87]. It was one of a number of hybrid solar-assisted heating seasonal thermal energy storage projects developed as part of the German research program "Solarthermie-2000" [82,85,88]. The system is used for space heating and hot water preparation for an apartment complex of 108 units. The system includes a 980 m^2 solar collection system on the rooftops of the buildings along with a doublet well system extending 30 m into the reservoir (Figure 6). A heat pump is integrated into the heat supply system for the preparation of returning the fluid to a useable temperature.

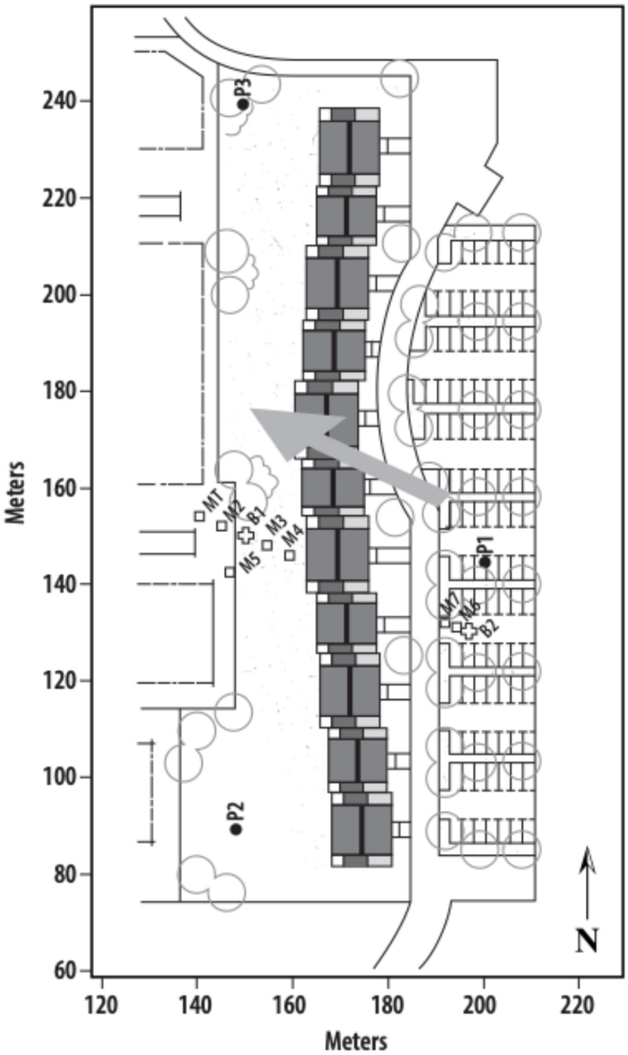


Figure 6. Map showing the Rostock-Brinckmanshöhe apartment complex with solar roofs and the location of the HT-ATES wells, indicated by cross symbols (B-1 and B-2) along with temperature monitoring holes, indicated by square symbols (M-1 to M-7) in Brinckmansdorf, Germany [81]. The arrow shows the direction of groundwater flow. Reproduced (in redrafted form) with the permission of the Secretariat of the International Energy Agency Energy Storage TCP and Dr. Thomas Schmidt.

3.3.1. Geology

The HT-ATES reservoir is located at a depth of about 15–25 m in Quaternary sediments consisting of feldspar-bearing quartz sands. The aquifer is overlain by a 12–17 m thick unit of glacial till consisting of boulders and clay, and itself overlies a 2.5 m thick unit of boulder clay described as silty, clayey fine sand [52,57,84]. The aquifer has a porosity of ~25%, with a reported hydraulic conductivity ranging from 6 to 9×10^{-5} m/s [52,82]. The aquifer unit also has a reported mean volumetric heat capacity of 2.7 MJ/m^3K and a mean thermal conductivity of 3.2 W/mK [82]. The initial reservoir temperature is 10 °C, and the groundwater is reported as being freshwater; no details regarding the water chemistry are given [52]. However, Fleuchaus et al. [10] reported that this project was given a special permit to allow operations due to high salt concentrations in the aquifer. The reservoir volume is estimated to be 20,000 m^3 [80].

3.3.2. Wells

This HT-ATES consists of a well doublet (hot well and cold well) with wells spaced 55 m apart and drilled to a depth of ~30 m [52,81,82,84]. Because the flow in the wells reverses direction seasonally, the wells both contain a downhole pump for production and a shallower injection pipe. The wells were completed with a gravel pack and a screen in the reservoir interval [80]. The design flow rate is 15 m^3/h. The portion of the wells above the groundwater level contains pressurized nitrogen to minimize the entry of oxygen into the system [82].

3.3.3. Charging/Discharging of Thermal Energy

The HT-ATES system is charged by water heated in the rooftop solar array (Figure 7). The water is delivered to a 30 m^3 storage tank—any excess hot water from this system is then injected during the summer into the HT-ATES hot well. A heat pump is integrated into the system, and a gas condensing boiler provides any additional heat requirements for the building complex that cannot be met by the solar and HT-ATES system [82].

Figure 8 depicts the charging and discharging heat balances and the hot and cold well temperatures in 2002 and 2003 [82]. Note that charging of the system (using water heated to 50 °C) occurs between March and October, with the retrieval of the stored thermal water for use in the district heating system during the winter months (January to March and October to December).

The amount of thermal energy stored and retrieved during the operation of the Rostock system in 2003 is depicted in Figure 9; just under half of the thermal energy that was injected into the HT-ATES (143 of 295 MWh_{th}) was retrieved and used for space heating and preheating of tap water during this year [82]. Note that the thermal performance of the system varies dramatically from year to year (Figure 10), with thermal recovery factors ranging from 24% to 87% [85,86]. The low thermal recovery factors observed for 2006 and 2007 can be attributed to a failure of a submersible pump during the winter of 2006–2007. The system thermal losses were higher than expected for the planned thermal recovery of the system and have been attributed to the relatively small size of the HT-ATES system [85,88].

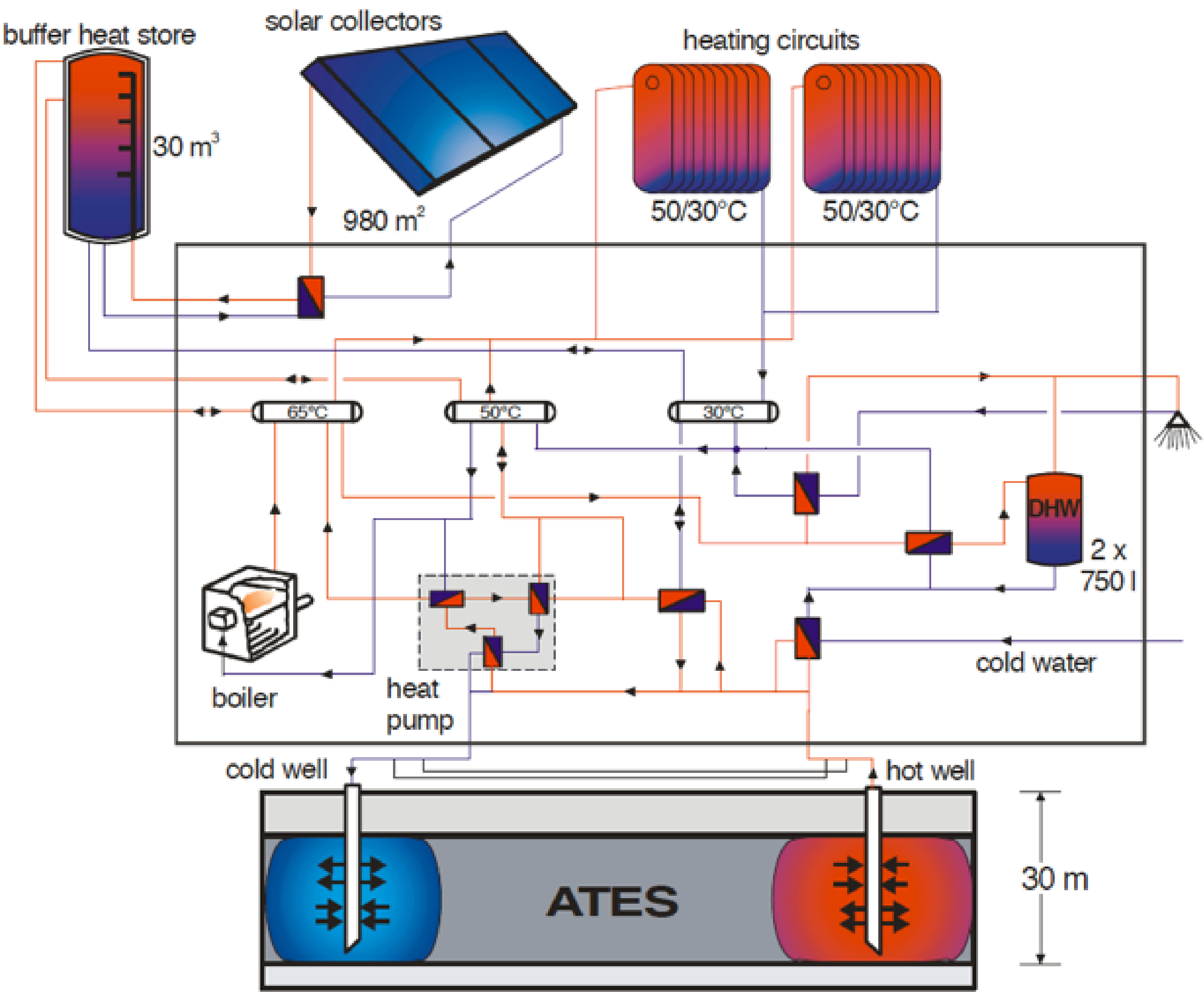


Figure 7. Schematic of the ATES system in Rostock [82]. Reproduced with the permission of the International Solar Energy Society and Prof. Dr. Müller-Steinhagen.

Yang et al. [89] performed a levelized cost of heat (LCOH) analysis for a number of seasonal thermal energy storage projects, including Rostock. They obtained a value of 264 EUR/MWh_{th} for this project using economic data reported by Schmidt and Müller-Steinhagen [82]. This is towards the high end of the range of 51 to 434 EUR/MWh_{th} for all of the different types of studied seasonal thermal energy storage systems, and significantly higher than heating energy costs estimated for solar and natural gas heating, which fall below 100 EUR/MWh_{th}. One reason for the high LCOH was the high price of the solar collectors used for this project—they were about 50% more than the average market price. This was due to the collector arrays being specifically designed as solar roofs [90]. Adjusting for this, Yang et al. [86] estimate a normalized LCOH of 229 EUR/MWh_{th} for the Rostock project, which is comparable to other reported values [24]. The thermal storage component was estimated to have a LCOH of 155 EUR/MWh_{th}—this is a bit surprising given that the two operational wells for this system are very shallow (30 m), so the cost of drilling and completing the wells should be fairly minor, but other system components (as well as the extensive monitoring system) may have added to this cost. More details on the costs of the different components for this project can be found in Benner et al. [91].

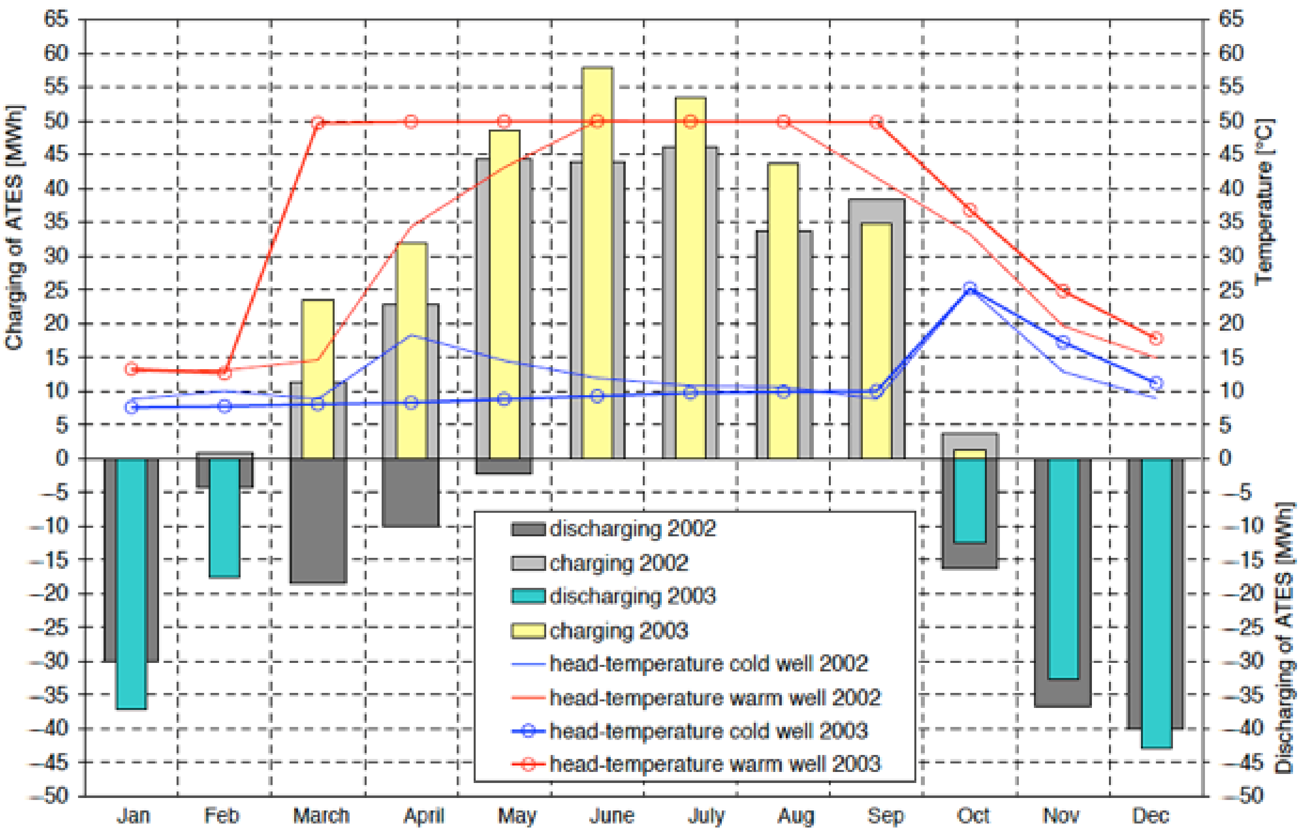


Figure 8. Heat balances and well temperatures for the Rostock HT-ATES system for the years 2002–2003 [82]. Reproduced with the permission of the International Solar Energy Society and Prof. Dr. Müller-Steinhagen.

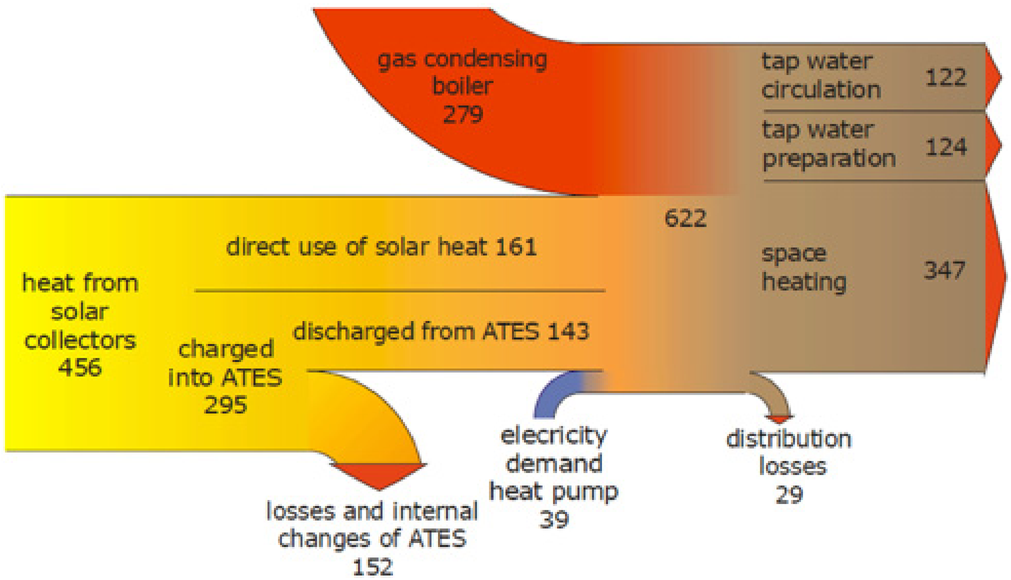


Figure 9. Energy flow diagram (with arrow widths proportional to energy amounts) for the Rostock solar HT-ATES district heating system for the year 2003. Numbers indicate MWh_{th} for each component of the system [82]. Reproduced with the permission of the International Solar Energy Society and Prof. Dr. Müller-Steinhagen.

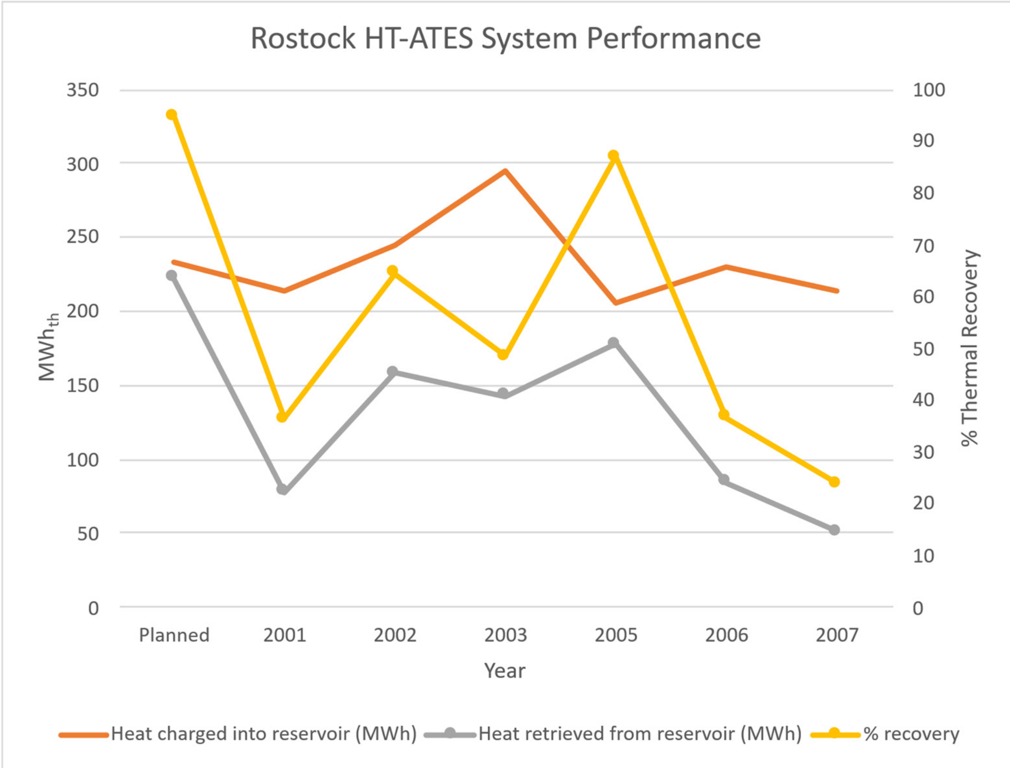


Figure 10. Planned and annual amounts of solar heat charging for the HT-ATES in Rostock, heat retrieved from the reservoir, and the percent thermal recovery. Data from [85,86]. No data were reported for 2004.

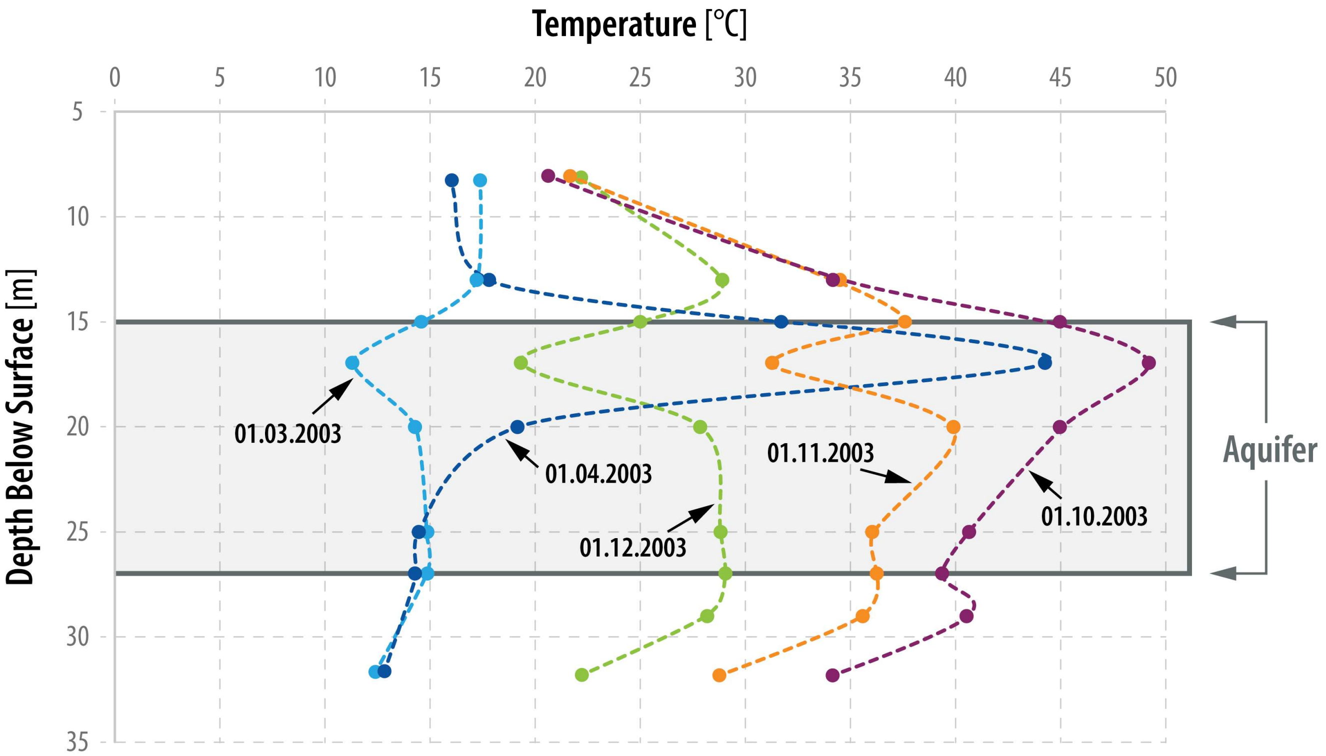
3.3.4. Thermal and Geochemical Modeling and Monitoring

The Rostock demonstration project was highly instrumented to facilitate monitoring of the system using a series of seven monitoring wells with more than 50 temperature sensors to detect any thermal and geochemical changes [72–80].

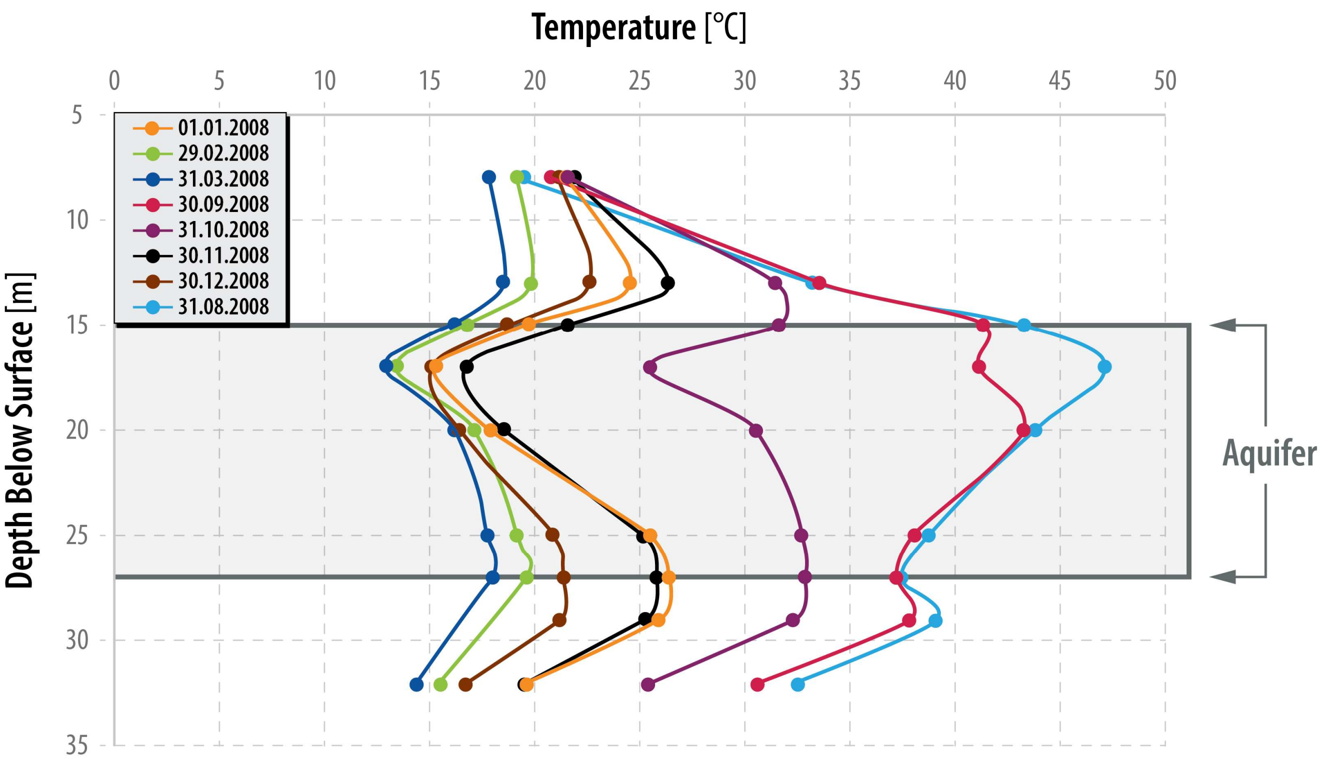
Hydraulic and thermal characterization data from the thermal aquifer were used to construct a thermal-hydraulic (TH) model to predict the size of the thermal reservoir around the hot well during operation, which would help determine the proper spacing between the two wells [80,84]. The numerical model, developed using the code FEFLOW, was used to simulate the thermal behavior of the system and compare model results with observations from monitoring boreholes [81]. The model suggests that temperatures above 30 °C are restricted to a zone with a thickness and width of about 25 m after 1 year of operation.

Figure 11 depicts two series of temperature profiles measured during 2003 and 2008 in a monitoring well located 5 m down gradient from the hot well. It shows some vertical heterogeneity in the aquifer permeability, with increasing temperatures as the hot well portion of the reservoir is charged during the summer, and exhibits cooler temperatures as hot water is withdrawn during the wintertime [82,85].

Schmidt et al. [80] note that the heating of the HT-ATES was limited to 50 °C to avoid changes in groundwater chemistry that might cause scaling. Schmidt and Müller-Steinhagen [82] mention that geochemical monitoring has been performed by Geothermie Neubrandenburg but no results are reported. Schmidt and Müller-Steinhagen [82] did report a breakthrough of groundwater to the surface at the cold well during a time of high flow rate in February of 2001 attributed to the screen in the well being blocked and a resultant elevated pressure in the wellbore. The flow was reduced by 20% until the screen was cleaned and new piping installed in the well in August of 2002.



(**a**)



(**b**)

Figure 11. Measured temperatures in the Rostock HT-ATES aquifer at a distance of 5 m from the hot well in the groundwater flow direction at different dates in (**a**) 2003—[82] and (**b**) 2008—[85]. Reproduced with the permission of the Secretariat of the International Energy Agency Energy Storage TCP, the International Solar Energy Society, and Prof. Dr. Müller-Steinhagen.

3.3.5. Lessons Learned

Rostock is the only HT-ATES system in Germany among those studied here that is still in operation. The annual performance of the system has varied significantly from year to year—these variations can be attributed to differences in energy supply and demand as well as operational issues with a leaking well and submersible pumps. In general, the system has been reported to have experienced relatively minor operational issues. The system is small in size, and due to mitigation measures (such as using nitrogen to prevent the influx of oxygen into the aquifer) has had just one reported scaling problem that impacted system performance (plugging of the well screen in the cold well in 2001)—the resulting discharge of water into the unconfined surface aquifer may have been averted with more robust well completion or with pressure monitoring. Failure of a downhole pump did result in major downtime during one winter season (2006–2007), which significantly impacted its ability to recover and use stored thermal energy during this period.

3.4. Dingolfing

Ueckert et al. [66,92] and Ueckert and Baumann [38] describe the field and modeling evaluation of the conceptual design of a proposed HT-ATES system in Dingolfing, in the vicinity of Munich, Germany [53]. Supported by the Bavarian State Ministry for Economic Affairs and the BMW Group, a series of single well push–pull tests were conducted to evaluate the design. The proposed ATES system would be coupled with seven combined heat power (CHP) plants producing 31 MW_e and 27 MW_{th}. To accommodate the excess thermal energy, groundwater was planned to be pumped at a rate of 60 kg/s, heated from its ambient 22 °C to 130 °C, and reinjected for storage. The initial conceptual doublet design for the project, shown in Figure 12, consists of a hot well and a cold well that would be operated at 80 L/s.

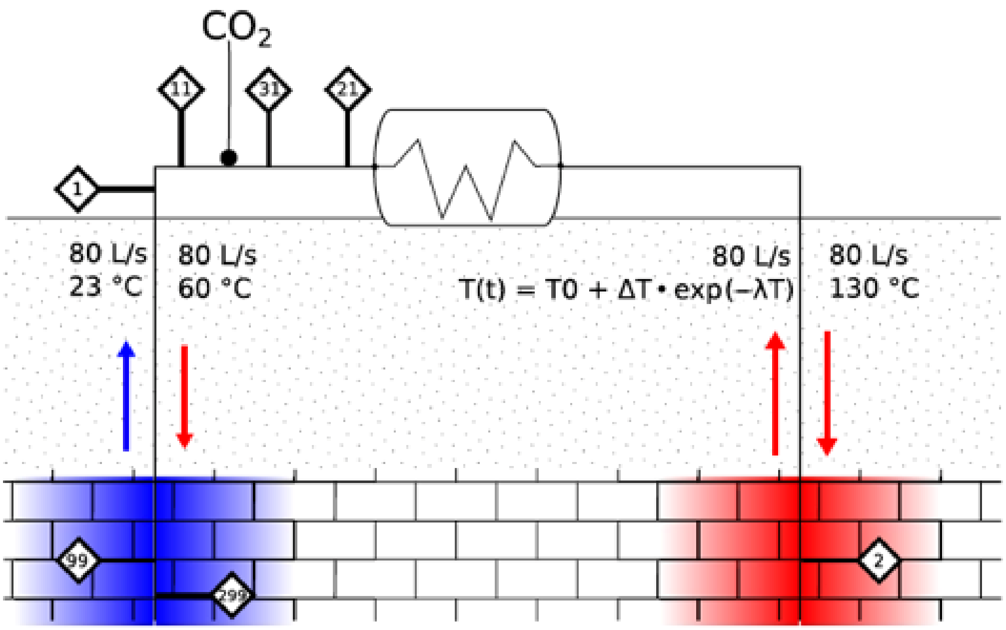


Figure 12. Conceptual model of original doublet system, consisting of hot and cold wells (blue arrows indicate cold water flow while red arrows indicate hot water flow) [38]. Reproduced under the terms of the Creative Commons CC BY license.

3.4.1. Geology

The project, located in the northeastern Bavarian Molasse Basin, targeted the highly transmissive (0.1 m^2 s^{-1}) upper Jurassic karstified carbonate (limestone, dolomite, and dolomitic breccia) Malm aquifer. The top of this aquifer was encountered at a depth of 244 m. The carbonate is capped by a thick (110 m) impermeable unit consisting of claystones and marlstones [38]. The reservoir fluid is a fairly dilute Na–HCO_3–Cl water (Table 3) with a formation temperature of 22.7 °C [38,66]. The carbonate aquifer flowed freely with rates up to 19.4 L/s and flowmeter logs indicated significant vertical heterogeneity, likely associated with variations in fracture permeability within the aquifer.

3.4.2. Wells

In order to collect field data to evaluate the design concept, a 472 m test well was drilled and encountered the Malm aquifer at a depth of 244 m [38]. Between October and December 2014, five push–pull tests were conducted to assess the suitability of the aquifer for HT-ATES (Figure 13). In these tests, progressively hotter (initial test 60 °C and final test 110 °C) tap water, amended with CO_2 to suppress the precipitation of carbonate minerals, was injected at a rate of 15 L/s for periods of 48 to 60 h, followed by production at a rate of 15 L/s for periods of 36 to 96 h. These tests were supported by thermal and geochemical modeling and laboratory studies to assess the energy balance and geochemical processes occurring during the tests [38,92].

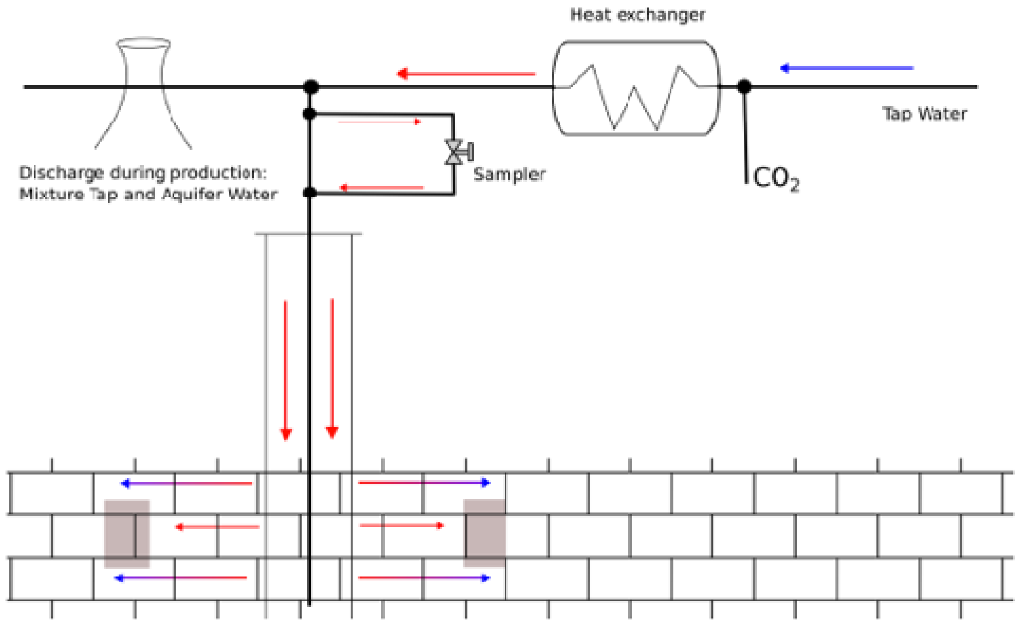


Figure 13. Setup of the heat storage push–pull test in Dingolfing [92]. Arrows depict the injection (push) part of test—the direction of the arrows is reversed when the well is discharged. The blue and red arrows represent cold and hot water flow, respectively. Reproduced under the terms of the Creative Commons CC BY license.

3.4.3. Charging/Discharging of Thermal Energy

Analysis of the push–pull tests indicated that water mixing within the aquifer occurred and resulted in an overall 48% energy recovery, which did not meet project expectations and was lower than predicted by 3D thermal modeling. The fourth stage of the push–pull test had an injected power of 5.5 MW_{th} (with an injection rate of 15 L/s and an injection temperature of 110 °C), but a thermal recovery of only 1 MW_{th} (Figure 14). These results, when projected to long-term operation, suggest that longer and/or increased numbers of charging cycles would be required thus increasing the virtual volume of the ATES system [38].

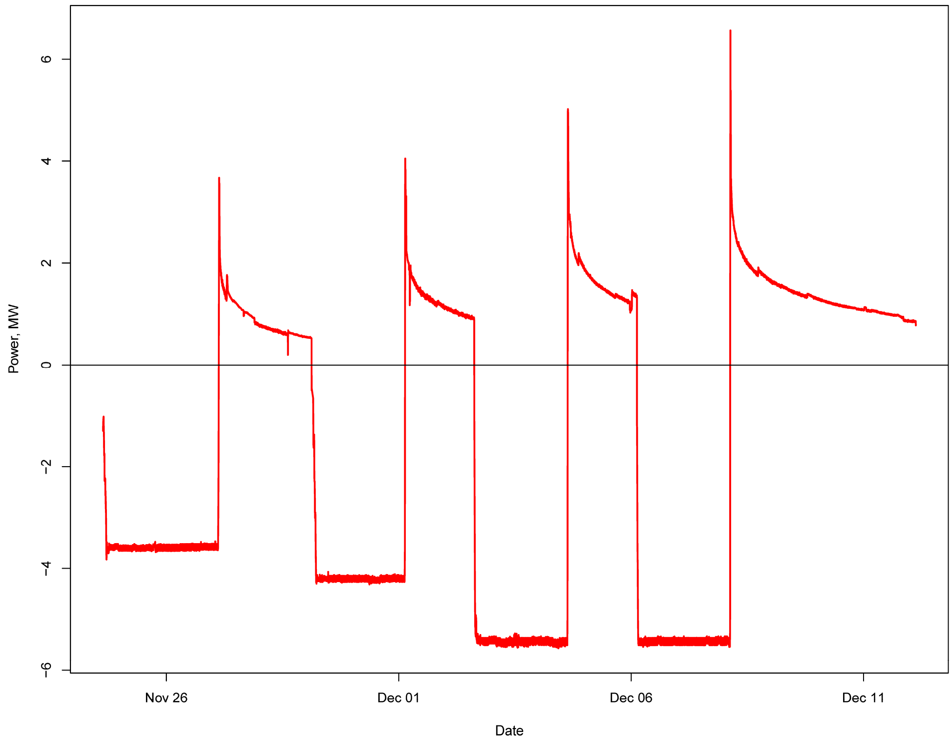


Figure 14. Injected and recovered thermal energy during the push–pull heat storage test [38]. Reproduced under the terms of the Creative Commons CC BY license.

3.4.4. Thermal and Geochemical Modeling and Monitoring

Laboratory and field tests indicated that the addition of CO_2 to prevent carbonate scaling during operation was an effective treatment [92]. Geochemical modeling using PHREEQC was used to predict the amount of CO_2 required as well as predicting the extent of aquifer matrix dissolution occurring in the cold well. Detailed studies by Ueckert et al. [92] assessing carbonate mineral precipitation suggest that $CaCO_3$ nuclei (calcite at $\leq$90 °C and aragonite at 110 °C) were present in the circulating water but that crystallization (and potential clogging) was inhibited by turbulent flow. Additional studies by Wanner et al. [28] found that potential pump cavitation and the formation of a free gas phase (i.e., boiling) were the likely causes of carbonate scaling in Malm aquifer geothermal wells. This observation indicates that careful attention to operating conditions (e.g., pumping rates) would be necessary for successful scale-free operation of the proposed ATES system.

Although the addition of CO_2 was effective in preventing carbonate scaling in the push–pull tests, forward long-term modeling showed that increasing amounts of CO_2 would have to be added during each operation cycle resulting in the dissolution of carbonate mineral in the aquifer, associated undesirable groundwater hardening at the cold well, and degradation of the ATES performance and lifetime [38]. The groundwater hardening could be alleviated by CO_2 stripping prior to the injection of water into the cold well. However, given that there is no technical solution to store the 5 t/d of stripped CO_2, this approach is inconsistent with the goals of the CHP-ATES system, which was to reduce overall CO_2 emissions.

Alternatively, a revised triplet conceptual design was developed that included a third warm (60 °C) well. In this design, groundwater would be pumped from the cold well through a heat exchanger and injected into the hot well during periods of excess CHP heat production. When stored heat is needed, water would be pumped from the hot well through a separate heat exchanger and injected into the warm well, effectively separating warm water injection from cold water extraction. Based on model results for this revised design, it was expected that the CHP-ATES system could operate for decades [38]. However, to date, the project has not become operational.

3.4.5. Lessons Learned

Developing a HT-ATES within a carbonate reservoir provided additional complications relating to the increased potential for calcite scaling. The use of injected CO_2 was predicted to be successful in mitigating calcite scaling, but this approach would require large amounts of CO_2 that would have to be managed when the fluids are produced from the thermal storage aquifer.

4. The Netherlands Case Studies

The Dutch have long advocated for the storage of thermal energy in aquifer systems, mostly at lower temperatures (<30 °C). Low-temperature ATES projects are numerous in the country, with more than 2200 open-loop ATES licenses granted through 2016 [9]. There were several HT-ATES projects that were operated and later abandoned (Utrecht and Zwammerdam); there are three HT-ATES projects currently in operation (Monster, Wageningen, and Middenmeer); and there is currently one recent HT-ATES project in the planning and development stages (Delft). There are several studies that provide overviews of the Dutch HT-ATES projects (e.g., [16,93,94]). Each of these projects is briefly reviewed below (Figure 1).

In addition to the projects reviewed in this study, there are a number of other HT-ATES projects that have been installed and are operating in the Netherlands (Heuvelgalerie Shopping Mall, Eindhoven; Dolfinarium, Harderwijk; 2MW, Haarlem; and Van Duijn, Steenbergen), but very little published data are available for these systems [16]. There are also some other projects in the early planning stages (Lingewaard, Rotterdam Nesselande, and Leewarden), but these projects do not have sufficient information available to consider them in this review.

In contrast to LT-ATES, the industrial deployment of HT-ATES in the Netherlands has been limited due to regulatory barriers, a lack of economic motivation (poor business case because of the competition with natural gas, including the decline of the application of combined heat and power installations), and past failures. An additional roadblock is the environmental concern that HT-ATES could adversely impact neighboring aquifer systems.

4.1. Monster (Koppert-Cress)

An ATES system has been operating since 2012 at the Koppert-Cress horticulture plant in Monster, South Holland, Netherlands [67,95,96]. The stored heat is used for climate control throughout the greenhouses on-site and involves solar collectors for additional heat capture and storage. Originally the ATES was designed to inject fluids heated to ~25 °C, but due to the heating demand being greater than expected, a permit was issued in 2015 to allow for injection of fluids up to 45 °C [96], thus making a transition from LT-ATES to HT-ATES. The HT-ATES consists of four warm and four cold wells, as depicted in Figure 15 [67]. However, the system only occasionally stores heat at >30 °C, so it is more aptly classified as an ATES with elevated storage temperatures rather than a HT-ATES (S. Beernick, personal communication, 20 October 2025).

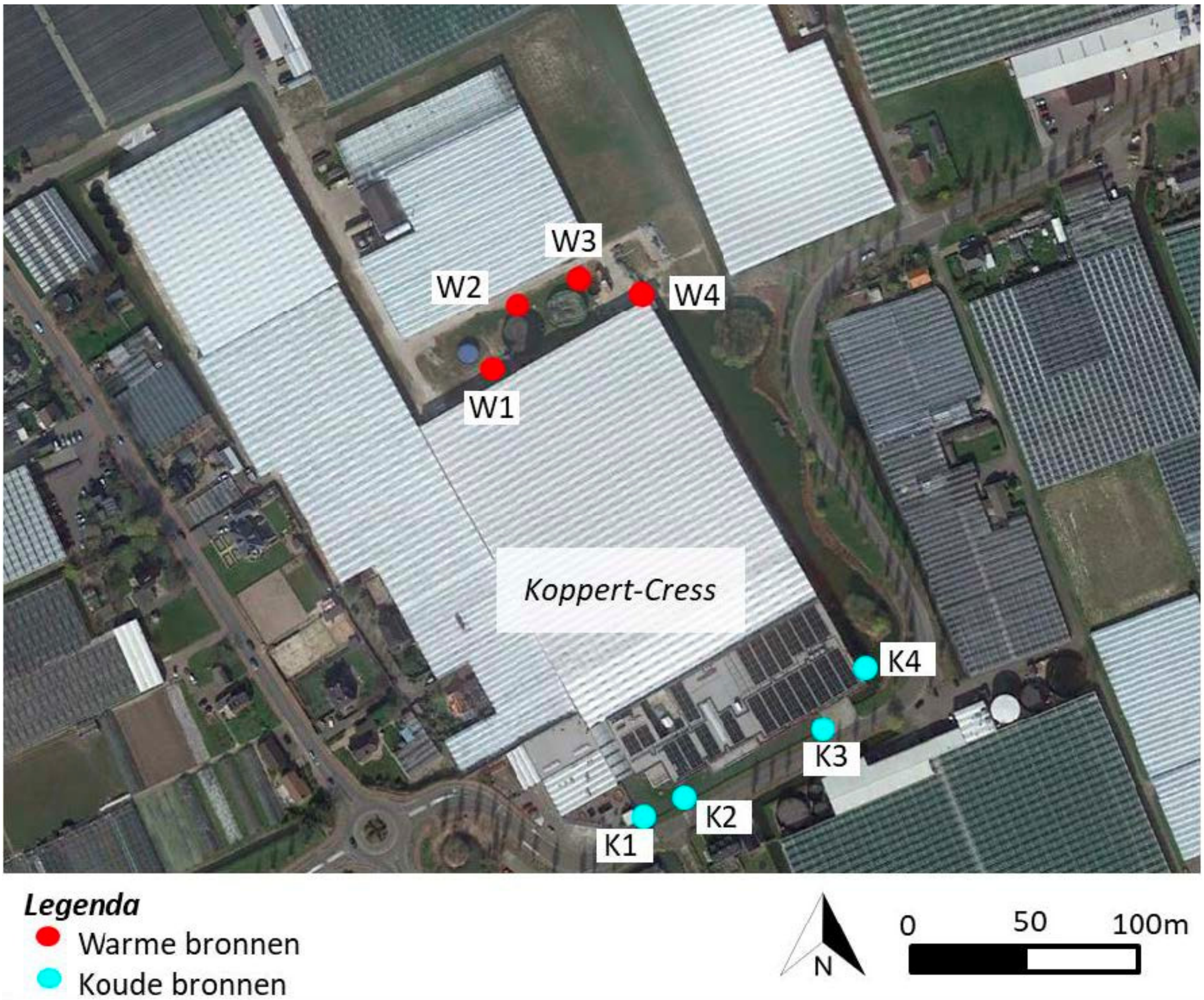


Figure 15. Locations of warm (W) wells and cold (K) wells at the Koppert-Cress ATES site [67]. Reproduced with permission from KWR.

4.1.1. Geology

The geology of the area consists of an alternating sequence of sand and clay layers of Pliocene to Pleistocene age. Two distinct sand intervals are utilized for the ATES: the upper aquifer is in the Peize–Waalre Formation between 55 and 75 m depth, and the lower aquifer is in the Maassluis Formation between 135 and 160 m depth—both intervals are described as fine to coarse sand, gravel, and with shells [67] (Stratigraphic nomenclature of the Netherlands www.dinoloket.nl). The aquifer has an ambient temperature of about 12 °C. The aquifers are characterized by sodium chloride brines with TDS values ranging from 9000 to 11,000 mg/L, with lesser amounts of magnesium, calcium, sulfate, and bicarbonate—the initial lower aquifer fluid is reported to be more saline than the upper [67]. A representative water chemistry analysis for the upper (PB2) interval is listed in Table 3 [67].

4.1.2. Wells

The ATES system has four warm wells (Figure 15), four cold wells, along with a number of monitoring wells [67]. The ATES wells have screened sections with filters in each of the aquifer intervals. Figure 16 depicts a well completion schematic for cold well K4 along with the results of flow measurements conducted in warm well W4 in 2018, indicating ~26 m^3/h of flow from the two flow zones in the deeper Maassluis Formation and ~16 m^3/h from the shallower Peize–Waalre Formation [67]. Because the wells are completed with multiple screened sections, this allows for mixing between the two aquifers.

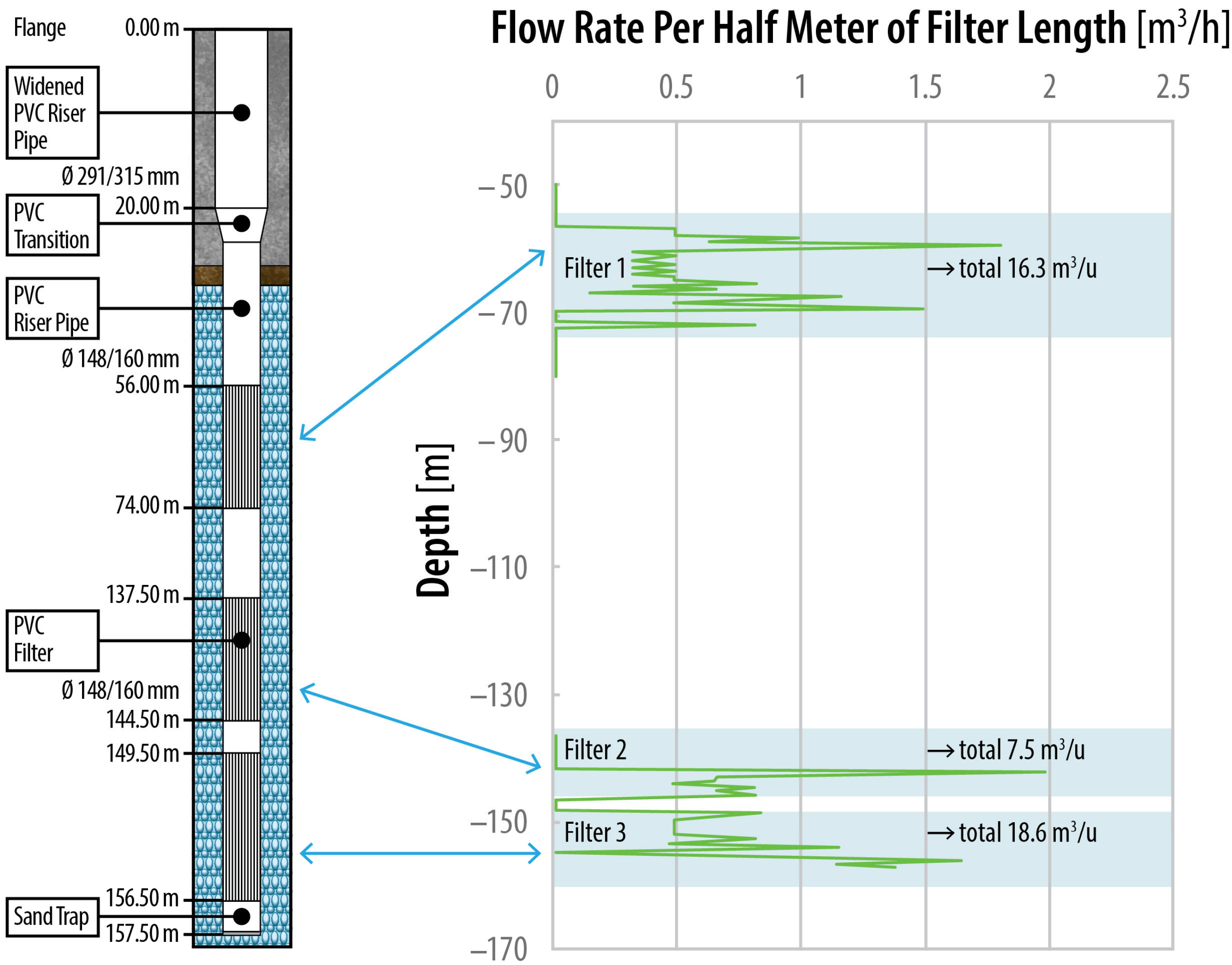


Figure 16. Left: Well completion schematic for cold well K4; Right: Flow test results in the stacked aquifers for warm well W4; Arrows connect the corresponding aquifer zones [67]. Reproduced (in redrafted form) with permission from KWR.

4.1.3. Charging/Discharging of Thermal Energy

The ATES is a component of a fairly complex heating and cooling system at the Koppert-Cress horticultural complex. The system includes the warm and cold thermal storage wells, a pond that collects heat in the summer, rooftop solar collectors, chillers (which generate heat), heat pump condensers, and a cogeneration plant. Figure 17 provides a schematic illustration of these different heat sources and how they are linked to the ATES [67].

The ATES system is operated as a diurnal, weekly, and seasonal thermal energy storage system, as it is used to balance both short-term and long-term energy storage requirements. Calculated recovery efficiencies are high (ranging from 0.79 up to 0.99) for short-term (daily to weekly) thermal storage once the thermal storage system has been charged (i.e., during the summer), because relatively little heat loss occurs over short time intervals [97].

The growth of the Koppert-Cress horticultural complex has led to changing thermal energy needs, resulting in increased temperature for the warm water storage allowing increased thermal energy storage and output with the same reservoir volume. The average temperature difference between the hot and cold wells in 2019 was greater than 12 °C. Heating needs currently outweigh cooling requirements for the overall system so that the cold storage portion of the system has grown faster than the warm storage. The operators plan to address this imbalance by recovering and storing additional available heat [67].

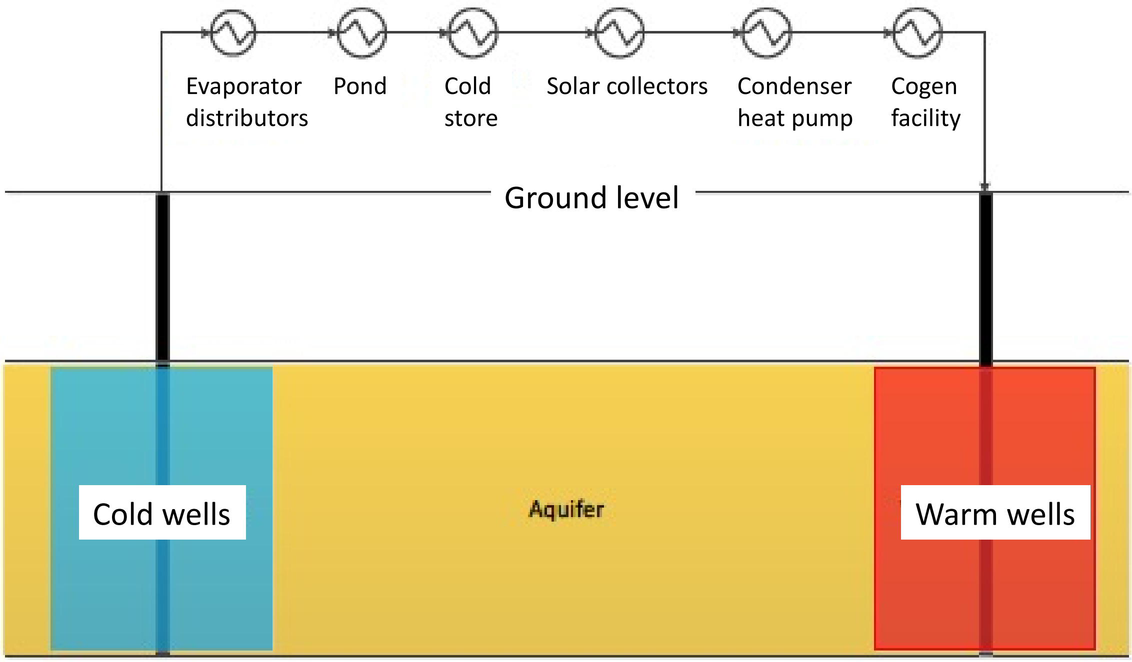


Figure 17. Schematic representation of the interconnected thermal sources for the integrated ATES system at Koppert-Cress [67]. Reproduced with permission from KWR.

4.1.4. Thermal, Geochemical, and Microbiological Modeling and Monitoring

The Koppert-Cress ATES system has an extensive monitoring program, with monitoring boreholes used to collect water samples for geochemical and microbiological monitoring, and boreholes instrumented with fiber optic cable for distributed temperature sensing (DTS) monitoring to evaluate thermal changes over time within the reservoir. A portion of this subsurface monitoring system is depicted in Figure 18.

The DTS system depicted in Figure 18 is used to monitor temperature changes away from the warm water borehole as a function of time [67]. Figure 19 depicts temperature changes occurring with increasing distance away from warm borehole 1. The largest temperature perturbations occurring in the monitoring stations closest to the warm well are most pronounced in the upper aquifer. The subsurface measurements can be used to constrain numerical simulations for evaluating how far thermal perturbations occur away from the clusters of warm and cold wells (Figure 20). A 3D model was created with multiple layers corresponding to the observed aquifers and aquitards, and groundwater flow and particle and heat transport were modeled by dynamically coupling the codes SEAWAT, MODFLOW, and MT3DMS [67]. Because of the imbalance between hot and cold storage, the modeled thermal perturbation around the warm wells only extends out ~20 m, whereas the perturbation around the cold wells extends out ~120 m, nearly reaching the warm well domain.

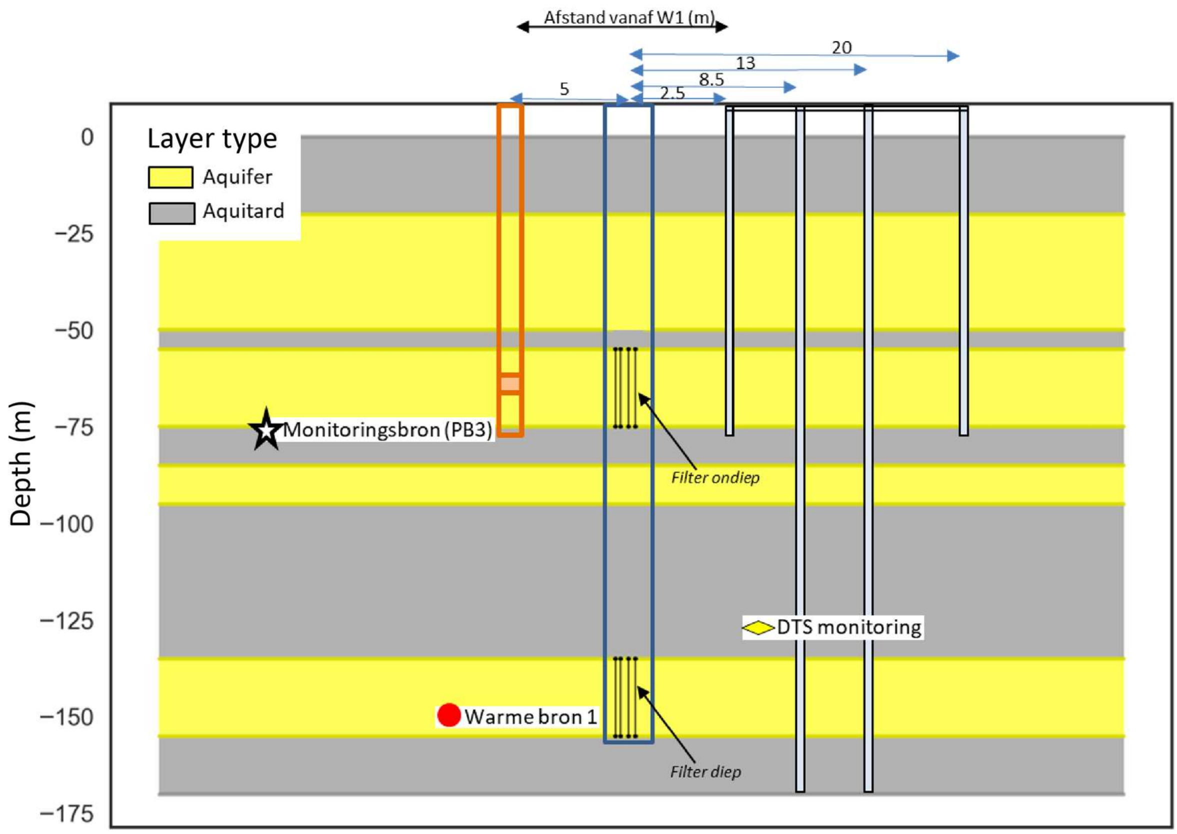


Figure 18. Cross-section around warm well W1 (showing completions in shallow and deep aquifers), one monitoring well (PB3), and four boreholes with distributed temperature sensing (DTS) monitoring [67]. Numbers along the upper axis indicate distance in meters from the warm well. Reproduced with permission from KWR.

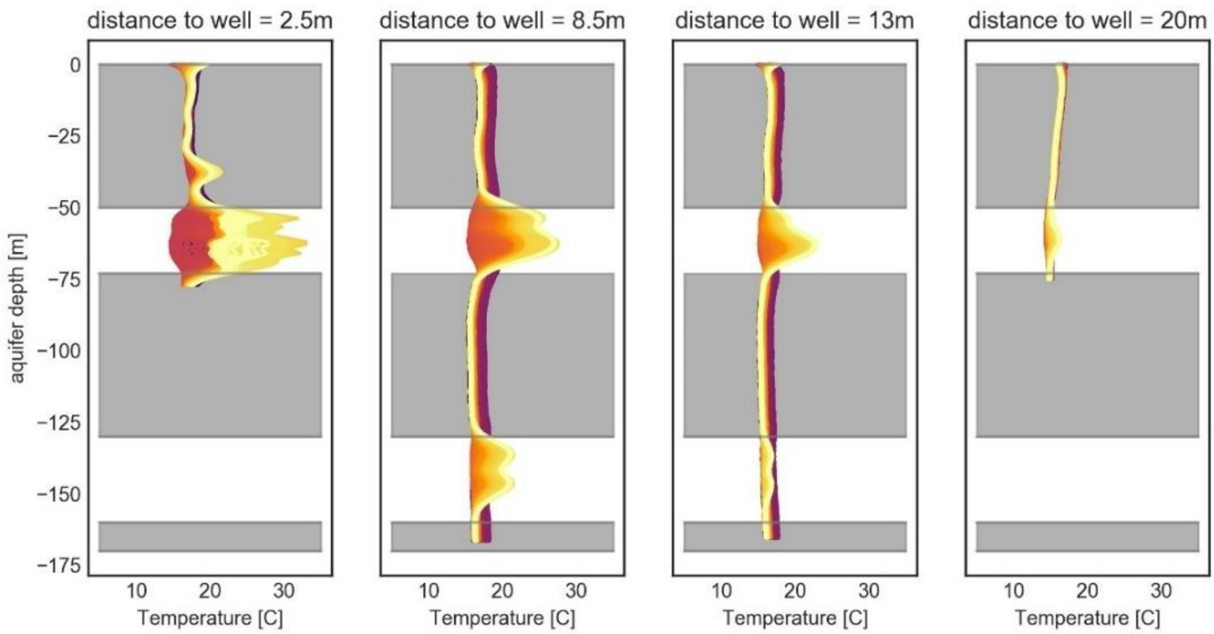


Figure 19. Cross-sections of the four DTS monitoring locations depicted in Figure 18, displaying subsurface temperature measurements from October 2019 to September 2020. The color of the line represents a different moment in time, and the variation on the x-axis represents the measured temperature [67]. Reproduced with permission from KWR.

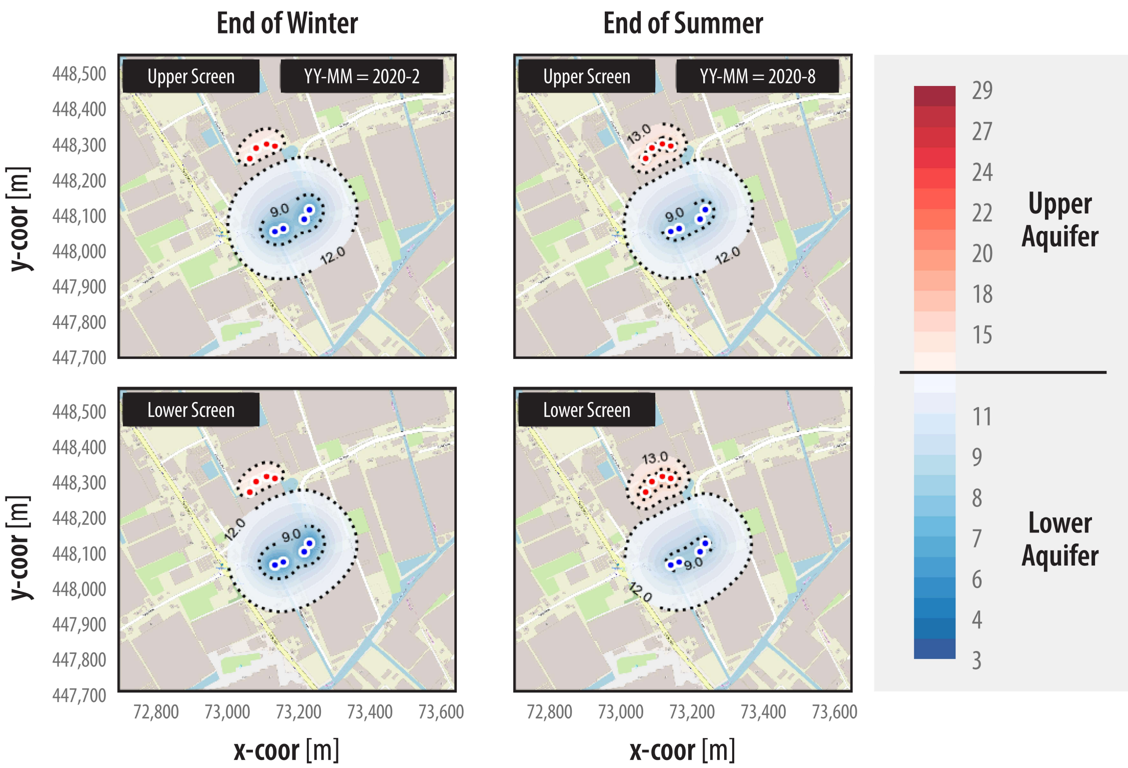


Figure 20. Numerical model depicting temperatures in the shallow (upper row) and deep (lower row) storage aquifers at the end of winter (left column) and end of summer (right column) for 2020. The background temperature of the groundwater is assumed to be 12.5 °C [67]. Reproduced (in redrafted form) with permission from KWR.

Water samples have been regularly collected from the monitoring wells and ATES system to evaluate changes in water chemistry and to determine if any changes occurred in the microbial community due to thermal perturbations in the subsurface. Observed changes in water chemistry can be attributed to the mixing of waters from the two aquifers, but no impactful changes (i.e., ones that would raise water quality issues) in the microbiology caused by increasing temperature have been observed to date [67]. No significant issues with scaling have been reported for the ATES.

4.1.5. Lessons Learned

Changing the ATES at Koppert-Cress in 2015 from a low-temperature to medium-temperature storage system to respond to changing heating demands has been successful. Bloemendal et al. [96] report that the ATES has resulted in annual savings of ~15 TJ natural gas equivalents and ~3.5 TJ of electricity. The use of short storage/recovery cycles has resulted in high utilization of the warm wells, and an imbalance between the cold and warm portions of the subsurface storage system. Prior knowledge of changes in thermal energy supply and demand could result in more optimal design of the system, and improved performance. Possible upgrades to the solar collectors may result in being able to inject even hotter water into the aquifers, which will help address the increased demand for hot water [67]. The monitoring system provides critical information needed to understand system performance and constrain numerical models used to predict future system behavior under different operational scenarios.

4.2. Delft

The Delft University of Technology (TU Delft) is in the process of designing an on campus comprehensive decarbonized geothermal energy system to transition from its current gas-fired campus district heating system. The new system is planning to use deep (~2 km) doublet wells to source hot water all year, coupled with a shallower HT-ATES subsystem that would store unneeded hot water from the deep aquifer during the summer months and allow for increased supply during the winter [17,97]. This system is conceived as an economical means to decarbonize the campus heating system and provide a field laboratory to test and improve technologies and operational methods. The deep wells that will supply the hot water to the campus have already been drilled (e.g., [98]), and plans are underway for developing the shallower HT-ATES well system. A schematic depiction of this deep well system is shown in Figure 21.

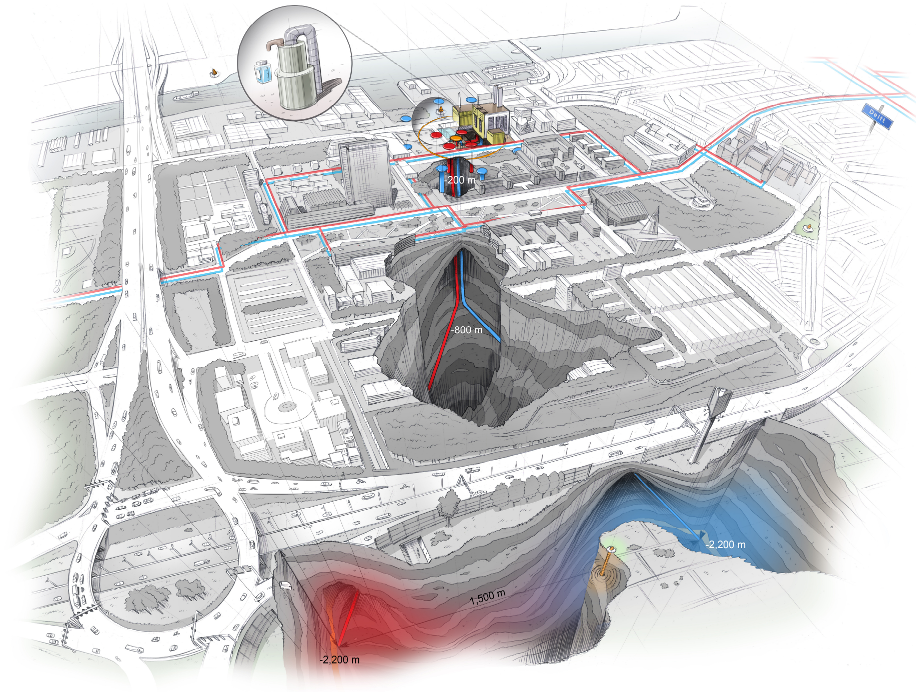


Figure 21. Conceptual illustration of the planned deep doublet well system for the TU Delft campus. Hot water (80 °C) from the production well (shown in red) would be used for heating the campus and water not needed for heating during the summer months would be stored in a HT-ATES system with intermediate depth wells. Figure (Total Shot Productions, 2019) from TU Delft campus geothermal project presentation [99]. Reproduced with permission from TU Delft.

4.2.1. Geology

The high-temperature geothermal doublet wells that will provide hot water for the district heating system and charge the deep HT-ATES system during the summer months were drilled to depths of ~2.5 km [98]. The deep doublet wells (known as the DAP wells) targeted the lower Cretaceous Delft sandstone, a massive fining upward sandstone sequence that is capped by the Rodenrijs claystone [97,98,100] (Stratigraphic nomenclature of the Netherlands www.dinoloket.nl). The expected initial produced water temperature is ~80 °C, with flow rates of up to 350 m^3/h [98]. This reservoir has been drilled successfully for geothermal production in 12 doublet systems in the area since 2010, so both temperature gradient and reservoir characteristics are relatively well known.

Two different aquifers were initially considered for the shallow HT-ATES system [17]. The Pleistocene Maassluis Formation is located at a depth of 130–190 m and consists of highly conductive very fine to coarse grained shell-bearing sandstones and lower conductivity silty claystones. The Ommelanden Formation, at a depth of 410–460 m, is part of the upper Cretaceous chalk group and is also reported to have elevated conductivity [17,97]. To reduce drilling costs and improve on project feasibility, the shallower Maassluis Formation has been selected as the targeted interval for the thermal storage reservoir for the pilot demonstration phase [12].

4.2.2. System Modeling and Evaluation

Prior to drilling, several initial modeling studies were conducted to evaluate the feasibility of a HT-ATES system as part of the TU Delft geothermal heating project (e.g., [17,101–103]), which predicts system behavior while evaluating several different configuration and usage scenarios. The primary rationale for the HT-ATES system is to balance the surplus heat that would be available from the proposed deep geothermal wells during the summer months with the thermal shortfall that would occur in the wintertime. Figure 22 shows the model results of shortages and surpluses of the proposed geothermal system that forms the basis of the design of the HT-ATES.

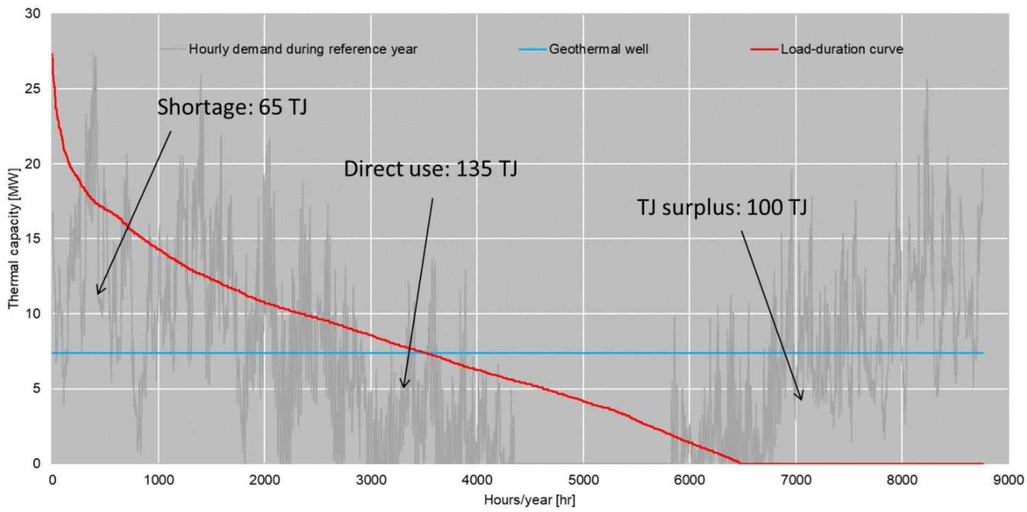


Figure 22. Annual thermal heat demand curve for the TU Delft campus (gray) compared with the constant thermal energy production from a geothermal well (blue) and a load duration curve (red). The energy supplied by the geothermal well (7.4 MW_{th}) was calculated based on a production temperature of 75 °C, a flow rate of 320 m^3/h, and a return temperature of 55 °C. Increased cascaded use with a return temperature of 35 °C would result in an increased thermal energy output of 14.8 MW_{th} [17]. Reproduced with permission of the International Geothermal Association and Dr. Martin Bloemendal.

Using geologic and hydrologic data obtained from the deep geothermal doublet wells [98], numerical models have been developed to predict the reservoir performance of the geothermal wells that will provide the hot water that will be seasonally stored in the TU Delft HT-ATES reservoir [104,105]. Detailed numerical models have also been generated to simulate the performance of the HT-ATES system under three different operational strategies [12].

Techno-economic models were created by Bloemendal et al. [17] to evaluate the economic viability of four distinct cases: (1) the DAP well heating system (deep geothermal wells) with TU Delft as the sole customer; (2) Case 1 with the HT-ATES system; (3) the DAP well heating system with TU Delft and the city of Delft as thermal energy off-takers, and (4) Case 3 with the HT-ATES system. Cases 2 and 4 were also considered using the shallower Maassluis Formation (requiring eight warm/cold wells and four hot wells) and the deeper Ommelanden Formation (requiring six warm/cold wells and four hot wells) as the host aquifers for the HT-ATES. The most attractive case from a financial standpoint was Case 4 (Figure 23); for both reservoir options, the projects had a positive net present value and would result in CO_2 emission reductions of over 23,000 tons/y [17].

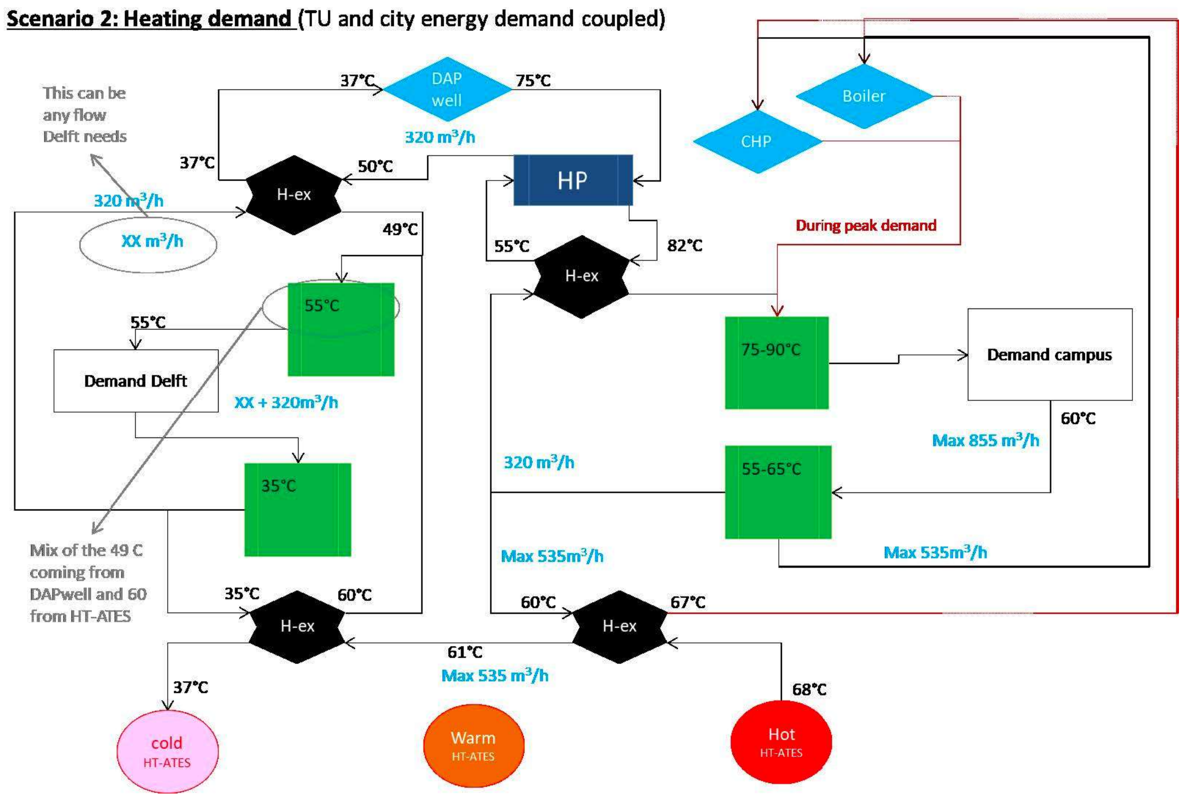


Figure 23. Schematic depiction of energy flows within Case 4—combined DAP well heating system combined with the HT-ATES system, with both TU Delft and the city of Delft as thermal energy off-takers [17]. Reproduced with the permission of the International Geothermal Association and Dr. Martin Bloemendal.

Numerical modeling using SEAWAT was conducted by Bloemendal et al. [17] to evaluate the effects of density-driven flow on the thermal plume within the HT-ATES. Figure 24 depicts the predicted temperature distribution after 50 years of operation. One option proposed to reduce thermal buoyancy effects was to use more saline ground waters from deeper formations to provide a density difference compensation; the buoyancy effect (relative to conductive heat loss) is more pronounced in thicker aquifers [101].

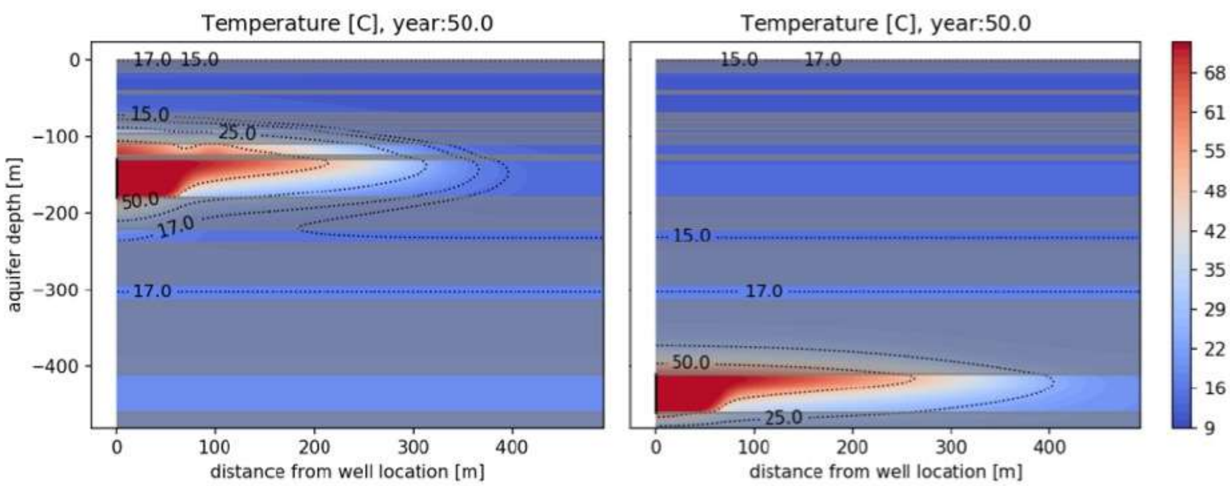


Figure 24. Numerical simulations depicting the temperature distribution after 50 years of HT-ATES operation for the Maassluis Formation (**left**) and Ommelanden Formation (**right**) [17]. Reproduced with the permission of the International Geothermal Association and Dr. Martin Bloemendal.

4.2.3. Lessons Learned

Although this project is still in the initiation phase, there are several key lessons learned that are important to highlight. The early techno-economic analysis was critical in identifying which of the system design options was most likely to result in a project that was economically viable. The coupled process models were helpful in indicating how the system was likely to respond over time, which helps with optimizing the well layouts. Cost considerations led to selecting the shallower Maassluis Formation for the HT-ATES reservoir, as significant savings would result from drilling shallower wells. Finally, there is a continual learning method being applied to the project, where new observations and data are being incorporated into existing models to reduce uncertainty and improve system optimization.

4.3. Utrecht

A HT-ATES system was developed and put into operation at Utrecht University in 1991 (Figure 25). The system utilized residual heat from the University's combined heat and power plant (CHP) in the summer months, when the hot water was not needed for heating purposes, that was supplied to the HT-ATES at a temperature of 90 °C [106]. The system was designed for an annual heat storage capacity of 6000 MWh_{th} and consisted of a well doublet. However, the system did not perform as originally predicted because of issues with the availability of heat to store, along with high return temperatures from the buildings (fluid produced from the aquifer below a certain temperature could not be utilized by the buildings, resulting in a lack of heat recovered from the stored fluids). After the warm well failed due to clogging in 1999, leading to injected warm water flowing to the surface, the system was abandoned [93,94].

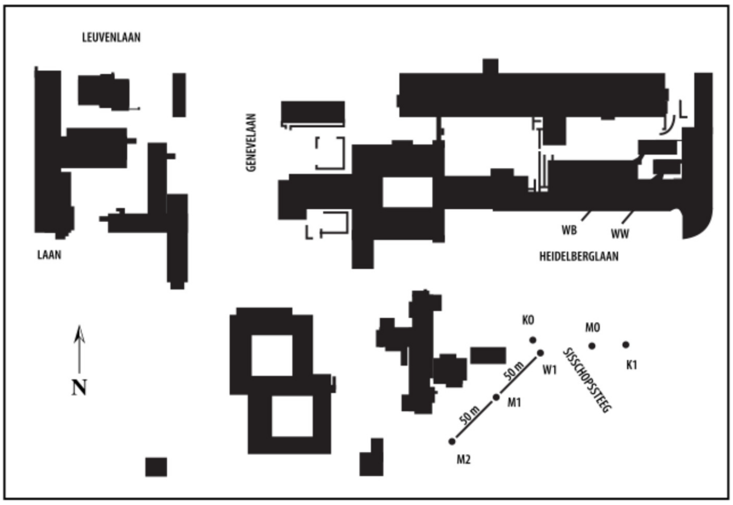


Figure 25. Location of the hot well (W1), cold well (K1), and monitoring wells (M0, M1, M1) for the University of Utrecht HT-ATES system [94]. Reproduced (in redrafted form) with permission from Dr. Benno Drijver, IF Technology.

4.3.1. Geology

The aquifer for the HT-ATES wells is in the Oosterhout Formation, located at a depth of 220–260 m [93,94]. This Pliocene age formation consists of alternating very fine to very coarse sandstones (often containing mollusk shells and bryozoans) and sandy to silty claystones [100] (Stratigraphic nomenclature of the Netherlands www.dinoloket.nl). The upper part of the reservoir contained fresh water (Cl < 50 mg/L) and the deeper part of the aquifer consisted of brackish water (500 mg/L Cl) [93]. A test well had measured hydraulic conductivity values ranging from 3 to 25 m/d [93].

4.3.2. Wells

The HT-ATES consisted of a cold well (K1) and a hot well (W1), located 60 m apart (Figure 25). In addition, several monitoring (M) wells were drilled to monitor changes in temperature over time. The geohydrologic profile and a well completion diagram for one of the wells are depicted in Figure 26.

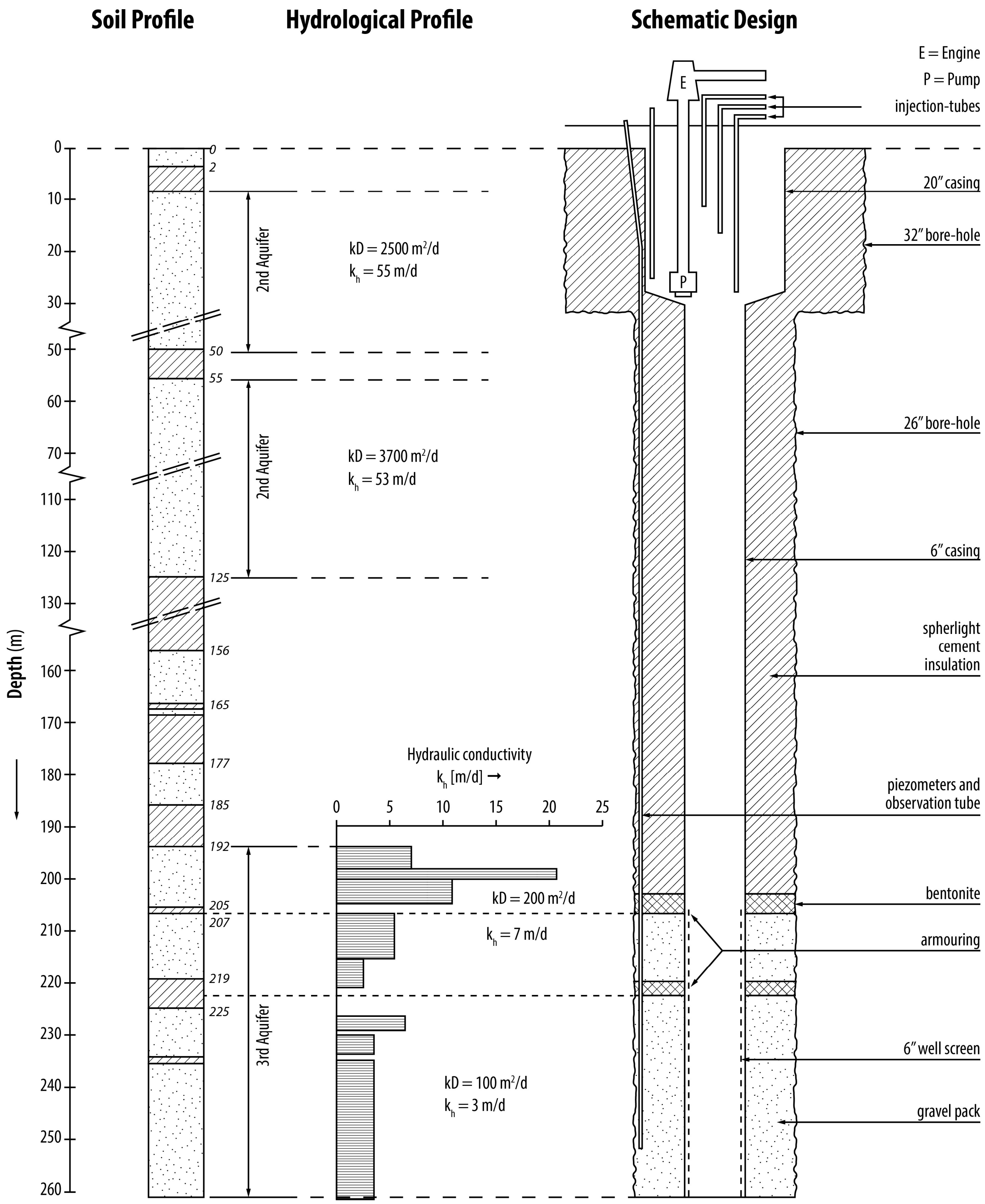


Figure 26. Geohydrologic profile and well completion schematic for one of the Utrecht HT-ATES wells [93]. Reproduced (in redrafted form) with permission from Dr. Benno Drijver, IF Technology.

Because of the elevated storage temperature, the wells were cased with glass fiber-reinforced epoxy (GRE) pipe. A 15.24 cm diameter stainless-steel well screen was chosen, together with a gravel pack. Low thermal conductivity backfill consisting of spherlite-cement was used to provide thermal insulation for the well. A line shaft pumps with the motor on the surface was installed initially but was replaced when it failed after five years with a submersible pump [93].

4.3.3. Charging/Discharging of Thermal Energy

The HT-ATES went into operation in 1991, beginning with a maximum injection temperature of 65 °C; after a few months, this was increased to 90 °C [106]. The planned operation of the system was to store 6000 MWh_{th} (21,600 GJ) of thermal heat per year, and to recover 59% of the stored heat during the winter. However, during the 9 years of operation, the thermal recovery only averaged about 33% (Figure 27), with a maximum annual thermal energy recovery less than 1800 MWh_{th} (6500 GJ) for all years of operation, and less than 140 MWh_{th} (500 GJ) of thermal recovery (and corresponding recovery efficiencies $\leq$ 15%) for the last two years. The low energy recovery was interpreted to result from the high return temperature cut-off for the buildings being heated and partly caused by failures of the CHP (less heat to store), rather than thermal losses in the subsurface [94].

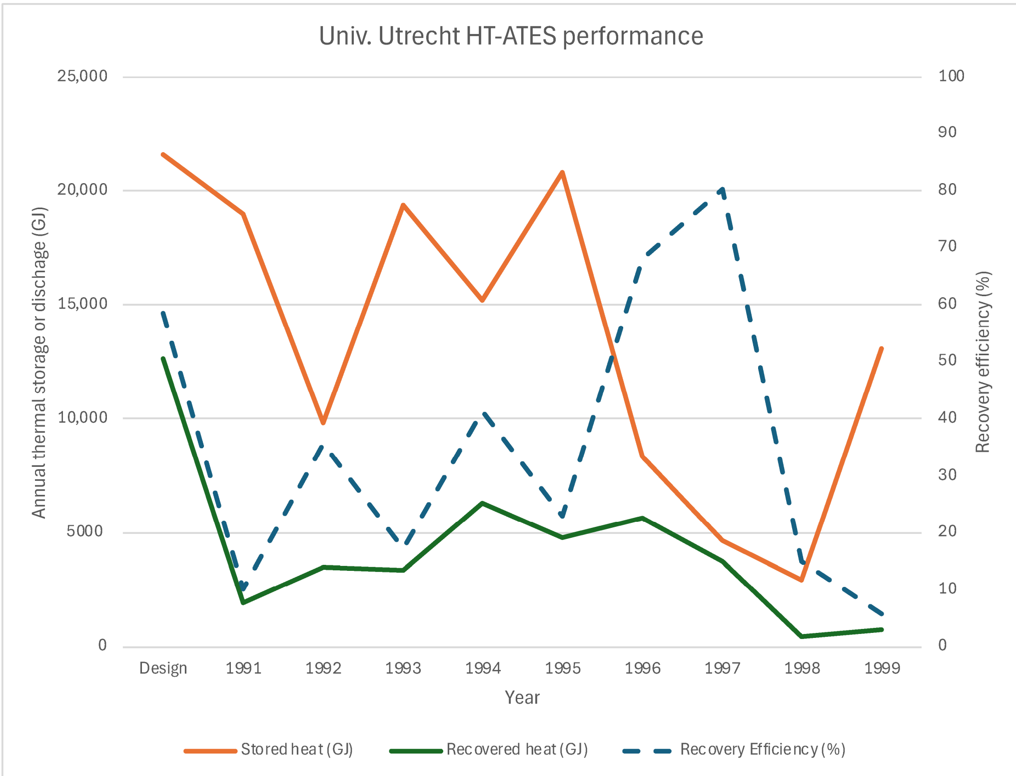


Figure 27. Planned and annual amounts of thermal charging for the Utrecht HT-ATES, heat retrieved from the reservoir, and the percent thermal recovery. Data from [94].

The hot well experienced significant clogging (either from clay swelling or calcite precipitation) after two years of operation, resulting in a flow reduction of 85%. The well was treated with HCl and hypochlorite, which partially restored flow (but it never achieved 50% of its original capacity). The hot well ultimately cracked and failed in 1999, leading to the system being abandoned [93].

4.3.4. Thermal and Geochemical Modeling and Monitoring

Thermal and geochemical measurements and modeling were conducted to help design, monitor, and operate the HT-ATES system. Monitoring wells were used to evaluate the seasonal evolution of the subsurface temperatures through the charging and discharging cycles. Thermo-hydraulic (TH) modeling was conducted to compare simulated thermal behavior with measurements made in the field (Figure 28).

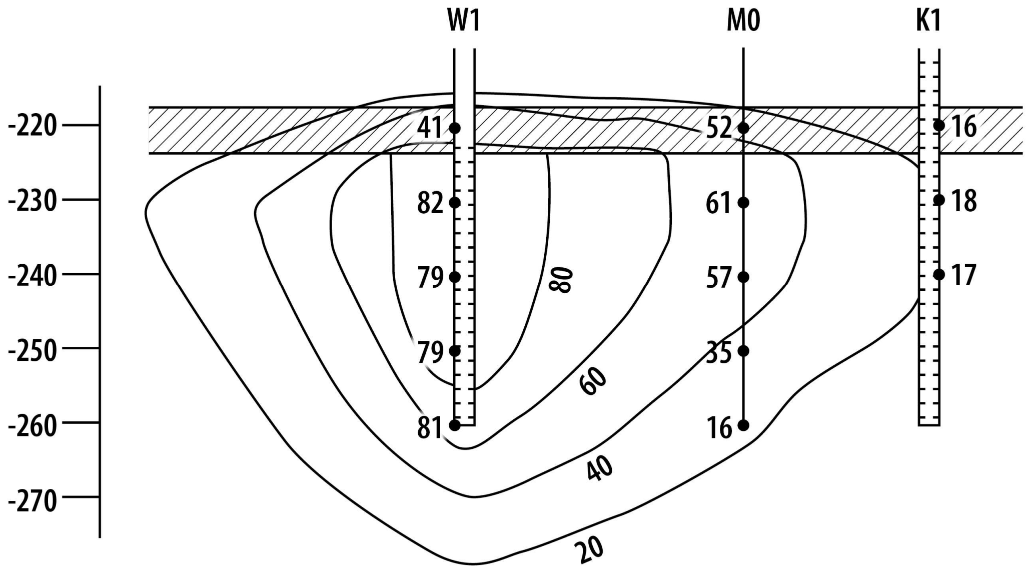


Figure 28. Measured (points paired with values along wells) and simulated (isotherms) temperatures (°C) between the hot (W1) and cold (K1) wells after the first storage cycle for the Utrecht HT-ATES system [94]. The y-axis depicts the depth (m) below the ground surface—this only shows the thermal reservoir and the caprock. Reproduced (in redrafted form) with permission from Dr. Benno Drijver, IF Technology.

One of the initial concerns for the Utrecht HT-ATES system was the potential for calcium carbonate scaling in the heat exchanger. A common remedy for this problem is to reduce the dissolved Ca concentration through Ca-Na exchangers. However, a potential drawback of this approach is clay swelling in the aquifer and associated pore space clogging [107]. PHREEQM-2D modeling was conducted to evaluate the potential for clay swelling by calculating the sodium adsorption ratio. The model results indicate that only a portion of the heated water should undergo ion exchange treatment; otherwise, the sodium adsorption ratio of the heated injected water could rise to levels (>11) where clay swelling in the reservoir could occur [107].

A cation exchange system was installed for the Utrecht University HT-ATES system that passes the water through a resin charged with Na^+. However, the cation exchange system had some operational issues relating to the fraction of water being treated (overtreatment could lead to clay swelling and undertreatment to carbonate scaling), resulting in major clogging issues and ultimately failure of the hot well [108]. The operation of the ion exchange system also consumed a large amount of NaCl to recharge the resin.

4.3.5. Lessons Learned

The primary issue with the Utrecht University system was that the district heating system could not efficiently use heat recovered from the stored thermal water because the return cut-off temperature was too high (i.e., not enough heat was extracted from the produced water). This mismatch in meeting the heating demands of the buildings was a major design flaw that resulted in lower thermal recovery efficiencies than were originally envisioned [10,93]. Although corrosion was not an issue, an unsolved geochemical process (either calcite scaling or clay swelling) led to greatly reduced flow rates in the hot well that significantly impacted system performance. The ion exchange system used to mitigate scaling did not function optimally and may have contributed to the decline in flow in the hot well [93].

4.4. Zwammerdam

The Hooge Burch health care facility in Zwammerdam operated a combined heat power plant (CHP) to produce electricity and heat. The design of the HT-ATES system called for groundwater to be extracted from the cold well (13 °C), to be heated to 90 °C using excess heat from the cogeneration plant, injected and stored in the aquifer during times of low heat demand, and recovered for later use by the health care facility for heating purposes. The HT-ATES system consisted of a well doublet separated by 67 m that are completed in a sandstone aquifer. The system was operated from 1998 to 2003, when it was abandoned because of its unfavorable economics [93,94,109].

4.4.1. Geology

The HT-ATES wells were completed in a medium-fine sandstone aquifer located at a depth of 135–151 m. The unit has a hydraulic conductivity of 5 m/d, and the aquifer consists of NaCl brine (4000 mg/L Cl) [93]. The aquifer is part of an alternating sequence of sands and clays [110].

4.4.2. Wells

The hot and cold wells were complemented with three monitoring boreholes (Figure 29). The doublet wells are at least 150 m deep, were completed with glass fiber-reinforced epoxy (GRE) casing, and the reservoir zone was completed with a stainless-steel screen and a gravel pack. To help insulate the wells, a spherlite-cement mixture was used as backfill material. Submersible pumps were installed in the doublet wells [93,110]. The wells were designed for a maximum flow of 25 m^3/h. The temperature measured in one of the wells in 1996 (prior to initiation of the HT-ATES system) at 150 m was 12.7 °C [110].

4.4.3. Charging/Discharging of Thermal Energy

The system was designed to store 2250 MWh_{th}/y of heat and discharge 1100 MWh_{th}/y, with an expected recovery efficiency of 49%. This would be achieved by pumping 41,000 m^3 of heated water into storage during the summer months (with an average storage temperature of 88 °C), and withdrawing an equal amount during the wintertime, with a return temperature of 40 °C [94,110].

However, the actual operational efficiencies of the system were far below the expected value, ranging from 3.5% in 1998 up to 11.3% in 2000. These much lower recovery efficiency values were due to two main factors: (1) much lower than expected pumped water amounts for the HT-ATES, which were on average only 58% of the planned amount; and (2) high cut-off temperatures for the returned fluids after heating (i.e., only partial utilization of the thermal energy of the produced fluids)—the average returned fluid temperatures from 1998 to 2001 ranged from 44 to 62 °C, significantly above the planned temperature of 40 °C. The resulting average annual system charging between 1999 and 2001 was just 1561 MWh_{th}/y (69% of the planned amount), and only 167 MWh_{th}/y for the thermal discharge, corresponding to just 15% of the planned amount [94,109,110].

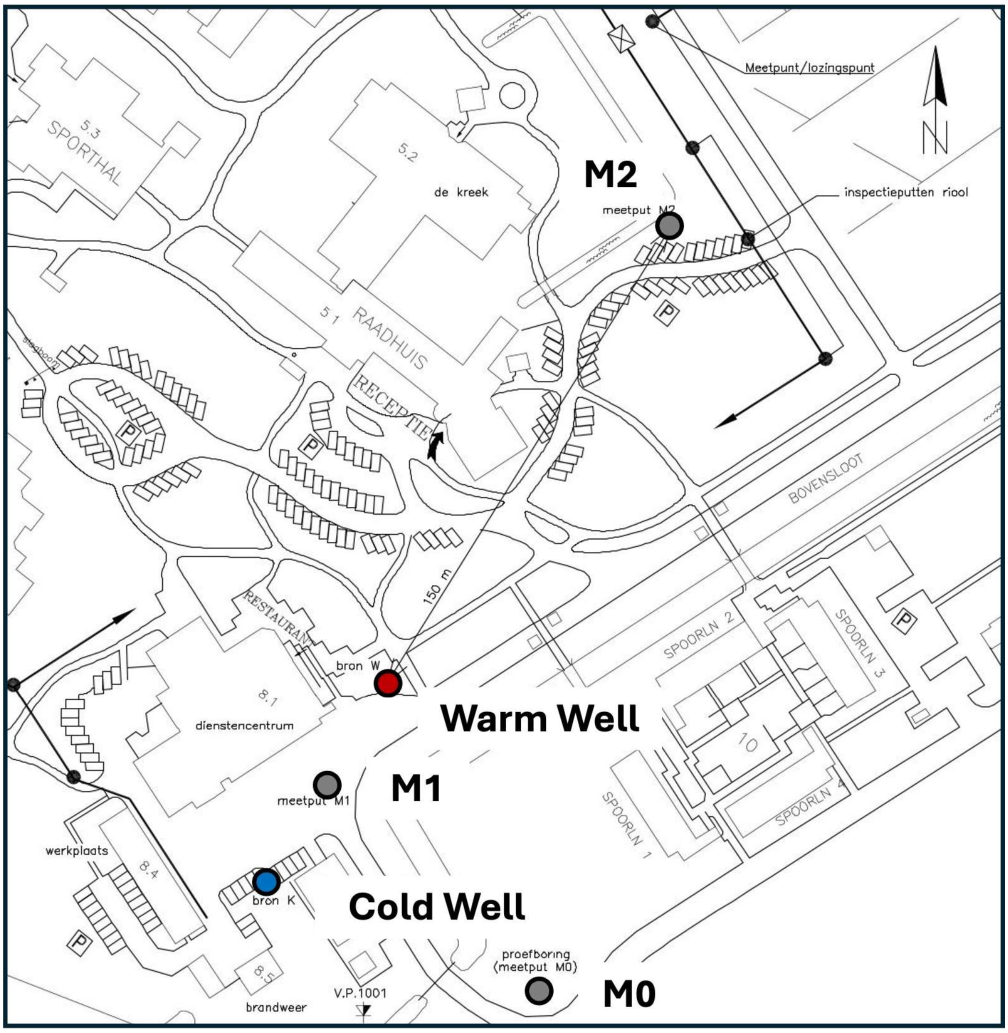


Figure 29. Location map of the warm and cold wells, along with three monitoring (M) wells at the HT-ATES in Zwammerdam [94]. Reproduced with permission from Dr. Benno Drijver, IF Technology.

4.4.4. Thermal and Geochemical Modeling and Monitoring

The license under which this system was permitted required extensive monitoring of the water chemistry, microbiology, hydraulic head, and subsurface temperatures [94]. This monitoring was accomplished through the usage data collected from three monitoring wells. Thermo-hydraulic (TH) simulations generated using the HstWin-3D computer code were used to predict how the heat storage system would perform over time, using the initial monitoring results for the few years of operation and extrapolating into the future. The model results show that strong temperature gradients developed in the underlying and overlying aquitards with a significant breakthrough of heated water (44 °C compared to 13 °C ambient) into the cold well within 4 years (Figure 30).

During operation, the Cl-rich (~4000 mg/L) groundwater was treated to prevent carbonate scale formation with 30% HCl at a rate of 200 mL/m^3. This amount of HCl was selected based on an assessment of the calcite saturation index calculated using the PHREEQC geochemical computer code. The addition of the acid resulted in a predicted decrease in groundwater pH from its nominal value of 7.0 to 6.2 [108]. While the decrease in pH was not of itself a concern, the release of toxic metals from mineral dissolution (postulated as pyrite) resulted in elevated (but below regulatory limits) toxic metal concentrations. In addition, the treatment is predicted to result in a 200 mg/L increase in the Cl concentration over time. Although this increase in Cl concentration was not a concern, it may be if this treatment is used in an aquifer with less saline groundwater [108].

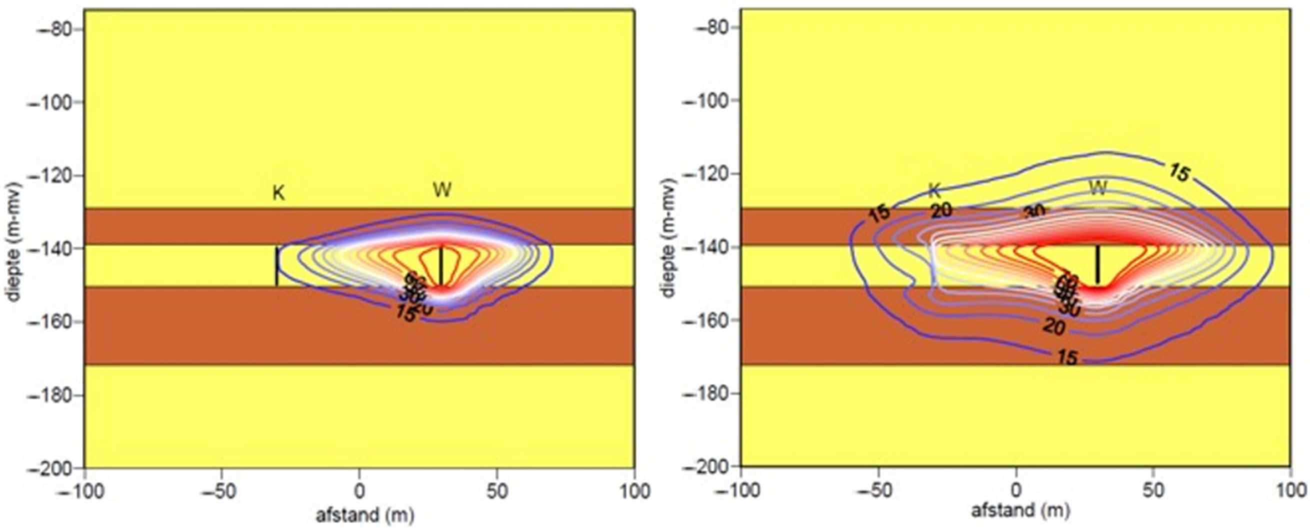


Figure 30. Model calculation of groundwater temperature (°C) profiles surrounding the hot (W) and cold (K) wells at the conclusion of the first (**left**) and fourth (**right**) charging seasons [94]. Reproduced with permission from Dr. Benno Drijver, IF Technology.

The HCl groundwater treatment was effective as there was no evidence of well scaling or clogging during the operational period. However, a post-operational analysis of the water treatment strategy concluded that only about 50% of the added HCl would have been required to prevent scaling [93]. Possible explanations for the reduced acid consumption include natural precipitation inhibitors, dissolution kinetics, and mixing of waters with differing temperatures.

4.4.5. Lessons Learned

The system encountered no major technical issues, but due to the way that it was operated (at low capacity with poor thermal recovery) the system was not viable economically and thus was taken out of operation in 2003. The main financial drivers were the feed-in fee for electricity production—the use of the cogeneration plant was reduced, and with the lower system efficiencies, heat storage was no longer deemed profitable. The use of HCl to prevent scaling in the thermal well appeared to be a successful way to avert carbonate scaling. For the system to perform as designed, the prescribed amounts of thermal storage and retrieval and more effective extraction of heat from the produced fluids are required. A greater separation between the hot and cold wells might be necessary to prevent thermal breakthrough from occurring.

4.5. Wageningen

Two ATES systems, an LT-ATES and a HT-ATES, have been operating since 2012 at the Netherlands Institute of Ecology of the Royal Netherlands Academy of Sciences (NIOO-KNAW) in Wageningen [93,94]. Two ATES systems were installed at this location, an LT-ATES in a shallow aquifer (~65 m depth), and a HT-ATES in a deeper aquifer (220–290 m depth). The hot water for the HT-ATES system is provided by a series of solar collectors [94]. Figure 31 shows the locations of the wells for each system on the NIOO-KNAW campus.

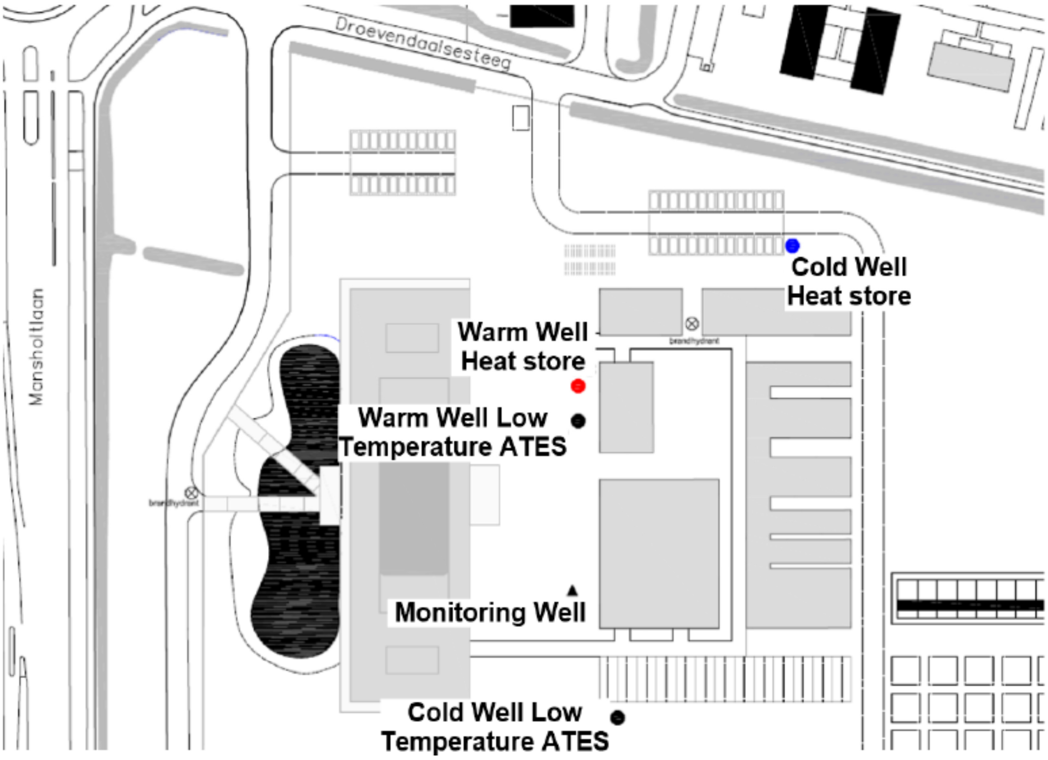


Figure 31. Locations of the ATES wells and monitoring well at NIOO-KNAW campus in Wageningen [94]. The heat store wells (depicted by red and blue dots) are the ones associated with the MT-ATES system. Reproduced with permission from Dr. Benno Drijver, IF Technology.

4.5.1. Geology

The two ATES systems are hosted by sand bodies in a series of alternating sequences of sand and clay layers. The shallow LT-ATES system is in a high permeability, coarse-sand aquifer, whereas the deeper HT-ATES wells were completed in the Oosterhout Formation at a depth of 220–290 m in a section with fine-grained sand. The hydraulic conductivity of this section varies from ~0.5 m/d in the upper 40 m of this aquifer down to values less than 0.02 m/d in the higher clay content lower 30 m [94]. This Pliocene age formation [100] (Stratigraphic nomenclature of the Netherlands www.dinoloket.nl) also hosted the HT-ATES aquifer at Utrecht. The formation fluids in the aquifer are brackish/salt water and have a temperature of ~14° C [93,94].

4.5.2. Wells

The HT-ATES consists of a doublet set of ~300 m deep wells (warm and cold) installed ~60 m apart (Figure 32). The wells are screened with stainless-steel from ~220 to 295 m depth and are cased with PVC pipe. Submersible pumps are deployed in each of the wells. There is one currently unused monitoring well that had been used to observe temperature changes; however, it lies outside of the area of influence of the HT-ATES system (Figure 32) [94]. The well system was designed for flows of 40 m^3/h; however, because of the low permeability in the lower part of the aquifer, coupled with some potential skin along the wellbore (this may have resulted from interaction of the near-wellbore area with freshwater drilling fluids, which may have caused clay swelling). The actual flow capacity of the wells is less than 50% of the expected amount. A flow test was completed in 2010 before system initiation revealed that an estimated 90% of the flow is entering the higher permeability upper zone (220–247 m) with the remaining 10% entering the lower portion of the aquifer (247–283 m) [109].

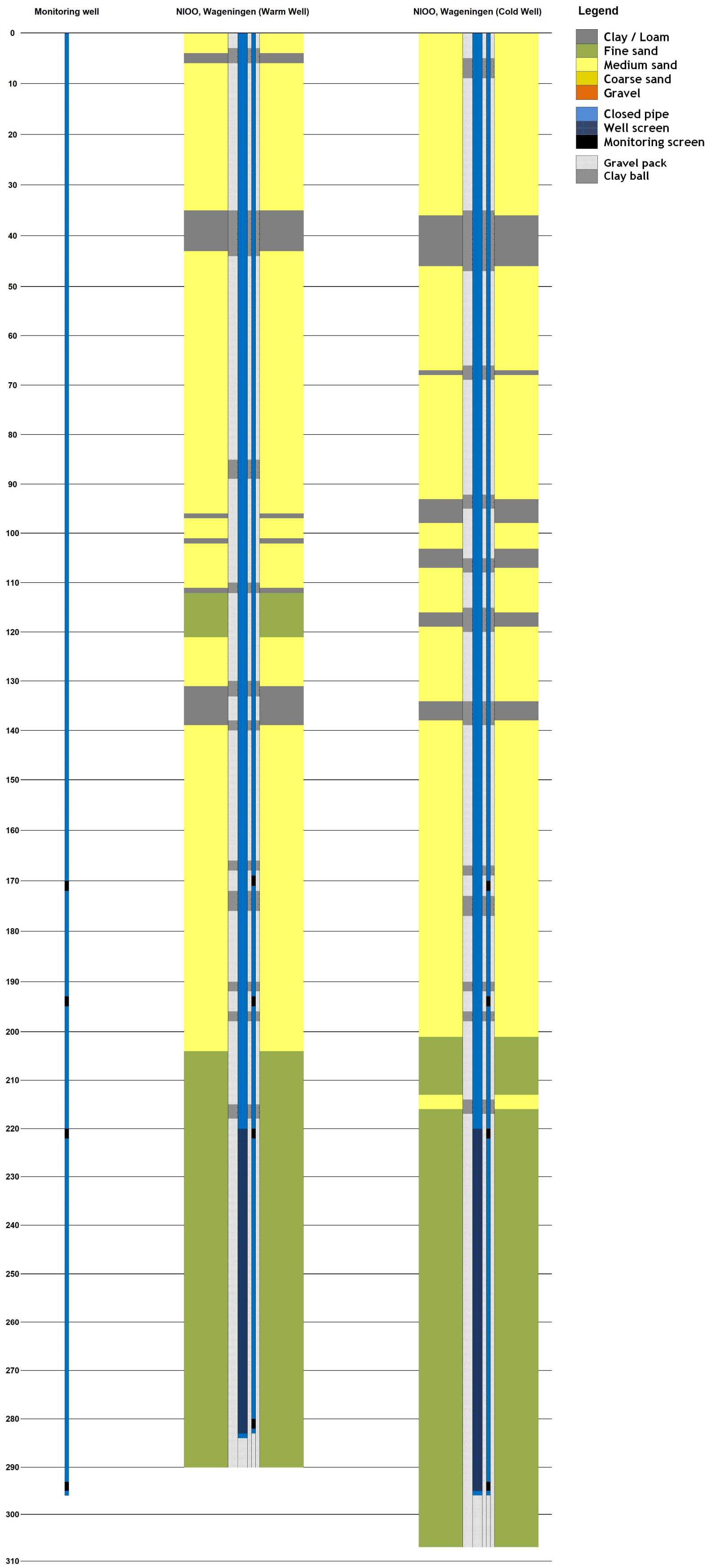


Figure 32. Schematic profiles of warm well, cold well, and monitoring well for the HT-ATES system at Wageningen. Depth profiles depict lithologies, screened zones, cased intervals, and zones with gravel packs [93,109]. Reproduced with permission from Dr. Benno Drijver, IF Technology.

4.5.3. Charging/Discharging of Thermal Energy

The original design of the system was intended to allow for 1283 MWh_{th}/y of stored energy, with an annual thermal recovery of 578 MWh_{th} (corresponding to a recovery efficiency of 45%). However, the amount of stored heat was much lower with values ranging from 100 to 320 MWh_{th}/y. The recovered heat was even lower, ranging from 0 to 55.5 MWh_{th} per year (Figure 33). These values represent annual thermal recovery efficiencies ranging from 0% to 18%, far below the expected value of 45% [94,109].

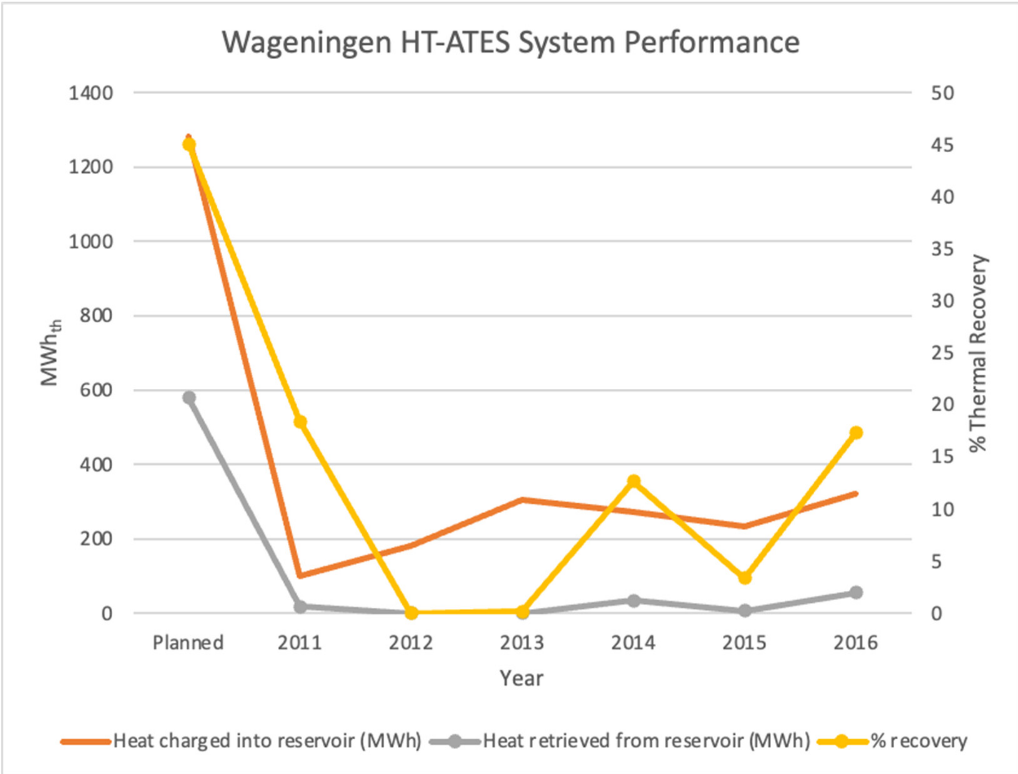


Figure 33. Planned and annual amounts of thermal charging for the Wageningen HT-ATES, heat retrieved from the reservoir, and the percent thermal recovery (data from [94,109]).

There are several causes for the performance falling below planned levels. As noted earlier, the low permeability of the lower portion of the HT-ATES aquifer results in lower than initially expected storage capacity and well flow rates, both of which impact system performance. Although some well treatment techniques (air surge, hydrogen peroxide) have been applied to attempt to improve the transmissivity of the lower portion of the aquifer, these were not successful [109]. The amount of thermal energy that was available for charging the system was much less than expected due to a reduced number of solar collectors. The nominal stored water temperature (45 °C) was very close to the building heating cut-off temperature (40 °C) resulting in minimal extraction of thermal energy from the stored water. In 2016, the cut-off temperature was lowered to 30 °C, which resulted in significant increase in energy recovery efficiency (3% in 2015 to 17% in 2016) [94,109].

4.5.4. Thermal and Geochemical Modeling and Monitoring

Most of the HT-ATES system monitoring has been subsurface temperature measurements. However, the fairly distant location of the single monitoring well renders it insensitive to the HT-ATES system, as it only exhibits temperature perturbations associated with the shallower LT-ATES system (Figure 34). Note that both the cold and warm wells exhibit thermal perturbations at the depth of the shallow aquifer associated with the LT-ATES and are more pronounced in the HT-ATES warm well, which is closer to the LT-ATES system (Figure 31). For the hot and cold HT-ATES wells, the main temperature shifts in the deeper aquifer occur in the upper, more permeable zone.

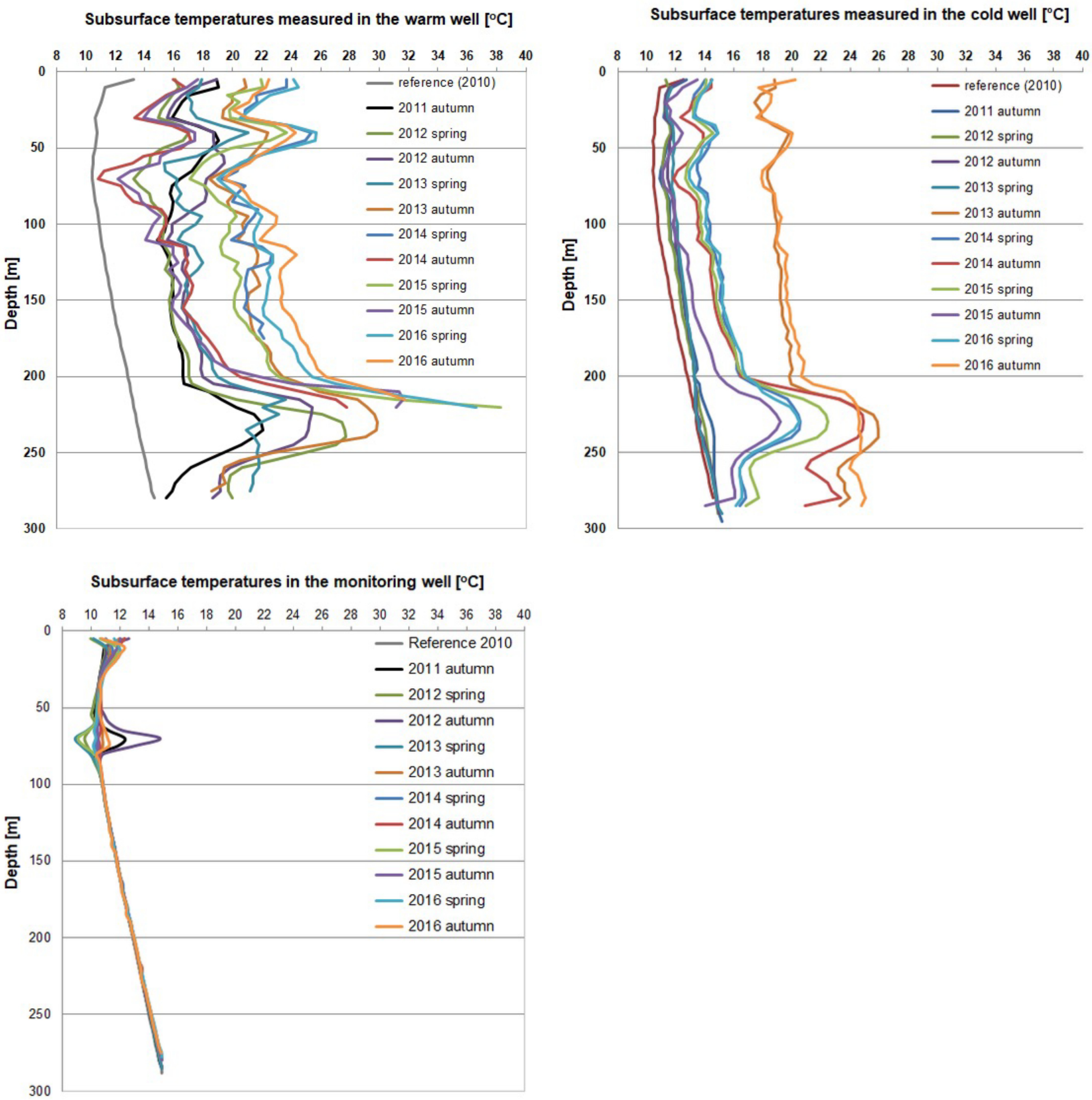


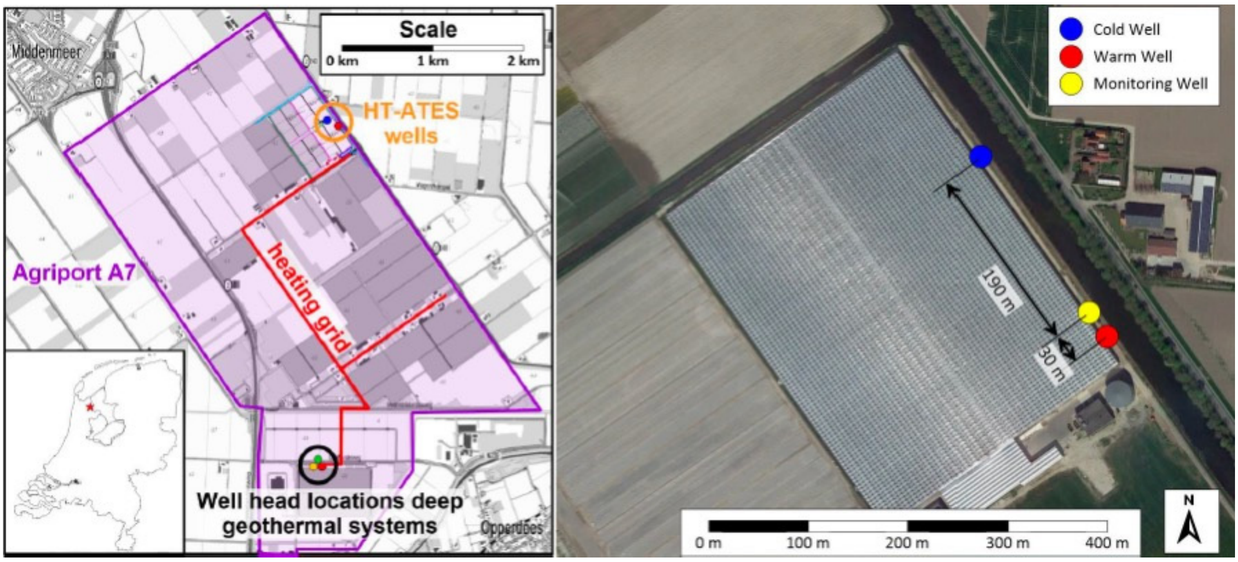
Figure 34. Measured variations in subsurface temperatures in the warm well (**left**), cold well (**center**), and monitoring well (**right**) for the MT-ATES system at Wageningen [94,109]. Reproduced with permission from Dr. Benno Drijver, IF Technology.

4.5.5. Lessons Learned

While the Wageningen ATES system continues to operate, it is still performing far below its design specifications. There are several lessons that can be gleaned from this example that could lead to improved performance for future sites. One issue that highlights the importance of thorough site characterizations was that much of the aquifer section selected for the HT-ATES system had suboptimal permeability, which impacted the well flow rates and reservoir storage capacity. A test hole should have been drilled to better characterize the subsurface geology and thermal regime. This would have helped better understand the storage capacity of the system and resulted in better system design. Better drilling fluids and well packaged materials should have been chosen based on the screen size and formation fluid chemistry. Clay swelling from drilling fluids (fresh water) is one potential cause of the lower permeability in the lower zone. Increasing the number of solar collectors would also improve the ability to fully charge the thermal storage aquifer, and lowering the cut-off temperature of the building heating system (as was performed in 2016) dramatically improves the thermal energy recovery. On a positive note, no decrease in well capacity over time was observed, suggesting that scaling has not been a problem, even without using a water treatment system [109].

4.6. Middenmeer

The HT-ATES demonstration site near Middenmeer (Figure 35), which initiated operations in 2021, is located at one of the largest greenhouse complexes in the Netherlands (~400 ha). At this complex, hot water (~85 °C) from deep (2500 m) geothermal wells (three doublets producing from the Permian Rotliegend sandstone) is piped from 7 km away to heat greenhouses at the Agriport complex [41,111–115]. Because little or no heat is required during the warm season, and stopping geothermal production is technically and financially not desirable, this demonstration project was developed to allow for seasonal storage of heat from the geothermal hot water on-site in a shallow aquifer (~360 m), which could be used to supplement the supply of hot water during winter months. Project objectives include the optimization of the HT-ATES system, testing high-temperature equipment (pumps, casing), investigating water treatment with CO_2 to avoid carbonate mineral scaling, and establishing the legal framework for such operation [116,117]. This demonstration site is part of the European Union HEATSTORE project, under the GEOTHERMICA–ERA NET co-fund [118].



(**Left**) (**Right**)

Figure 35. (**Left**) Map of the Agriport A7 area, with the deep hot geothermal wells to the south, and the HT-ATES wells to the north. (**Right**) Layout of the HT-ATES wells (red—hot well, yellow—monitoring well, blue—lukewarm well). Figure from [111]. Reproduced with permission from Dr. Benno Drijver, IF Technology.

4.6.1. Geology

Based on the results of an initial test well used to evaluate several possible aquifers, the Maassluis (280–420 m deep) Formation was selected to host the HT-ATES at the site [111] (Figure 36). The Maassluis Formation, of the early Pleistocene age, is present almost everywhere above the marine deposits of the Oosterhout Formation. It consists of a varied succession of shallow marine and coastal deposits, comprising horizontal sand and clay beds. It is overlain by fluvial sands and tidal deposits (sands and clays) of the Waalre Formation [41,119]. The groundwater in the Maassluis Formation consists of NaCl brine with a TDS of about 17,600 ppm [41].

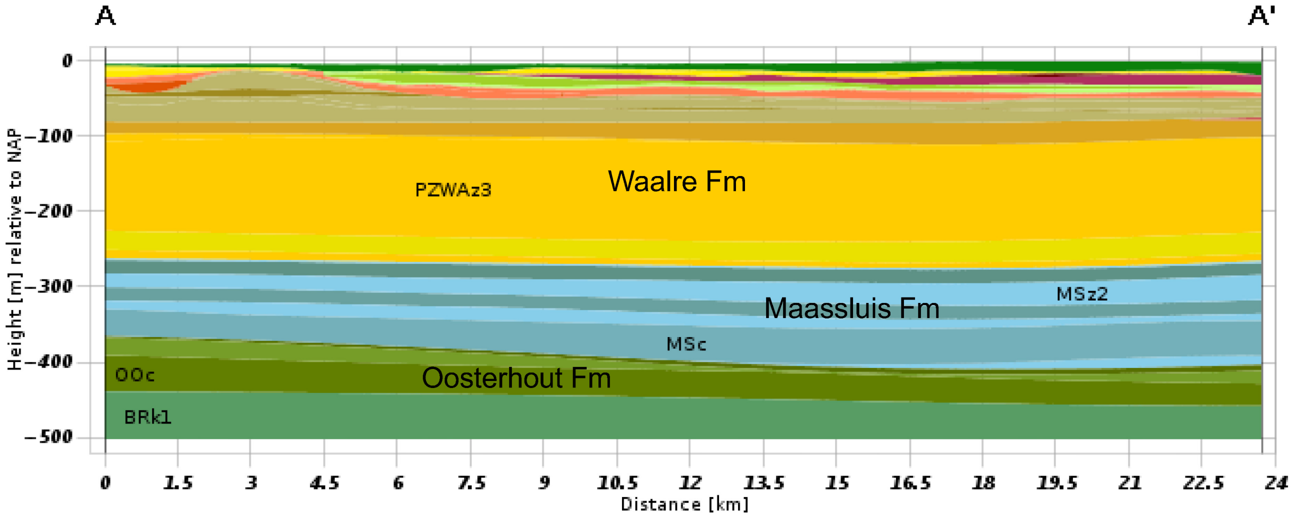


Figure 36. NE (A) to SW (A') cross-section of the Middenmeer area (adopted from [41], from REGIS II v.2.2 (regional geohydrological information system), 2017). Reproduced with permission from TNO.

4.6.2. Wells

A test well was drilled in 2019 to a depth of 471 m (Figure 37) to evaluate the hydrologic properties of the two candidate aquifers [41]. The aquifer in the Maassluis Formation (the fourth aquifer) had a maximum flow rate of 150 m^3/h, while the deeper aquifer in the Oosterhout Formation (the fifth aquifer) had a slightly lower flow rate of 100 m^3/h. This deeper reservoir also had significant levels of methane (~151 mg/L), which would pose a safety risk [41]. The upper aquifer also appears to have a more homogeneous grain size, which reduces the possibility of sand production at high flow rates [41].

The hot and lukewarm wells were drilled to depths of ~380 m, completed with glass fiber-reinforced epoxy (GRE) casing, and have stainless-steel filters for the screened production zones of the wells. The hot, cold, and monitoring wells have fiber optic cable installed to allow for continuous monitoring of the temperature [111,113,115,116]. The wells are designed to accommodate a flow rate of 150 m^3/h, similar to the test well. The spacing between the hot and cold wells is 220 m, with the monitoring well offset from the hot well by 30 m (Figure 35). The first injection phase to charge the HT-ATES with hot water was initiated during the summer of 2021 [111].

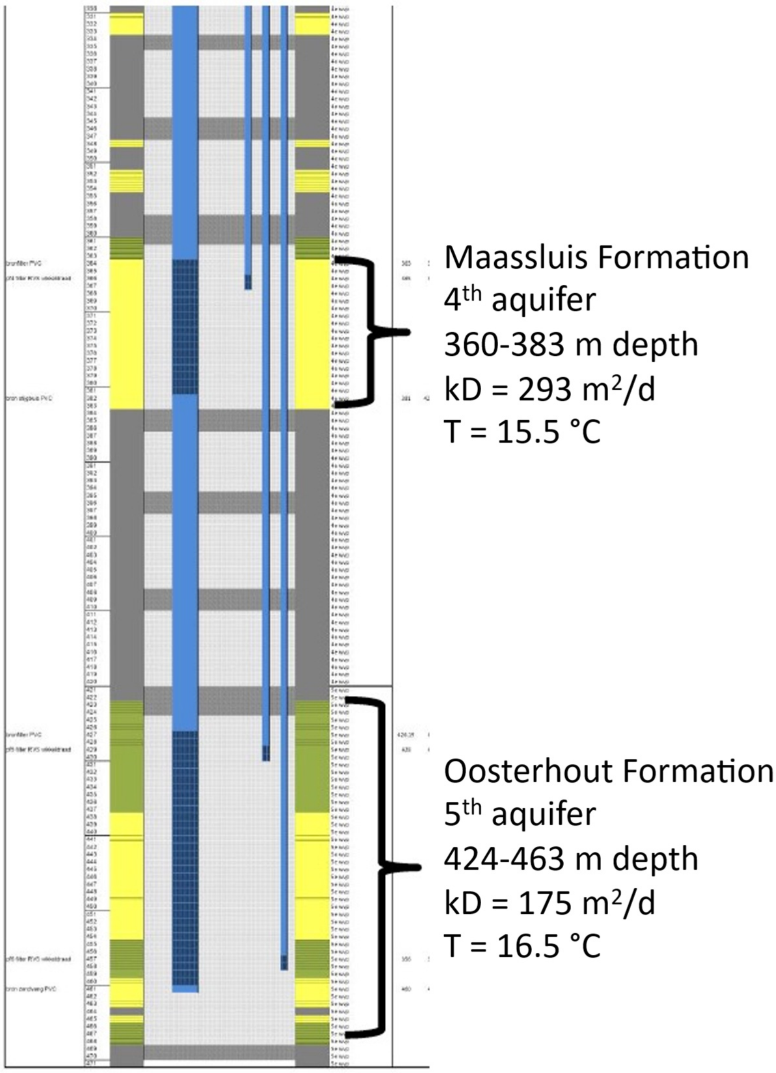


Figure 37. Middenmeer test well stratigraphy (adapted from IF Technology, 2019 [112]), with key properties for the two potential HT-ATES aquifers [41]—the shallower aquifer was subsequently selected. Reproduced with permission from TNO.

4.6.3. System Modeling and Evaluation

Heat obtained from 85 °C water from the off-site geothermal system is transferred using a heat exchanger to HT-ATES reservoir water at the surface, and this heated water is injected on-site for storage during the warm season and re-used during the wintertime. The calculated seasonal storage size is about 27 GWh [113,115]. Geochemical and reactive transport modeling studies using TOUGHREACT have shown that scaling by carbonate minerals is expected around the hot well but could be avoided by co-injection of CO_2 [41,111]. This work was supported by batch geochemical reaction experiments conducted at 80–85 °C using relevant rock and water samples, which did not display evidence for significant carbonate scaling [41].

The technical and economic efficiency of the Middenmeer system has also been modeled using ROSIM-DoubletCalc3D to establish a business case model and identify ways to optimize the system design and operation [111,120]. These models were run to predict future system performance (Figure 38) and suggest that the thermal recovery efficiency of the system will increase over time. The actual annual thermal energy recovery efficiencies for the first two years of operation were 27% and 41%, respectively [115], lower than the initial model predictions, but also showing increasing values with time.

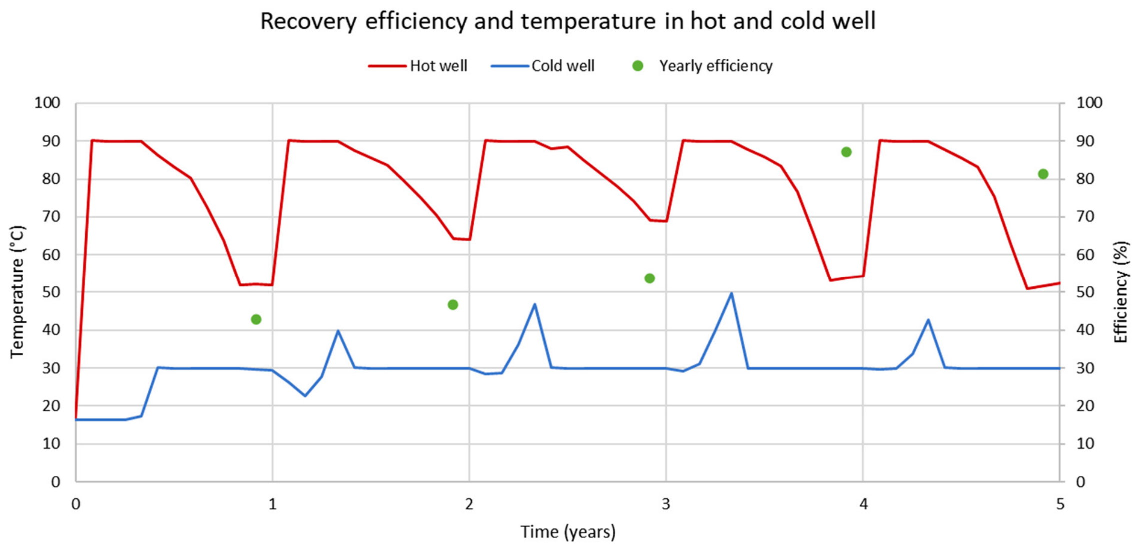


Figure 38. Simulated performance of the Middenmeer HT-ATES system, depicting predicted temperatures of the hot and cold wells over five annual cycles along with estimated annual thermal recovery efficiency values [111]. Reproduced with permission of Dorien Dinkelman.

A distributed temperature sensing (DTS) system was used to monitor changes in the storage aquifer temperature through several years of operational thermal loading and unloading cycles. This continuous temperature dataset was used to history match and update the numerical reservoir model for the Middenmeer HT-ATES system [113,115]. Adjusting key rock properties in the model (such as porosity, permeability, density, thermal conductivity, and heat capacity) enabled a much closer match between the modeled and observed temperature profiles over time in the wells [113,115]. An important observation relating to the monitoring well at the Middenmeer site is that it was initially used for flow testing, and thus its design is not optimal for DTS monitoring [115].

A comprehensive risk assessment of this project was also conducted by a group of experts [121], who evaluated the following factors for the Middenmeer project: (1) recovery efficiency, (2) demand and price forecast accuracy, (3) water treatment performance, (4) scaling, (5) sand production/erosion, (6) gases in fluids, (7) corrosion, (8) skin formation due to drilling fluids, (9) reservoir quality, and (10) temperature effect on the reservoir. Of these factors, only one was considered high risk (large consequences and likely occurrence): demand and price forecast accuracy. Other risk factors that were seen as having moderate importance included recovery efficiency, water treatment, scaling, and reservoir quality. Following the first year of operation, three of the main identified technical risks (carbonate scaling, sand production, and heat losses through the hot well casing) and the mitigation methods used to address them were evaluated [114]. Based on the laboratory experiments and geochemical modeling work, CO_2 was added as a water treatment step to lower the fluid pH and reduce carbonate saturation, and surface monitoring equipment was installed to allow for sampling and testing of water chemistry to evaluate the efficiency of this treatment process. Pressure monitoring of the wells and heat exchanger was also conducted as an independent check for potential scaling that would interrupt flow within the system. To avoid future hardening of water over repeated cycles, the CO_2 dosing has been reduced. To address the risk of sand migration, which could cause clogging in the injection well, a sand filter system was installed. Examination of the filters indicate that only a limited amount of very fine sand and silt has been produced, and that minimal skin effects have been observed in the wells. To reduce heat losses from the hot well, alternating sand and clay layers were used as backfill material for the casing installation. Higher heat losses were observed during periods of lower flow rates. Future wells might consider use of insulated casing to reduce thermal losses.

4.6.4. Lessons Learned

Early site characterization using the test well was critical in evaluating the two aquifer options for siting the HT-ATES reservoir. These tests indicated that the shallower aquifer had the desired porosity and flow characteristics. Selection of the upper aquifer resulted in improved project economics achieved from cost savings realized from drilling shallower wells, and also avoided complications associated with the presence of methane in the lower reservoir. Batch geochemical experiments and reactive transport modeling were used to evaluate the potential for carbonate scaling and assess potential mitigation strategies. Integration of geochemical and thermal monitoring data collected during systems operations into the modeling work will help refine these results. DTS monitoring data allowed for history matching of the reservoir model, allowing for adjustment of rock property parameters in the model that resulted in much better correspondence between model predictions and actual field observations. Water treatment using CO_2 to reduce the potential for carbonate scaling has been successful. Higher than predicted thermal losses were observed during flow through the well casing—this can be mitigated by having higher flow rates and through the use of insulated casing materials.

5. Summary of Key Findings

The HT-ATES systems that have been attempted in Germany and the Netherlands have had a checkered history. Of the four HT-ATES systems reviewed in Germany, one was abandoned after the initial field investigations and modeling, two sites were suspended after several years of operation due to underperformance, and only one system (Rostock) remains in operation. Of the six sites reviewed in the Netherlands, the Wageningen and Monster HT-ATES projects are still in operation (but underperforming), the Utrecht and Zwammerdam HT-ATES projects that were operational have now been abandoned, the Middenmeer HT-ATES project is in the early stages of operation, and the Delft project is still in the planning and development phase. There are many (>10) new HT-ATES projects in addition to the ones described here that are currently in the planning and development stages in Europe. Here are a few common observations for the reviewed projects:

- Each project needs to consider site-specific conditions. The local geology and hydrogeology are critical factors in selecting an aquifer suited for thermal energy storage—i.e., a suitable site has to have an impermeable cap to prevent flow to adjacent aquifers, the permeability has to be high enough to permit lateral flow between wells, but low enough to counteract/prevent vertical buoyancy flow, the system needs to be in an area with minimal background groundwater velocity, and the type of mineralogy and fluid chemistry need to minimally cause detrimental geochemical interactions (e.g., [3]). Proper site characterization conducted (and preferably a test drilling) at an early phase of the project will lead to more accurate predictions of system performance and identify potential operational and technical issues.
- Monitoring systems have been very useful in observing system performance and identifying potential operational issues. Data obtained from these systems can be used to calibrate reservoir models, which in turn can be used to predict future performance using different operational scenarios to allow for system optimization.

- The effectiveness (and profitability) of the HT-ATES projects depends on the efficiency of thermal energy storage and recovery, which is impacted by the energy supply and demand, the cut-off temperatures for the thermal energy that is extracted, and the performance of the subsurface energy storage system. Changes in thermal energy supply and demand can negatively impact the thermal energy recovery coefficient, and these changes have posed a major issue for many of the failed projects.
- The project economics will depend on a variety of factors, such as the thermal efficiency of the system, the extent to which the off-takers can take full advantage of the thermal energy, the cost of the wells (which depends on the depth of the aquifer), and the operational costs needed to keep the system running reliably (e.g., [17,23]). However, the benefits provided by having seasonal storage balance out variable thermal energy demands can make these costs competitive. Having higher temperature storage provides a greater energy density for the storage system, which could lead to improved performance and economics. Small thermal plumes generally experience relatively greater thermal losses than large ones due to their larger surface area to volume ratio, and larger systems benefit from the economy of scale [24].
- Many of the early HT-ATES projects were quite small, so a single operational issue (such as a corroded pump or leaking well) could shut down the entire system. Building more robust systems that are resilient enough to continue running due to system redundancy makes these projects more attractive to off-takers.
- Incorporating lessons learned from past projects should help avoid some of the pitfalls that were experienced. Updating design models based on new field and operational data is critical to generating reasonable expectations for systems performance and properly assessing the risks of such projects (e.g., [10]).

6. Failure Modes and Possible Mitigation Methods

Various HT-ATES projects described above encountered both technical and non-technical challenges that impacted project success. Table 4 summarizes the technical issues that were highlighted in Table 2 and described in the previous case studies and provides suggestions on how to avoid and/or mitigate these effects.

Table 4. Key technical challenges and potential mitigation strategies for HT-ATES.

Technical Challenges	Potential Solutions
Geological and hydrogeological factors	
• Incomplete subsurface characterization • Formation heterogeneity • Caprock integrity • High groundwater flow velocities	• Perform a detailed review of existing geological, geophysical, and hydrogeological information for the proposed site • Drill test boreholes to characterize subsurface geology and aquifer properties • Run geophysical surveys to map out extent and thickness of major units • Conduct flow tests to obtain site-specific hydrogeological properties • Evaluate effectiveness of reservoir seal in preventing upward flow into freshwater aquifers • Develop thermo-hydraulic flow models to predict system behavior and performance • Evaluate how thermal buoyancy can impact migration of stored thermal water

Table 4. *Cont.*

Technical Challenges	Potential Solutions
Geochemical factors	
• Scaling of minerals with retrograde solubility (carbonates and sulfates) • Corrosion • Biofouling • Dissolution of metals • Contamination of potable water aquifers • Swelling clays causing reduction in fluid flow	• Collect and analyze water and gas chemistry of aquifer fluids and mineralogy of reservoir rocks, both in initial site characterization and as part of ongoing operational monitoring • Conduct reactive transport modeling simulations to predict potential scaling and corrosion reactions • Conduct batch experiments using relevant rock and fluid samples under planned reservoir conditions to evaluate potential geochemical processes • Evaluate water treatment approaches (such as ion exchange or pH modification) to reduce potential for scaling, corrosion, and causing clay swelling in the reservoir, and install treatment systems if needed • Evaluate potential impacts of chemical treatments to system • Evaluate how changes in temperature and fluid chemistry might mobilize metals • Evaluate potential scaling inhibitors (both naturally occurring and added) • Conduct a detailed assessment of aquifer microbiology to assess potential for biofouling and generation of corrosive fluids • If multiple reservoir horizons are used, evaluate the potential impacts of mixing different reservoir fluids on scaling and system performance
Thermal energy recovery efficiency and system performance	
• Changes in availability of hot water source used to recharge HT-ATES • Changes in temperature of hot water source used to recharge HT-ATES • Changes in dispatching of hot water from HT-ATES • Changes in energy being extracted from HT-ATES • Lack of understanding of heating/cooling requirements for fluid temperatures from HT-ATES, especially cut-off temperatures	• Develop a flexible scalable system design that can adapt to thermal input and output changes while retaining efficiency • Install thermal monitoring systems (DTS) to provide continuous temperature data for the HT-ATES system • Conduct thermal and chemical modeling to evaluate potential impacts to system performance and efficiency caused by changes in temperature and flow rates • Develop cascaded uses of stored water to improve system efficiency and project economics • Utilize techno-economic models to evaluate potential design and system use scenarios to evaluate their impacts of economic viability of system • Ensure that there is clear communication between HT-ATES system designers, heat suppliers, and off-takers
System design and construction, maintenance, and operational reliability	
• Thermal breakthrough between hot and cold wells • Failure of well completion (clogging of filters due to precipitation of hydrous ferric oxide minerals, biofouling, leaking of casing, etc.) • Corrosion and failure of pumps • System downtime caused by maintenance and equipment failure issues	• Design and install monitoring systems to assess system performance • Use non-reactive materials in well construction • Develop comprehensive system models to evaluate optimal design configurations for hot, cold, and monitoring wells • Continuously update system models to optimize system performance and identify problems • Ensure the initial system design allows for flexible system operations • Engineer redundancy of key system components (i.e., multiple hot and cold wells, heat exchangers, pumps) to avoid system downtime • Control redox conditions by preventing entry of oxygen to subsurface through use of pressurized nitrogen gas in the wellbores • Evaluate potential impacts of cavitation due to high pumping rates on degassing of fluids, leading to potential precipitation of carbonates • Avoid free-fall reinjection of water into an unpressurized open annulus space, which could affect redox conditions of reservoir • Select drilling fluids for wells that avoid causing clay swelling in reservoir intervals

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Abbreviations

The following abbreviations are used in this manuscript:

ATES	Aquifer thermal energy storage
BMW	Bavarian Motor Works
CH	Cogeneration heating
CHP	Combined heat and power plant
DG	Deep geothermal
DTS	Distributed temperature sensing
EU	European Union
GJ	Gigajoule
GRE	Glass fiber-reinforced epoxy
HT-ATES	High-temperature aquifer thermal energy storage
IHC	Industrial heating and cooling

JKH	Jakob Kaiser house
LCOH	Levelized cost of heat
LT-ATES	Low-temperature aquifer thermal energy storage
MELH	Marie Elisabeth Lüders house
MW	Megawatt
MWhth	Megawatt hour thermal
PBHC	Public building heating and cooling
PLH	Paul Löbe house
PVC	Polyvinyl chloride
RHC	Residential heating and cooling
RTG	Reichstag Building
SH	Solar heating
STES	Seasonal thermal energy storage
TDS	Total dissolved solids
TH	Thermal-hydraulic
TJ	Terajoule
TU Delft	Delft University of Technology
UTES	Underground thermal energy storage

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