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State-of-the-art of MT- and HT-ATES in the Netherlands and innovations of the ACCEL-UTES project

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1 INTRODUCTION

Approximately half of the European energy consumption is used for heating and cooling, and the sector still mostly relies on fossil fuels (Eurostat_Electricity and heat statistics) (Heat roadmap Europe, 2017). In order to increase the sustainability of heating and cooling, the sector needs to increase its share of sustainable sources. District heating (and cooling) networks (or heat networks in short) provide an effective way for using large, centralized sustainable energy sources such as industrial waste heat, geothermal heat and wind and solar energy. In contrast to gas as a source for heating, such sustainable sources cannot easily and quickly upscale or downscale their supply when energy demand changes. Thermal energy storage at various time scales is required to match sustainable energy supply with energy demand for heating and cooling, thereby providing flexibility and security of supply. Whereas short term storage options, such as thermal energy storage in tanks, or batteries on various scales are readily available, large scale and long term (seasonal) storage remains a challenge to implement because of the large required space use. Seasonal Underground Thermal Energy Storage (UTES) can provide a solution for this challenge. The advantage of storing heat in the subsurface is that large volumes of heat can be stored at high storage density (energy/surface m2). This makes subsurface storage an excellent option for highly populated areas (Dinkelman et al., in press). Aquifer Thermal Energy Storage (ATES) is the type of UTES with the largest storage volumes (Dinkelman et al., in press) and is considered the a key technology for seasonal storage in the Netherlands.

In the Netherlands 3 types of ATES systems are distinguished based on their maximum storage temperature (Low, Medium, High):

- LT-ATES: up to 25°C
- MT-ATES: 25 - 50°C
- HT-ATES: 50 - 90°C

The Netherlands has great experience with low temperature ATES systems. Worldwide approximately 2800 LT-ATES systems had been realized in 2018, with >2500 of these systems being located in the Netherlands (Fleuchaus et al., 2018). Most of these systems are used both for heating in winter and for cooling in summer. In contrast to higher temperature storage systems LT-ATES does not store heat from an external source, but makes use of the difference between indoor building temperature and subsurface temperature over the seasons. MT- and HT-ATES systems are not as common, both in the Netherlands and worldwide. The advantage of MT-/HT-ATES is that they can directly provide heat at up to 100 MW for medium or high temperature heat networks without, or with low(er) deployment of heat pumps. Compared to heat networks with LT-ATES and heat pump, or electrification of individual households, heat networks with a sustainable heat source and MT-/HT-ATES for seasonal buffering prevent the issues currently experienced with net congestion. The storage capacity (5 – 20 GWh) and energy density of these systems make them well suitable for storage of surplus heat from geothermal systems or industrial waste heat. Since MT-/HT-ATES is highly cost-competitive compared to electricity storage options such as batteries or hydrogen storage, they can also be used in power-to-heat solutions (Dinkelman et al, in press).

This paper presents a state-of-the-art summary of MT- and HT-ATES in the Netherlands with primary focus on HT-ATES, and builds upon the state-of-the-art described by Drijver et al. (2019). After the end of the HEATSTORE

project in 2019 (www.heatstore.eu), research and field studies have taken a flight, and important insights have been gained from the one and only operational, commercial HT-ATES system of Europe, located in Middenmeer, the Netherlands. This paper is based on past and present systems, literature and results from Dutch research programmes. It closes off with innovations being addressed in the ACCEL-UTES project, which started in September 2024 and aims at constructing a HT-ATES system at the Utrecht Science Park.

2 GEOLOGICAL POTENTIAL OF HT-ATES IN THE NETHERLANDS

In the a Dutch-nationally funded research project (www.warmingUP.info) subsurface criteria have been defined for the screening of geological potential for HT-ATES in The Netherlands (Dinkelman et al. 2020; Dinkelman and Van Bergen, 2022), see Table 1. Based on these criteria qualitative potential maps were generated (Dinkelman et al. 2020; Dinkelman and Van Bergen, 2022). In the WarmingUP project a tool was developed utilising a TNO developed 3D thermal simulator (ROSIM) and an economic model for the generation of national quantitative potential maps. A detailed description of the tool, as well as the resulting potential maps for maximum flow rate, power output and Unit Technical Cost (UTC) are published on the ThermoGIS website (www.thermogis.nl). ThermoGIS is a public, web-based geographical information system for the display of regional geothermal potential in the Netherlands.

The relevant depth interval for MT- and HT-ATES in the Netherlands is considered to be ~100-500 m. Most potential is available in the West-Northwest of the Netherlands in the Tertiary Maassluis Formation (**Error! Reference source not found.**), and potentially in the Oosterhout and Breda Formations. In the Southwest and Northeast the Brussels Sand shows potential, although this aquifer is often located at greater depth than 500 m.

Hydrogeological models, displaying subsurface layers relevant for ATES application such as alternation of sand and clay layers, as well as hydraulic parameters, form the basis for these potential maps. Currently, the available models are not very reliable for the relevant depth interval. Within e.g. the WarmingUP GOO or the Horizon-Europe GO-FORWARD project, the models are being improved by adding reprocessed or newly obtained drilling data, seismic data and insights from forward stratigraphic modelling. The potential maps will be updated once improved models are available.

Table 1. Subsurface criteria for HT-ATES systems applied in The Netherlands, updated in the WarmingUP GOO project to differentiate between hydraulic and thermal sealing of the clay layer on top of the storage aquifer.

Criterium	Unit	Storage temperature	Showstopper	Risk	Suitable
Lithology	-		Silt/clay	carbonate or glauconite-rich sand	Sand
Depth top aquifer	m - mv		no showstopper	< 50	> 50
Total thickness storage aquifer	m		<15	15 - 20	> 20
Effective thickness storage aquifer	m		<15	15 - 20	> 20
Hydraulic sealing by clay above storage aquifer[1]	m		<4	4 to 8	> 8
Thermal sealing by clay above storage aquifer[2]	m		<10	10 to 15	> 15
Sealing layer below storage aquifer[3]	m		no showstopper	<5	> 5
Hydraulic transmissivity storage aquifer	m^2/d	80-90°C	< 100	100-250 and > 600	250 - 600
		70-80°C	< 100	100-250 and > 800	250 - 800
		60-70°C	< 100	100-250 and > 1000	250 - 1000
Distance from groundwater protection zones or other heat storage systems	m		<300	300 - 500	> 500

[1]number of meters of clay in the 15 m directly above the storage aquifer
[2]total number of meters of clay in the 30 m directly above the storage aquifer
[3]number of meters of clay directly below the storage aquifer

3 MT & HT-ATES SYSTEMS IN THE NETHERLANDS

Figure 2 shows an overview of past, current and potential future systems in the Netherlands. Six MT-ATES systems have been operational for a variable number of years, and one system in Groningen is under development, with maximum temperatures of 40-45°C. Two HT-ATES systems in Utrecht and Zwammerdam had been operational for a few years but had to close down. The system at the campus of Utrecht University was operational from 1991 to 1999 and stored waste heat from a combined heat and power installation in the summer when primarily electricity was needed. This system was unique in the world for a long period of time because of the high storage temperature of 90°C. It had to close down due to well problems; the hot well experienced severe clogging by either carbonate scaling or clay swelling, despite intensive water treatment. Also, the warm well started to leak. Although the heat losses during storage were low, very low recovery

efficiencies of 27% were reached due to a mismatch in production temperature and temperature required by the heat network, and most of the stored heat remained in the storage aquifer (Drijver, 2012; Drijver et al., 2019). The system in Zwammerdam also stored high temperature heat from a combined heat and power installation in the summer, and was used for heating of a care facility in winter. It performed well with an average thermal efficiency of 65% but turned out not to be economically viable (Drijver, 2012; Drijver et al., 2019).

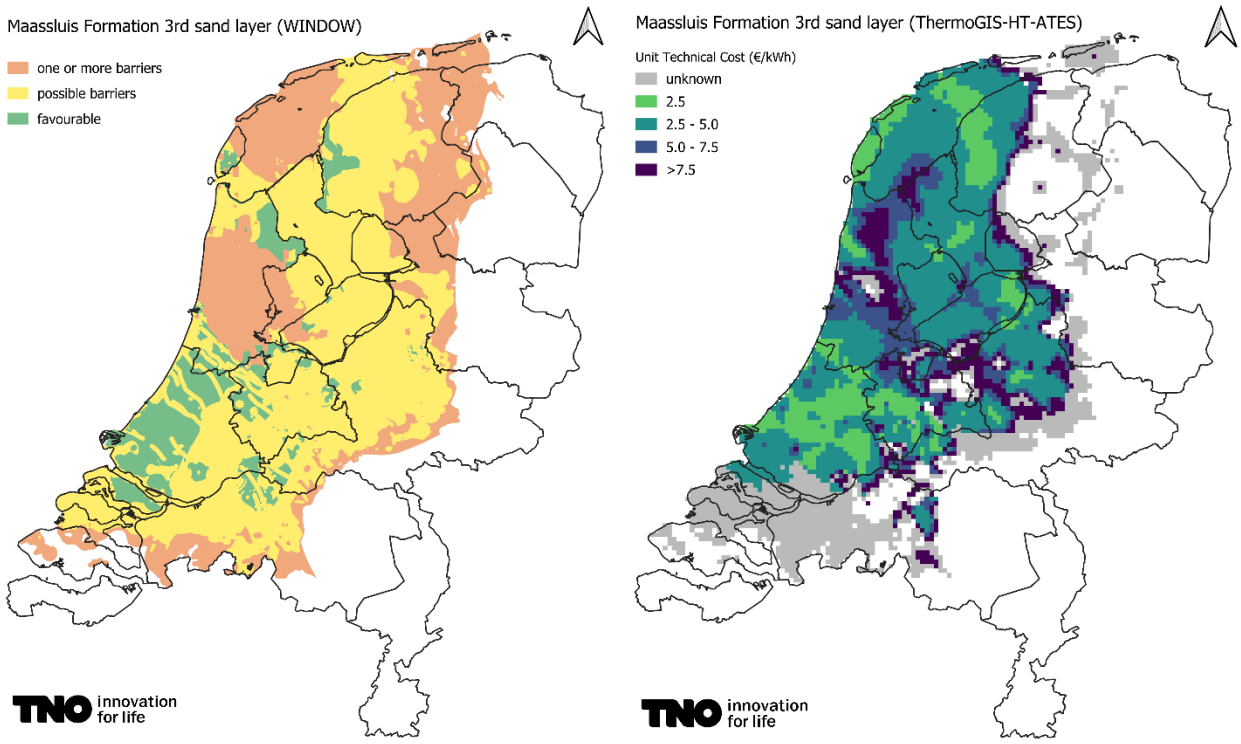


Figure 1. Potential maps for the third aquifer of the Maassluis Formation. Left: Qualitative map based on the subsurface criteria as shown in Error! Reference source not found. **(Dinkelman et al. 2020). Right: Unit technical cost map from ThermoGIS-HT-ATES (ThermoGIS v2.4, www.thermogis.nl).**

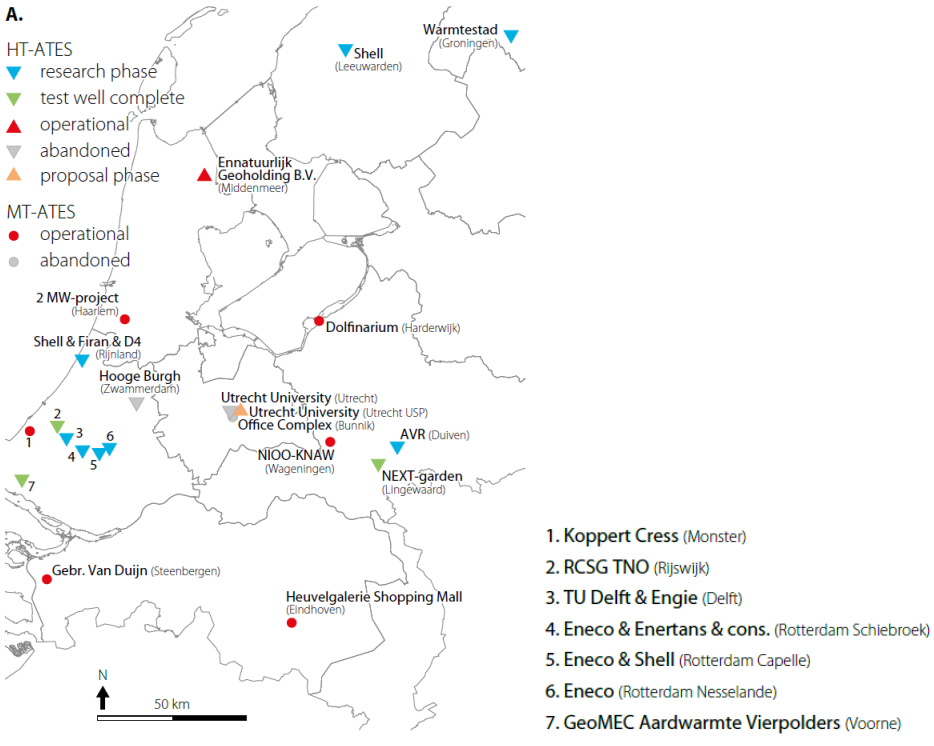


Figure 2. Status of MT-ATES and HT-ATES (research) projects in the Netherlands (from various publicly available information as of 2023).

The HT-ATES system in Middenmeer was designed and realized within the HEATSTORE project and has been successfully operational since 2021. Excess geothermal heat is stored at an average temperature of 83°C in summer, at a depth of 360 - 380 m, and recovered at ~80 to 45°C for direct heating of greenhouses in winter. It was designed for pumped groundwater volumes of 440,000 m^3 during heat storage and 440,000 m^3 during heat recovery. In that way the HT-ATES is able to store 28,000 MWh of heat per year at a maximum power of 10 MW and recover 20,000 MWh with the thermal power ranging between 2 and 8 MW(Oerlemans et al., 2023). It is currently the only operational HT-ATES system in the Netherlands and even in Europe.

Within the WarmingUP and WarmingUP GOO research programmes[1], new systems have been or are being investigated. These systems are currently in various stages between initial screening (quick scans) and design but none of them have reached a positive Financial Investment Decision yet.

4 INSIGHTS FROM DESIGN, OPERATIONS AND PERFORMANCE

4.1 Well design

HT-ATES systems rely on well-functioning wells for cyclic storage and production of the hot water. The well technology plays an important role for allowing optimal injection and production, also on the long term. Generally, two or more separate, typically vertical wells are realized for storage/production (hot well(s)) and for providing 'working water' (cold/warm well(s)). Other well configurations are possible, such as Multiple Partially Penetrating Wells (Bloemendal et al., 2020), but these are not (yet) typically used for MT- or HT-ATES systems.

The well materials need to be able to withstand the high temperature, primarily during storage when the temperature is highest. The tubing and well screen piping of drinking water or LT-ATES wells are typically constructed out of PVC as this is a strong, cheap and lightweight material that is easy to use (Bloemendal et al., 2020). At temperatures >45°C the strength decreases too much and PVC cannot be used any more. Therefore, much heavier and expensive stainless steel or Glass Reinforced Epoxy (GRE) needs to be used for hot wells. The type of stainless steel or GRE depends on the relevant downhole pressures, which in turn depend on the applied flow rates and aquifer transmissivity. Depending on the return temperature for heat use, the warm well(s) can be constructed out of the cheaper material to reduce costs (in such a case stringent measures preventing accidental hot water injection into the warm well must be put in place). In addition to the high temperatures, the design of the system should take into account the cyclic thermal expansion and shrinkage of all components of the hot well (including e.g. casing, wellhead, monitoring pipes) during operations and provide enough space to prevent damage (Bloemendal et al., 2020).

4.2 Maximum flowrates

Maximum flowrates per well are key input in the techno-economic evaluation of an ATES system as part of the energy system. The required power output and flowrates define the number of wells that are needed. Maximum flow rates are limited by a maximum velocity at the borehole wall in order to prevent excessive sand production and fines mobilization, primarily during extraction. Related risks are well clogging, damage to pipes and pumps and caving around the screens (Oerlemans et al., 2022). Guidelines are available in the Netherlands for relatively shallow, highly unconsolidated sediments from the drinking water industry and LT-ATES experience, and are typically corrected for higher temperatures (Peters et al., 2022). These guidelines, prescribing maximum flow velocities of 2 times the hydraulic conductivity (in m/d) (NVOE, 2006) are, however, limiting the flowrates for storage at higher temperatures and somewhat deeper MT-/HT-ATES systems.

A temperature increase can have several beneficial factors but also counteractive effects on clogging. Increased density (minor) and viscosity (major), result in a decreasing particle mobilization (through decreased drag- and lift forces acting on the rock particles) and increasing hydraulic conductivity, whereas increased repulsive electrostatic forces result in increasing mobilization. For a quartz dominated sand layer, a temperature increase from 20°C to 80°C allows an increase in flow rate by approximately 2.4 times, whereby the impact of viscosity decrease is dominating (van Eimeren 2022). The NVOE guidelines have been adapted for the temperature effect on viscosity and density (IF Technology, 2012; Peters et al., 2022). Besides the higher temperature, the NVOE guidelines do not include the in situ stress as a function of depth (Buik and de Kruif, 2020). At greater depth, the higher pressure makes it more difficult to mobilize sand, which would allow higher maximum flow rates with depth (Drijver et al., 2020). Well tests in the test drillings from the HT-ATES in Middenmeer, and from the potential systems in Rotterdam Nesselande, Leeuwarden and Delft have demonstrated that the guidelines can be

[1] Innovatief Duurzaam Warmtecollectief - WarmingUp

exceeded substantially without significant sand/fines production, after initial flushing of the wells directly after completion (Drijver et al., 2020; Jansen et al., 2023a; Jansen et al., 2023b). Nearly four years of operations in Middenmeer at maximum flow rates up to 3.8 times the prescribed flowrate by the NVOE guidelines did not result in any issues with sand production or clogging (Oerlemans et al., 2022; IF Technology, personal communication). Based on the results from Middenmeer, a correction factor of 'depth/100' (based on tests from the cold well) or 'depth/150 m' (based on tests from the monitoring well) could be deduced (Drijver et al., 2020). Further research should aim at providing a generic correction to the NVOE guidelines applicable to any (future) system, in order to improve the economic viability of MT-/HT-ATES systems (Drijver et al., 2020; Oerlemans et al., 2022), and support selection of well completions for sand control (Peters et al., 2022).

4.3 Operational challenges and water treatment

One of the most important operational risks is related to scaling and clogging of the hot wells by carbonates. Groundwater in the Netherlands is typically saturated with carbonates and when it is heated to temperatures > 50°C the decrease in carbonate solubility might result in carbonate supersaturation and hence precipitation, followed by clogging of the heat exchanger, the wells or the storage aquifer around the wells. Different water treatment methods have been applied in the past to handle this. For the HT-ATES system in Utrecht Ca/Na ion exchange was used. The produced, cold water was led through a container with negatively charged particles to which sodium was adsorbed. The calcium then partially exchanged with the sodium in order to decrease the calcium concentration, thereby lowering the calcite saturation index (Drijver, 2012). The treatment required continuous attention, and adaptation of the dosing based on manual measurements. Too little ion exchange could result in carbonate precipitation, too much exchange in clay swelling. In the end, the hot well experienced severe clogging, despite the intense monitoring activities, by either one of those processes. In Zwammerdam, partly based on the experiences from the system in Utrecht, another water treatment method was selected. Here, HCl was used to lower the pH in order to increase the carbonate solubility before heating. The method was successful in preventing carbonate precipitation and clogging, but the use of HCl requires careful treatment since it is a very aggressive acid (Drijver, 2012). For large scale HT-ATES systems, the requirement of injection of large quantities of HCl would be a possible downside. Based on geochemical simulations and lab tests using analysed water samples and sediment taken from the test drilling in Middenmeer, the risk of carbonate precipitation was considered to be high (Dijkstra et al., 2020; Oerlemans et al.2022). In the HT-ATES system in Middenmeer a new additive was chosen; CO_2 dosing was applied to lower the pH of the water (acidification) and thereby increase the carbonate solubility (Oerlemans et al., 2022). Chemical monitoring within the HTO-PEN project showed no indications of carbonate scaling within the first four operational years, and the addition of CO_2 was systematically decreased over time. Even though geochemical simulations predicted that higher dosages were needed to prevent carbonate precipitation (Oerlemans et al.2022; Koenen, 2023), no carbonate scaling has been observed after four years. Probably natural inhibitors or a shift from ammonium to ammonia at increasing temperatures, thereby reducing the carbonate alkalinity, could decrease the potential and/or the rate of carbonate precipitation (Drijver, 2012; Griffioen, 2020). The groundwater composition, and primarily the concentration of magnesium, phosphate, ammonium and dissolved organic carbon, needs to be considered while determining the potential of carbonate scaling and required water treatment (Drijver, 2012). In order to prevent overdosing of CO_2 with the risk of increasing the acidity and hardness of the groundwater, ongoing research focuses on the impact of the concentration of these components and reliable calculations of required dosing.

4.4 System performance

The thermal recovery efficiency (η), defined as the ratio between the recovered and stored amounts of thermal energy, is an important indicator for the success of an ATES system. Since heat losses occur at the boundary of the stored hot water body, η highly depends on the geometric shape of the stored water body, which in turn depends on the stored volume, aquifer thickness, porosity and heat capacity, and on buoyancy flow (upward flow of hot water due to differences in temperature dependent density and viscosity) (Doughty et al., 1982; Buscheck et al., 1983; Schout et al., 2014; Beernink et al., 2024). Hydraulic and thermal properties of the (preferably thick) sealing clay layer further influence heat losses towards the overburden and aquifer permeability and anisotropy are key parameters for buoyancy flow. Because of heating of the subsurface, heat losses decline with each operational year and η = increases. The feasibility study of Rotterdam Nesselande showed the significance of a proper sealing layer below the aquifer; the absence of a continuous clay layer below the aquifer allowed attraction of cold water from below the aquifer during heat recovery, thereby negatively impacting the thermal efficiency (Kleinlugtenbelt et al., 2023).

Apart from the thermal efficiency, the absolute amount of energy recovered is an important parameter for the (economic) performance of an MT-/HT-ATES system. In addition to geological factors, system design and

operational factors can significantly impact the efficiency, as well as the total heat output. As heat losses result in declining production temperatures during the recovery phase, a cut off temperature is required below which the recovered heat is of no use for the heat network. A lower cut off temperature directly leads to an increase in recovered heat when heat demand is sufficiently high.

Feasibility studies performed within WarmingUP and WarmingUP GOO have shown a strong positive correlation between the temperature difference between hot and cold/warm wells and the performance, indicating that low return temperatures in the heat network are highly favorable (Kleinlugtenbelt et al., 2023). Yet, these large temperature differences also increase the sensitivity of the efficiency to the aquifer thickness and its hydraulic conductivity, and efficiencies can become as low as 20% if buoyancy flow leads to excessive heat losses (Beernink et al., 2024), demonstrating the importance of suitable aquifer characteristics for specific heat storage requirements.

In order to prevent negative and promote positive interference between the hot and warm plumes in the aquifer, the well distance for a conventional doublet, or the well configuration for multiple wells, should be optimized. Other operational factors that impact the performance are imposed flow rates, and duration of infiltration and recovery periods. These can be optimized for maximum efficiency and total heat output (Dinkelman et al., 2024), but in practice they will highly depend on the fluctuating and often unpredictable (sustainable) heat supply and demand evolution.

For the HT-ATES in Middenmeer, both the thermal efficiency and heat output increased over the first 4 operational years; heat delivery has increased from 2,470 MWh in year 1 to 6,490 MWh in year 3, with thermal efficiencies of respectively 28% and 44% (Drijver, 2024). Yet, they were lower than initially anticipated (Figure 3) for several reasons (Drijver, 2024):

- Lower heat supply by the geothermal systems resulting in smaller storage volumes in the aquifer, which cause larger relative losses.
- Higher return temperature at the warm well than anticipated in the 3rd year (36.6°C instead of 30°C).
- Heat loss from the casing between surface and well screen. The average loss attributed to this mechanism for this system was calculated to be around 7%, which is a considerable loss factor, which justifies mitigation in future projects.

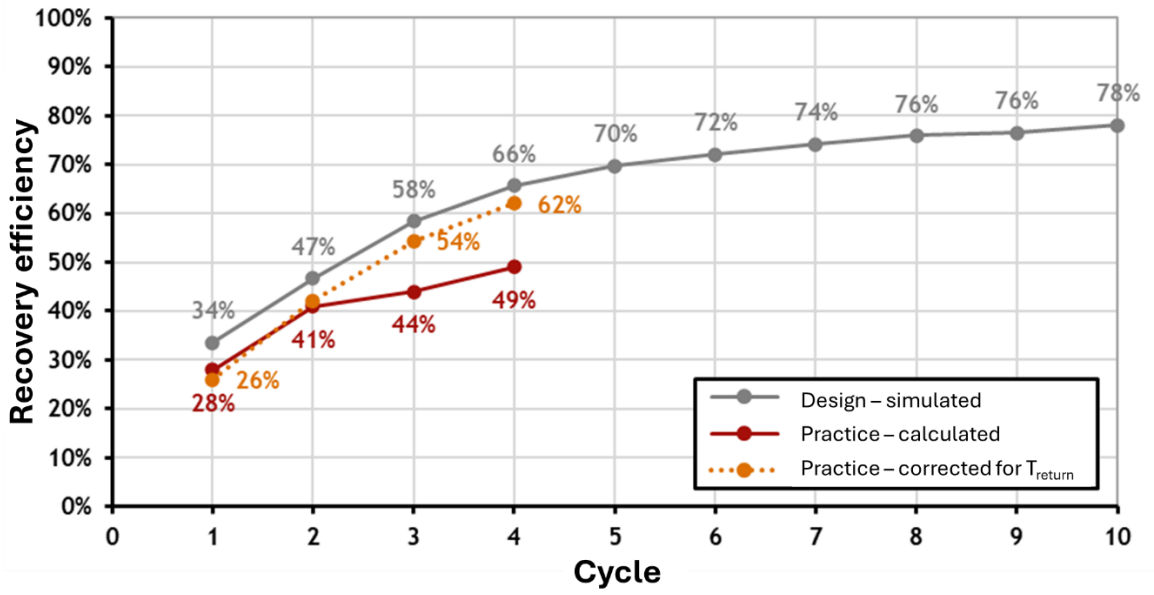


Figure 3. Expected and actual thermal efficiency values, infiltrated and recovered volumetric and energetic values for the first three operational years of the HT-ATES in Middenmeer. The green striped line shows the predicted efficiency in year 3 if the return temperature would have been 30 instead of 36.6°C. The cut off temperature for the system is ~45°C.

Heat networks exist at various scales and temperature levels, and can be fed by a number of different heat sources. The cut off temperature for a MT-/HT-ATES system depends on the required temperature level of the heat network and the availability and temperature of heat from other sources. A possibility to decrease the cut

off temperature is the use of a (water-water) heat pump to boost the production temperature. A large heat pump can boost the MT-/HT-ATES temperature prior to feeding into the heat network if a specific temperature is required, or decentralized, small heat pumps can be used at the level of the individual users. Heat pumps are expensive and require, depending on the conditions and corresponding COP, much electricity to operate. When the heat pumps are used in cold winter periods, when sustainable energy supply is (currently) typically low, this can result in (increased) issues with net congestion and the increased use of grey electricity.

All the considerations on the integration of a HT-ATES in the energy system are highly case specific and require techno-economic optimization at the level of the district heating network. The DesignToolkit[2], a simulation platform for conceptual design of heating networks, including a coupled thermal subsurface and heating network simulator, is highly useful for this purpose in the initial phase of heat network development (Dinkelman et al., 2024). More detailed HT-ATES design and operational optimization, for which tooling is currently being developed in the WarmingUP GOO project, would be needed in a later phase.

Another possibility for the use of heat pumps is the power to heat application in which, typically during the summer, excess green electricity is used to operate the heat pump and the heat is subsequently stored in a MT-/HT-ATES system.

The design and operations of a system can be optimized for a specific case to aim for maximum thermal efficiency and heat delivery using thermal and/or heat network simulators (Dinkelman et al., 2024). However, in practice the thermal efficiency is highly determined by the actual heat supply and demand, which are influenced by many external factors acting on the entire energy system as experienced in Middenmeer. Besides techno-economic optimization, other stakeholder interests play an important role in complex decisions regarding the improved sustainability of heating for the built environment.

Overall, the thermal efficiency and the absolute heat delivery benefit from large storage volumes in a thick aquifer with intermediate hydraulic conductivity, a large temperature difference between the hot and warm/cold wells and a low cut off temperature. This requires a heating network with large amounts of excess heat in summer at high temperatures, the possibility to use heat at low temperatures, a low return temperature, and high heat demand in winter.

5 ENVIRONMENTAL IMPACTS

The impact of a MT-/HT-ATES system starts with pumping water from the warm side of the system to the hot side, which may cause mixing of different types of groundwater from different depths within the storage aquifer, which may concern different salinities. Variations in the redox conditions with depth are also possible, but in that case mixing should be avoided in order to minimize the chances of inducing redox reactions that could lead to well clogging risks.

Temperature increases occur from cyclic heat storage in the storage aquifer, corresponding heating of over- and underlying layers and radial heating from the hot well(s), and to a lesser extent the warm/cold wells during hot/warm water infiltration and recovery. Within the storage aquifer the temperatures go up and down in the zones around the cold/warm and hot well(s) with each cycle. Because of the higher injection temperatures, these temperature variations are larger around the hot wells.

In the overlying, and to a lesser extent underlying confining layers a progressive heating is expected. For the HT-ATES in Middenmeer, these effects are visualized in Figure 4 for the storage aquifer and the upper and overlying layers. The temperature measurements at the monitoring well show the expected processes of the arrival of the heat front a few days after the start of the first storage cycle, the buoyancy effect, heat conduction, dispersion and heat loss to confining layers, and retreat of the heat front during heat recovery.

Because of the buoyancy effect, the temperature in the underlying clay shows a cyclic pattern of heating and cooling, whereas the heating in the overlying clay layer is continuous, but accelerates and slows down over time. After three operational years, the upward heating of the clay reached ~30 m from the top of the storage aquifer. In subsequent cycles heating is shown to slow down over time, which is explained by the heat lost in previous years. This causes a gradually decreasing temperature gradient, a decreasing heat flux into the overlying clay layer and limits heat losses from the storage aquifer in subsequent years. The temperature data at the monitoring well was used to calibrate a hydro-thermal dynamic simulation model, providing insight into the hydraulic and

[2] Design Toolkit - WarmingUp

thermal properties of the sand and clay layers, and allowing improved predictions of future thermal efficiencies and thermal evolution within and outside the storage aquifer (Szklarz et al., 2024, Koenen et al., in preparation).

Radial heating from the well casing of the hot wells, and to a lesser extent the warm wells, impacts overlying layers, primarily sand layers because of their higher thermal conductivity and natural groundwater flow. Monitoring at the MT-ATES of NIOO (storage temperature up to 45°C) showed several degrees temperature increase in a shallow aquifer at a distance of >50 m from the hot well, implying a significant thermal impact around the hot well. The thermal impact is expected to be strongly local and temporary: once hot/warm water injection or production ceases, temperature levels will go back to their natural background values over time. At the monitoring well of the HT-ATES system in Middenmeer, 30 m from the hot well, first indications for a thermal breakthrough from the hot well have been observed in the shallow aquifer above the storage reservoir after three operational years (IF Technology, pers. comm). The next operational years will provide crucial data on the thermal impact and the reversibility during the resting period.

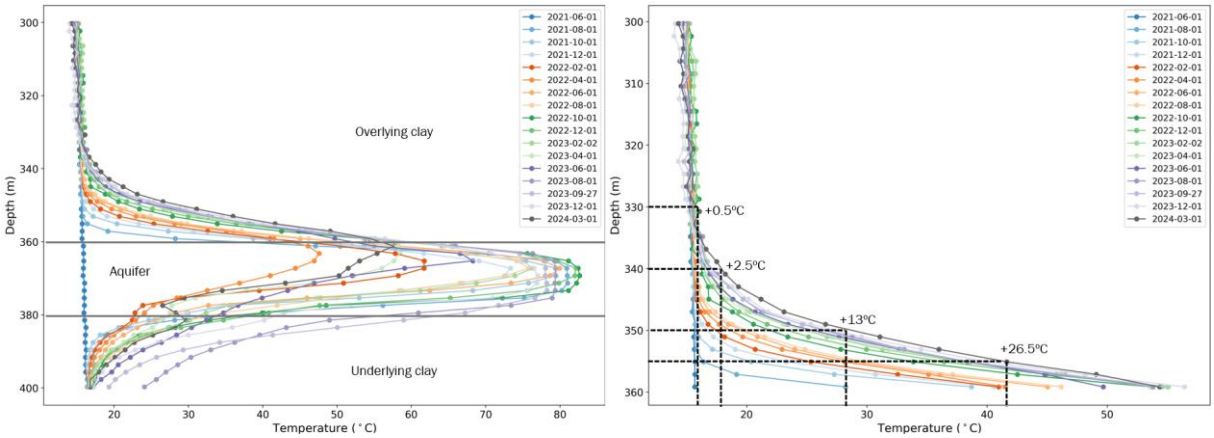


Figure 4. Bi-monthly temperature profiles from DTS data along the monitoring well in Middenmeer for the first three operational years. Left: for the aquifer with over- and underlying clay layers, depth interval 300-400 m. Right: zoom in of the overburden section, depth interval 300-360 m.

Both water mixing and temperature increases can induce chemical and microbiological changes. Temperature induced changes have shown to be minimal, or very slow for kinetically controlled reactions, at temperature ranges for LT-ATES systems, up to 25°C (Drijver, 2012; Schout and Hartog, 2021). At higher temperatures, organic material decomposition, carbonate precipitation, silicate mineral dissolution, shifts in sorption equilibria and microbiologically-induced methanogenesis and/or sulphate reduction are commonly known effects, primarily from theoretical and laboratory studies. In practice, these effects are highly location specific, as they depend on the geochemical and microbiological conditions, in combination with the experienced temperature evolution. At the MT-ATES at both Koppert Cress and NIOO, observed geochemical changes such as increased sulphate and decreased arsenic concentrations were attributed rather to mixing of water than to temperature increase (Guglielmetti et al., 2021). At the HT-ATES in Middenmeer, most of the observed chemical and microbiological changes could be attributed to the drilling of the monitoring well with fresh water, making use of a organic drilling fluid. Observed temperature-induced effects were small and included a (minor) increase in silicium, methane and arsenic, probably related to silicate dissolution, microbiologically induced methanogenesis and dissolution of arsenic-containing iron and manganese hydroxides respectively (Schout et al., 2023).

6 LEGAL FRAMEWORK

The Netherlands is known for its well-developed regulatory framework regarding ATES systems, reflected by the global lead in the deployment of ATES systems. For LT-ATES there is streamlined permitting procedure, which was instated in 2012 (Schulz-van Haegen, 2012). The implementation of the Environment and Planning Act (Omgevingswet) in January 2024 has further simplified the permitting process, with the intention of minimizing regulatory hurdles and accelerating adoption for LT-ATES (Oerlemans and Bakema, 2020).

MT-/HT-ATES are allowed but requires dedicated decision making by the provincial board who is the competent authority for ATES. The permitting process typically involves several stages, which may include pre-consultation, permit application, and decision-making. The Environmental Desk (Omgevingsloket) acts as a centralized online platform for managing permit applications and offers essential information regarding the environment and related permit requirements. Local authorities, including municipalities and provinces, are instrumental in assessing and issuing permits to ensure compliance with environmental regulations and safety standards. To

also streamline this process, an assessment framework for permitting has been established together with market and provinces (Bloemendal et al., 2021).

7 CONCLUSIONS AND INNOVATIONS DEVELOPED IN ACCEL-UTES

With one operational HT-ATES system in the Netherlands and several other demo's on their way to installation, the technology reaches TRL 7-8. Various lessons for design, integration, operation and permitting have been identified and reported, which help other projects, developers and authorities to enable/accelerate HT-ATES adoption. Nevertheless, more development is needed. In the currently running ACCEL-UTES project (Figure 5) the construction of a HT-ATES system at the Utrecht Science Park is envisaged, including the following innovations:

- Detailed site characterization HT-ATES: Demonstration of advanced exploration methods for improved capacity estimates and design;
- Demonstration of technical innovations for enhanced HT-ATES technical performance on well pipes, wellhead and operational envelopes for pumps. These include the implementation of thermal insulation of well pipes to minimize thermal losses, reduction of surface footprint of the wells, and mitigation of sand production;
- Further enhancement and practical application of design tools (extending from Design Toolkit) for HT-ATES integration in evolving energy systems comprising multiple sources and consumers, capable of optimizing source strategies and P2H options;
- Development of standards and blueprints for fast-track market uptake and improving environmental and monitoring guidelines.

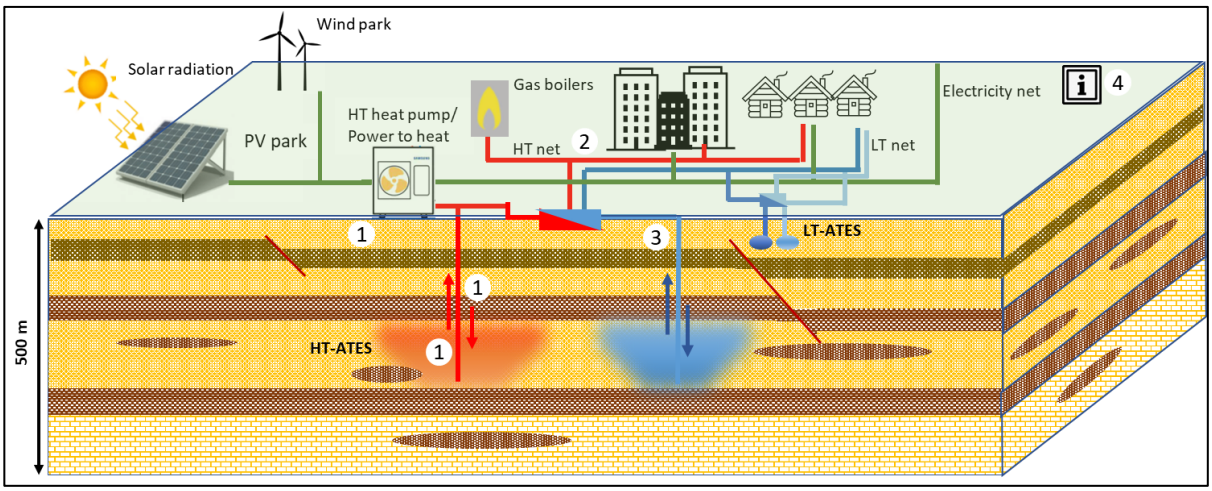


Figure 5. Schematic overview of ACCEL-UTES implementation at University of Utrecht. Highlighting the key innovations: 1) De-risking and engineering of HT-ATES system; 2) design and optimization of HT-ATES integration in USP multi-commodity energy system; 3) Construction and operational demonstration of HT-ATES at USP; 4) Fast-track market uptake

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