HEATSTORE
Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned

Prepared by: Anders Juhl Kallesøe (ed), GEUS
Thomas Vangkilde-Pedersen (ed), GEUS

Jan Erik Nielsen, PlanEnergi
Per Alex Sørensen, PlanEnergi
Guido Bakema, IF Technology
Benno Drijver, IF Technology
Bas Pittens, IF Technology
Nick Buik, IF Technology
Patrick Egermann, Storengy
Charlotte Rey, Storengy
Charles Maragna, BRGM
Virginie Hamm, BRGM
Luca Guglielmetti, University of Geneva
Florian Hahn, GZB
Isabella Nardini, GZB
Joris Koornneef, TNO
Knud Dideriksen, GEUS

Checked by: GEUS: Thomas Vangkilde-Pedersen

Approved by: GEUS: Thomas Vangkilde-Pedersen
TNO: Holger Cremer,
HEATSTORE coordinator

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HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority - 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage, which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2019.04.26	Ver. 0 Final report

Table of Content

Appendices

I: *HEATSTORE – State of the art HT-ATES in the Netherlands – Evaluation of thermal performance and design considerations for future projects*

II: *HEATSTORE – Design considerations for high temperature storage in Dutch aquifers*

1 Introduction

This report summarizes experiences and lessons learned on Underground Thermal Energy Storage (UTES) systems from the participating EU project partners and is supplemented with input from publications on other relevant cases in, and outside, Europe.

The report covers important experiences from the first pre-investigation phase and feasibility studies and throughout the construction phase, system integration and operations. Furthermore, different national legislative, political and public issues are described.

The HEATSTORE project and this report comprise four different UTES systems:

- High Temperature Aquifer Thermal Energy Storage (HT-ATES)
- Borehole Thermal Energy Storage (BTES)
- Pit Thermal Energy Storage (PTES)
- Mine Thermal Energy Storage (MTES)

The ideas behind MTES is state of the art and the HEATSTORE demonstration site in Bochum, Germany, will be the first of its kind. Experiences and lessons learned regarding this specific system is therefore not existing, see chapter 5.

In Appendix I and II, specific report contributions from partners are included. These contributions have served as an important basis for this deliverable.

2 HT-ATES (High Temperature Aquifer Thermal Energy Storage)

2.1 The ATES system

ATES can take place by injection and later re-production of hot water in aquifers in both shallow and deep geological formations. The aquifers can be both unconsolidated sand units, porous rocks like sandstones or limestone or e.g. fractured rock formations. Deep aquifers provide an option for high temperature storage (HT), which is defined as systems with injection temperatures > 60ºC. Injection temperatures in shallow aquifer units in the upper few hundred meters of the subsurface is, however, in most countries, restricted to a few tens of degrees Celsius (Low Temperature storage). Medium temperature (MT-ATES) systems are defined as heat storage at temperatures ranging from 30-60ºC[1].

Figure 2.1 illustrates the principles of seasonal heat storage by the use of ATES in district heating. In the summer e.g. solar collectors will add surplus heat to the aquifer. The heat is then stored for the winter period, where it is used in the district heating network. Large heat pumps can be installed to boost the temperature depending on the outlet temperature from the aquifer storage.

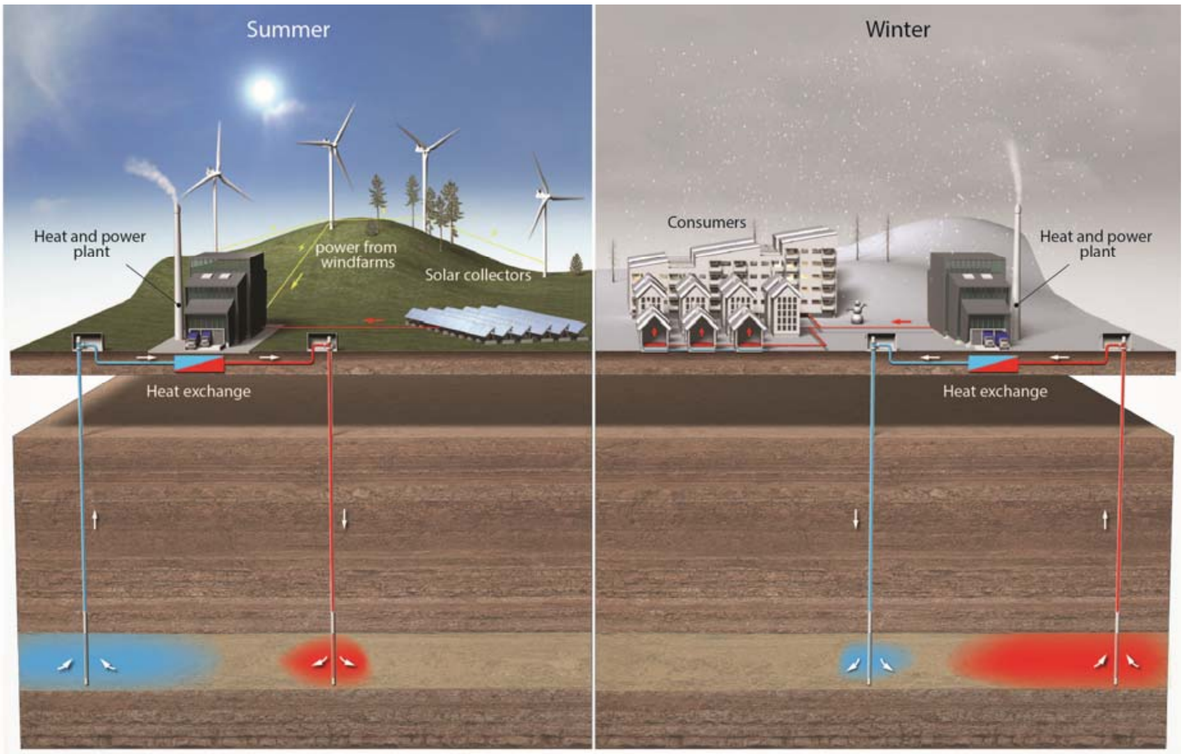

Figure 2.1 The principles of seasonal heat storage by the use of ATES in a district heating network (GEUS)

Low temperature (< 30°C) heat and cold ATES systems are the most common systems, especially in the Netherlands with around 2,500 operating systems. When looking at systems with injection temperatures above 30-40°C, the number of implemented systems are very few, and only 5 high temperature systems (>60°C) are currently in operation worldwide[2].

[1] Danish Energy Agency, 2014. Status and recommendations for RD&D on energy storage technologies in a Danish context.
[2] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.

Two of the first systems in Europe to demonstrate the High Temperature ATES approach were Plaisir Thiverval-Grignon in France (1985-1987) and Utrecht University in The Netherlands (1991-1997). The system in France were designed to store excess heat from a waste incineration plant and the intended storage temperature was 180°C. Due to problems with well clogging in especially the injection wells, the demonstration site was closed down. At Utrecht University the HT storage was stopped due to well problems and a system integration mismatch regarding the required temperatures and the temperatures the storage could provide[3]. The two cases are described further in section 2.6.

Fleuchaus et al.[4] have recently compiled an ATES review giving an overview on the development in ATES implementations worldwide, see Figure 2.2. In this review the pioneer systems Plaisir Thiverval-Grignon and Utrecht University are shown on the timeline below.

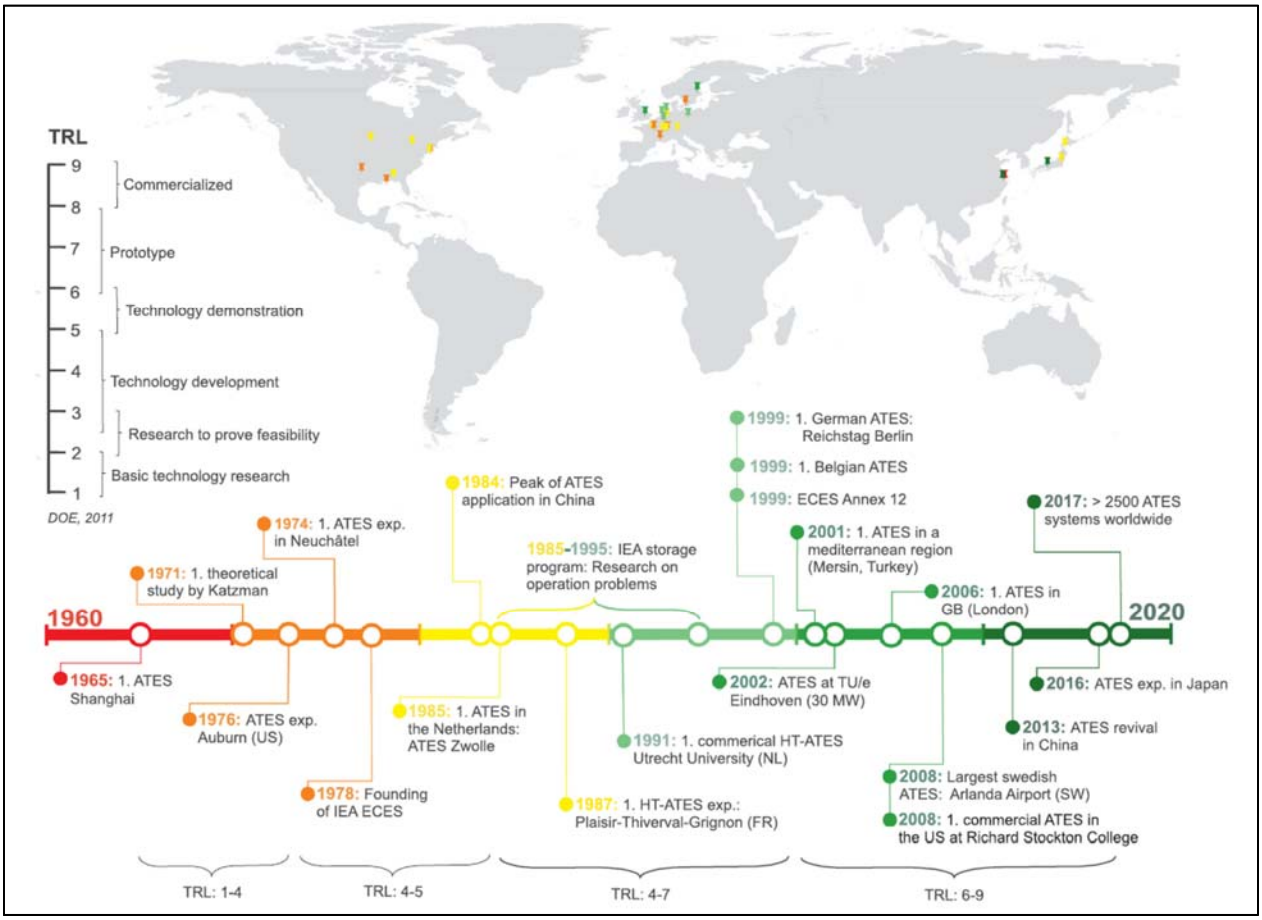

Figure 2.2 ATES timeline and development worldwide (reprinted from Renewable and Sustainable Energy Reviews, Vol 94, Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. Worldwide application of aquifer thermal energy storage – A review, 861–876, Copyright (2018), with permission from Elsevier[4])

At present three HT-ATES systems are located in Germany. In Berlin the German Reichstag building has a storage for 60°C hot water in a depth of 300 m (and a cold storage in shallow

[3] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.
[4] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.

aquifers)[5] and the Neubrandenburg plant[6] has a storage for 80°C hot water at a depth of 1250 m. A third HT-ATES plant is under construction at the BMW facility in Dingolfing[7] with planned storage of 130°C hot water at 500 to 700 m of depth.

The advantages of ATES systems include very large storage potential, low operational costs and high long-term profitability. The known technical challenges mainly include high return temperatures on the surface site and hydro-geochemical challenges such as precipitation and scaling in wells and pipes. Weathering of the geological formation and other geochemical and rock mechanical effects resulting in formation damage are also known challenges which could be encountered at the demo sites in the HEATSTORE project. Besides the need of research and demonstration of technical issues, legal aspects are currently regarded as barriers for the deployment of HT-ATES, which is touched upon in chapter 6.

2.1.1 Demo sites and case studies in HEATSTORE project

Six HT-ATES demo-sites and case studies are included in the HEATSTORE project[8]:

- ECW (Demo, The Netherlands)
- NIOO (Case study, The Netherlands)
- Koppert Cress (Case study, The Netherlands)
- Geneva Concept (Demo site, Switzerland)
- Bern Concept (Demo site, Switzerland)
- Balmatt in Flanders (Demo site, Belgium) – deep geothermal

In The Netherlands the demo pilot operated by ECW (Energie Combinatie Wieringemeer) will demonstrate a full scale HT-ATES storage with temperatures up to 90ºC. Besides this demo site two existing ATES case studies operated by NIOO and Koppert Cress are included in the HEATSTORE project. The system operated by NIOO has been designed for heat storage up to 45ºC and for the Koppert Cress system a conversion of low-temperature ATES to high temperatures (45ºC) will be in focus.

In Switzerland two demo pilots will be carried out. In Geneva the HEATSTORE pilot will assess the heat storage potential for the development of a HT-ATES System connected to a waste-to-energy plant located in Cheneviers (Canton of Geneva). The subsurface conditions will be constrained by drilling and testing at two different locations where the potential reservoir in the Cretaceous limestone is located at 600 and 1000 m´s of depth.

In Bern the pilot project aims to store waste heat from the nearby power generation site Bern-Forsthaus. The power generation site is operated by the local utility company Energie Wasser Bern (EWB) and contains a combined-cycle plant, waste-to-energy plant and wood-fired power station for electricity and heat production. For the pilot heat storage system an exploration well, ~ 500 m deep will be drilled to reach the Lower Freshwater Molasse USM. The goal of this project is to assess the feasibility of the ATES system and if the results are positive, to drill more wells to realize a fully functional heat storage system, which, in its final implementation, is aimed to store up to 7–10 MW_{th} waste heat at a storage temperature of 120°C maximum.

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[5] Sanner, B., Kabus, F., Seibt P. & Bartels, J. 2005: Underground Thermal Energy Storage for the German Parliament in Berlin, System Concept and Operational Experiences. Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.
[6] Kabus, F., Wolfgramm, M., Seibt, A., Richlak, U. & Beuster, H. 2009: Aquifer thermal energy storage in Neubrandenburg-monitoring throughout three years of regular operation. Proceedings of the 11th International Conference on Energy Storage.
[7] https://www.hydro.geo.tum.de/fileadmin/tubvhgt/www/documents/Pressemitteilung_BMW.pdf
[8] GEOTERMICA, High Temperature Underground Thermal Energy Storage (HEATSTORE), full proposal, 2018.

The Belgium demonstration pilot at Balmatt is in the context of HEATSTORE focusing on optimized system integration of a deep geothermal HT-ATES system into the local district heating network.

2.2 Lessons learned – line up

In Table 2.1 below the important lessons learned from existing medium-high temperature ATES systems are lined up. The table summarises the conclusions from the more thorough report text in the following sections.

The focus regarding HT-ATES is primarily on sedimentary **unconsolidated** aquifers.

Table 2.1. Line up of lessons learned regarding HT-ATES/ATES systems

<table>
<tr><th colspan="3">HT-ATES systems – Lessons learned</th></tr>
<tr>
<td>Pre-investigation (feasibility study)</td>
<td>• Screening of ATES potential (availability of aquifer/reservoir) (2.3.1)
• Stakeholder involvement from the start (2.3.1)
• Make a test drilling before the design phase. Include pump testing and geophysical borehole logging (2.3.4)
• Calculate the thermal efficiency with 3D heat transport models (3D geological and hydrological model) (2.3.6.1, 2.3.6.2)
• Use of hydro-chemical modelling for a first assessment of the necessity of water treatment. In-situ testing with local groundwater is recommended (2.3.7)</td>
<td rowspan="2">External factors (political, legislation) : (see also chapter 6)

Regulations on injection temperatures in aquifer (generally maximum is 20-25°C)

A need for accurate and reliable regulations

Generally legal questions have to be addressed and finalized in regulations/laws

Risks of not getting a permit or long (timely) permit procedure

Lack of knowledge among important stakeholders

Lack of subsurface management</td>
</tr>
<tr>
<td>Construction</td>
<td>Drilling
• Reverse rotary with air-lift is considered as standard technology for HT-ATES because of well diameter and clean drilling process (2.4.1)

Design
• Based on experiences it is recommended to use star-shaped well configurations (2.4.3)

Materials
• It is recommended to use submersible pumps in the wells - not shaft pumps (2.4.4)
• For submersible pumps in the warm wells specifically ESP (Electric Submersible Pump) is suitable for high temperatures. ESP's are commonly used in oil & gas or geothermal applications. (2.4.4)
• For submersible pumps in the cold wells standard low temperature submersible pumps can be used (2.4.4)
• Cold wells can be constructed with PVC screens and casings in situations where temperatures is < 60°C (2.4.4)
• Insulation of the well casing can minimize heat losses of the store and prevent heating up shallow (fresh water) aquifers (2.4.4)
• Use of materials resistant to corrosion (2.4.4)

Recommendations for general specifications and design of HT-ATES are presented in the HEATSTORE deliverable D1.2 report "General specifications and design for UTES systems"</td>
</tr>
</table>

HT-ATES systems – Lessons learned		
System integration	• Make systems which can store at least 300.000 m^3 of water (2.5.1) • Experience from The Netherlands show that a thermal power of minimum 5 MW is required to prevent high thermal losses (2.5.1) • Ensure that the usable (cut-off) temperature from the storage is as low as possible (2.5.2) • Put the heat storage system at base load in wintertime (2.5.3) • The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in buildings have not been adapted to the possible extraction temperatures from the heat storage (2.5) • Charging period of the storage needs to be included in the planning (2.5) • Well capacity (and declining well capacity) needs to be evaluated and not overestimated (2.5)	

HT-ATES systems – Lessons learned		
Operations feedback	**Monitoring (2.6.1)** • It is highly recommended to monitor the system properly in order to diagnose and optimize the system • To monitor the heat and water quality in the aquifer, it is advised to install a separate monitoring well at a certain distance to the hot well of the HT-ATES system • For monitoring temperature it can be considered to use fiber optic techniques instead of measuring temperatures in the wells or monitoring lines using temperature sensors • Performance monitoring is essential to optimize the system and to be able to deliver the energy efficiency that the system was designed for **Maintenance (2.6.2)** • Clogging due to clay swelling is a known problem (Ca/Na ion exchanges) • Production differences in the vertical extent of the screen is a known challenge • Repeated regeneration of wells should be implemented in the maintenance budget • Break-down of water-level transmitters in the wells can happen due to high storage temperatures • Cables of submersible pumps in warm wells is affected due to water treatment with HCl • It is not recommended to monitor temperatures in the hot wells next to the well casing due to heat radiation from the hot well casing to its surroundings • Do visual inspection of well heads, valves, transmitters and heat exchangers for leakage and corrosion as preventive maintenance • Check the state of the well pumps by measuring the electrical resistance between the phases • Back-flushing of injection wells at maximum capacity is generally recommended **Water treatment (2.6.4)** • The geochemistry is important and may be affected by mixing of waters, change of temperatures and change in pressure • It is advised to consider water treatment at temperatures >50ºC • Water treatment with ion-exchange should **not** be used • HCl-treatment is proven to be a reliable technique to prevent clogging • High HCl consumption is major disadvantage in respect to public acceptance and high operational costs **System and recovery efficiency (2.6.3)** • Due to too high cut-off temperatures the recovery efficiency is low and a large amount of potentially useful heat is left behind in the underground. This does not only reduce the recovery efficiency, but also increases the thermal impact of the specific system	

HT-ATES systems – Lessons learned		
Conclusions	• Many HT-ATES systems have so far been designed in a too small scale which makes them vulnerable for high thermal losses – experiences from the Netherlands show that a thermal power of at least 5 MW is required (2.5.1) • Use aquifers with a horizontal hydraulic conductivity between 3-7 m/d, i.e. a permeability between 3.5-8 Darcy (experiences from Dutch aquifers) (2.6.3) • When high temperature storage systems are made in too coarse sand, energy losses by density driven groundwater flow will be large (2.6.3) • The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in the building was not adapted to the possible extraction temperatures from the heat store (2.5) • Buoyancy flow and thermal breakthrough are known challenges (2.6.2) • More research is needed on water treatment, such as the use of CO_2 as treatment agent (2.6.4) • Future research should focus on component selection to prevent corrosion and improve knowledge on scaling of wells and heat exchangers • Future research should focus on thermal efficiency in different geological conditions (computer modelling and field testing) (2.6.3)	

2.3 (Pre-)investigation and feasibility studies

2.3.1 The geological conditions

The geological conditions is the key prerequisite for establishing a HT-ATES system. Without the availability of a suitable aquifer with favourable properties and dimensions it is not feasible to establish HT-ATES. A first screening of the geological conditions in the specific areas of interest is therefore crucial.

Depending on the geography, geological setting and availability of existing data and knowledge the geological screening can be more or less demanding and time consuming. In some countries national web tools for surface screening of suitable aquifers, groundwater interests etc. can be a starting point. In Figure 2.3 is shown a screenshot from a Danish web tool useful in a first screening for suitable areas. The web application displays potential areas for geological heat storage (ATES or BTES) based on existing knowledge combined with relevant information on locations of heat producing units, areas of drinking water interest etc.

A first positive outcome of the initial screening of the geological conditions will result in further questions on parameter characterisation that need to be answered/estimated. In the screening phase the properties of these subsurface parameters are more or less unknown. A test drilling with hydraulic testing at the site of interest in the investigation phase will give important knowledge and be a foundation for further decision making.

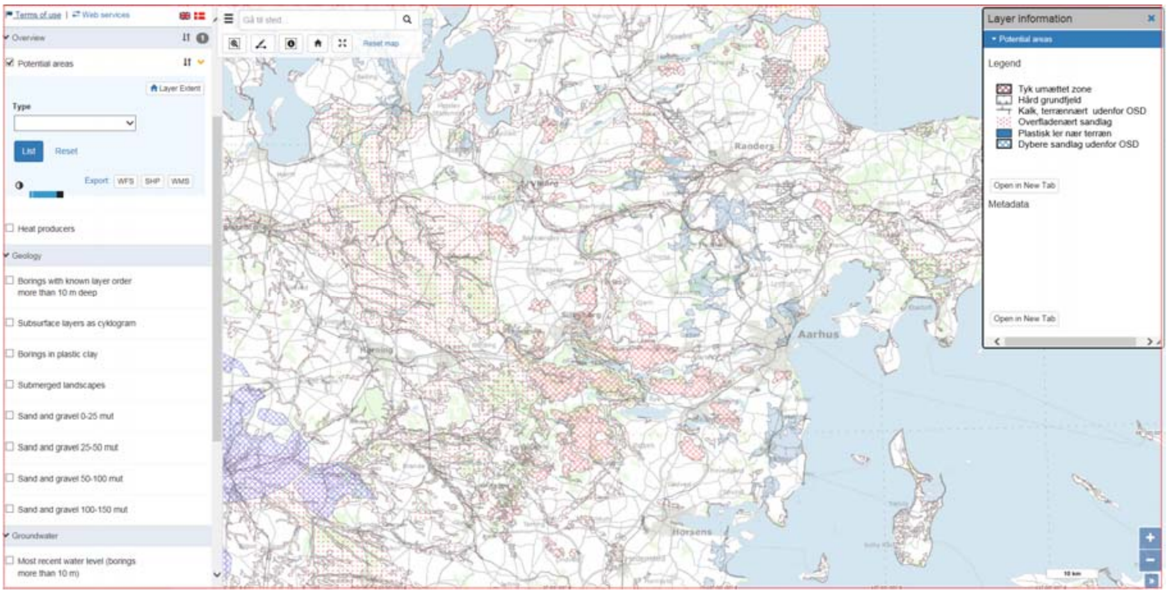

Figure 2.3 Screenshot from a Danish web tool designed for screening of areas with potential for geological heat storage[9]

The wide range of important parameters to address in the subsurface characterisation regarding HT-ATES are summarized in the following:

Geological and hydrogeological parameters:
- The geological and hydrogeological settings
- Aquifer dimensions – depth to aquifer, aquifer thickness, lateral dimensions, aquifer boundaries
- Aquifer heterogeneity
- Aquifer permeability
- Aquifer porosity
- Aquifer anisotropy
- The characteristics of confining top layers

Hydrological (groundwater) properties:
- Regional groundwater direction and velocity
- Hydraulic gradient and pressure
- Hydraulic conductivity/transmissivity
- Specific storage
- Fracture network: density, orientation, conductivity, connectivity (e.g. chalk or fractured rock aquifers/reservoir)
- Well connectivity

Geochemical properties for the groundwater:
- Chemical composition
- pH value of groundwater
- Dissolved gases
- Density and viscosity
- Isotopes
- Eh (oxidation/reduction potential), TDS (Total Dissolved Solids), TSS (Total Suspended Solids)

[9] GEUS web tool for screening of geological storage potential (heat storage) (www.geus.dk)

Thermal properties:

- Temperature and thermal gradient
- Thermal conductivity
- Heat capacity
- Thermal diffusivity (a measure for the rate of heat transfer of a material from the hot side to the cold side)

For deep geothermal systems the following reservoir properties are also relevant:

- Mineral composition of reservoir rock
- Density of reservoir rock
- Pressure in deep reservoirs
- Compressibility

2.3.2 Thermal energy demand

The thermal energy demand is an essential parameter in order to define if the geological conditions meets the required size and capacity of a potential HT-ATES system. The geological storage needs to be able to provide the necessary storage volume in order to achieve a sustainable heat storage. The type of application on the ground will determine how the HT-ATES will be integrated. Is the storage e.g. intended to be integrated with solar district heating, fed by industrial waste heat or suited for a third kind of application. The aspects of energy demand and system integration with the energy grid are described in section 2.5.

2.3.3 Stakeholders and groundwater interests

Typically the subsurface is subject to various interests (e.g. areas of drinking water interests). In the initial planning of a HT-ATES system, stakeholder involvement is important at an early stage. A mutual understanding between the stakeholders right from the first permit to the start of operation will serve to close the potential gap of insight between the different parties along the way.

Looking into the subsurface interests, knowledge of the thermal impact of an ATES system on the surroundings is relevant for existing groundwater users, especially possible drinking water supplies and for other ATES systems. Minimizing and documenting the thermal impacts is therefore not only relevant for the specific project under consideration, but also on the scale of an area with several other projects. This could often be the case in urban areas where space is limited and where the planning of well field layouts potential can be challenging[10].

2.3.4 Test drilling

If the results of the preliminary screening justify further investigation, a test drilling at the specific site is normally required[11]. One or more test drillings are important in order to estimate some of the uncertain or unknown parameters mentioned in section 2.3.1. Often aquifers suitable for high temperature heat storage have only been subject to limited investigations. One of the main reasons is that these aquifers have normally not been considered for drinking water extraction or low temperature cold/heat storage.

[10] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.
[11] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

Exploration through a test drilling is then necessary to confirm where the layers are located and what the water quality is. Important hydrological information about the aquifer is gained by performing a pumping test. Estimation of hydraulic conductivity only based on grain size in e.g. fine-sand (this usually concerns hydraulic conductivity <5 m/d) is too inaccurate. During the test drilling key parameters such as groundwater composition, groundwater chemistry, grain size in aquifer (important for design of screen and gravel pack) and characteristics and structure of the top confining layer. Knowledge on the top layers is important in the environmental assessment and when modelling the expected thermal efficiency of a system[12].

To reduce the costs, a test drilling can be used as a monitoring well later on. In the Netherlands it is typically a requirement in the permit for a heat storage project that the test drilling shall be used as a monitoring well afterwards.

Applying geophysical borehole logging to the test well can be very helpful. Borehole logging can contribute to the understanding of the aquifer heterogeneity, estimation of clay content and to derive thermal and hydraulic parameters[13].

2.3.5 Risk analysis

Despite the potential high profitability of an HT-ATES plant, the risks and barriers often seems to prevent investors from investing in MT-HT ATES systems. The main reasons for this are probably:

- The risk of not getting a permit
- The geological risk of not finding a suitable aquifer in the area of interest
- A time consuming test period and permitting procedure

The risk of not getting a permit can be evaluated very early in the decision process and (in most cases) through a desk top study. The screening of the geological conditions is discussed in the section above and is a more time consuming process and crucial for a successful project.

A time consuming permitting process can pose a barrier (together with the geological risk) and cause decision makers/owners to avoid ATES, even areas where the geological conditions for heat storage in an aquifer are found to feasible[14].

2.3.6 Modelling subsurface dynamics

3D modelling of the subsurface geology and the hydro- and geochemical dynamics are an important requirement in the investigation phase to forecast the thermal impact etc. of an aquifer heat storage.

2.3.6.1 3D geological modelling

The aim of a 3D geological model is to represent the geology with a sufficiently high degree of detail. Focus should be on the dimensions and lithological characteristics of the main storage aquifer and the top confining layers. A 3D geological model should optimally be considered dynamic and open for updates from the investigation phase and through the system operation phase. If further data are acquired, giving better insight in the geology, it is recommended that the

[12] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.
[13] Visser, P. W. et al. 2015: The thermal impact of aquifer thermal energy storage (ATES) systems: a case study in the Netherlands combining monitoring and modeling. Hydrogeology Journal, 2015, no. 23, pp. 507-537.
[14] Danish Energy Agency, 2014. Status and recommendations for RD&D on energy storage technologies in a Danish context.

model is updated. This will potentially improve the heat transport modelling regarding thermal impact on the surroundings etc.

Figure 2.4 is showing a Danish example of a 3D geological model[15] representing a geological setting of Quaternary and Miocene unconsolidated sediments interrupted by deep erosional Quaternary buried valleys and faulting. The deep Miocene aquifers are potential subjects for heat storage.

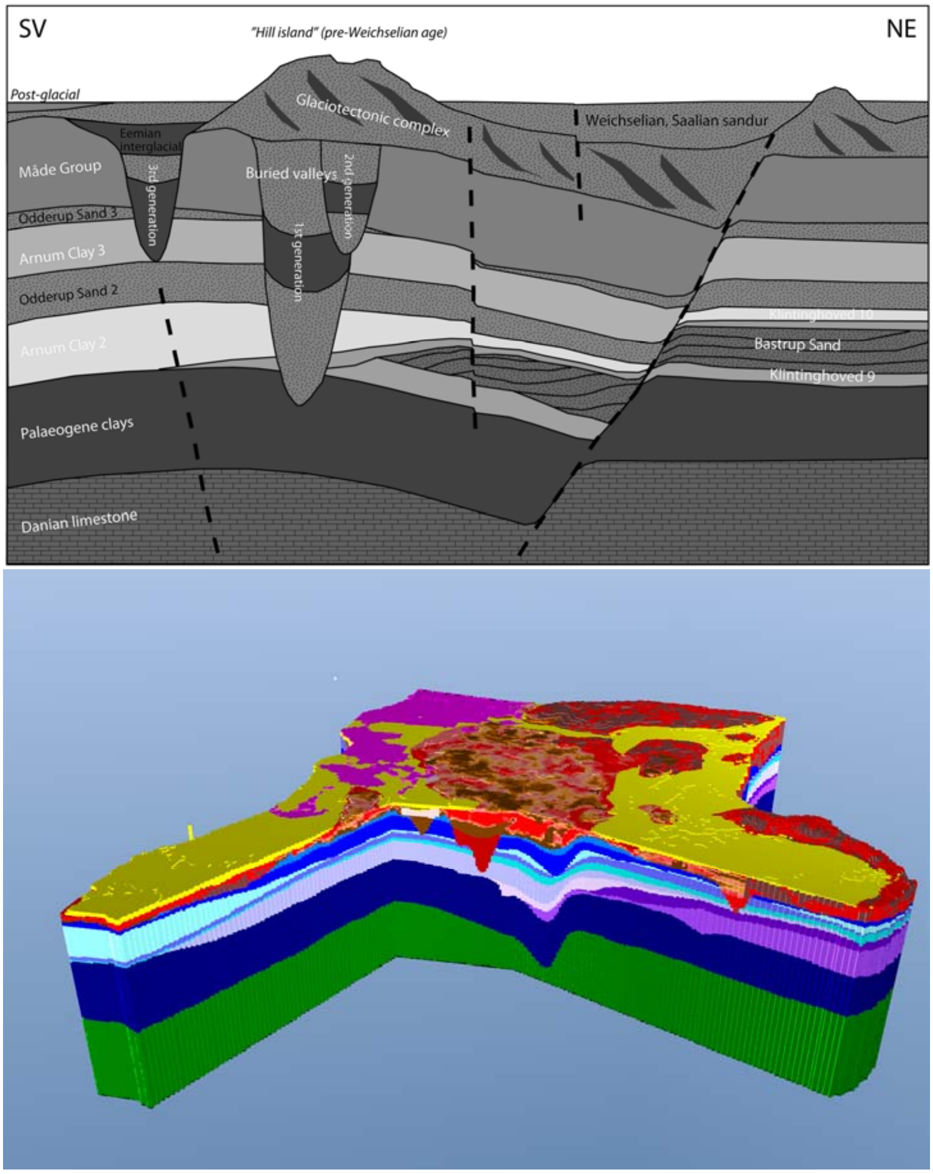

Figure 2.4 Examples from a local 3D geological model in the south western part of Denmark. The geological succession consists of upper glacially disturbed Quaternary deposits above unconsolidated Miocene deposits. The maximum depth of the cross section in the upper part of the figure is approx. 600 m. The Lower figure shows a 3D voxel model build using the software GeoScene3D (from[15]).

[15] Jørgensen, F. et al. 2014: 3D geological model in the south-western part of Denmark (Tønder). GEUS publication, report 2014/39.

As illustrated in Figure 2.4 the geological risk due to subsurface complexity is a critical factor that can be minimized by thorough geological understanding and modelling. It can be necessary to obtain additional knowledge on the geology by more test drillings (see 2.3.4) or geophysical investigations such as seismics or e.g. airborne electromagnetic surveys. In urban areas, which are often the areas of interests for HT-ATES applications, collecting geophysical data can be very difficult.

2.3.6.2 Hydrological modelling

The hydrological modelling aims to simulate and predict groundwater flow and expected heat transport in the aquifer.

The reliability of the predicted effects in the groundwater modelling depends on the input from the geological model, hydrological data and system input parameters. These input are e.g. usage pattern of the system (pumped water quantities, extraction and infiltration temperatures and variation over time), the properties of the system (locations of wells, screen lengths and screen depths) and the subsurface (heterogeneity, permeability). The model schematization is also important. For example, a 3D thermal transport model is required to simulate the effects of density-driven groundwater flow[16].

Heterogeneity in the aquifer is an important parameter difficult to characterize in the hydrological modelling. Often the aquifer is assumed to be homogeneous, but in reality heterogeneity affects the distribution of the stored heat in the subsurface and Bakema and Drijver[16] describe such experiences. Nevertheless, this influence on the storage efficiency is usually limited. If, however, there is strong heterogeneity or if the cold and warm wells are close to each other, the influence of heterogeneity can then become an important factor.

Groundwater and heat transport modelling requires a dynamic approach. Especially modelling ATES with seasonal changes in extraction and injection rates and temperatures.

Bakema and Drijver[16] gives their view on experiences in modelling seasonal changes in ATES: When modelling heat storage in the subsurface, it is usually assumed that there is one period in which heat is stored continuously and one period in which heat is continuously supplied (for example two periods of six months). The average time that the supplied heat is stored is in that case about half a year. In practice, the system is controlled by the supply and the demand for heat, which varies over time. As a result, the flow rate and the pump direction of the heat storage system also varies over time. Due to the fluctuating pump regime (mainly pumped back and forth in the mid-season) the average storage period will be in practice somewhat shorter than half a year. Because heat losses due to processes such as heat conduction, regional groundwater flow and density-driven flow are rather medium-term, a somewhat shorter average storage time will result in a somewhat higher average extraction temperature. Using uniform longer charging and discharging periods, the modelling can therefore give a slightly less favorable picture. When the cut-off temperature is reached during the winter season, the average storage time is also somewhat shorter. In principle this is favorable for the storage efficiency, but the fact that the cut-off temperature is reached is (obviously) detrimental to the storage efficiency[16]. Not because of excessive heat losses but because of insufficient heat recovery.

[16] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

One of the lessons learned regarding modelling from the research work published by Visser et al.[17] is that the thermal impact is strongly controlled by actual operational conditions of the ATES system, which differs markedly from design conditions. It is therefore recommended that sensitivity analysis are carried out to evaluate the effect of ranges in hydraulic and thermal input parameters, but also operating conditions.

Available tools for heat flow modelling are e.g. HST3D, Modflow/SEAWAT or FEFLOW.

2.3.7 Geo/hydro-chemical modelling

It is generally recommended to do hydro-chemical modelling as a first assessment of the necessity of water treatment, especially when storage temperatures exceeds 50ºC. Experiences from pioneer HT-ATES systems supports the relevance of assessing possible hydro-chemical changes when injecting warm water into the storage aquifer.

Low-High Temperature ATES systems may have an impact on groundwater quality in different ways. Firstly, extraction and injection and mixing of shallow groundwater with deeper groundwater can have an important influence on groundwater quality. Trace elements and organic carbon can e.g. be mobilized because of changes in the natural redox conditions. Also there is a risk that contaminants can be introduced in deeper pristine groundwater. Also changes in water temperature and pressure as well as degassing are potential challenges to undesirable changes in water chemistry. Earlier studies found that heterogeneous aquifers cause: 1) more groundwater-sediment reactions, and 2) more pronounced stratification of groundwater in the aquifer[18]. These are important conclusions to keep in mind.

Bakema and Drijver[16] recommend to do in-situ testing with local groundwater in combination with modelling.

2.3.7.1 Geochemical modelling in deep geothermal reservoirs

Geochemical modelling has been fairly widely employed within the field of geothermal exploitation. Examples include reactive transport modelling of dissolved and super critical CO_2 injected into carbonate-bearing reservoirs and of calcite scaling in geothermal wells (e.g. Wanner et al.[19]). Geochemical modelling codes have also been linked to other codes to allow more extensive calculations of the coupled thermal-hydrologic-mechanical-chemical (THMC) processes to simulate, for example, the overall effect of the injection of colder water into the hotter reservoir[20]. Alternatively, THMC models developed from scratch have been used to simulate the evolution of permeability in fractures[21].

[17] Visser, P. W. et al. 2015: The thermal impact of aquifer thermal energy storage (ATES) systems: a case study in the Netherlands combining monitoring and modeling. Hydrogeology Journal, 2015, no. 23, pp. 507-537.
[18] Possemiers, M., Huysmans, M. & Batelaan, O. 2014: Influence of Aquifer Thermal Energy Storage on groundwater quality: A review illustrated by seven case studies from Belgium. Journal of Hydrology: Regional Studies 2.
[19] Wanner, C., Eichinger, F., Jahrfeld, T., and Diamond, L. W. (2017): Unraveling the formation of large amounts of calcite scaling in geothermal wells in the Bavarian Molasse Basin: a reactive transport modeling approach. Procedia Earth and Planetary Science 17, 344-347.
[20] Taron, J. and Elsworth, D. (2009): Thermal–hydrologic–mechanical–chemical processes in the evolution of engineered geothermal reservoirs. International Journal of Rock Mechanics & Mining Sciences 46, 855–864
[21] Ogata, S., Yasuhara, H., Kinoshita, N., Cheon, D.-S. and Kishida, K. (2018): Modeling of coupled thermal-hydraulic-mechanical-chemical processes for predicting the evolution in permeability and reactive transport behavior within single rock fractures. International Journal of Rock Mechanics and Mining Sciences 107, 271–281.

Geochemical modelling is not without complications and suffers from uncertainties that are mainly related to the input parameters and inadequacies in databases used during the modelling. For input parameters, modelling typically requires knowledge about the solution composition, the mineral assemblage, and the partial pressure of gasses. Modelling of reaction kinetics requires knowledge of the reactive surface area of the phases, a parameter that is notoriously difficult to estimate. For a range of minerals (e.g. oxides, carbonates, sulphides) and acid gasses (e.g. CO_2 and H_2S), solubility and reaction kinetics depend hugely on pH, a parameter that can be complicated to determine accurately in solutions from reservoirs with high pressure and temperature, in particular if they contain acid gasses, that can exsolve prior to pH measurement.

The databases contain data for description of the thermodynamic state of the system based on theoretical frameworks of variable complexity as well as data for the calculation of reaction rates. In general, the adequacy of both the theoretical frameworks and the data of the databases decrease with increasing temperature, pressure and salinity. Given that geothermal reservoirs are often situated well below ground, at high pressure and temperature, and contain saline formation water, some efforts have been made to determine the uncertainty of the modelling (e.g. Haase et al.[22]). Finally, the number of elements and redox states defined in the databases, that are capable of handling non-ambient conditions, are also smaller allowing modelling of only main elements. Thus, for geothermal systems, where data can be scarce or uncertain or where databases are likely to be poorly defined, modelling is complicated and results are often qualitative rather than quantitative, providing answers to "what if?" rather than "how much?" or "how long?"

A variety of codes exists for geochemical modelling, each of which has variable capabilities for calculating non-ideal behavior of ions and gasses, heterogeneous equilibria, sorption, and reaction kinetics. Moreover, codes can often be coupled with several databases, containing data that are suited for variable conditions (i.e. temperature, pressure and salinity). Finally, some codes are inherently capable of modelling subsurface transport (e.g. CrunchFlow[23]) or can be coupled to other software to allow such modelling (e.g. PHREEQC[24]).

2.4 Construction

In this section available existing experience and research regarding construction of HT-ATES systems is described. More specific detailed descriptions and considerations regarding drilling techniques, materials, well design and configurations for HT-ATES systems can be found in the HEATSTORE deliverable D1.2 report “General specifications and design for UTES systems”.

2.4.1 The drilling process – HT-ATES in unconsolidated sediments

The drilling process can be divided in HT-ATES applications in medium depths and unconsolidated sediments (c. 0-800 m) and deep geothermal applications (at depths >800 m). This section

[22] Haase, C., Dethlefsen, F., Ebert, M. and Dahmke, A. (2013) Uncertainty in geochemical modelling of CO_2 and calcite dissolution in NaCl solutions due to different modelling codes and thermodynamic databases. Applied Geochemistry 33, 306–317.
[23] Steefel, C. I. and Molins, S. (2016) CrunchFlow Software for Modeling Multicomponent Reactive Flow and Transport: USER’S MANUAL. Lawrence Berkeley National Laboratory, Berkeley, USA.
[24] Parkhurst, D. L. P. and Appelo, C. A. J. (2013) Description of input and examples for PHREEQC. Version 3 – A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey, Techniques Methods, book 6, chapter A43, pp. 1-497.

describes experiences from well drillings in unconsolidated sediments (especially Dutch experiences from drilling of ATES wells) [25,26].

The aim of ATES well drilling, well completion and well development (cleaning) is to establish a well that: 1) has a good specific capacity, 2) produces a minimum amount of fines, and 3) is not prone to clogging.

Considerations in the choice of a reliable drilling technique/method are: 1) it is necessary that reliable soil samples can be obtained, 2) a minimum intrusion of drilling mud into the aquifer, and 3) minimize the amount of drilling mud used and avoid the use of a type of mud that is hard to remove afterwards (for that reason, the use of bentonite as a drilling mud additive should be avoided).

Figure 2.5 Picture from drilling site at the NIOO HEATSTORE case study in the Netherlands (IF Technology)

[25] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.
[26] Bakema, G., Pittens, B., Buik, N. & Drijver, B.; 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.

The *reverse rotary* drilling method meets the requirements mentioned in the text above for well drilling in unconfined aquifers. Reverse rotary with air-lift is applied as standard technology for HT-ATES because of a large well diameter and a clean drilling process. A sketch of the principle in reverse rotary with air lift is shown in Figure 2.6. In short the drilling mud flows into the annular space between drill pipe and borehole wall downwards by gravity. The cuttings at the drill bit in the bottom of the hole are continuously brought out to the surface through the drill pipes with air lift. The cuttings from the geological formations and the drilling mud are then drained into a sedimentation tank where representative geological samples can be collected[27].

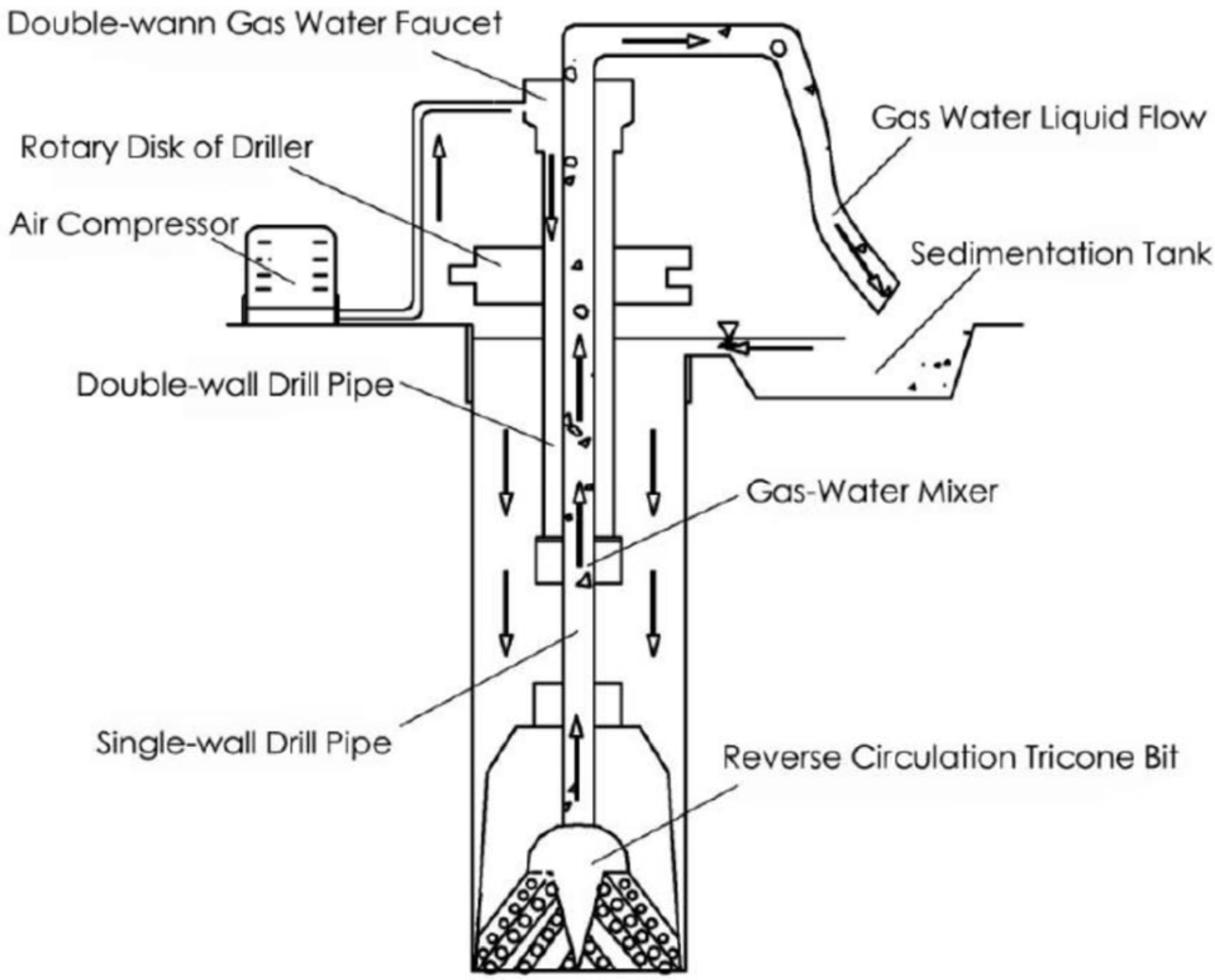

Figure 2.6 Principle of reverse rotary (circulation) drilling with air lift (reprinted from Procedia Engineering, Vol 73, Xiumin, M., Yue, C. & Luheng, Q., Research and application of Gas-lift Reverse Circulation Drilling Technology to Geothermal Well Construction in Dalian Jiaoliu Island, 252-257, Copyright (2014), with permission from Elsevier[27])

[27] Xiumin, M., Yue, C. & Luheng, Q. 2014: "Research and application of Gas-lift Reverse Circulation Drilling Technology to Geothermal Well Construction in Dalian Jiaoliu Island", Procedia Engineering 73, 2014, pp. 252-257

A geophysical borehole log will, as mentioned in section 2.3.4 (Test drilling), give input to more accurate information on the soil sequence and on the depth of the fresh to salt water transition zone, if this is an issue in the specific area. Logging of gamma and SP (Spontaneous Potential) are necessary for information on clay content and coarseness of the sand[28].

Fine grained deposits (clays, silts and the drilling mud) are challenging factors in the drilling process in unconsolidated sediments. These fine materials can penetrate the part of the formation adjacent to the borehole as described by IEA DHC/CHP[28]. Here it is described that the effort required for development of wells for ATES systems (and the associated cost), is considerably higher than for wells that are only used for production and that 2-3 weeks of time for drilling and completion is not exceptional. Even in case of thorough development efforts, there are many examples of wells that show improvement of the specific capacity after some time of use. Apparently because part of the drilling mud remnants was not removed during the well clean-up and was mobilized during the operational phase. During preventive maintenance in the operational phase, mobilized fines can be removed by extracting groundwater at maximum capacity from the injection well for a short period of time[28].

2.4.2 Deep geothermal drilling

In the drilling of deep geothermal wells, the drilling rigs and equipment are similar to the ones used in the oil & gas industry. The drilling process of deep geothermal differs in several ways from the approach used at more shallow or intermediate depths. Deep geothermal drilling encounters many changes in geological formations as the drilling progress in depth. This leads to higher risks of e.g. open hole collapse, failure in equipment or sudden changes in inflow-outflow balance of drilling fluid. The deep geothermal drilling process operates with both vertical and deviated drilling (an inclination between 25º to 45º). A deviated drilling introduces a higher risk as the drilling process is more complicated. The advantages on the other hand is that maybe only one drilling site at the surface is necessary for the drilling of both an extraction and injection well. Figure 2.7 shows an overview of a drilling site for deep geothermal drilling. The whole drilling process is also a lot more space demanding, thus larges areas are needed for the drilling rig, a yard for equipment etc.

[28] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.

Figure 2.7 Deep geothermal drilling in Sønderborg, Denmark, in 2010 (from[29])

The well architecture for deep geothermal drilling should be designed to minimize the drilling hazards and also protect the intermediate aquifers from the future heat storage activities. In the well design casing of steel, fiberglass or composite material are used in order to prevent borehole collapse. Different parameters such as fractures in the geological formations, unconsolidated layers, formation pressure and expected geochemical composition must be taken into account. The area between well bore and casing are subsequently cemented to prevent vertical connections between different geological formations and space for intruding gas or liquids[29].

2.4.3 Well configurations

In the following is given an introduction to experiences in the well design for HT-ATES systems.

The design of an ATES well field depends on several factors related to the specific site and both surface and subsurface parameters/possibilities [28,30]:

- The design should minimize thermal interference between the production and injection wells as thermal interference will have direct consequences on the production temperature
- The design should prevent undesirable hydraulic and thermal impact in the surrounding areas.

Bakema and Drijver[30] points out that if the need for capacity of a HT-ATES system exceeds a doublet (one cold and one warm well), a star shaped configuration will be preferable. If wells are configured in a star-shape with warm wells in the middle surrounded by a ring of cold wells, the cold wells will insulate the heat around the warm wells, see Figure 2.8. This is experienced to increase system efficiency with up to 10%.

[29] Drejebog om geotermi 2014: "Etablering og drift af geotermiske anlæg til fjernvarmeforsyning"; Dansk Fjernvarmes Geotermiselskab, GEUS, Ross Engineering and Grøn Energi, January 2014
[30] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

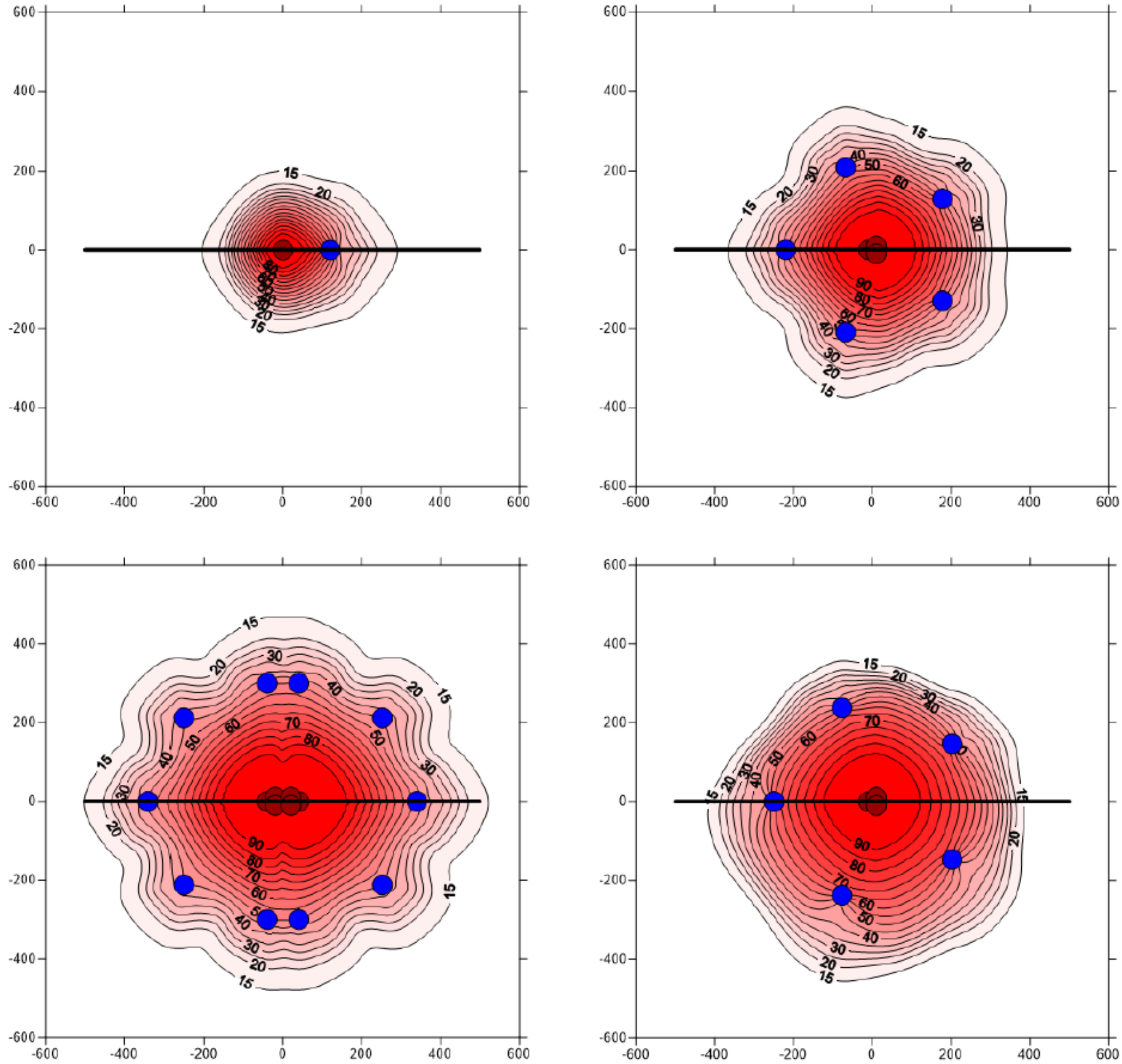

Figure 2.8 Modelled star shaped well configurations. A simple doublet is shown at the upper left figure. Temperature contours are in degrees Celsius (IF Technology)

2.4.4 Well design and materials

In the following is given an introduction to experiences in the choice of materials for HT-ATES systems.

The most frequent problems concerning materials in ATES are corrosion and clogging of the wells. In the selection of materials the groundwater composition/chemistry has to be taken into account and the main aspects influencing corrosion resistance are salinity and the presence of oxygen[31].

Lessons learned on how well clogging is best prevented is discussed in section 2.6.2.

[31] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.

2.4.4.1 Well casing and screens

Generally insulation of the well casing(s) can minimize heat losses of the storage and also prevent heating up shallow (fresh water) aquifers. Regarding pipes and screens Bakema et al. [32] recommends the material to be GRE (Glass Reinforced Epoxy) or stainless steel if storage temperatures exceeds > 60°C in the planned HT-ATES system. For high temperature wells up to 95°C GRE is preferred above steel or stainless steel. Cold wells can be constructed with PVC screens and casings in situations where temperatures are < 60ºC.

Regarding the gravel pack around the well screen IEA DHC/CHP[33] gives the following advice:

- The thickness of the gravel pack varies between a minimum of 100 mm to a maximum of 300 mm
- The grain size of the gravel and the size of the screen slots have to be adjusted to the grain size distribution of the selected reservoir layers according to the rules already applied for designing gravel pack well completion
- To prevent mixing of different types of groundwater and to be sure the water is extracted and injected at the depth selected, low permeability layers (e.g. clay, loam) that were perforated have to be sealed during backfilling

For maintenance the wells needs to be back-flushed readily at the end of each season to maintain a low injection resistance. To be able to do this a larger diameter in the wells are needed than is normally expected for a standard water extraction water supply well.

2.4.4.2 Pumps

Experience with pumps from the first pioneer HT-ATES systems showed problems with the use of deep shaft pumps[34]. Bakema et al.[32] recommend to use submersible pumps in the wells. Specific ESP pumps (Electric Submersible Pump) commonly used in oil & gas or geothermal applications are suitable for high temperatures in the warm wells and are often equipped with downhole monitoring to measure the performance of the pump, and other well monitoring. The oil & gas type ESP pumps are oil-filled and a so-called “food-grade” oil is available to avoid environmental damage in case of oil leakage.

In the cold wells standard low temperature submersible pumps (normal ATES Electric Submersible Pumps) can be used. These are typically suitable for temperatures up to 60ºC.

2.5 System integration

Heat storage by the use of HT-ATES can be applied in areas where large thermal storage capacities are required. The expected important markets are found to be:

- large-scale storage of residual heat from the industry
- large-scale storage of residual heat from waste incineration plants
- large-scale storage of residual heat from power plants or Combined Heat and Power (CHP)
- In combination with district heating networks e.g. including solar thermal collectors

[32] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.
[33] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.
[34] Sanner, B. & Knoblich, K. 1999: Advantages and problems of high temperature underground thermal energy storage. Bulletin d'hydrogéologie No 17, Centre d 'hydrogéologie, Université de Neuchlitel.

HT-ATES can offer a buffer storage for short-term heat storage, for peak shifting or seasonal storage. An important basic condition for HT-ATES is that the residual heat is available for free (or almost for free). Otherwise it will be difficult to establish a profitable business case. The heat source could be surplus heat from industry as mentioned or from solar thermal collectors.

The energy demands, specification of network and characteristics of heat sources are essential to collect in order to achieve a profitable heating and storage system. The efficient integration of geothermal energy in district heating asks for a match between the requirements of the clients (e.g., demand profiles, temperature profiles), the specifications of the network (e.g., size, base load, peak load, supply and return temperatures) and the characteristics of the geothermal source (i.e., production temperature, flow rate, flexibility)[35]. Also the charging period of the storage to the designed temperature levels needs to be included in the system integration.

2.5.1 Size of storage

Based on Dutch experiences Bakema & Drijver[35] summarizes that if a specific aquifer storage volume is less than 100,000 m³ per season, the storage is very sensitive to variations in temperature and hydraulic conductivity. The consequence are likely to be large differences between the theoretically calculated and actual recovery efficiency. Therefore Bakema & Drijver recommend to aim for systems that store at least 300,000 m³ of hot water. Connected to the recommendation is that medium storage temperatures (50°C) has a lower effect on the system efficiency, than if the storage temperatures are high (90°C).

As described, the size of the system must be sufficiently large, since small systems have relatively low recovery efficiencies. In Bakema & Drijver it is further highlighted that a rule of thumb for the demand side is a required thermal input of at least 5 MW in order to reach an acceptable storage efficiency. Compared with Low-Temperature ATES systems the capacity ranges between 0.1 and 0.3 MW for small-scale and between 5 and 30 MW for large-scale systems[36].

2.5.2 Cut-off temperatures

The recovery efficiency of the storage is determined not only by the heat loss in the subsurface, but also by the minimum usable extraction temperature from the hot well. This is referred to as the "cut-off temperature". This cut-off temperature controls the maximum cumulative heating power that can be supplied under design conditions. The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency. Figure 2.9 shows the relationship between cut-off temperature and the amount of heat that can be extracted from the subsurface with heat storage at 90ºC. Lowering the cut-off temperature with 10ºC can increase the recovery efficiency significantly (e.g. by 10 to 15%)[35].

[35] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.
[36] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.

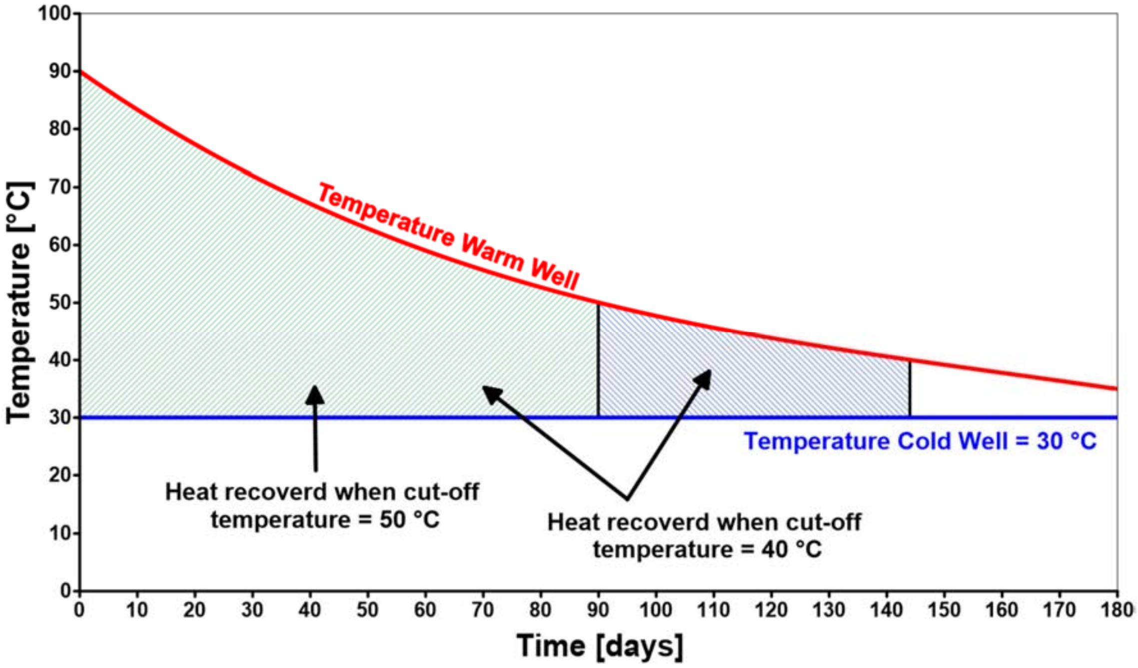

Figure 2.9 The relationship between cut-off temperature and the amount of heat that can be extracted from the subsurface with heat storage at 90ºC (IF Technology)

2.5.3 Base load

The aquifer heat storage is a slow-reacting system because: a) the heat must come from a large depth (e.g. 150-300 m), and b) the pipe systems must be heated up. To minimize start-up losses and heating losses, it is recommended to use the heat storage as the base load of the heating system rather than using it only for e.g. peak load situations. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat[37].

2.6 Existing operations feedback

2.6.1 Monitoring

Proper monitoring of an HT-ATES system is important in understanding the operational system. In practice the actual performance of a system will differ from the prerequisites given in the design phase. Monitoring data are thereby an important source for:

- Diagnosing issues that differ from design assumptions
- Optimizing the system (performance monitoring) to be able to deliver the energy efficiency it was designed for
- Preventing potential problems e.g. thermal leakage
- Scheduling maintenance operations

In IEA DHC/CHP[38] the following experiences on performance and maintenance monitoring is given (quote):
Monitoring data can be used to determine and optimize the energy performance of the open-loop system. Because of the interaction with the surface part of the system, the monitoring also requires

[37] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.
[38] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.

data from the building system. For this purpose, the energy flow, the supply and return temperatures, as well as the electricity consumption of the heat pumps and circulation pumps need to be monitored with a five or ten minute interval for the groundwater loop and the building heating and cooling loops.

In practice, the actual load and/or energy demand of buildings often turn out to be (significantly) different from the values available in the design stage. This may negatively influence the thermal efficiency of the ATES system:

- When the actual thermal load is lower than designed for, the ATES system will have more part load operation, resulting in a higher electricity consumption and increased thermal losses from transport piping per MWh delivered.
- When the thermal balance in the underground is significantly changed due to the different annual heating and/or cooling demand of the buildings, provisions might be required to restore the balance in order to avoid interference between extraction and injection wells or undesired environmental impacts.

A major issue is detecting a leakage in the loop and deterioration of a well at an early stage. A leakage is detected from pressure loss in the loop during stand-still periods. A good way to monitor the well quality is by trending the specific well capacity, i.e. yield in m^3/h divided by drawdown in m, as derived from monitoring results of the groundwater flow rate and the water level in the well. An early warning system of potential well clogging is important, since the clogging process accelerates over time. When a clogged well is redeveloped in time, it can be used for at least several decades. However, when a well has been severely clogged once, it will keep on clogging rapidly after each cleaning action[38].

Bakema et al.[39] also states a number of considerations regarding monitoring of HT-ATES wells:

- Because of heat radiation from the hot well casing to its surroundings, in most cases it is of no use to monitor the temperature in monitoring lines in the same borehole next to the well casing.
- If monitoring pipes are installed in the HT-ATES well, it should be considered to use GRE pipes and GRE or SS316 screens when temperatures in the well exceed 40 C.
- To monitor the heat and water quality in the aquifer, it is advised to install a separate monitoring well at a certain distance to the hot well of the HT-ATES system. Depending on the expected temperatures, it should be considered to use GRE pipes and GRE/SS316 screens in this monitoring well. If a test drilling is done, this borehole could be completed as monitoring well.
- In case the HT-ATES well is cemented, monitoring lines above the target aquifer cannot be installed anymore in the annulus between borehole and well casing. These monitoring lines should be installed in a separate nearby monitoring well.
- For monitoring temperature it can be considered to use glass fiber techniques instead of measuring temperatures in the wells or monitoring lines using temperature sensors that are installed from above. Reasons to do so:
    - temperature over depth in the monitoring lines can be influenced by heat convection in these lines (hot water going up);
    - Using a glass fiber cable gives more detailed information (continues measurement over the whole length of the well);
    - Measuring temperatures by hanging in T-sensors in the monitoring pipes is time-consuming especially at great well depths.

[39] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.

2.6.1.1 Modelling thermal impact based on monitoring results

The thermal impact on the surroundings in the subsurface is strongly controlled by actual operational conditions of the ATES system, which can differ markedly from the design conditions. In the design phase the impact assessments is based only on design-operational conditions which is subject to several limitations and assumptions. Visser et al.[40] describes that updating and simulating model results based on monitoring data will improve the predictions on e.g. thermal impact on the environment.

2.6.2 Maintenance

A sustainable operation of the ATES system for many years requires preventive maintenance. The maintenance comprises many different aspects. In a recently published IEA DHC/CHP report[41] the following preventive maintenance actions are highlighted (LT-ATES):

- Plan one to two site visits a year, depending on the level of remote monitoring. The focus of the preventive maintenance is on avoiding well deterioration and well pump failure.
- When the thermal balance in the underground is significantly changed due to the different annual heating and/or cooling demand of the buildings, provisions might be required to restore the balance in order to avoid interference between extraction and injection wells or undesired environmental impacts.
- Assessment of the proper functioning of the well pump frequency drives, the valves, the sensors and indicators (temperature, pressure and flow), the safeguards, as well as the control unit.
- The state of the well pumps can be checked by measuring the electrical resistance between the phases.
- Back-flushing of injection well(s) at maximal capacity for about one hour per well to remove collected fines. Back-flushing is scheduled preferably near the end of the winter season and the end of the summer season. To remove the fines from the system, the groundwater extracted during back-flushing is not returned to the aquifer, but discharged to (e.g.) the sewer. During back-flushing the specific capacity of the wells is also assessed. This action can be performed automatically or from remote using the ATES control system.

2.6.2.1 Preventing well clogging

Clogging of wells is a frequent problem in ATES applications world-wide[42]. The local hydro-geochemical composition of the groundwater, high concentrations of dissolved gas in the water, fine-grained materials in a heterogeneous aquifer and clay swelling are all known factors that may initiate clogging of typically the injection wells.

For example, if a pressure reduction occurs during upward transport of the water, formation of gas bubbles can be initiated resulting in a rapid clogging of the injection well. Changes in temperature levels regarding heat storage could initiate chemical reactions such as precipitation of carbonates (for carbonates the solubility decrease with increasing temperature and thus the risk of scaling increases), se section 2.6.4.

[40] Visser, P. W. et al. 2015: The thermal impact of aquifer thermal energy storage (ATES) systems: a case study in the Netherlands combining monitoring and modeling. Hydrogeology Journal, 2015, no. 23, pp. 507-537.
[41] IEA DHC/CHP, 2018: Integrated Cost-effective Large-scale Thermal Energy Storage for Smart District Heating and cooling. Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling, draft September 2018.
[42] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.

Clay swelling has also been a problem in HT-ATES applications and is a consequence of water treatment with ion exchanges, as it was seen at e.g. Utrecht[43], see also section 2.6.8. Here it was found that too large volumes of water were treated with Ca/Na ion-exchangers resulting in problems with swelling of clays.

In order to prevent clogging and scaling in wells and pipes different actions can be applied:

- Tested water treatment (see section 2.6.4)
- Repeated regeneration of wells
- Maintain pressure as constant as possible in the system all the time
- Continuous analyses of possible changes in groundwater composition/chemistry

In the well design it is recommended to plan for the length of the screen to be as long as possible in the main aquifer in order to prevent e.g. clogging[44].

2.6.3 Recovery efficiency

The recovery efficiency is one of the main parameters that determines the overall energy savings of a HT-ATES system. It is affected by storage specifics and local hydrogeological conditions that may lead to heat loss and changes in the minimum usable extraction temperature (cut-off temperature) from the hot well(s). The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency, see 2.5.2.

As Bakema and Drijver[44] describes, existing systems often show a clear difference between the predicted recovery efficiency and the actual recovery efficiency. This can often be explained by the fact that the recovery efficiency of MT-ATES / HT-ATES is sensitive to variations in the storage volume, the storage temperature, the cut-off temperature and the permeability of the aquifer.

In the investigation phase it is important to address the uncertainties in the above mentioned parameters. A specific project can for example be feasible with a large storage volume and a high storage temperature, but not feasible in case of a smaller storage volume and/or a lower storage temperature. In certain cases, it may be useful to carry out additional research to reduce the uncertainties in the key parameters and thus to obtain more certainty about the feasibility in practice.

Density driven groundwater flow leads to higher heat recovery efficiency at low storage temperatures compared to high temperatures. The reason for this is the density difference between the ambient groundwater and the hot stored water (lower density). Density driven flow has the largest impact in high permeable aquifers. The vertical permeability therefore becomes an important parameter. It is found that aquifers with high permeabilities are subject to large heat losses. For Dutch conditions and thus based mainly on experience with sandy unconsolidated aquifers Bakema and Drijver[44] suggests that the optimal hydraulic conductivity is found to be between 3 and 7 m/d which correspond to a permeability range between 3.5 and 8.5 Darcy.

[43] Jenne, E. A., Andersson, O. & Willemsen A. 1992: Well, Hydrology, and Geochemistry Problems Encountered in ATES Systems and Their Solutions, in: Jenne, E. A., editor. Aquifer Thermal Energy (Heat and Chill) Storage: Proceedings of the 27th intersociety energy conversion engineering conference, 1992, San Diego, CA.
[44] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

Bakema and Drijver[45] presents the relationship between the main parameters determining the storage efficiency. For high-temperature heat storage systems (seasonal storage), based on many model calculations, a relationship has been derived between the recovery efficiency and the following parameters:

- the stored volume of hot groundwater (V);
- the well screen length / thickness of the aquifer (H) used;
- the temperature of the natural groundwater in the storage aquifer (Ta) and the temperature of the stored water (Ti);
- the horizontal and vertical conductivity (kh and kv) of the aquifer used.

Figure 2.10 shows the recovery efficiencies calculated with this relationship as a function of the storage volume at different hydraulic conductivities, storage temperatures and well screen lengths. The graphs are based on a number of assumptions:

- The volumes of water that are pumped during storage and recovery are equal
- The cold well temperature is equal to the ambient groundwater temperature in the storage aquifer (assumed to be 12ºC)
- The efficiency is given for the fourth year
- Interaction between the warm and cold well is insignificant
- Heat losses by regional groundwater flow are negligible
- Vertical hydraulic conductivity (k_v) is half of the horizontal hydraulic conductivity (k_h)

Simulated storage temperatures varies from 30ºC to 90ºC and are based on screen lengths of 25 m and 50 m. Observations from the graphs show:

- The recovery efficiency at low storage temperatures is higher than at high temperatures. The lower efficiency for higher temperatures is caused by density driven flow (the higher the storage temperature, the bigger the density difference between the ambient groundwater and the stored water, and the higher the density driven flow).
- When higher temperatures are stored, the recovery efficiency significantly decreases with increasing hydraulic conductivity of the storage aquifer. This is explained by density driven flow, which is stronger in more permeable aquifers.
- A small well screen length results in a higher recovery efficiency for the same storage volume, because the relative impact of density driven flow is smaller. A drawback of a small well screen length is that the capacity per well is also smaller (resulting in higher investment costs).
- The recovery efficiency significantly improves when the storage volume is increased, especially at high storage temperatures.

[45] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

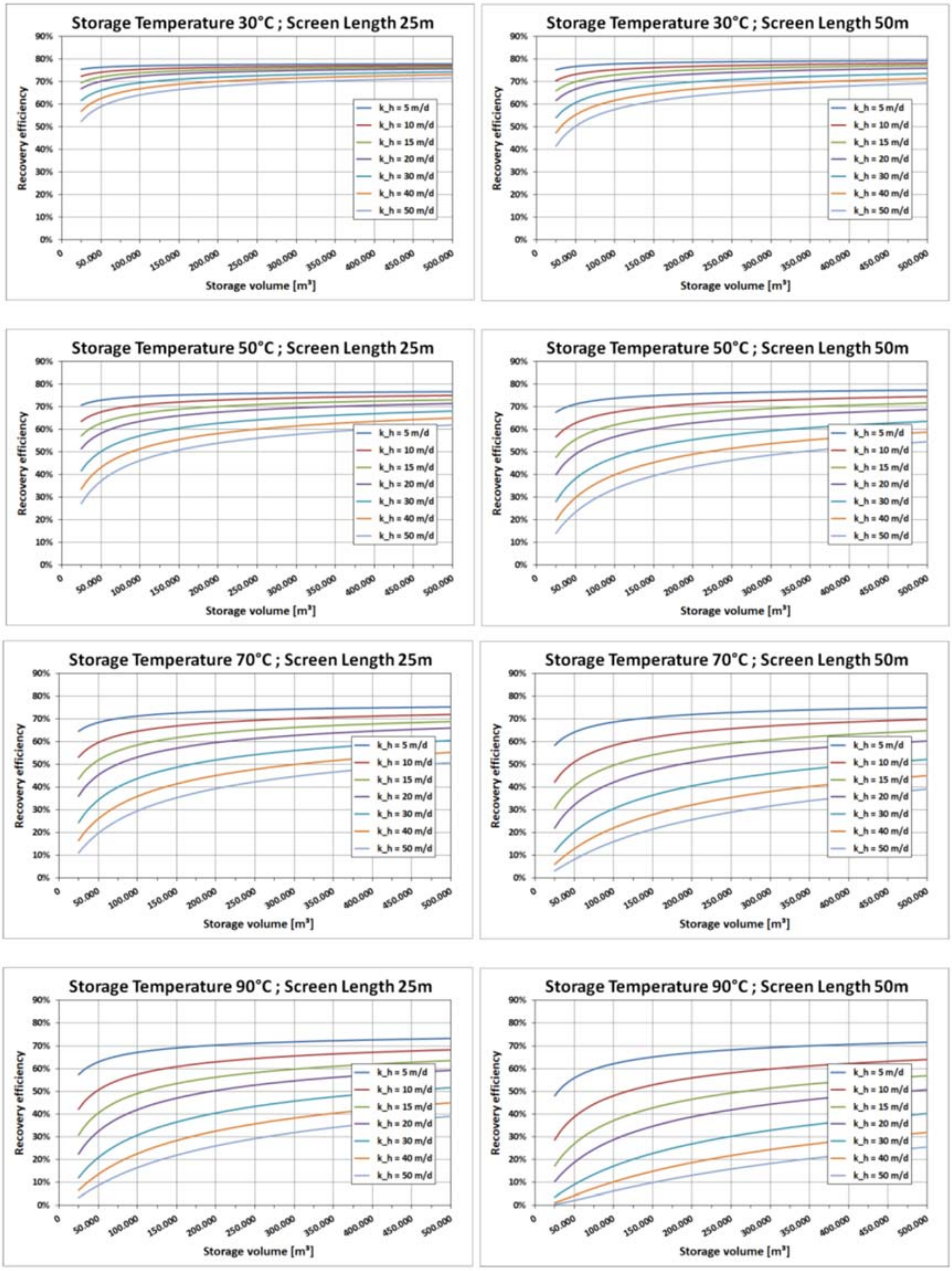

Figure 2.10 Recovery efficiency for different storage temperatures and aquifer thickness values. The graphs are based on a number of assumptions: 1) the volumes of water that are pumped during storage and recovery are equal, 2) the cold well temperature is equal to the ambient groundwater temperature in the storage aquifer (assumed to be 12ºC), 3) the efficiency is given for the fourth year, 4) interaction between the warm and cold well is insignificant, 5) heat losses by regional groundwater flow are negligible, and 6) vertical hydraulic conductivity (k_v) is half of the horizontal hydraulic conductivity (k_h) (IF Technology).

2.6.4 Water treatment

Lessons learned from existing HT-ATES applications shows that water treatment can be necessary depending on local geological conditions and groundwater composition. High storage temperatures may affect geochemical processes within an ATES system, and can potentially also cause mixing of water with a further impact on the groundwater chemistry. Based on different experiences with water treatment the following considerations are important[46]:

- Use of hydrochemical modelling for a first assessment of the necessity of water treatment
- In-situ testing with local groundwater is recommended
- Especially at temperatures above 50ºC water treatment should be considered
- Do not use ion-exchangers (can result in clay swelling)
- HCl treatment is proven technology to use in water with high pH. The main disadvantage is the use of large volumes of HCl
- It can be considered to use reaction inhibitors to decrease or prevent chemical reactions

Water treatment by the use of CO_2 is a promising technology and is to be tested further in the Dutch demonstration pilot in the HEATSTORE project[47].

If the subsurface conditions are right, water treatment can be avoided. For example no water treatment is used operating the HT-ATES system at the German Reichstag with a storage temperature up to 70°C. Based on the groundwater composition data, the natural groundwater seems to be calcite saturated, so in this case heating the storage is possible without the necessity of water treatment[48].

Aspect of water treatment in the design phase will be described further in the HEATSTORE deliverable D1.2 report “General specifications and design for UTES systems”.

2.6.5 Environmental issues

The environmental issues regarding HT-ATES are related to impact on the subsurface. The hydrogeological uncertainty will define to a high degree the environmental impact risk. The primary concern from stakeholders, partners and operators is the risk of thermal impact on surroundings and leakage through the confining top layers. The environmental assessments should focus on:

- Preventing leakage to upper shallow groundwater system or to the surface
- Preventing thermal impact on surrounding areas with drinking water interests
- Preventing thermal impact on neighbor ATES applications
- Preventing unexpected hydro- and geochemical challenges in the storage aquifer
- Preventing unexpected microbiological challenges in the storage aquifer

A proper preventative monitoring program of the parameters important for these environmental aspects are therefore crucial. Geochemical and microbiological issues are generally challenging to address. They will be partly dependent on the local site conditions. The effects on e.g. the geochemical and microbiological development in HT-ATES applications are still to be investigated further, especially regarding high temperatures.

[46] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.
[47] GEOTERMICA, High Temperature Underground Thermal Energy Storage (HEATSTORE), full proposal, 2018.
[48] Sanner, B. & Knoblich, K. 2004: Thermische Untergrundspeicherung auf höherem Temperaturniveau: Begleitforschung mit Messprogramm Aquiferspeicher Reichstag. Schlussbericht zum FuE-Vorhaben, Universität Giessen.

2.6.6 Existing HT-ATES overview

Known existing HT-ATES systems (past and ongoing) are compiled in Table 2.2 below. Experiences from five of the system are described in more detail in the following sections.

Table 2.2 Overview on existing HT-ATES systems

Year	Location/Project	Status	Heat source	Storage temperatures	Aquifer depths
1976	Auburn University, Mobile/AL, USA	E/C	Hot waste water	55°C	41-61 m
1982	SPEOS, Lausanne-Dorigny, Switzerland	C	Waste water treatment	69°C	-
1982	Hørsholm, Denmark	D/C	Waste combustion	100°C	10 m
1982	University of Minnesota, St. Paul, USA	E/C	-	115°C (150°C)	180-240 m
1987	Plaisir Thiverval-Grignon, France	E/C	Waste combustion	180°C	500 m
1991	Utrecht University Netherlands	D/C	CHP	90°C	4-45 m
1998	Hooge Burch, Zwammerdam near Gouda, Netherlands	D/C	CHP	90°C	135-151 m
1999	Reichstag, Berlin, Germany	D/O	CHP	70°C	300 m
2004	Neubrandenburg, Germany	O	CHP	75-80°C	1,250 m
2015	Duiven, Netherlands	FS	Waste combustion	>140°C	-
Planned	BMW, Dingolfing, Germany	FS	-	130°C	500-700 m
2019 -	HEATSTORE pilot (ECW), Netherlands	D	Surplus geothermal heat	90°C	300-400 m
D = demo site , E = Explorative, C = Closed, FS = feasibility study; O = in Operation; CHP: Combined Heat and Power					

2.6.7 Case example 1 - Plaisir Thiverval-Grignon (France)

Thiverval-Grignon is located 30 km west of Paris. This ATES was built in 1985-1987 to store excess heat produced by a municipal waste incineration plant. The plant provided heat at 200°C to feed a district heating network (DHN), with inlet temperatures up to 150°C and outlet (return) temperatures between 60°C and 70°C. The intended storage temperature was 180°C, and a calculated energy efficiency at 60% could be reached if the heat was unloaded down to 80°C. The expected heat storage capacity was 20 GWh[49,50].

The ATES design was 4 wells at approx. 500 m depth: one central well for hot water injection (storage) and 3 wells for warm water unloading. The 16 m thick “Wealdien” (part of Néocomien) aquifer was targeted as it is known for its alternation of clay (impervious cap rock) and sand. The storage media was a quite homogeneous unconsolidated sand, whose measured hydraulic conductivity ranged from 4.0 to 6.3 × 10^{-5} m/s, with an approx. 5% weighted clay content.

The water (geothermal fluid) was treated to prevent carbonate precipitation in the heat exchangers when storing heat, and silica-aluminates precipitation when unloading which may have caused well clogging. The water treatment was designed so that in the heat storage phase, lime and iron

[49] Commissariat à l'Energie Atomique. 1990. Stockage intersaisonnier de chaleur de Plaisir Thiverval-Grignon. Rapport final des essais. Rapport DMT 90/332.
[50] Commissariat à l'Energie Atomique. 1990. Stockage de chaleur de Thiverval-Grignon. Analyse des essais complémentaires en doublet. Rapport DMT 90/350.

chloride were used to decarbonize water (softening it from 15°f to 2°f). In the heat unloading phase, lime, iron chloride and sodium aluminate were used for de-silication, the objective being to lower the silicate concentration from 170 g/m^3 to 45 g/m^3. The storage treatment was later extended with a reaction tank for acidification, sodium hydroxide and sodium sulfite addition.

A “cold” test was first carried out to estimate the hydraulic properties of the aquifer, followed by a low temperature test (40°C and 70°C) to test thermal regulations, the aquifer behaviour and efficiency of water treatments and to pre-heat the aquifer. In a third phase the heat was injected at a temperature increasing from 60°C to 180°C for 3100 hours. The measured temperatures were in line with simulations. However, particles inflow damaged the pumps. In September 1989 the injection well was definitively damaged. In 1989/1990, two outer wells were used as a doublet storage at a lower temperature (120°C) and lower flow rate (an average of approx. 20 m^3/h against 40 m^3/h in the 180°C storage configuration). From a hydraulic point of view, the lower temperature storage worked as expected. Two major problems were not solved by the tests:

1) The strategy to prevent well clogging through silica precipitation was designed for a temperature of 120°C, which is reported to have been unsatisfactory at 180°C.
2) The injection was more difficult than extraction. According to 1990 expertise from CEA (Comissariat à l’Energie Atomique), one explanation may be that the clay particles (c. 5% of the aquifer mass) were eroded during the injection and trapped in the vicinity of the well, which dramatically caused a pressure drop close to the well, reducing the injection flow-rate. Sudden changes of flow direction from storing to unloading caused particle inflow that damaged the pumps. One suggested solution is to increase the well diameter especially in the clayey parts, so that to decrease the velocity flow close to the well. Lower flow rates (and velocities) in the 120ºC storage test may explain why it worked as expected. Steel corrosion has probably masked the real problem, particle clogging, and temperature is reported to have little influence on the phenomena.

From a technological point of view the lessons learned are numerous:

- The well operations must be controlled based on analysis of injection and productivity indices (see problems point 2) above)
- Ion exchange resins are especially relevant to prevent the risk of calcium precipitation
- Geothermal fluids must be absolutely isolated from the atmosphere when circulating at the surface
- Water filtration at the surface must be excellent
- Well specifications: extractible sieve, accurate dilatation measurement, tubing and equipment not subject to oxygen corrosion
- Surface installations must be as simple as possible (short pipes, as few valves as possible)
- Limit the operation to temperatures admissible to the immerged pump
- Need for accurate and reliable regulations

Besides, the objectives of the project were ambiguous: It was both a demo site (TRL7-8) and a pilot site aiming at understanding the physical and chemical processes at state (TRL 5).

2.6.8 Case example 2 - University of Utrecht (The Netherlands)

The heat storage at Utrecht University has been unique in the world as the only high temperature ATES system. The heat storage was put into operation in 1991. In 1999 the warm well was damaged and the storage was taken out of service. The ATES stored residual heat from the university's combined heat and power plants in the summer period. The heat storage consisted of a cold and a warm well, both in the third aquifer (formation of Oosterhout) at a depth of 220-260 m. The storage was designed for a storage capacity of 6 MW_{th} and a storage quantity of 6,000 MWh/year (21,600 GJ); the predicted recovery efficiency was 59%.

In the design phase a test drilling was performed. The main aquifer consists of medium fine sands with a hydraulic conductivity between 25 and 3 m/d. Because of potential high thermal losses the upper high permeable part of the aquifer was not used. The upper part of the aquifer consists of fresh water (Cl^-< 50 mg/l); the deeper part of brackish water (500 mg/l Cl^-).

The high storage temperatures required the use Glass Fiber Reinforced Epoxy (GRE) or composite casing GRE. Slotting a GRE screen with small size slots was found impossible so a stainless steel screen was chosen. Suitable and payable high temperature submersible pumps were not at the market in 1991, so a line shaft pump (LSP) with the motor on the surface was installed instead.

Regarding water treatment ion-exchange was used. The groundwater passed an ion exchanger and calcium from the groundwater was absorbed by the resin where it was exchanged by sodium. This reduced (among other things) the calcium concentration in the groundwater and the calcium carbonate saturation degree. In this way, the precipitation of calcium carbonates was prevented. After some time, the resin became saturated and had to be regenerated with sodium. After regeneration the resin could be reused.

The measured average recovery efficiency of the storage was 33% over the nine years of operation, see Table 2.3. In the period 1994-1997 the efficiency was 53%. The low recovery efficiency was partly due to failures of the CHPs (less heat stored). More importantly, the return temperature (= cut-off temperature) from the building was far too high. As a consequence, the heat storage could add little heat to the central heating system as the cut-off temperature was reached after extraction of a limited amount of water. The result was that the storage still contained a lot of heat at the end of the winter. In summary, the low average recovery efficiency of 33% was mainly caused by the high return temperatures from the University building and not by heat losses in the subsurface[51].

[51] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

Table 2.3 Yearly recovery efficiencies for the Utrecht University HT-ATES in the operation period from 1991-1999

Year	Stored heat (GJ)	Recovered heat (GJ)	Efficiency%
Design	21.600	12.660	59
1991	18.979	1.927	10
1992	9.836	3.503	37
1993	19.380	3.350	17
1994	15.225	6.301	41
1995	20.792	4.765	23
1996	8.330	5.670	68
1997	4.648	3.729	80
1998	2.903	435	15
1999	13.079	765	6
Average			33

2.6.9 Case example 3 - The German Reichstag (Berlin)

At the German Parliament building (Reichstag building) two aquifers at different depths are used to store cold (c. 60 m) and heat (c. 300 m). The underground storage is operational since 1999, however, the full capacity of the total system and the final operational strategy could not be tested before completion of the energy network and all buildings involved in 2003. Both storage systems, after minor teething, performed to satisfaction, see illustration in Sanner et al.[52]

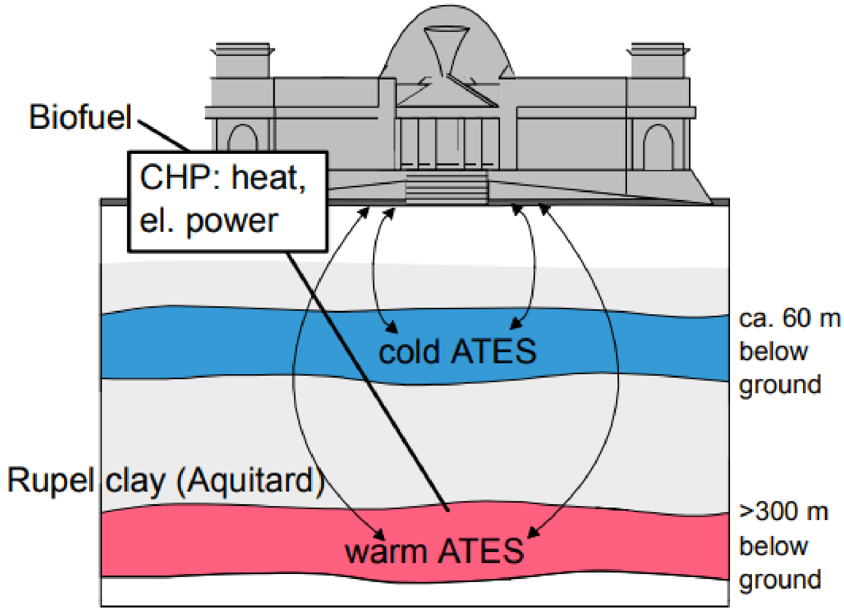

Figure 2.11 Illustration of HT-ATES system at the German Reichstag, Berlin (from[52]).

[52] Sanner, B., Kabus, F., Seibt P. & Bartels, J. 2005: Underground Thermal Energy Storage for the German Parliament in Berlin, System Concept and Operational Experiences. Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.

The design temperature at the warm well is 70°C while charging. No water treatment is used at the Reichstag building heat store[53]. According to Kranz & Bartels[54], the storage temperature is limited to 70ºC because of geochemical aspects. They state that the solubility of silicates at higher temperatures is the limiting factor, but this probably should have been carbonates (instead of silicates). Based on the groundwater composition data, the natural groundwater seems to be calcite saturated. Apparently, in this case heating to 70ºC is possible without the necessity of water treatment.

2.6.10 Case example 4 - Hooge Burgh Zwammerdam (The Netherlands)

The Hooge Burgh in Zwammerdam was in operation from 1998 to 2009[55]. The Hooge Burgh care institution in Zwammerdam has a co-generation plant (CHP) for electricity and heat production. The installation was also equipped with a high temperature heat storage at a depth of approx. 180 m. Heat was stored at 90ºC when the CHP was running for electricity production and when the heat demand was smaller than the heat production. The stored heat could later be used for heat supply to the health care institution. The heat storage consisted of a cold and a hot well, both in an aquifer at a depth of 135 to 151 m. The distance between the cold and the hot well was approx. 67 m. The storage was designed for storage of 2,250 MWh of heat per year. The expected recovery efficiency was 49%.

The heat storage was carefully managed for 5 years. After that, the heat storage was taken out of operation for financial reasons. The reason was that the CHP was the main source of heat. The CHP was controlled by electricity demand. The electricity was then returned to the grid at a favorable rate. Monitoring data showed that the feed-in fee for electricity production and heat storage profits were financially unattainable. It was decided to reduce the CHP in operating hours and not to use the heat storage anymore.

The system was put into operation in 1998. In 2003, hardly any water was pumped and in the following years the system was no longer used. In 2009, the license was withdrawn on request. Three monitoring wells are still present at the heat storage. As prescribed in the Groundwater Act license, measurements were performed on chemistry, microbiology, hydraulic head and subsurface temperature.

The expected recovery efficiency was determined for the initial situation in which an average of 41,000 m³ of groundwater was pumped in summer and winter; this is therefore 82,000 m³ per year. The measurement data shows that less groundwater was pumped than expected:

- In 1999 to 2001, an average of approx. 47,500 m³ per year was extracted; this is 58% of the expected quantity.
- The expected amount of energy stored in the summer period was 2,250 MWh (charging) and the amount of heat to be recovered in the winter period was 1,100 MWh (discharging).
- In 1999-2001, an average of 1,561 MWh per year was charged and 167 MWh discharged. (69% of the expected amount of energy was charged, and only 15% of the expected amount of energy was discharged).

[53] Sanner, B. & Knoblich, K. 2004: Thermische Untergrundspeicherung auf höherem Temperaturniveau: Begleitforschung mit Messprogramm Aquiferspeicher Reichstag. Schlussbericht zum FuE-Vorhaben, Universität Giessen.
[54] Kranz, S. & Bartels, J. 2010: Simulation and Data Based Optimisation of an Operating Seasonal Aquifer Thermal Energy Storage. Proceedings World Geothermal Congress 2010. Bali, Indonesia, 25-29 April.
[55] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

Based on the extraction/infiltration patterns shown in Table 2.4, the groundwater system was modelled. The calculations assumed that the storage was stopped after 2001 (insufficient data available for 2002). Subsequently another 96 years were simulated (so 100 years has been calculated) to see how the thermal effects develop in time after stopping the HT-ATES.

Table 2.4 Extraction and infiltration data from HT-ATES Hooge Burgh Zwammerdam

	Charging (heat storage)			Discharging (heat recovery)		
year	pumped water volume [m³]	average extraction temperature [°C]	average infiltration temperature [°C]	pumped water volume [m³]	average extraction temperature [°C]	average infiltration temperature [°C]
1998	19,226	13	71	2,513	54	44
1999	18,923	25	81	4,944	72	62
2000	24,662	37	86	21,097	59	55
2001	22,424	44	82	21,162	58	54

After stopping the heat storage (in the model after 2001), the residual heat will spread gradually and at the same time the temperature level will decrease. The calculated temperatures in 2005, 2011, 2020 and 2038 are shown in cross sections in Figure 2.12. The temperature in the subsurface does not deviate more than 2ºC from the natural groundwater temperature approximately 35 years after storage has ceased. From the calculations it follows that about 70 years after the storage is stopped the temperature in the subsurface does not deviate by more than 0.5ºC from the natural groundwater temperature. It has to be noted, that in this project relatively small amounts of heat have been stored. Therefore, the residual heat “dilutes” relatively rapid. For a larger scale HT-ATES, the thermal effects are expected to be much more pronounced and last much longer after ending the project[56].

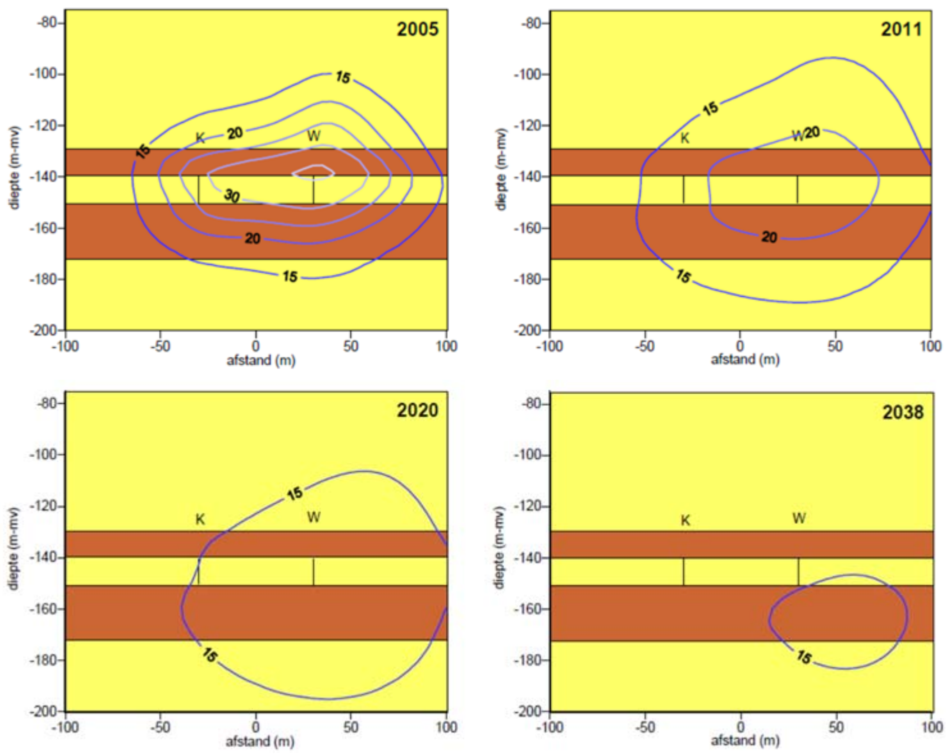

Figure 2.12 Simulated temperature development in aquifer storage after stopping heat injection in year 2001 (IF Technology)

[56] Bakema, G. & Drijver, B. 2018: State of the art HT-ATES in the Netherlands - Evaluation of thermal performance and design considerations for future projects. IF Technology.

2.6.11 Case example 5 - Geostocal (France)

The GEOSTOCAL research project (2007-2011) was funded by the “Agence Nationale de la Recherche” (ANR) under BRGM coordination. The objective was to study the technical, economic and energetic viability of a seasonal heat storage of surplus heat from incineration plants in the deep Dogger limestone aquifer. The case study was located in Ivry close to Paris. The targeted reservoir depth was 1460 m with an initial temperature of 65°C. The storage temperature was a priori limited to 95°C in order to prevent any modification of the water equilibrium between dissolved and solid minerals, and induced dissolutions or precipitations. The reinjection temperature was set to 45°C.

Several well configurations were considered: doublet (2 wells), triplet (3 wells) and quadruplet (4 wells). An integrated energetic model was designed to assess the energy mix in the network for several configurations (see Figure 2.13). The loading and unloading temperatures as a function of the cumulated unloaded mass from the aquifer had been calibrated with a numerical thermo-hydraulic model of the aquifer[57].

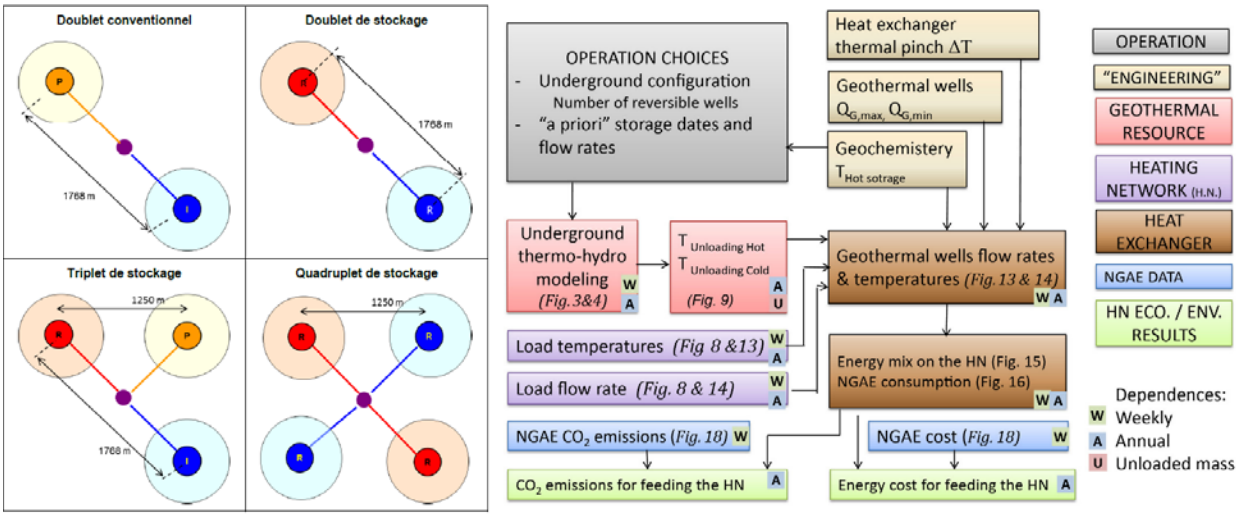

Figure 2.13 Left: studied architectures (I, P and R, are for injection, production and reversible wells, respectively), right: overview of the energetic model (from[58])

An “overproduction” (surplus production) concept has been introduced - a mix of conventional geothermal production and heat storage. The triplet with overproduction, see Figure 2.13, turned out to have the higher net present value (NPV) computed on a 30 years perspective. In other words, this solution was the most beneficial from an economic point of view.

[57] Réveillère, A., Hamm, V., Lesueur, H., Cordier, E., & Goblet, P. 2013: Geothermal contribution to the energy mix of a heating network when using Aquifer Thermal Energy Storage: Modeling and application to the Paris basin. Geothermics, 47, 69–79.
[58] Réveillère, A., Lesueur, H. & Jorio M. 2011: Stockage saisonnier de chaleur en aquifère: Outils de comparaison énergétique et économique des solutions techniques. Application au cas d’Ivry. Rapport BRGM/RP-59822-FR.

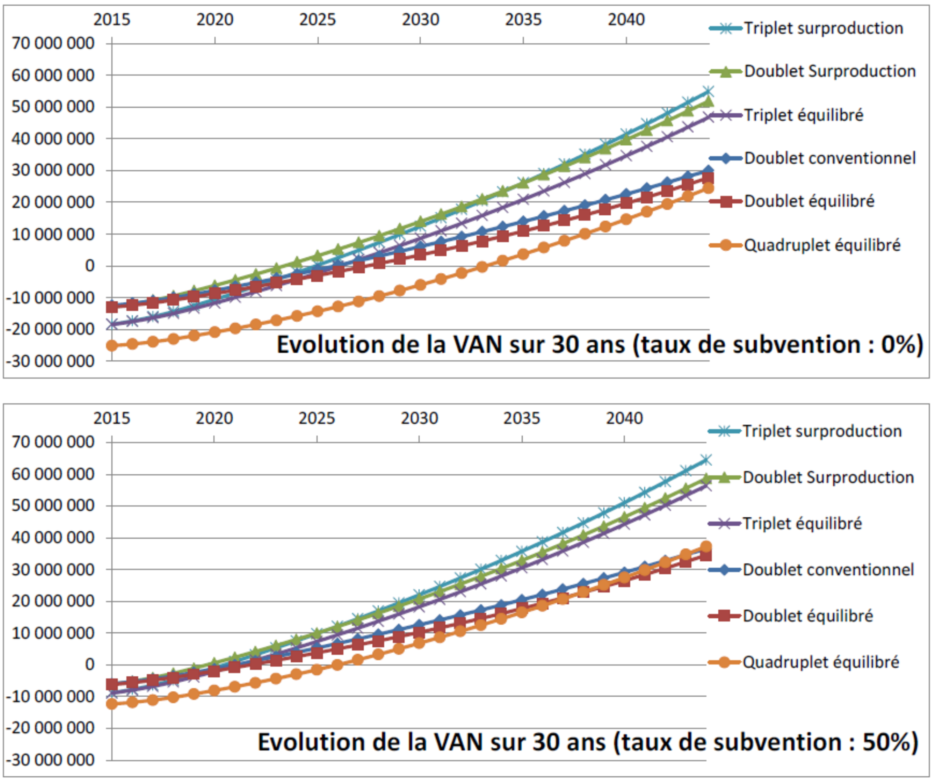

Figure 2.14 Upper graph: estimation of the net present value per year without subsidies and lower graph: with a 50% subsidy (from[59])

A preliminary geochemical study of the fluid evolution was carried out. It pointed out the risk of calcite precipitation when the water was heated and silicate precipitation when the water was cooled. These two phenomena could be avoided by filtration[59]. These feasibility studies did not lead to a full-scale demonstrator. The reason may be that the heat would have been unloaded at a temperature below 95°C (the storage temperature), while the Paris heat network operates with pressurized water at a temperature above 100ºC.

2.6.12 Case example 6 - Saint Paul, Minnesota University (USA)

This large scale experiment was constructed in 1985 at the Minnesota University campus[60]. The main system consists of a doublet separated by 255 m and equipped with a water softening system to prevent clogging (Figure 2.15). Both wells are completed in the same shallow aquifer units located between 180 and 240 meters below the surface (Franconia and Ironton & Gallesville formations, Figure 2.16). These aquifer formations hold very good properties and correspond to medium-fine sands with some clay laminations. The aquifer units are capped above and below by interbedded siltstone and shales. Both wells were equipped with dedicated screen completion and gravel pack to avoid problems with the capacity. This doublet was also accompanied by a complete monitoring system able to capture the development of the temperature profile at various distances and directions, and thereby to qualify the effects of the aquifer heterogeneity (Figure 2.15).

[59] Réveillère, A., Lesueur, H. & Jorio M. 2011: Stockage saisonnier de chaleur en aquifère: Outils de comparaison énergétique et économique des solutions techniques. Application au cas d'Ivry. Rapport BRGM/RP-59822-FR.
[60] Hoyer, M. C., Hallgren, J. P., Lauer, J. L., Walton, M., Eisenreich, S. J., Howe, J. T. & Splettstoesser, J. F. 1991: Aquifer thermal energy storage (ATES) project. Report on the second long-term cycle. University of Minnesota, report, December 1991.

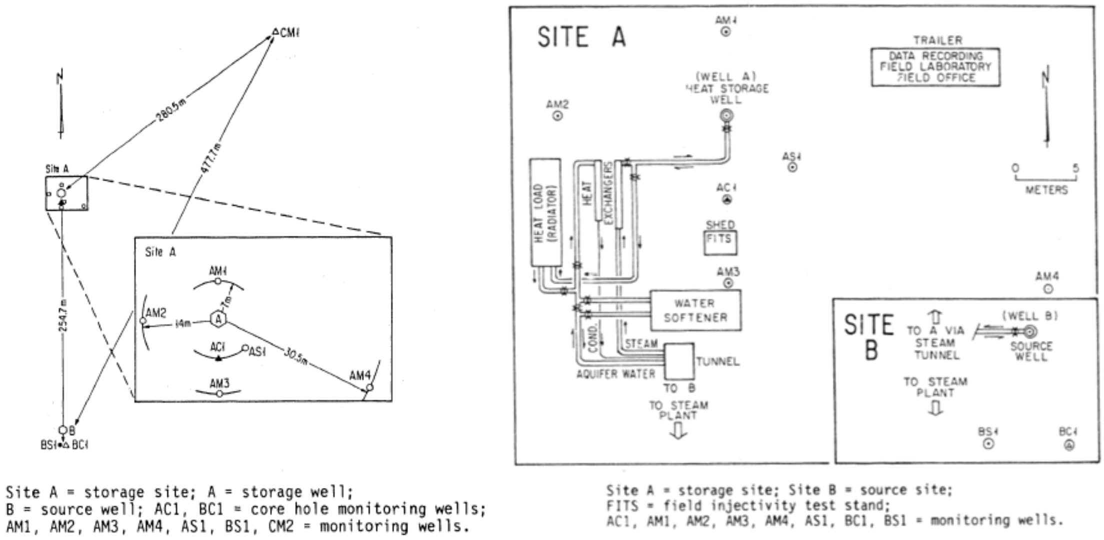

Figure 2.15 General implementation of the Saint Paul system with the monitoring wells and the two sites with the injection and production wells (courtesy of the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy[61])

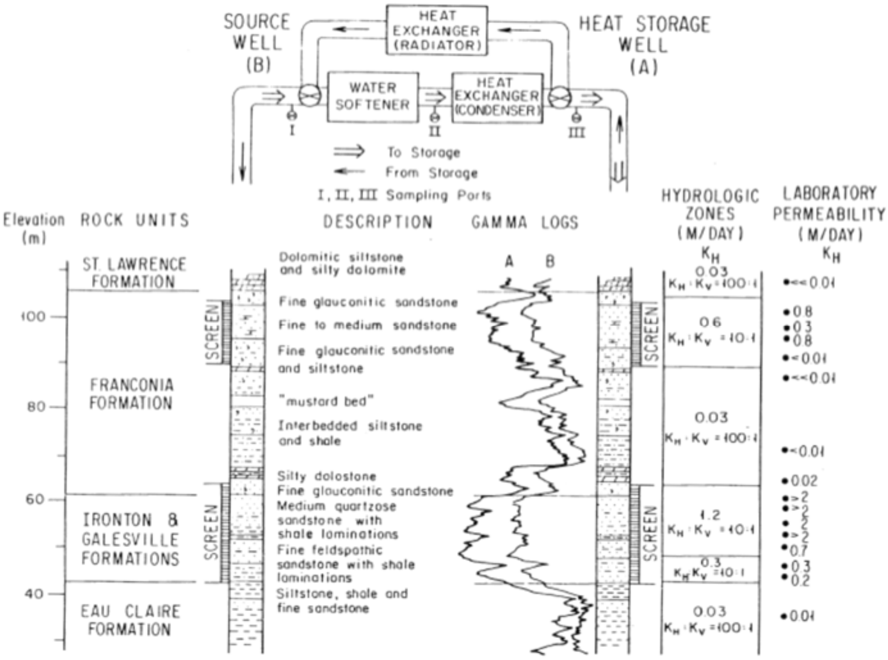

Figure 2.16 Stratigraphic column at the Saint Paul test site with the associated properties and the main components associated with the doublet (courtesy of the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy[61])

The system was tested by injection of very hot water (118°C) during a period of 2 months, then a period of storage (2 months) followed by a production phase for 2 months. A total of 94,000 m^3 of water were injected into the aquifer, equivalent to 9,000 MWh. The withdrawal enabled to recover 61% of the heat injected. The production was stopped when the temperature reached 55°C (temperature still valuable for heating without using a heat pump). Half of the heat recovered corresponded to a temperature higher than 85°C (Figure 2.17).

[61] Hoyer, M. C., Hallgren, J. P., Lauer, J. L., Walton, M., Eisenreich, S. J., Howe, J. T. & Splettstoesser, J. F. 1991: Aquifer thermal energy storage (ATES) project. Report on the second long-term cycle. University of Minnesota, report, December 1991.

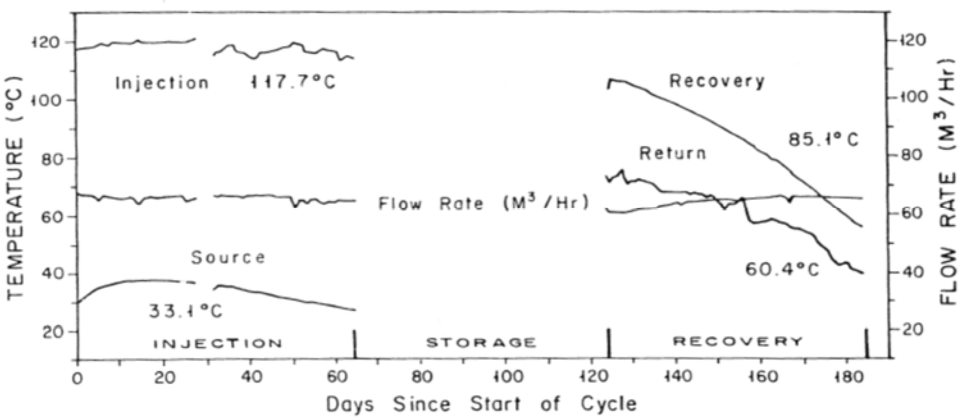

Figure 2.17 Evolution of the temperatures and flowrates during a complete cycle of injection, storage and recovery (courtesy of the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy[62])

The installation of an ion-exchange water softening system to process the source water was very important to prevent carbonate scaling in the heat exchanger and in the injection well. The softener lowered hardness of the source water from 160 mg/L $CaCO_3$ to less than 10 mg/L $CaCO_3$. Sodium concentrations in the source water increased from ~44 mg/L to ~122 mg/L in the water softener.

The monitoring system detected a heat leakage towards an upper aquifer through a failing packer. Monitoring results were used to calibrate a numerical model and to improve the heterogeneity in the thermal response for the main aquifer units as shown in Figure 2.18.

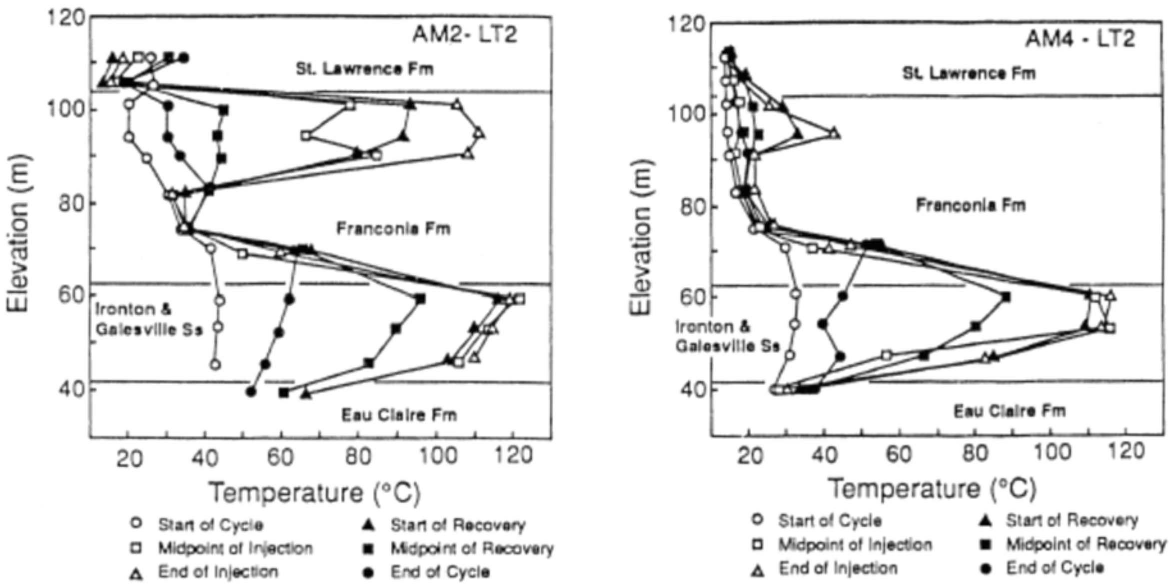

Figure 2.18 Vertical temperature profiles in 2 monitoring wells – AM2 shows a thermal response in both reservoir units whereas AM4 only shows a response in the deepest reservoir unit (courtesy of the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy[62])

[62] Hoyer, M. C., Hallgren, J. P., Lauer, J. L., Walton, M., Eisenreich, S. J., Howe, J. T. & Splettstoesser, J. F. 1991: Aquifer thermal energy storage (ATES) project. Report on the second long-term cycle. University of Minnesota, report, December 1991.

2.7 Economics

Only a limited amount of cost data is available for the implementation of HT-ATES.

For any heat storage, including HT-ATES, it is important to find the best or optimum sizing for the individual parts of the system. This can be done by systematically running a series of simulations to identify the best (generally the least cost) combination of major component sizes to achieve the design objectives. Generally the specific cost drops significantly as the size of the storage increases.

Comparing ATES with other, more conventional, energy systems, the initial investments costs are relatively high (market barrier), however the payback time of these systems can potentially be low. A break-down of the total investment cost shows that a significant part of an HT-ATES application is related to well drilling, well completion and submersible pumps.

The operational costs of a HT-ATES include system maintenance, monitoring, electricity costs (pumps) and potential heat purchase. The fixed expenditures (equipment maintenance and monitoring program) are less difficult to calculate than the more dynamic costs dependent on e.g. energy price levels.

Furthermore parameters that influence the investment cost per unit of thermal energy produced are: 1) how many hours of energy production the system can deliver (full load hours), 2) the maximum flow rate, and 3) temperature rates in and out of the system (ΔT).

The economic lifetime of a HT-ATES system is challenging to determine based on experiences from the few existing systems. So far a short technical life time has been a barrier in calculating representative economic lifetimes of a high temperature system. The lessons learned on the technical issues and the technical development of material, drilling, well completion etc. contribute to new solutions. The relatively short lifetimes of the early systems are therefore no longer considered to be representative.

3 BTES (Borehole Thermal Energy Storage)

3.1 The BTES system

BTES uses the natural heat capacity in a large volume of underground soil or rock to store thermal energy.

The principle of BTES is to heat up the subsurface and cool it down again by circulating a fluid in plastic u-tube pipes installed in a large number of closely spaced so-called closed loop boreholes or Borehole Heat Exchangers (BHE) and completed with a sealing grout, see Figure 3.1. The distance between the boreholes is typically in the range of 2-5 m and BTES is normally limited to boreholes of approx. 20-200 m depth. The thermal losses depend on the thermal and hydraulic properties of the subsurface (heat losses by conduction and density driven flow), the shape of the storage volume (defined by the lay-out of the boreholes) regional groundwater flow (heat losses by advection) and heat losses to the surface.

Temperatures up to approx. 90°C can be stored[63] and BTES can be used to store excess heat from industries, incineration plants and heat from renewable energy sources such as solar thermal for use in district heating. BTES is ideal for integrating heat from various sources, e.g. heat pumps, solar thermal and CHP (Combined Heat and Power) plants in combined energy systems utilising power to heat (heat pumps) in periods with excess electricity production and store heat from periods with need for electricity production from CHP. Due to a relatively low heat transfer coefficient, BTES storage does not react very fast. In cases where fast reaction is required a fast reacting buffer storage (e.g. water tank) can be used[63,64].

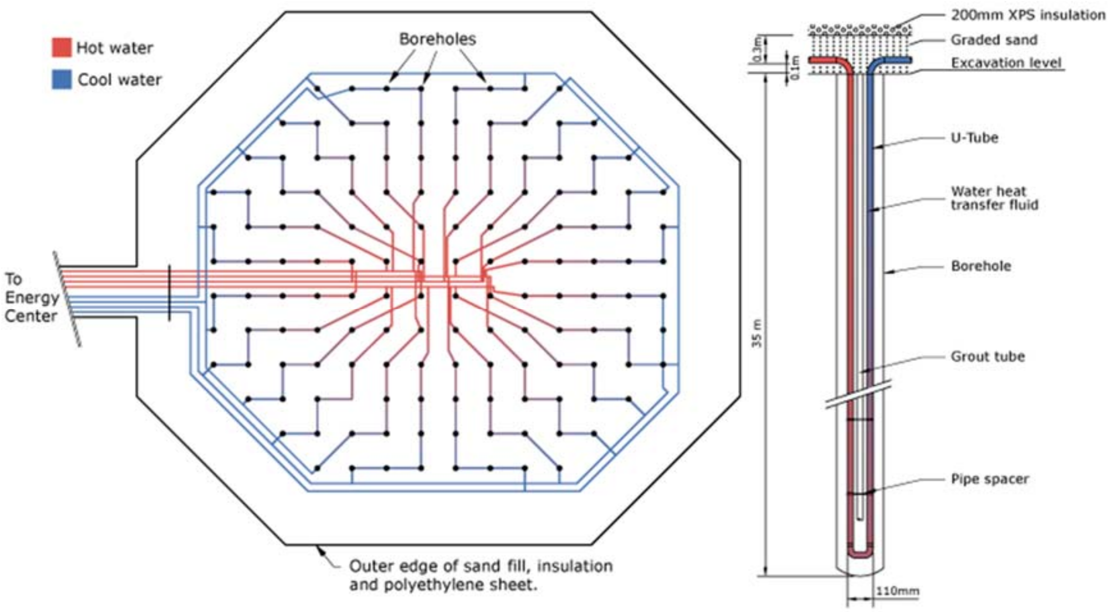

Figure 3.1 Layout of a borehole thermal energy storage and cross-section of a single borehole and u-tube (from[63]).

[63] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[64] Danish Energy Agency, 2014. Status and recommendations for RD&D on energy storage technologies in a Danish context.

3.1.1 BTES demo site in the HEATSTORE project

The HEATSTORE project includes a BTES demonstration system to be established in France. The French demonstration project will provide heating for two administrative buildings of Storengy's main natural gas storage facility located in Chémery (region Centre – Val de Loire) with a yearly heat load of 135 MWh. The heating will be provided from 265 m^2 of solar panels combined with a BTES charged and discharged through 12 radial lines of 4 boreholes in series. The main objective of this project is to improve the overall efficiency of such coupled systems based on the combination of solar thermal and BTES.

3.2 Lessons learned – line up

In Table 3.1 below the important lessons learned from existing BTES systems are lined up. The table summarises the conclusions from the more thorough report text in the following sections.

Table 3.1 Line up of important lesson learned from existing BTES systems

BTES systems – Lessons learned		
Pre-investigation (feasibility study)	• Always perform initial feasibility screening incl. geological conditions (using available information), existing or planned heat load and heating infrastructure and modelling of the entire planned system (3.3.1, 3.3.2 and 3.3.6) • The required preliminary geological paramaters of the site are: geology, groundwater flow, thermal properties etc. (3.3.1) • Significant groundwater flow will cause advective heat loss and should be avoided (3.3.3) • The higher the heat capacity the better (3.3.4) • A low thermal conductivity of the storage volume increase the recovery efficiency, but decrease the rate of charging/discharging, which is favoured by high thermal conductivity and medium thermal conductivities may be the most favourable (3.3.4) • Perform a test drilling to verify the ground conditions and the estimated drilling costs (3.3.5) • Always perform a thermal response test to verify the thermal properties of the site (3.3.4)	*External factors (political, legislation):* (see also chapter 6) A clear regulative framework adapted to BTES has to be finalized in some countries Risks of not getting a permit or long (timely) permit procedure Lack of knowledge on the technology among important stakeholders

Construction	**Materials and system design** • The BTES design should preferably be cylindrical in order to maximize the storage volume to surface area ratio and minimize the heat loss (3.4.1 and 3.5.2) • The layout of boreholes locations are important and should be optimized according to both the most favourable cross section area per borehole and distance between drilling locations required by the drilling contractor (3.4.1) • Normally the tubing of the borehole heat exchangers are connected in order to heat up the storage from the center and outwards, and vice versa when discharging as this will reduce the heat loss and optimize the efficiency (3.4.1) • Regarding tube material, high quality cross-linked high density polyethylene (PEX) tubes are normally used as they are strong, chemical resistant and can withstand high pressures and high temperatures (3.4.2) • Double u-tubes are more efficient than single u-tubes, but coaxial tubes are, at least theoretically, the most favourable (3.4.1) • It is recommended to use so-called spacers to separate the down- and upflow tubes and avoid a “shortcutting” heat transfer between the tubes (3.4.1) • Open tubes with direct contact between the heat carrier fluid and the borehole wall (rock/soil) should be avoided as operation problems were previously experienced in older systems in Sweden (Luleå and Emmaboda) (3.4.2) **Drilling and grouting** • The drilling cost may account for approx. 50% of the total construction costs (3.4.3) • Soft sediments can be more challenging and time consuming than hard rock and normally direct rotary mud drilling is considered to be the most efficient method for soft sediments (3.4.3) • The drilling contractor will normally require a “safety distance” between boreholes in order not to risk drilling through neighbour boreholes if the borehole path is deflected from vertical (3.4.3) • It is recommended to use a casing during drilling in soft sediments to avoid cavities and excessive use of expensive grout as well as collapsing boreholes (3.4.3) • Sealing of the boreholes using a cementing grout is always recommended (and often also required by the authorities) in order to protect the groundwater resources and is also necessary in unsaturated conditions to obtain a reasonable high thermal conductivity between the tubes and the surrounding soil (3.4.3) • Grouting must be carried out from the bottom of the borehole and upwards (3.4.3) • It is recommended to use a thermally enhanced grout in order to reduce the “thermal resistance” of the borehole (3.4.3) **Top insulation, monitoring, environmental impact** • A top insulation of the BTES is necessary to reduce the heat loss and may account for 25% of the total construction costs (3.4.4)	Several fields of expertise are needed to establish a complete BTES system Initial investments costs relative high BTES is relative dependent on cheap or almost free surplus heat Missing common quality standards or certification of professionals is a potential barrier

BTES systems – Lessons learned		
	• The top insulation must be designed taking local climate and BTES temperatures into consideration together with the actual need for reducing the heat loss (3.4.4) • Foam glass gravel have been used as insulation material, but is expensive and mussel shells has proven to be significantly more cost-efficient option (3.4.4) • A BTES system should always include dedicated boreholes for temperature sensors both in- and outside the storage volume to monitor the storage temperatures and heat loss to the surroundings (3.4.5) • The environmental impact of increased ground temperatures in connection with HT-BTES can potentially lead to microbiological and geochemical changes, but the subject is not well investigated (3.4.6) • Antifreeze is hardly necessary in the heat carrier fluid in HT-BTES, but is also not necessarily a significant environmental problem, while different types of additives can potentially be more problematic (3.4.6) *Recommendations for general specifications and design of HT-BTES are presented in the HEATSTORE deliverable D1.2 report "General specifications and design for UTES systems"*	
System integration	• HT-BTES is relevant in combination with especially solar panels, waste incineration, industrial waste heat and power to heat applications (3.5) • A BTES reacts relatively slowly during charging and discharging and normally a buffer heat storage like e.g. a water tank is necessary as part of the system (3.5) • All elements and subsystems and their interaction with each other must be modelled and designed carefully using e.g. TRNSYS or other model tools (3.5.1) • For modelling of the BTES performance, it is important to represent the borehole depth, number of boreholes and borehole spacing as correctly as possible as well as defining parameters such as the thermal conductivity, heat capacity and diffusivity of the soil/rock, the combined thermal conductivity of the tubes and grout (the borehole resistance) and the thickness and thermal conductivity of the top insulation (3.5.1) • The thermal properties of the ground can impact both the efficiency of the BTES in terms of heat loss and the total system efficiency e.g. in terms of solar fraction used (3.5.2) • The local climate should be taken into consideration in the design of a BTES system, but is not likely to have a major impact on the system performance (3.5.3)	

BTES systems – Lessons learned		
Operations feedback	• In general, the maximum and minimum storage temperatures, respectively, during charging and discharging are ranging between 30˚C and 60˚C and sometimes up to 70-80˚C (3.6.10) • Where it can be observed/calculated, the storage efficiency is ranging between 45% and 60% and is lower than expected/modelled (3.6.10) • In general a start-up period of a few years should be expected to heat up the storage and the surroundings (3.5.1, 3.6.10) • A buffer system is necessary to take full benefit from e.g. the solar panel-BTES coupling (3.6.10) • Lower performance than expected can be due to the modelling approach used in the planning and choice of parameters not reflecting the actual conditions (3.6.10)	
Conclusions	• A storage is a passive system and the economical and energetic efficiency will be defined by the input and output parameters in terms of temperatures and heat load, the thermal properties of the storage and the entire system integration • The design of each project must be adapted according to the specific geological parameters of the actual site (soil/rock types, groundwater level, groundwater flow, thermal properties etc.) (3.3) • Each element of the system should be optimized in the design phase using well-validated pre-design tools (3.5.1) • The specific costs drops significantly with increasing storage size and BTES systems should generally be larger than 20,000 m^3 of storage volume in order to be financially viable (3.7)	

3.3 (Pre-)investigation and feasibility studies

3.3.1 Screening process

The first part of a feasibility screening for BTES is to consider the existing or planned heating infrastructure and heating demand. All parts of the future energy system including the BTES, the heat source for the BTES and the demand side system (district heating network, building complexes etc.) should be taken into account and their interaction with each other under the specific climate conditions should be modelled in terms of e.g. system temperature levels and charging and discharging capacity of the storage[65].

As part of the screening process, the geological conditions including hydrogeology in terms of groundwater flow and groundwater level as well as the thermal properties of the soil/rock on the site must be evaluated. The screening must also include any stakeholder and e.g. groundwater interests and possible environmental issues and a risk analysis.

3.3.2 Geology

The preferred geological conditions for BTES are drillable ground with a high heat capacity and low natural groundwater flow and a preliminary screening of the local geology in the area of the planned storage is mandatory. A screening based on existing well records can typically provide a reasonable idea of the geological layers to be expected in terms of depth and soil or rock type as well as the existence and strength of any groundwater flow and the depth of the water table. The existing geological information will also typically provide important information in order to select the best drilling and grouting technique for the specific site[66].

Based on an initial geological screening a reasonable idea of the expected thermal properties of the different geological layers encountered in the storage volume can also be estimated using existing table values of e.g. heat capacity and thermal conductivity. However, table values may vary from region to region as a consequence of geological variations, and hence it must be evaluated which set of values will be better to use, and take some uncertainty into account[65], see also section 3.3.4.

3.3.3 Groundwater

A comprehensive screening of the local hydrogeological conditions in terms groundwater level and possible groundwater flow is also of importance as water flow through and around the storage volume will imply heat loss by advection and should be avoided to the largest possible extent. Thus a BTES should be placed above the groundwater table or in geological conditions with low hydraulic conductivity and therefore no or little groundwater flow such as e.g. tight clay or till, tight limestone, sedimentary rocks with low permeability or un-fractured crystalline rocks[67].

In case of “unavoidable” zones with unwanted high groundwater flow, e.g. in the upper geological layers, such zones can be insulated with thermally reducing grout in the boreholes to minimize the

[65] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[66] Sørensen, Per Alex. 2019: “Best practice” for implementation and operation of the large scale Borehole and Pit Heat Thermal Storages (BTES and PTES) in Brædstrup, Marstal, Dronninglund and Gram, Denmark. PlanEnergi.
[67] Catolico, N., Ge, S. & McCarteny, J. S. 2015. Numerical Modeling of a Soil- Borehole Thermal Energy Storage System, u.o.: Soil Science Society of America.

heat loss, whereas a thermally enhanced grout will typically be used in other zones in order to increase the heat transfer from the borehole to the storage volume[68,69].

In case of a BTES partly below the groundwater table (and minor groundwater flow), it may, in some cases, be necessary to lower the groundwater table during construction depending on drilling-, u-tube installation- and grouting technique[70].

3.3.4 Thermal properties

Both heat capacity and thermal conductivity in the subsurface is a result of the mineralogy, rock or soil density, degree of saturation, and temperature and the higher the heat capacity, the more heat can be stored in the BTES.

For thermal conductivity, a high thermal conductivity will increase the ability to charge heat into the storage volume, but will at the same time increase the rate for heat conduction away from the borehole causing the thermal plume to grow also during discharge. This increased ability of the heat to move outward away from the boreholes results in lower temperatures near the boreholes and therefore a lower gradient for heat to flow back towards the boreholes in the discharge phase. In case of a lower thermal conductivity, higher temperatures will remain near the boreholes, creating a higher gradient to drive heat flow back towards the boreholes during discharging allowing a greater portion of the heat to be recovered.

The work of Catolico et al.[71] shows that BTES heat extraction efficiency increases with decreasing soil thermal conductivity. In a numerical modelling scenario, a soil with a low thermal conductivity of 0.5 W/mK showed 47% higher BTES efficiency in the first year than a soil with a thermal conductivity of 2.0 W/mK. The model only includes a set of two BTES boreholes, but Sibbitt & McClenahan[8] presents similar modelling results for large arrays of BTES boreholes.

Other modelling scenarios carried out by Catolico et al.[71] also suggest that the BTES system heat extraction efficiency decreases with convective heat losses associated with high soil permeability for both saturated and unsaturated soils. The high permeability allows convective processes to carry heat upward and away from the boreholes. Furthermore, lower relative permeability in unsaturated soils hinders the convective processes below a critical threshold intrinsic permeability, leading to higher efficiencies than for saturated soils and, the overall heat extraction efficiency of unsaturated systems at all permeability values was shown to be higher than for saturated systems due to the insulating effect of air and a lower effective thermal conductivity. But again this was based on modelling of only two boreholes and not considering the ability to charge the storage.

On the other hand, the modelling results in Sibbitt & McClenahan[70] also show, that low thermal conductivity decrease the ability to charge the storage and that the size and shape of the storage in terms of number and depth of boreholes is also important (see also section 3.5.2). Thus, it is a compromise and it has been suggested that medium thermal conductivities may be desirable for

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[68] Mangold, D. & Deschaintre, L., 2015. Seasonal Thermal Energy Storage - Report on State of the Art and Necessary Further R+D, Stuttgart: International Energy Agency - Solar Heating & Cooling Programme (SHC), Task 45 Large Systems.
[69] Mangold, D. & Schmidt, T., 2007. The next Generations of Seasonal Thermal Energy Storage in Germany, Stuttgart: Solites - Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems.
[70] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[71] Catolico, N., Ge, S. & McCarteny, J. S. 2015. Numerical Modeling of a Soil- Borehole Thermal Energy Storage System, u.o.: Soil Science Society of America.

thermal energy storage systems[72,73] and careful modelling of the actual design and conditions is needed in order to optimize the operation of a BTES under specific conditions[74,75,76].

A number of look-up tables exists for e.g. thermal conductivity of different soil/rock types and in Table 3.2 an overview is given based on different sources from Germany, the UK and Denmark, while Table 3.3 present newer measured values from Denmark.

Table 3.2 Thermal conductivity of different sediment and rock types (from[77])

Sediment/rock	Thermal conductivity W mK^{-1}	Recommended values W mK^{-1}	Estimated specific heat extraction rate (W m^{-1}) VDI (2001)	MCS (2011)
Clay and silt (dry)	0.4–1.0*	0.5*	–	–
Water-saturated clay and silt	1.1–3.1*	1.8*	35–50	21–34
Palaeogene clay, Denmark	1.34–1.56†	–	–	–
Sand (dry)	0.3–0.9*	0.4*	25	–
Water-saturated sand	2.0–3.0*	2.4*	65–80	26–45
Water-saturated gravel	1.6–2.5*	1.8*	–	–
Till/loam	1.1–2.9*	2.4*	–	–
Clayey till, Denmark	2.00–2.31‡	–	–	–
Chalk, England	1.79 ± 0.54§	–	–	–
Chalk, Denmark	1.45–1.86†	–	–	–
Quartzite	5.5–7.5§	6.0§	–	–
Granite	3–4§	3.4§	65–85	33–45

* VDI (2010). † Balling *et al.* (1981). ‡ Porsvig (1986). § Banks (2008).

Table 3.3 Thermal conductivity of some common, shallow, Danish sediments (from[78])

Sediment type	Number of samples	Average thermal conductivity W mK^{-1}	Range W mK^{-1}	One standard deviation W mK^{-1}
Gyttja	3	0.68	0.58–0.86	0.15
Smectite-rich clay	3	0.98	0.80–1.14	0.17
Silty clay	10	1.15	0.90–1.42	0.17
Chalk*	4	1.62	1.49–1.80	0.13
Mica-rich, fine-grained sand	8	1.81	1.48–2.19	0.27
Till	19	1.89	1.40–2.66	0.30
Glacial sand, gravelly	4	2.24	1.98–2.43	0.19
Pure quartz sand	3	2.75	2.41–3.34	0.51

* Selected data from Balling *et al.* (1981).
Measurements were conducted with a needle probe (Hukseflux 2008) using water-saturated samples.

72 Socaciu, L.G. 2011. Seasonal sensible thermal energy storage solutions. Leonardo Electron. J. Pract. Technol. 19:49–68.

73 Başer, T. & J.S. McCartney. 2015. Development of a full-scale soil-borehole thermal energy storage system. In: M. Iskander et al., editors, Proceedings of the International Foundations Conference and Equipment Exposition (IFCEE 2015), San Antonio, TX. 17–21 Mar. 2015. Am. Soc. Civ. Eng., Reston, VA. p. 1608–1617.

74 Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

75 Lanahan, M. & Tabares-Velasco, P. C. 2017: Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. Energies 2017, 10, 743; doi:10.3390/en10060743.

76 Catolico, N., Ge, S. & McCarteny, J. S. 2015. Numerical Modeling of a Soil- Borehole Thermal Energy Storage System, u.o.: Soil Science Society of America.

77 Vangkilde-Pedersen, T., Ditlefsen, C. & Hojberg, A.L. 2012: Shallow geothermal energy in Denmark. Geological Survey of Denmark and Greenland Bulletin 26, p. 37-40.

78 Ditlefsen, D., Sørensen, I., Slott, M. & Hansen, M. 2014: Estimating thermal conductivity from lithological descriptions – a new web-based tool for planning of ground-source heating and cooling. Geological Survey of Denmark and Greenland Bulletin 31, p. 55–58.

A Thermal Response Test is typically conducted in a test borehole at the actual BTES site and will provide an average value for the thermal conductivity to be expected for the storage volume as well as the thermal resistance of the BTES boreholes and the results are essential for design calculations of the BTES.

Normally the borehole will be completed with fluid-filled tubes and grout like the future BTES boreholes. The Thermal Response Test is then carried out by heating up the fluid with a steady power load and monitor the heat transfer into the ground surrounding the borehole as the fluid is circulated in the tubes.

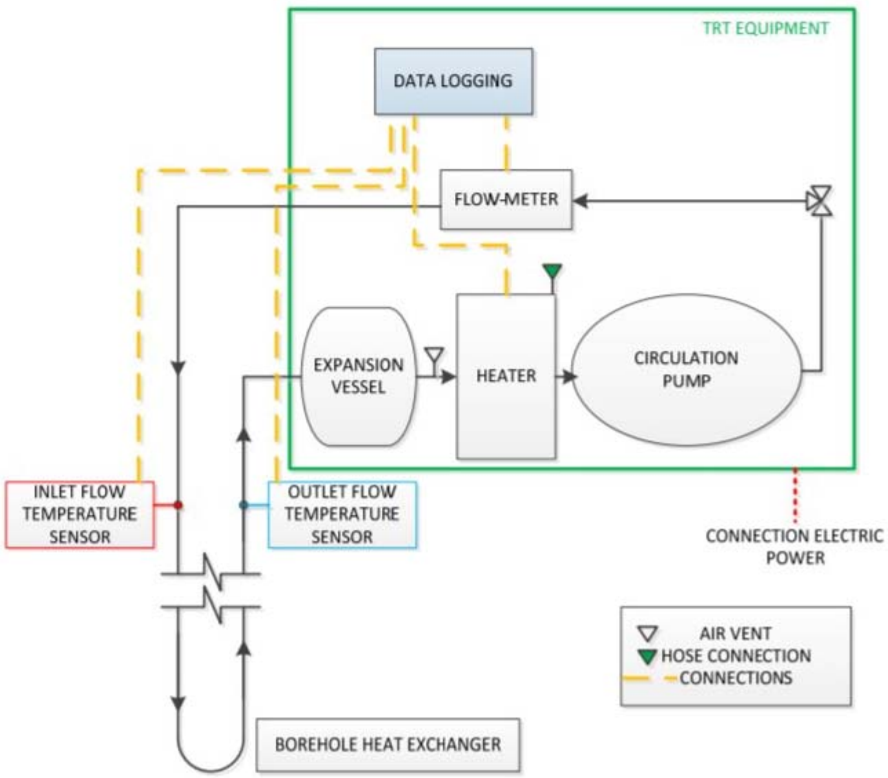

Figure 3.2 Scheme of the main components of Thermal Response Test equipment (from[79])

Figure 3.2 shows the principle and a scheme of the main components of a Thermal Response Test equipment. A heater provides a steady heat load and the flow and inlet/outlet temperatures are measured and logged. Interpretation of the results is typically carried out using the so-called "Infinite Line Source" method[80,81,82,83].

[79] Pagola, M. A. & Bjørn, H. 2014: D8 Guidelines for equipment, methods and calibration. Part 2. Thermal Response Test. GeoEnergy - Tools for ground source heating and cooling based on closed loop boreholes, EUDP projekt, J.nr. 64011-0003.
[80] Gehlin, S. 2002. Thermal Response Test. Method Development and Evaluation. Doctor of Philosophy, Luleå University of Technology.
[81] Signorelli, S., Bassetti, S., Pahud, D. & Kohl, T. 2007. Numerical evaluation of thermal response tests. Geothermics, 36, 141-166.
[82] Banks, D. 2008. An Introduction to Thermogeology. Ground Source Heating and Cooling., Oxford, Blackwell Publishing.
[83] Monzó, P. M. 2011. Comparison of different Line Source Model approaches for analysis of Thermal Response Test in a U-pipe Borehole Heat Exchanger. Master of Science Thesis Energy Technology 2011 Master of Science Thesis, KTH School of Industrial Engineering and Management.

3.3.5 Test drilling

If the results of the preliminary screening justify further investigation, a test drilling at the specific site is normally required in order to more accurately assess the details of the subsurface in terms of geology, soil/rock properties, groundwater conditions and thermal properties.

A test well will also be very useful for performing a Thermal Response Test as mentioned above to better define the effective thermal properties of the location, which are needed for modelling the BTES performance.

Finally a test well will provide important information to assess the necessary time and cost for completing the entire drilling work for establishing the BTES. A test drilling can in the worst case also serve to indicate if another type of storage than BTES should be considered according to the drilling and evaluation results.

3.3.6 Modelling subsurface dynamics

As part of a pre-investigation/feasibility study for BTES the subsurface dynamics should be modelled based on the available information on site characteristics and soil properties.

BTES modelling tools range from in-depth analysis allowing for subsystem design, to whole building simulations that incorporate more simple subsurface heat transfer models into energy design analysis. The selection of tools therefore depends on the desired type of analysis and studies looking at district heating network/building/community scale use analysis tools such as EnergyPlus and TRNSYS, while more detailed multiphysics tools such as FEFLOW, COMSOL and TOUGH2 or more BTES focused codes as EED (Earth Energy Designer), GLD (Ground Loop Design) or GLHEPRO are used to model the heat transfer characteristics of BTES[84,85].

3.4 Construction

In this section available existing experience and research regarding construction of HT-BTES systems is described. Further recommendations can be found in the HEATSTORE deliverable D1.2 report “General specifications and design for UTES systems”.

3.4.1 Well design and configuration

The outer shape of the BTES storage volume is defined by the pattern and depth of the BTES boreholes. BTES is generally designed to be approximately cylindrical in shape in order to maximize the volume to surface area ratio and minimize the heat loss, but other three dimensional shapes may also be used. The influence of different cylindrical aspect ratios (length to diameter) on storage efficiency and system performance is addressed in the section 3.5.2.

Also the distance between boreholes or the cross section area for a given individual borehole is important for the efficiency of the BTES. During construction of the BTES in Brædstrup in Denmark, the optimal cross section area for a borehole was calculated to 7.76 m^2 and the drilling operator required a 3 m distance between individual boreholes. Calculations proved, that the most

[84] Lanahan, M. & Tabares-Velasco, P. C. 2017: Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. Energies 2017, 10, 743; doi:10.3390/en10060743.
[85] Ditlefsen, D., Møller, I., Højberg, A. L., Thorling, L., Sørensen, I., Bjørn, H. & Balling, N. 2014: D25 Opsummerende projektrapport samt D23 Anbefalinger og guidelines. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.

cost-efficient way of achieving this was to place the boreholes in a honeycomb pattern rather than a square pattern[86], see Figure 3.3.

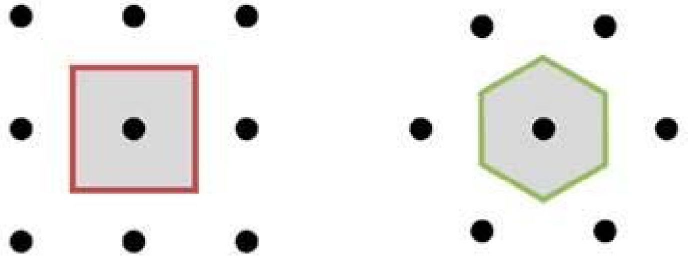

Figure 3.3 Top view of borehole section areas of 7.76 m^2 for a square pattern and a "honeycomb" pattern (from[86])

Typically, the u-tubes in several boreholes are connected in series to form a circuit following an approximately radial path through the storage. The flow direction for charging is from the BTES center to the outer edge and from the outer edge to the center, for discharging in order to maximize the process and minimize the heat loss. A number of parallel circuits are used to distribute the flow throughout the entire storage volume[87,88], see also Figure 3.4 showing how boreholes are connected in series from the center and outwards.

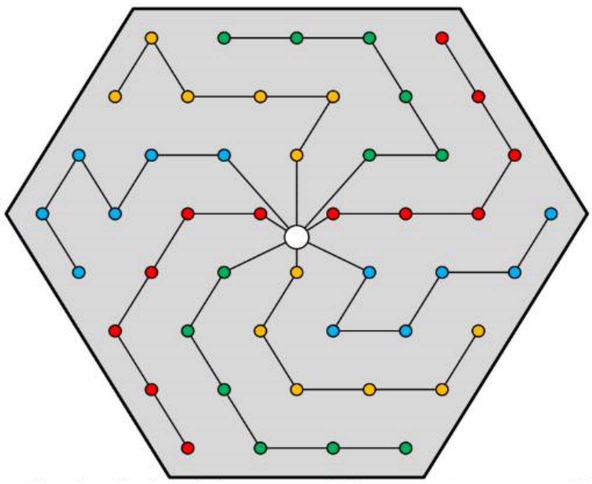

Figure 3.4 Example of pipe layout for a BTES in Brædstrup, Denmark. Only connection to one of the u-tubes in each borehole are shown (from[86]).

Field testing with Thermal Response Tests in single boreholes installed with three different tube configurations: single u-tube, double u-tube and coaxial (see Figure 3.5) showed, that double u-

[86] Sørensen, Per Alex et al. (2013). Boreholes in Brædstrup. Final report.
[87] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[88] Lanahan, M. & Tabares-Velasco, P. C. 2017: Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. Energies 2017, 10, 743; doi:10.3390/en10060743.

tubes was more efficient than single u-tubes[89]. Theoretically, the coaxial configuration should be the most effective, but the field test failed to prove this, probably because the inner tube was not properly centralized in the outer tube[90]. It is generally recommended to use so-called spacers to separate and keep the down- and upflow tubes in place for both u-tubes and coaxial tubes and avoid a "shortcutting" heat flow between the tubes. An analysis based on modelling in FEFLOW has shown, that increasing the distance between the down- and upflow tubes for a single u-tube in a single borehole from 6 cm to 10 cm was increasing the efficiency of the heat extraction[91].

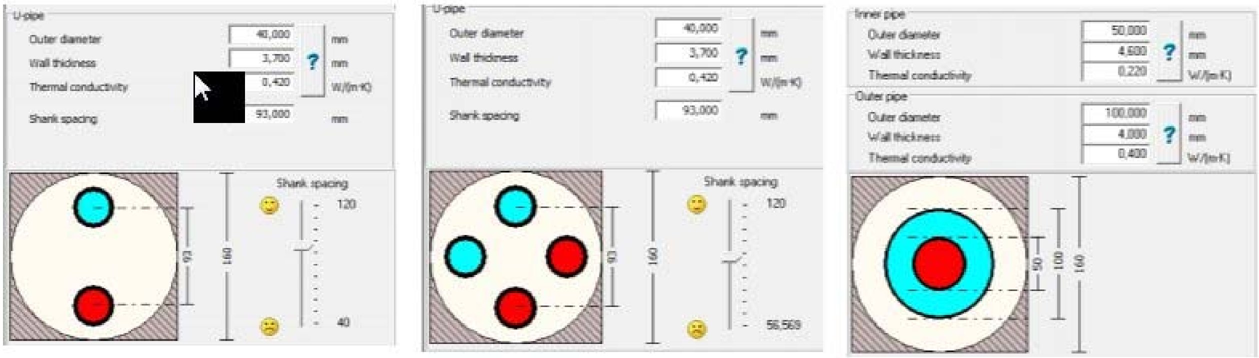

Figure 3.5 Different types of u-tube configurations: single u-tube (left), double u-tube (middle) and coaxial u-tube (right) (from[92,93])

Malmberg et al.[94] describes simulation of a large-scale BTES using TRNSYS. The BTES was modelled as part of a district heating system in order to be able to store excess heat from summer operation of a CHP-plant on a seasonally basis to increase the flexibility between energy supply and demand.

The BTES was simulated with both double u-tubes and coaxial tubes and in a number of different configurations in terms of number and depths of boreholes. The most favourable results was obtained with 1.400 boreholes with double u-tubes and 1.300 boreholes with coaxial tubes, respectively, and in both cases with a borehole depth of 300 m and 5 m spacing between boreholes. The coaxial tubes was modelled to have a lower borehole resistance than the u-tubes, leading to an increased storage capacity of the system and thereby a need for less boreholes. A geometry with 1.500 boreholes to a depth of 275 m with double u-tubes showed similar results regarding energy, power and system temperatures.

[89] Sørensen, I. & Pagola, M. A. 2014: D11 Aktiviteter på testsite. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.
[90] Bjørn, H. 2014: D10 Rapport over bore- og grout-teknik. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.
[91] Højberg, A. L. & Rasmussen, P. 2014: D20 Modellering af varmetransport. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.
[92] Bjørn, H. & Poulsen, S. E. 2014. D7 Rapport over termiske egenskaber for materialer Grout, rør og briner. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.
[93] Earth Energy Designer. Version 3.16, Blocon, 2010.
[94] Malmberg, M., Mazzotti, W., Acuña, J., Lindståhl, H. & Lazzarotto, A. 2018: High temperature borehole thermal energy storage – A case study. IGSHPA Research Track, Stockholm, September 18-20.

The three systems showed a potential to store around 107 GWh/year and to extract around 93 GWh/year with the use of a GSHP. The resulting discharge temperature from the BTES ranges between 40-70°C. The pressure drop in the tubes was overall rather high for the simulated systems, with up to 6 bars using double u-tubes, a borehole depth of 300 m and 3 boreholes in series. If the number of boreholes in series would be reduced the pressure drop would decrease significantly, both as the total tube length is decreased in each loop and because the number of borehole loops would increase resulting in a lower volumetric flowrate in each loop. It was not tested how this would affect the thermal performance of the system. Using coaxial tubes would decrease the pressure drop, and thus the required operational energy for the circulation pumps in the BTES by about 30%. Thus, the simulation shows that using coaxial tubes would both improve the heat exchange and decrease the required pumping energy, but Malmberg et al.[95] states that further investigation is needed to ensure the market availability of a coaxial tubes able to withstand the high temperatures of such BTES application.

3.4.2 Tube materials

For the tubing of the boreholes, high quality cross-linked high density polyethylene (PEX) tubes is normally used because it is strong, chemical resistant and is able to withstand the pressures and temperatures encountered during an expected long period of operation. PEX-a tubing is available with a claimed 50 year durability for continuous operation at 70 C and 8.5 bar and 15 year claimed durability for continuous operation at 90°C and 6.9 bar (in both cases with a 1.25 safety factor).

Factory made PEX-a u-tube heat exchangers comprised of a single piece of tubing (without connections in the bottom) are available and are often used for BTES application since they avoid the risk of a connection failure at the bottom of a borehole. The necessary connections between adjacent u-tubes and from u-tubes to headers, are typically made with corrosion resistant metal fittings and clamps. Durability is paramount since the connections become very difficult to access, once buried and any connections at the bottom of a borehole should be considered inaccessible[96].

For BTES systems that will only be operated at lower temperatures, the designer may consider lower-cost non-cross-linked polyethylene (PE) tubing, as sometimes used with ground source heat pumps. However, greater care must be taken in handling and protecting the non-cross-linked PE tubing since it is much easier to damage[96].

A few older systems in Sweden (Luleå and Emmaboda, see also section 3.6.2 and 3.6.3) were built with an open coaxial collector design, where the heat carrier fluid was in direct contact with the borehole wall. This caused unwanted gas formation in the system and in Emmaboda chemical reactions with the surrounding rocks/borehole wall and should be avoided.

3.4.3 The drilling process

Together with the insulation placed over the top of a BTES storage volume, the drilling work is one of the major cost items for construction of BTES[96]. In Crailsheim in Germany, the total cost for the BTES is reported to be 520 k€, with the insulation accounting for about 24% and drilling the boreholes for about 52% of the cost[97].

[95] Malmberg, M., Mazzotti, W., Acuña, J., Lindståhl, H. & Lazzarotto, A. 2018: High temperature borehole thermal energy storage – A case study. IGSHPA Research Track, Stockholm, September 18-20.
[96] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[97] Schmidt, T. & Miedaner, O. 2012: Solar District Heating Guidelines – storage. Fact Sheet 7.2, from the EU Project www.solar-district-heating.eu.

Drilling in soft sediments is often regarded more challenging and time-consuming than drilling in hard rock[98,,99]. Direct rotary mud drilling is normally considered to be the most efficient method in relation to speed, cost and quality of the borehole, but so-called sonic drilling is also available. It is generally recommended to use a casing during drilling in soft sediments in order to avoid cavities and excessive use of expensive grout and to avoid collapsing boreholes[98].

A borehole can be deflected from the vertical line by for example larger stones or boulders in the subsurface. Therefore, the optimal pattern of boreholes is not only determined by storage efficiency parameters, but may also involve consideration of a “safety distance” between boreholes in order to avoid crossing the trajectory of neighbour boreholes and destroying them[100].

The drilling activities can often be associated with a number of requirements to obtain a drilling permit and some countries has especially high focus on protection of groundwater resources. Most often it will therefore be required to seal the BTES boreholes with a cementing grout in order to protect the groundwater against pollution transport in the borehole and to avoid shortcutting aquifers in different levels in the subsurface. The sealing of the boreholes will also serve to protect the environment against any leakage of carrier fluid in case of damage of tubes in the boreholes and finally the grout provides a reasonably high-conductivity thermal connection between the tubes and the surrounding soil and which is absolutely necessary in unsaturated conditions with dry boreholes.

When the heat exchanger tubes, typically u-tubes, are installed into each borehole, an additional tube which is open at the bottom is typically also inserted for grouting. Once the u-tubes have been fully mounted, grout is pumped through the open tube to completely fill the space between the u-tube and the borehole wall. The grout tube can either be kept at the bottom of the borehole or slowly withdrawn during the grouting process as the space is filled. The first option is more common in Europe while the second is generally preferred in the U.S. Grouting from the bottom requires a high pressure and potentially a risk of damaging the grout tube, while there is a risk of leaving un-grouted voids if the grout tube is raised to fast during withdrawal.

The grouted u-tubes constitute most of the heat exchange surface area with the soil of the storage volume in the ground, but a small additional heat exchange area is achieved through the horizontal interconnections between u-tubes and the piping connecting the BTES to the above-ground part of the system.

While a high thermal conductivity of the soil/rock in the underground storage volume is not necessarily an advantage regarding the BTES efficiency (but for the charge/discharge rate), see also section 3.3.4 and 3.5.2, the thermal conductivity between the u-tubes and the soil should be as high as possible in order to achieve the highest possible transfer of heat. Therefore the thermal conductivity of the grout is of importance and use of thermally improved grout is recommended. Grout thermal conductivity typically ranges from 0.8 to -2.4 W/mK.

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[98] Vangkilde-Pedersen, T., Sørensen, I., Ditlefsen, C.B., Bjørn, H. & Højberg, A.L. 2011: D1 Knowledge sharing workshop. GeoEnergy - Tools for ground source heating and cooling based on closed loop boreholes, EUDP projekt, J.nr. 64011-0003.
[99] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[100] Sørensen, Per Alex. 2019: “Best practice” for implementation and operation of the large scale Borehole and Pit Heat Thermal Storages (BTES and PTES) in Brædstrup, Marstal, Dronninglund and Gram, Denmark. PlanEnergi.

Modelling results for a single borehole with single u-tubes[101] have shown that the difference in efficiency between using a standard grout and a thermally improved grout was up to 13%. As the thermal conductivity of the grout is usually lower than that of the soil/rock, and also since grout is expensive, the drilling diameter should be kept as small as possible, but also taking the desired distance between down- and upflow tubes into consideration.

Laboratory tests of different commercially available thermally improved grout products[102] showed, that the thermal conductivity was generally lower than indicated in the product declarations and that the thermal conductivity was decreasing as desiccation progressed. Furthermore, the recommended mix was very thin (low concentration) with relatively fast settling of material and development of a water phase above the grout over time. Also practical experience shows that re-filling of grout after some time may be required. Therefore, it is recommended to use as little water as possible when preparing (mixing) the grout, but also taking injectivity and risk of poor sealing in case of voids into consideration. Batch mixing of the grout and careful control of the used volume of grout is also generally recommended.

Experiments with freezing and thawing of grout[103] have shown potential problems with exfoliation of the grout which can increase the permeability of the grout and thus the sealing quality. The problem seems to increase if freezing/thawing occurs immediately after grouting and it is recommended to avoid frost for 40 days after hardening of the grout.

3.4.4 Top insulation

Insulation of the top of the BTES is another costly element of the construction and is also very important for the efficiency and performance of the storage. Therefore the top insulation must be carefully designed taking the local climate and the BTES operating temperature into consideration.

The top insulation has three functions 1) insulation against heat loss, 2) bearing capacity towards the overburden, and 3) draining of rain water and insulation against water infiltration into the ground.

In Sibbitt & McClenahan[104] it is recommended that the interconnected u-tubes and headers are first covered with an approx. 0.5 m thick layer of insulating material which is again covered with a membrane. Then another approx. 0.5 m thick layer of insulating material followed by a geotextile cloth and 1 metre of native topsoil. The insulation layer should generally extends somewhat beyond the outer ring or row of boreholes.

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[101] Højberg, A. L. & Rasmussen, P. 2014: D20 Modellering af varmetransport. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.

[102] Bjørn, H. & Poulsen, S. E. 2014. D7 Rapport over termiske egenskaber for materialer Grout, rør og briner. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.

[103] Vangkilde-Pedersen, T., Sørensen, I., Ditlefsen, C.B., Bjørn, H. & Højberg, A.L. 2011: D1 Knowledge sharing workshop. GeoEnergy - Tools for ground source heating and cooling based on closed loop boreholes, EUDP projekt, J.nr. 64011-0003.

[104] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

During construction of the BTES in Brædstrup in Denmark[105] two types of insulation meeting the demands were identified: Foam glass gravel at a price of 80 €/m³ and a lambda value of 0.08 W/mK and mussels shells at a price of 10 €/m³ and a lambda value of 0.112 W/mK (crushed to 60% volume). It was decided to use mussel shells and tests showed that the layer of mussel shells should be approx. 0.5 m and that a semi-permeable membrane should divide the layer in two to avoid convection. The insulation design in Brædstrup can be seen in Figure 3.6.

In the lower part of Figure 3.6, the top of a borehole is shown. The top of the hole is modified to allow the pex tubes to leave the hole without sharp curves. After the tubes have been connected and tested for leaks, the first layer of mussel shells is installed. When this has been sufficiently compressed the semi-permeable membrane consisting of an ordinary foil as typically used in the building industry (under tiled roofs to stop the wind without stopping humidity to leave the house) is installed. On top of this a new layer of shells is placed and compressed. This in turn is covered by a non-woven geotextile to protect a semi-permeable roof foil from being damaged by the shells and which function is to prevent rainwater infiltration into the insulation but to allow humidity to pass from the relatively warm insulation into the soil above. On the top side, the roof foil is protected by a drainage matt consisting of two layers of geotextile with a woven grid of polycarbonate in between. To further facilitate the drainage of rainwater, a 5 cm layer of gravel is placed on top of the matt and to maintain the drainage capacity of the gravel a further geotextile is placed on top of the gravel. 0.5 m of soil finalize the cover.

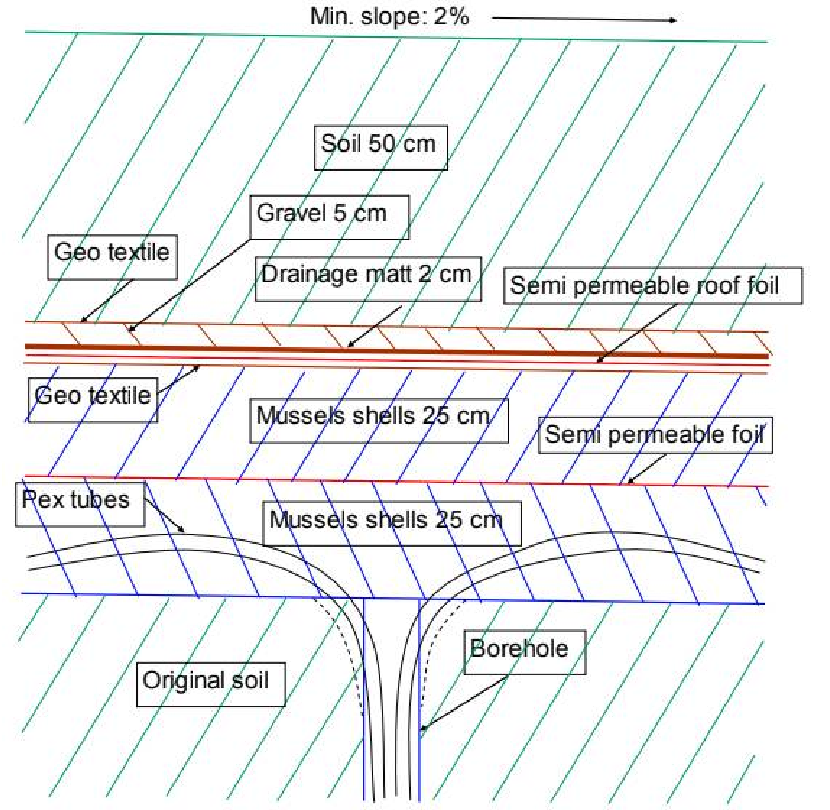

Figure 3.6 Example of design of top insulation from the Brædstrup BTES, Denmark (from[105])

[105] Sørensen, Per Alex. 2019: “Best practice” for implementation and operation of the large scale Borehole and Pit Heat Thermal Storages (BTES and PTES) in Brædstrup, Marstal, Dronninglund and Gram, Denmark. PlanEnergi.

3.4.5 Monitoring

Most existing BTES systems include additional boreholes dedicated to installation of temperature monitoring equipment for evaluation of the performance. The Brædstrup BTES in Denmark includes the following sensors for evaluation of the storage performance[106], Figure 3.7:

- Temperature sensors in the BTES connection in-/outlet pipes
- Volume flow sensors in the BTES connection in-/outlet pipes
- Ground temperature sensors inside the storage volume (see Figure 3.7)
- Ground temperature sensors around the storage volume (see Figure 3.7)
- Heat flux sensors and two assigned temperature sensors in the cover insulation (see Figure 3.7)
- Possibility to take samples of the cover insulation material

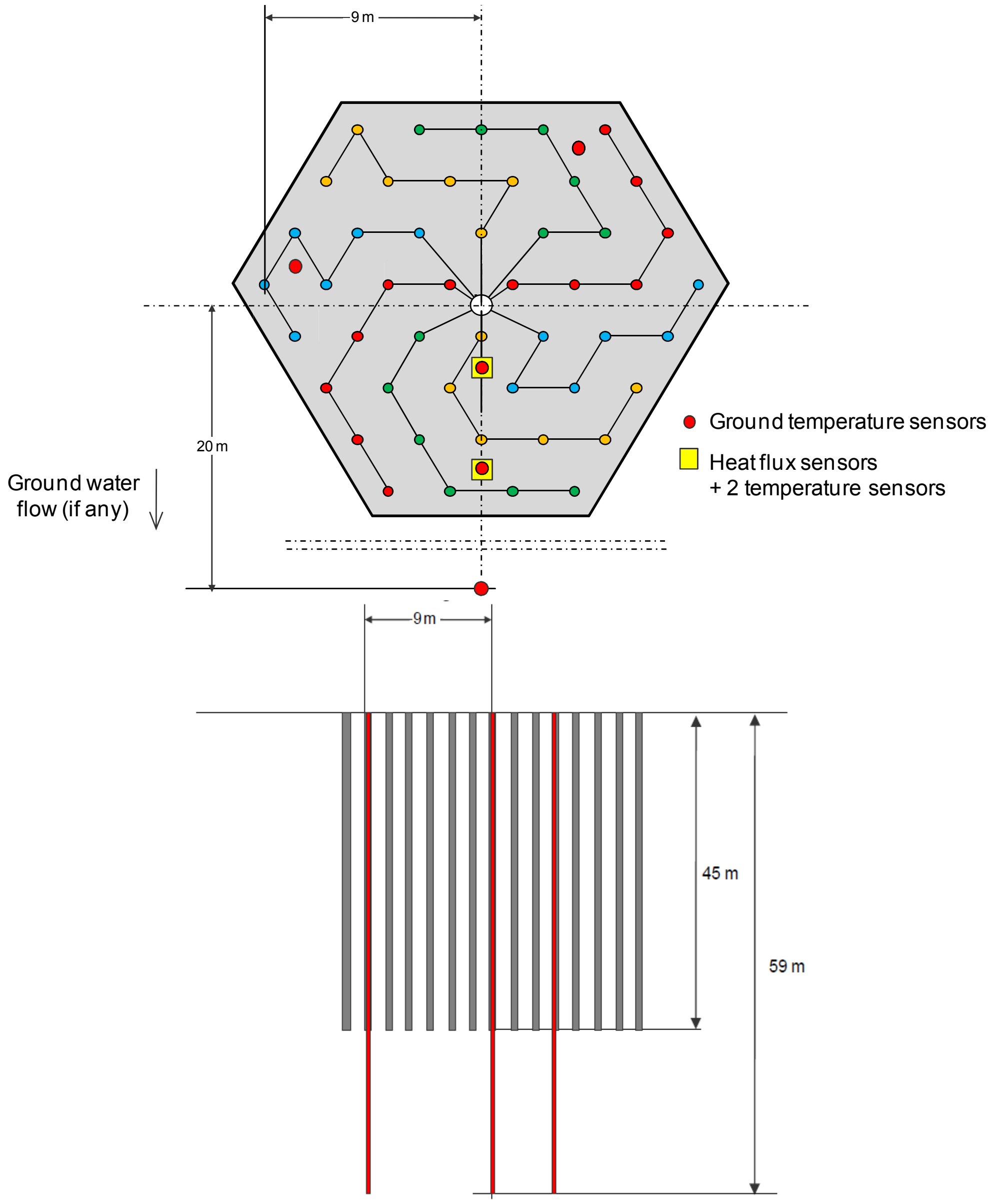

Figure 3.7 Monitoring sensors in and around the BTES volume in Brædstrup (from[106])

[106] Sørensen, Per Alex et al. (2013). Boreholes in Brædstrup. Final report.

Figure 3.7 shows the sensor positions in- and outside the storage volume. First, four temperature sensor strings were located inside the storage volume in order to monitor the charging and discharging. The sensor strings are deeper than the storage volume and the idea was also to be able to estimate/detect the direction of eventual groundwater flow below the storage (the bottom of the storage is located approx. 5 m above the local groundwater level) and then place another temperature sensor string outside the storage volume in the direction of the identified groundwater flow, if any.

The vertical distribution of the temperature sensors in and around the storage volume was planned to take into account areas where increased temperature gradients are expected:

- The surface of the storage (= bottom of insulation layer)
- The bottom area of the storage volume, 45 m b.g.l. (= borehole depth)
- The local groundwater level, 52 m b.g.l.

The vertical distribution of the temperature sensors according to this is was then:
+0.5, 0, -1, -2, -3, -4, -5, -10, -15, -20, -25, -30, -35, -40, -45, -49, -50, -51, -52, -53, -54, -59 m

With: (+) indicating meters above insulation layer bottom, (-) indicating meters below insulation layer bottom and (0) corresponding to level of insulation layer bottom[107].

In section 3.6 the location of temperature monitoring boreholes is described for other existing BTES systems where this information has been available.

3.4.6 Environmental issues

A subject where further investigation is needed is the influence on microbiology and geochemistry from HT-BTES applications. BTES systems operating at temperatures above 40°C can increase the risk of causing geochemical disturbance and affecting the microbiological balance in the ground[108]. Several studies have shown no evidence for increasing number of bacteria or growth of pathogens related to increased temperature in the ground, but have showed a change in the composition of bacterial species[109]. However, this is one subject regarding HT-UTES where the information is very limited[110]. Furthermore, heating the soil can result in desiccation of the pore water and increase the mobility of gases in the soil matrix and cause e.g. gases such as radon to escape to the surface, but this is also a subject that should be investigated more.

A desk study review of environmental impact from Borehole Heat Exchangers has previously been performed in Denmark[111], but only heat extraction from the ground and thus decreasing ground temperature was considered. The study shows that a temperature decrease most likely will have an impact on the biological activity, but only in the sediments very near the borehole.

[107] Sørensen, Per Alex et al. (2013). Boreholes in Brædstrup. Final report.
[108] Gehlin, S. E. A., Spitler, J. D. & Hellström, G., 2016. Deep Boreholes for Ground Source Heat Pump Systems - Scandinavian Experience and Future Prospects. Orlando, Florida. January 23-27.
[109] Bonte, M., Stuyfzand, P. J., Hulsmann, A. & Beelen, P. V., 2011. Underground Thermal Energy Storage: Environmental Risks and Policy Developments in the Netherlands and European Union. Ecology and Society, 1 March.16(1)(22).
[110] Malmberg, M., Mazzotti, W., Acuña, J., Lindståhl, H. & Lazzarotto, A. 2018: High temperature borehole thermal energy storage – A case study. IGSHPA Research Track, Stockholm, September 18-20.
[111] Thorling, L., Johnsen, A. R., Juhler, R. & Ditlefsen, C. 2014: D21 Mulige miljømæssige påvirkninger fra lukkede jordvarmeboringer. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.

The review in Denmark also comprised possible environmental effects of the use of antifreeze and other additives in the heat carrier fluid in Borehole Heat Exchangers, again primarily for heat extraction. Most types of antifreeze currently used (ethanol, isopropanol, glycol) are expected to be relatively easily decomposed in hours or weeks and the possible decomposition products are normal for decomposition of organic compound, not expected to accumulate in the groundwater and have a very low toxicity[112].

While antifreeze is hardly necessary in HT-BTES, different types of additives may be used and can be a threat for e.g. groundwater resources in case of leakage. Some of the additives known to be used are:

- Ethylhexanoic
- Sodium 2-ethylhexanoate
- Sodium hydroxide
- Tolyltriazole
- Benzotriazole

For ethylhexanoic and sodium 2-ethylhexanoate, the Danish Environmental Protection Agency does not consider these to be more problematic than e.g. ethanol in terms of toxicity and degradability based on the current level of knowledge. However, more knowledge on decomposition and transport rates could be advisable before e.g. wider use in numerous large-scale BTES systems[112].

Also sodium hydroxide is not regarded to be more problematic than ethanol based on the current level of knowledge, but it could be relevant with more knowledge on possible effects on groundwater chemistry in terms of e.g. dissolution of metals.

Tolyltriazole is regarded very toxic for organisms living in water and is not easily decomposed and the Danish Environmental Protection Agency does not currently recommend to use it in Borehole Heat Exchangers. A German investigation also mentions that both Tolyltriazole and Benzotriazole should be investigated further and that both are not easily decomposed in e.g. groundwater aquifers. Therefore, a leakage can imply long exposure and significant groundwater transport due to low sorption to the soil matrix[112].

Boreholes may constitute a leakage pathway for seepage of polluted water if they are not properly sealed with grout as well as for unwanted transport of groundwater between aquifers with different groundwater chemistry. Often the local groundwater authorities will have specific priorities for protection of the groundwater quality.

Despite potential environmental issues related to the heat carrier fluid used in the Borehole Heat Exchangers, there are very few examples of leakage[113] and typically the system will include a pressure-drop alarm and controls to prevent large amounts of carrier fluid to leak. In general, the risk of BTES to have a negative environmental impact is probably relatively low as long as e.g. the boreholes are carried out and completed according to state-of-the-art regulation and recommendations.

[112] Thorling, L., Johnsen, A. R., Juhler, R. & Ditlefsen, C. 2014: D21 Mulige miljømæssige påvirkninger fra lukkede jordvarmeboringer. GeoEnergi, Energianlæg baseret på jordvarmeboringer - udvikling af markedsfremmende værktøjer og best practice, EUDP projekt, J.nr. 64011-0003.
[113] Vangkilde-Pedersen, T., Sørensen, I., Ditlefsen, C.B., Bjørn, H. & Højberg, A.L. 2011: D1 Knowledge sharing workshop. GeoEnergy - Tools for ground source heating and cooling based on closed loop boreholes, EUDP projekt, J.nr. 64011-0003.

3.5 System integration

Until now, BTES applications has mostly been designed for use in larger building complexes, communities of residential houses and as part of district heating networks. Existing systems are sourced by solar panels or industrial waste heat and for smaller systems (not HT-BTES) by cooling of buildings during summertime. Future use will probably also include heat from waste incineration and power to heat applications

BTES systems in combination with solar systems often include a relatively small buffer water storage tank to work with the primary BTES storage. The buffer is able to provide high heat transfer rates to meet peak solar production and load events and will compensate for the lower heat transfer capability of the BTES by distributing peak inputs and loads over longer periods of time. This approach allow for a lower total borehole length for the same system performance. The cost of the buffer storage is a trade-off against the cost of more borehole meters to be drilled and installed in the BTES[114].

3.5.1 System modelling

To predict the behaviour and performance of a BTES in an energy system, and hence to define the optimal design, it is necessary to account for the performance of all of the subsystems and their interactions with each other as well as with the heat load and the weather. Mathematical models representing each of the components are connected together to simulate the whole system. Several different simulation tools for system level analysis are available, e.g. TRNSYS, EnergyPlus, and ESP-r, with TRNSYS being one of the most commonly used for simulating large scale seasonal storage systems in many countries[114].

TRNSYS is a flexible software tool that can be used for simulating the behaviour of transient systems, including e.g. dynamic heat input from solar panels. It is based on a robust algebraic and differential equation solver and is supplied with a large library of component models. It includes a powerful graphical interface that greatly simplifies the assembly and interconnection of the component models necessary to represent a system. Successful modelling in TRNSYS demands knowledge of the software and a good understanding of the systems being simulated.

In order to include all the systems a BTES interacts with, it is usually necessary to include parameters such as the heat load imposed by a district heating system or building complex etc., the heat supply from each source (e.g. a solar collector array), seasonal storage scheme and meteorological data. The simulation is typically carried out using a time step of 1 to 10 minutes, to simulate how the components interact and how the system behaves and performs for at least one year. With seasonal storages, the warm-up period can be several years and 5 or 10 year simulations may be required to achieve quasi-steady operation.

When modelling a BTES in TRNSYS, the geometry of the storage volume is often modelled as a cylinder with a vertical axis of symmetry and uniformly placed boreholes. It is important to represent the borehole depth, number of boreholes, total borehole length and borehole spacing as correctly as possible. It is also necessary to define parameters such as the thermal conductivity, heat capacity and diffusivity of the soil/rock, the combined thermal conductivity of the tubes and grout (the borehole resistance) and the thickness and thermal conductivity of the top insulation.

[114] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

Lanahan & Tabares-Velasco[115] has performed a critical review on BTES systems including modeling and system design and conclude among other things that:

- Community scale BTES requires a "charging" period of a few years for the design system temperature to be reached;
- BTES is less geographically limited than ATES;
- Coupled diurnal and seasonal storage increases the overall utilization of captured solar energy;
- Performance metrics for BTES systems and components can be inconsistent across the field, however BTES efficiency is always defined as the fraction of energy extracted divided by the energy injected;
- Although there are a handful of studies coupling BTES at the component model with a system level simulation, most previous studies have not bridged the modeling gap between the two levels of modeling.

3.5.2 Size and shape of BTES

The performance of a BTES does not only depend on the thermal properties of the storage volume and the technical design. Since insulation is placed only over the top surface of the BTES, the outer shape or aspect ratio (diameter/depth) of the BTES volume has an impact on the heat loss. In Sibbitt & McClenahan[116] results of more than 200 detailed TRNSYS simulations are presented. The simulations were performed to examine how much soil type and BTES shape affect the annual efficiency of a combined BTES and solar system sized to serve the Drake Landing solar community in Canada.

Four soil types (dense rock, heavy saturated soil, heavy dry soil and light dry soil), three collector areas, six borehole depths (17.5 to 210 metres) and three total borehole lengths (3780, 5040 and 6300 metres) were included. The associated thermal conductivity values of the soil/rock were 3.46, 2.42, 0.87 and 0.35 W/mK, respectively.

Figure 3.8 illustrates some of the key results for the simulated systems which all have the same number of solar collectors and all have a BTES with the same total borehole length as the actual Drake Landing BTES, see also section 3.6.1.

The horizontal axis covers the range of the number of boreholes in the simulated systems; since the total borehole length is constant, the BTES shapes near the left side of the graph are more "pencil shaped" (aspect ratio << 1) while those on the right are more "pancake shaped" (aspect ratio >> 1). The BTES aspect ratio (depth/diameter) is equal to 1 when the number of boreholes are 144 boreholes and this is labelled on the figure.

The four solid lines near the top of the graph show the solar fraction delivered by the solar system for each of the four different soil types examined and lower on the graph, the four broken lines show the BTES efficiency for each of the same four soil types.

[115] Lanahan, M. & Tabares-Velasco, P. C. 2017: Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. Energies 2017, 10, 743; doi:10.3390/en10060743.
[116] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

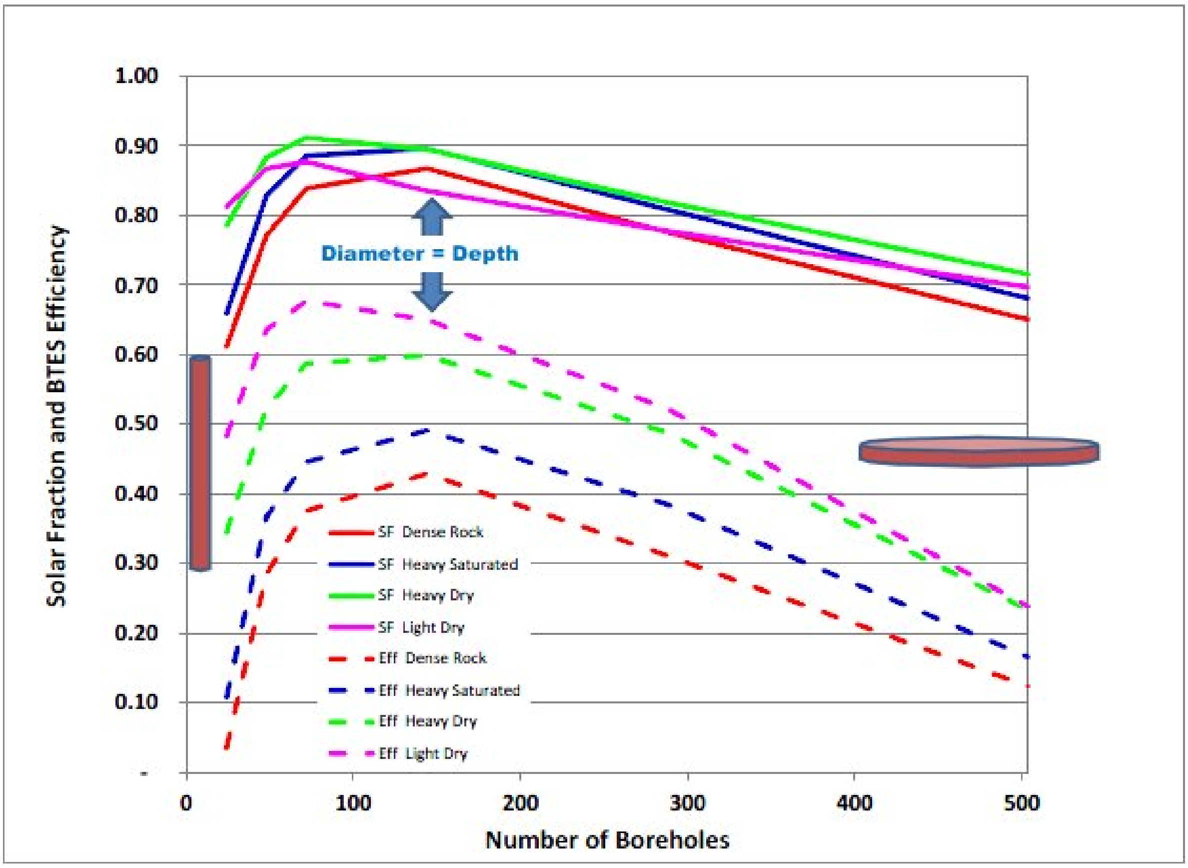

Figure 3.8 Impact of soil type and BTES shape on overall efficiency in terms of solar fraction and storage efficiency for a 52 home community (from[117])

Probably the most important result from Figure 3.8 is that soil type has a relatively modest impact on overall system performance in terms of solar fraction for aspect ratios greater than 0.3 (> 70 boreholes in the plot), at least for the system design and climate simulated. Similarly, for the range of relatively normal BTES aspect ratios (0.3 to 3), BTES shape has only a moderate impact on overall system performance (solar fraction), while the BTES efficiency varies significantly.

The results also show that the soil conditions which result in maximum BTES efficiency do not produce the maximum solar fraction. The light dry soil delivers the highest BTES efficiency but show approx. 5% lower solar fraction efficiency for the system than heavy dry soil. This is because the light dry soil with low thermal conductivity provides high storage efficiency due to a relatively small heat loss, but on the other hand, the low thermal conductivity decrease the ability of the storage to take up the heat from the solar system at the required rate, see also section 3.3.4.

Figure 3.9, also from Sibbitt & McClenahan[117], show the results for another set of detailed simulations for a very similar, but significantly larger, system designed to supply 400 apartment units and 654 houses rather than the 52 houses at Drake Landing. The simulated system has 22,200 m^2 of solar collectors (gross area), a 1250 m^3 buffer tank and a BTES with 60,000 m of borehole length. While the results show very similar trends to those in Figure 3.8, there are some important differences. First, the annual storage efficiency tends to be much higher for the larger systems, as would be expected with the increase in storage volume to surface area ratio. Also, the curves for overall performance, in terms of system solar fraction, tend to be flatter with high

[117] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

performance being available over a broader range, including relatively “flat” cylindrical shapes. Finally, the difference in solar fraction between heavy saturated soil and dense rock versus both the heavy and light dry soils appears to be somewhat more pronounced.

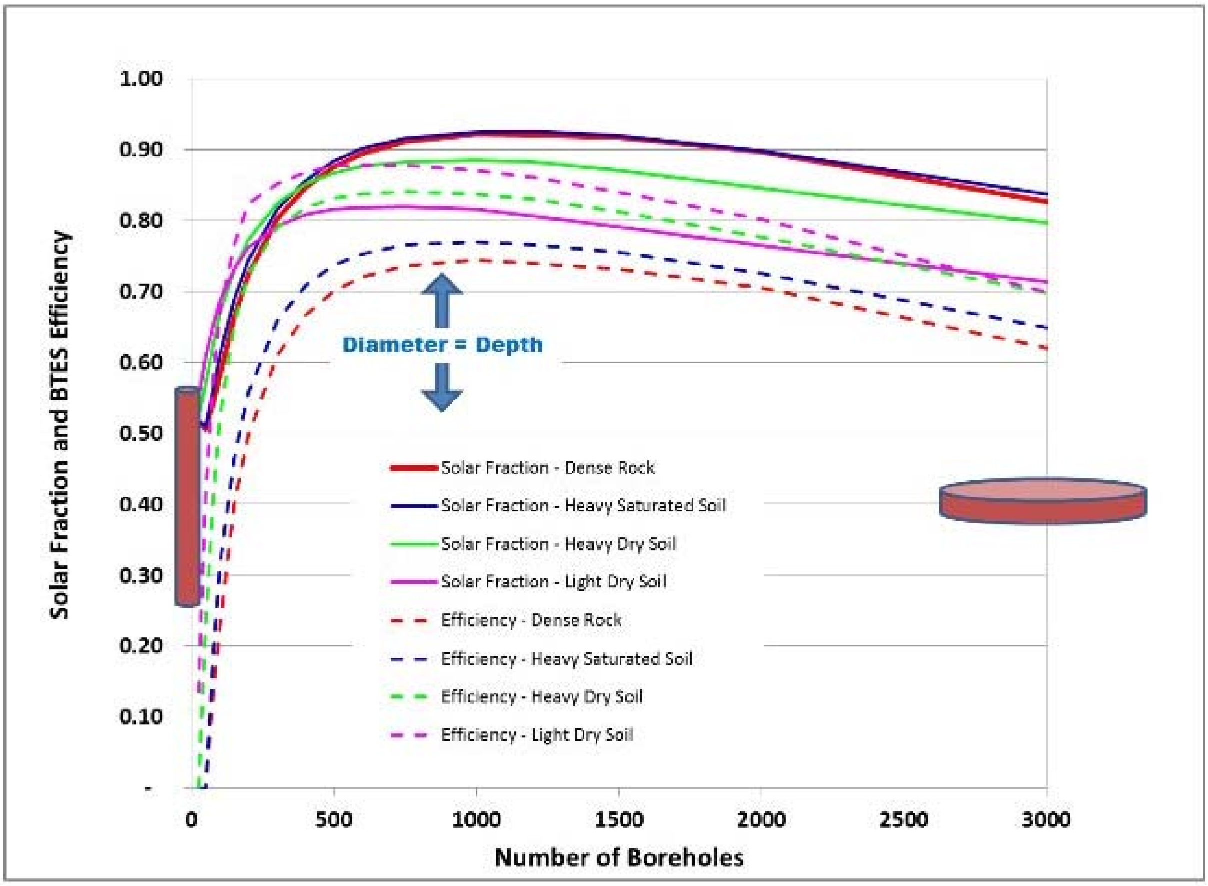

Figure 3.9 Impact of soil type and BTES shape on overall efficiency in terms of solar fraction and storage efficiency for a 1054 home community (from[118])

In Mangold & Deschaintre[119] it is stated that compared to an above-ground tank storage, the volume of a BTES has to be 3-5 times larger because of the lower heat capacity of the ground than water. Furthermore, it is stated that the minimum volume of a BTES in order to be energetically and financially viable should be around 20,000 m^3. With respect to size, one advantage of BTES is that it can be planned in a modular design making it possible to easily connect additional boreholes.

[118] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[119] Mangold, D. & Deschaintre, L., 2015. Seasonal Thermal Energy Storage - Report on State of the Art and Necessary Further R+D, Stuttgart: International Energy Agency - Solar Heating & Cooling Programme (SHC), Task 45 Large Systems.

3.5.3 Climate

The system simulations described in section 3.5.2 were based on weather data for Drake Landing, Calgary, Alberta in Canada[120]. To assess the influence of climate on the BTES performance and overall system performance, the same system size as the actual Drake Landing system were simulated using weather data for 4 additional Canadian locations. Table 3.4 shows how the available solar radiation and the heating loads compare for all 5 locations where Calgary have both the highest heating load and the highest available solar radiation, but Vancouver the mildest climate in terms of Heating Degree Days.

Table 3.4 Heating load and climate data for 5 locations in Canada used to assess the impact of climate on solar fraction and BTES efficiency (from[120])

	Vancouver	Calgary	Toronto	Montreal	Shearwater
Heating Load (GJ)	**1015**	**2677**	**2015**	**2440**	**1920**
Heating Degree Days (C-days)	**2818**	**4980**	**3873**	**4363**	**4116**
Incident Irradiation (MJ/m^2)*	**5023**	**6343**	**5275**	**5296**	**5188**
Latitude (N)	**49.2**	**51.1**	**43.7**	**45.5**	**44.6**
Longitude (W)	**123.2**	**114.0**	**79.6**	**73.8**	**63.5**

In general, the shape of the BTES efficiency curves and system solar fraction curves for the other 4 climatic situations looked similar to those for Drake Landing, Calgary, see Figure 3.8 in section 3.5.2. Vancouver showed the greatest differences, since the heating load was smallest (38% of that in Calgary) and the incident radiation was also the lowest (79% of Calgary).

In Vancouver, the modelled system was over-sized with all soil types and a range of BTES shapes allowing the system to provide 100% of the heating load with solar energy. BTES efficiencies were all lower despite the milder climate, again suggesting over-sizing of the system.

In Shearwater and Toronto the solar fractions were higher than in Calgary with very similar BTES efficiencies in Toronto but slightly lower in Shearwater. In the Montreal climate, the solar fractions tended to be 10-15 percentage points lower, but with the most effective BTES shapes having similar efficiencies to those in Calgary.

While it is highly unlikely, and definitely not recommended, that a design optimized for one location would be constructed without re-optimization in significantly different climates, these model results from Canada suggest that climatic variations is not likely to have a very large impact on BTES performance[120].

[120] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

3.6 Existing operations feedback

A total of 8 HT-BTES systems described in detail in the literature have been identified as well as 4 less well-described HT-BTES systems and 5 low-temperature BTES systems. Out of the 17 identified systems, 11 is located in HEATSTORE partner countries and 6 in other countries.

The size of the systems varies significantly and appears to have an impact on the BTES efficiency although other parameters like the true shape factor and the maximum storage temperature can also play a major role. The identified BTES systems are described in the following, and in Table 3.13 in section 3.6.10, at the end of this chapter some of the identified parameters for the BTES systems are summarized.

3.6.1 Drake Landing, Canada

The Drake Landing Solar Community (DLSC) is located in the town of Okotoks (Alberta, Canada). The project started in 2006 and was the first of this kind in North America. It provides heat for a group of 52 high energy-efficiency houses through an integrated system combining solar panels and a BTES[121]. Roughly 2300 m^2 of solar panels are installed at the roofs of the garages creating 4 continuous well oriented lines of collectors. The BTES system is composed of 144 boreholes with a depth of 35 meters and grouped in 24 parallel circuits (6 boreholes each), see Figure 3.10. The BTES is connected to the solar panels and an "Energy Centre" which contains pumping units, auxiliary boilers, control systems and two short-term thermal storage (STTS) tanks with a combined water volume of 240 m^3. The STTS acts as a buffer between the collector loop, the "community" heating network, and the BTES field, charging and discharging thermal energy as required and thus serving to balance both the variations in energy demand and power consumption, see Figure 3.11.

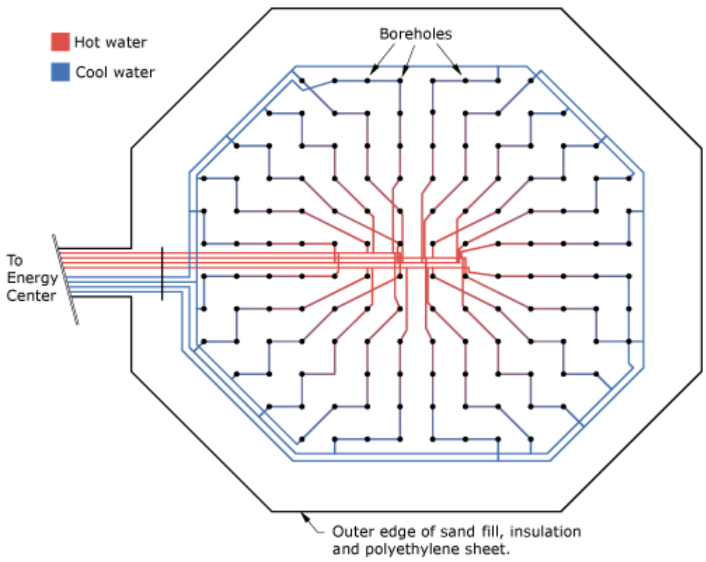

Figure 3.10 Aerial view of the Drake Landing BTES (from[122])

[121] Sibbitt, B., T. Onno, D. McClenahan, J. Thornton, J. Brunger, & B. Wong. 2007. The Drake Landing Solar Community project: Early results. In: 2nd Canadian Solar Buildings Conference, Calgary, AB, Canada. 10–14 June 2007. Univ. of Calgary, Calgary, AB.

[122] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

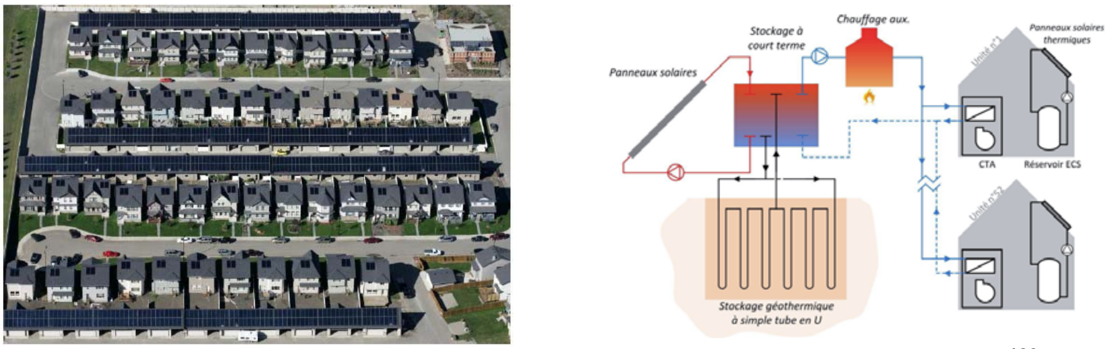

Figure 3.11 Left: Aerial view of the Drake Landing Solar Community (from[123]) and right: diagram of the system (reused from https://doi.org/10.1016/j.egypro.2012.11.097 with permission by Elsevier Ltd. under Creative Commons license CC-BY-NC-ND https://creativecommons.org/licenses/by-nc-nd/3.0/ and courtesy of University of Minnesota[124])

The injection and withdrawal temperatures vary from 80°C down to 30°C (Figure 3.12, left) and thus the system can be classified as a HT-BTES. The solar and BTES system is designed to deliver 90% of the total energy demand, which is achieved through a combination of direct use from the solar panels and indirect use of the stored solar heat in the BTES as shown in Figure 3.12 (right).

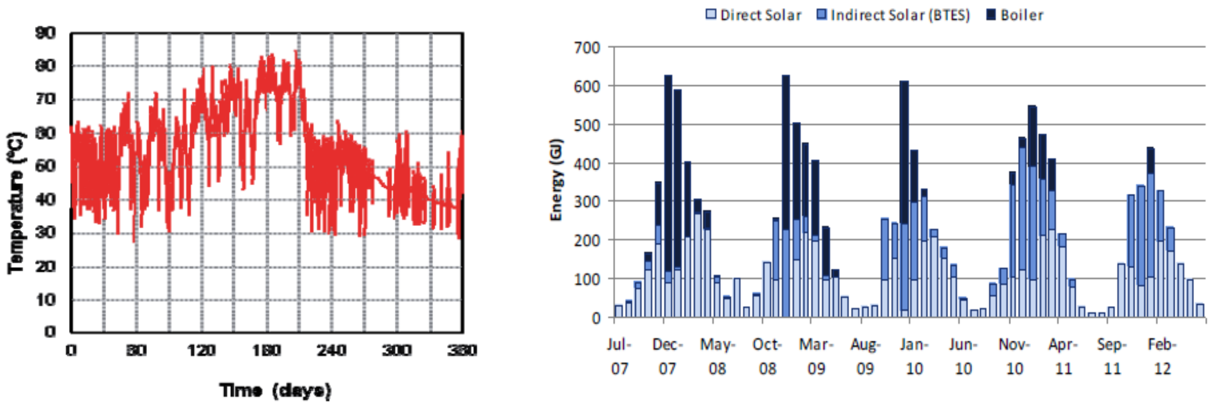

Figure 3.12 Left: Injection/withdrawal temperature over 1 year period (from[125]) and right: monthly energy supplied to the distribution loop (reused from https://doi.org/10.1016/j.egypro.2012.11.097 with permission by Elsevier Ltd. under Creative Commons license CC-BY-NC-ND https://creativecommons.org/licenses/by-nc-nd/3.0/ and courtesy of ASCE Library[123])

In line with what was originally planned during the design phase, it took some years for the subsurface BTES system to gain in efficiency. After three years of significant thermal losses in order to heat up the near-BTES volume, the BTES system reached an efficiency around 50% during the fourth and fifth seasonal charging/discharging cycles and it is expected to further increase (Figure 3.13, left). Figure 3.13, right shows the average temperature in the BTES as the cycles are repeated. The whole system had been modelled and designed with the TRNSYS

123 Sibbitt B., McClenahan D., Djebbar R., Thornton J., Wong B., Carriere J. & Kokko J. 2012: The performance of a high solar fraction seasonal storage district heating system – five years of operation, Energy Procedia 30 (2012), pp. 856-865.
124 Verstraete A. 2013: Étude d'une communauté solaire avec stockage thermique saisonnier par puits géothermiques, Université de Montréal.
125 Zhang R., Lu N. & Wu, Y. 2012: Efficiency of a Community-Scale Borehole Thermal Energy Storage Technique for Solar Thermal Energy, GeoCongress 2012.

software, which proved to be accurate (e.g. the solar fraction was estimated to be 89% in the fourth year against 86% measured on site).

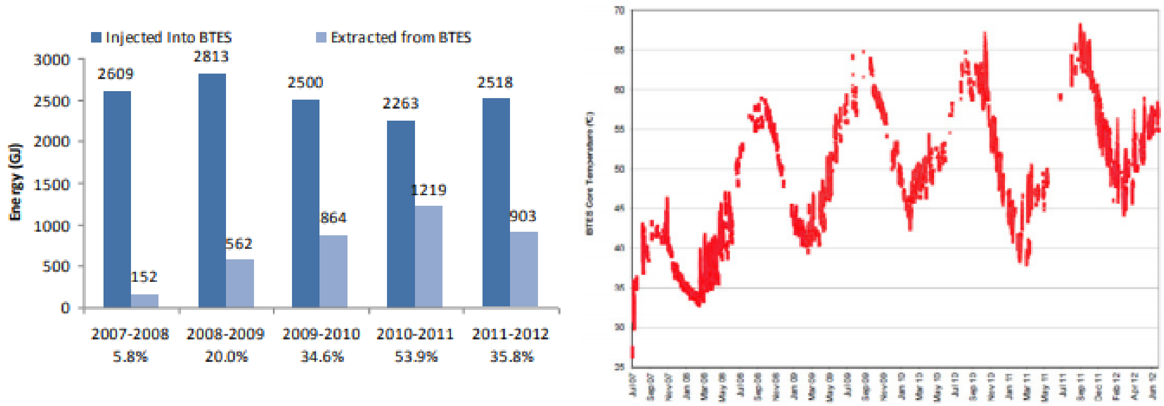

Figure 3.13 Left: energy injected into and extracted from the BTES and right: average BTES temperature (reused from https://doi.org/10.1016/j.egypro.2012.11.097 with permission by Elsevier Ltd. under Creative Commons license CC-BY-NC-ND https://creativecommons.org/licenses/by-nc-nd/3.0/[126])

The design parameters for the Drake Landing BTES have been synthetized in Table 3.5 by Malmberg[127].

Table 3.5 Design parameters for Drake Landing (from[127])

HT-BTES in Okotoks			
Start of operation	2007	Storage shape	Cylindrical
Storage volume [m3]	34 000	Ground type	Soil
Number of boreholes	144	Thermal conductivity [W/(m*K)]	2.0
Borehole depth [m]	35	Volumetric heat capacity [MJ/(m3*K)]	2.3
Total borehole length [m]	5 040	Insulated [Yes/No]	Yes
Borehole spacing [m]	2.25	Insulation material	XPS
Borehole diameter [mm]	150	Insulation thickness [mm]	200
Collector type	Single U-tube	Source of charge	Solar thermal
Collector diameter [mm]	25	Injection power [GJ]	2 530*
Collector material	RAUGEO PEXa	Extraction power [GJ]	1 370*
Collector temperature resistance	95	Charging temp [°C]	~50-65
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	70**
Number of boreholes in series	6	Storage minimum temp [°C]	39**
Total collector length in series [m]	210	HP for extraction [Yes/No]	No

* Mean value between years 2007-2014 (Leidos Canada, 2014). **As of year 2012-2013 (Leidos Canada, 2014).

126 Sibbitt B., McClenahan D., Djebbar R., Thornton J., Wong B., Carriere J. & Kokko J. 2012: The performance of a high solar fraction seasonal storage district heating system – five years of operation, Energy Procedia 30 (2012) 856 – 865.
127 Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

More information on Drake Landing is available at: https://www.dlsc.ca/ and here the following project status is given:

- 10th year of reliable operation with no unscheduled interruptions in heating delivery operations
- 100% solar fraction in the 2015-2016 heating season, meaning all the heat required by the houses for space heating was supplied by solar energy
- Consistent solar fractions above 90% over the last 5 years, with an average of 96% for the period 2012-2016

3.6.2 Luleå, Sweden

This HT-BTES project was in operation between 1983 and 1989. It consists of 120 boreholes with 4 m spacing and a depth of 65 m, see Figure 3.14. The heat source was waste heat from a steel plant[128]. Each borehole was equipped with open circulation collectors of coaxial design with a thermally insulated centric pipe. When charging, hot water was pumped to a central pipe from which the water was directed into 24 parallel lines. Each of these consisted of 5 boreholes connected in series, to a collecting pipe at each long side of the store (Figure 3.15).

Measurements show that the average storage temperature rapidly reached 60-65°C (Figure 3.16) with injection and withdrawal temperatures in the order of 82°C and 30°C (estimated values). During five years of operation, 13 GWh was injected with a BTES efficiency typically in the order of 45-55% depending on the specific cycle (Figure 3.17).

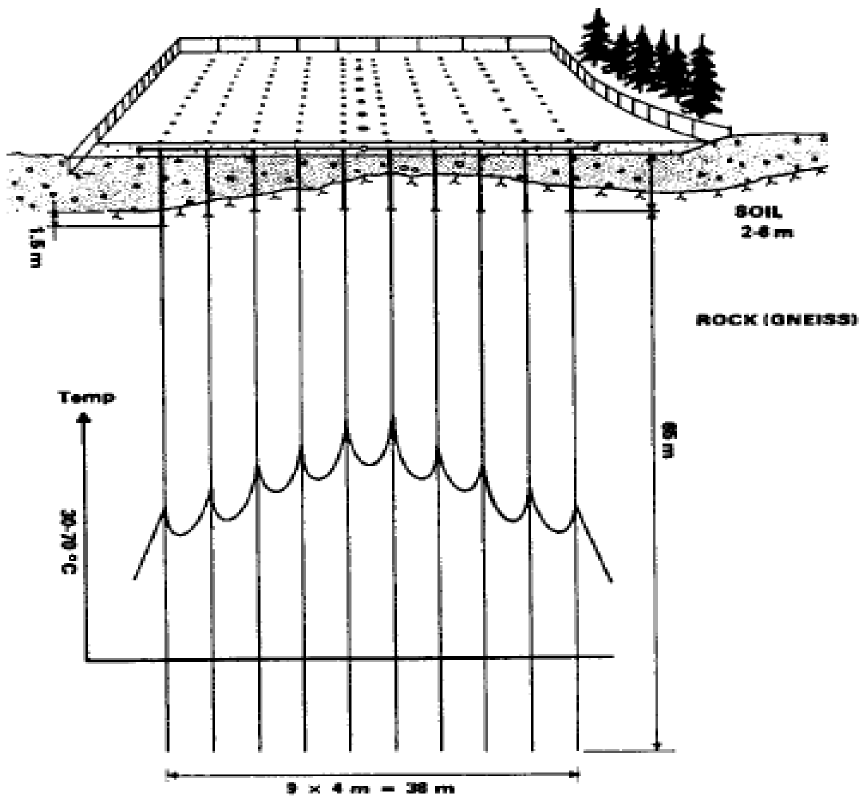

Figure 3.14 Outline of the Luleå BTES system (from[128])

[128] Hellström G. 2012: UTES Experiences from Sweden, presentation from Lund University, Sweden and NeoEnergy Sweden Ltd.

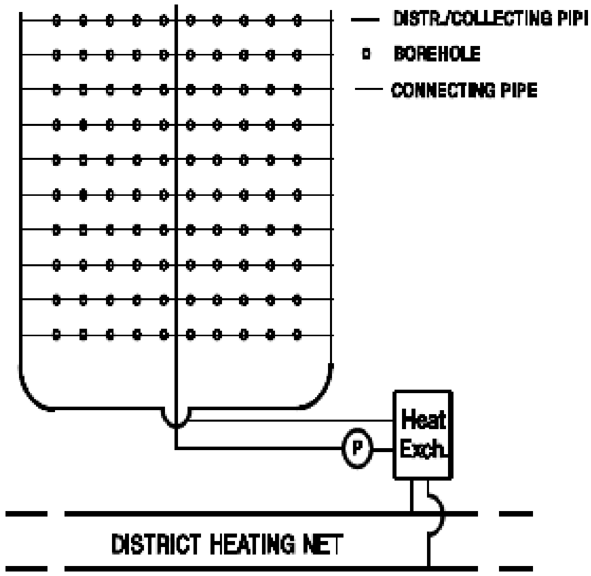

Figure 3.15 Outline of the Luleå BTES system (from[129])

During the first year of operation of the Luleå BTES problems occurred with large amount of gas in the pipes as a result of the open coaxial collector design. This was corrected by installing a vacuum pump. No problems occurred however with chemical reaction between the heat carrier fluid and the rock. Overall, the system was performing below expected values concerning energy storage and extraction and the operations was stopped in 1990[129].

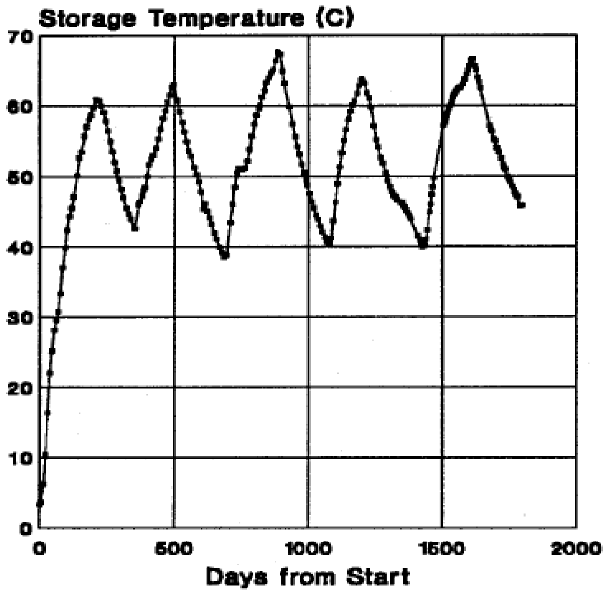

Figure 3.16 Evolution of the average temperature for the Luleå BTES (from[130])

[129] Nordell, B. 1994: Borehole Heat Store design optimization, PhD thesis from Lulea University of Technology, Sweden.
[130] Hellström G. 2012: UTES Experiences from Sweden, presentation from Lund University, Sweden and NeoEnergy Sweden Ltd.

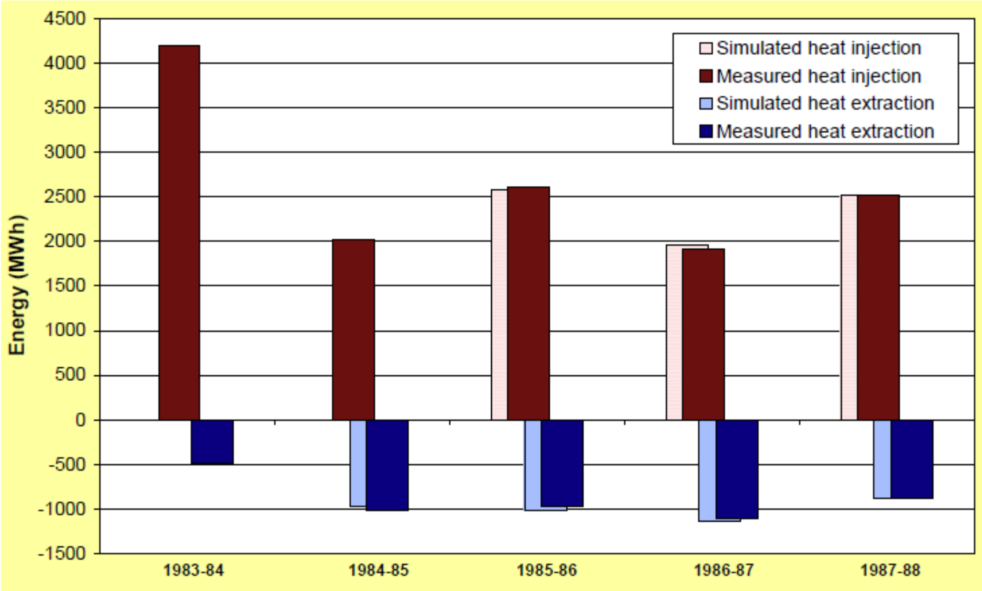

Figure 3.17 Measured and simulated energy balance 1983-1988 for the Luleå BTES (from[131])

The design parameters for the Luleå BTES have been synthetized in Table 3.6 by Malmberg[132].

Table 3.6 Design parameters for Luleå (from[132])

HT-BTES in Luleå			
Years of operation	1983-90	Storage shape	Rectangular
Storage volume [m3]	115 000	Ground type	Rock
Number of boreholes	120	Thermal conductivity ground [W/(m*K)]	3.42
Borehole depth [m]	65	Volumetric heat capacity ground [MJ/(m3*K)]	2.28
Total borehole length [m]	7800	Insulated [Yes/No]	No
Borehole spacing [m]	4	Insulation material	-
Borehole diameter [mm]	152	Insulation thickness [mm]	-
Collector type	Open Coaxial	Source of charge	Waste heat
Collector diameter [mm]	Unknown	Injected energy/year (expected) [GWh]	2.3 (2.8)
Collector material	Unknown	Extracted energy/year (expected) [GWh]	1.0 (1.6)
Collector temperature resistance	Unknown	Charging temp [°C]	70-85
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	65
Number of boreholes in series	5	Storage minimum temp [°C]	30
Total collector length in series [m]	325	HP for extraction [Yes/No]	Yes

[131] Hellström G. 2012: UTES Experiences from Sweden, presentation from Lund University, Sweden and NeoEnergy Sweden Ltd.
[132] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

3.6.3 Emmaboda, Sweden

This HT-BTES project was put in operation in 2010. It consists of 141 boreholes with 4 m spacing and a depth of 149 m, see Figure 3.18, left. The heat source is waste heat from a foundry[133]. The storage encounters seven parallel coupled sections, A-G, of which three forms an inner “hot core”, C-E. The latter is for short term storage at high temperatures during the winter season. Within each of the sections 20 holes are coupled in series two by two. Each section is connected to two manifolds, one for supply and one for the return. These are in turn connected to two main manifolds, which is now placed in a minor building.

Two additional boreholes have been drilled and dedicated for temperature monitoring at different depth levels (Figure 3.18, left). The measured temperatures show that the average storage temperature progressively reached 40-45°C (Figure 3.18, right) during four years with injection and withdrawal temperatures in the order of 60°C and 30°C.

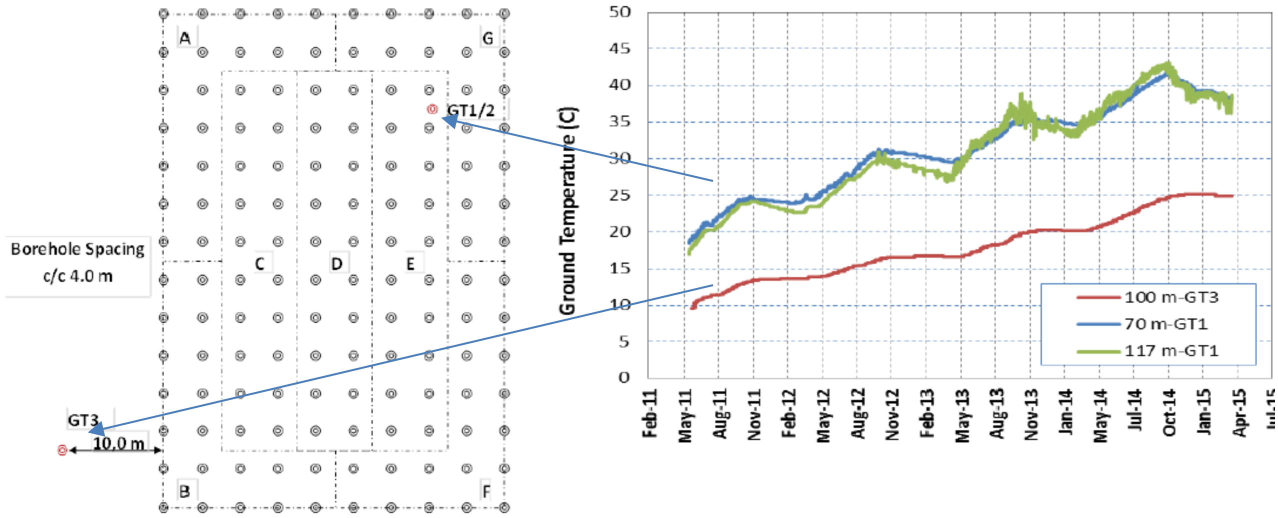

Figure 3.18 Left: Plan of the Emmaboda BTES boreholes and monitoring boreholes (GT) and right: measured storage temperature (GT1) 70 m and 117 m below ground surface and (GT3) at a depth of 100 m, 10 m outside the storage volume (from[134]).

Up to 2015, around 10 GWh were injected in the BTES, but only a smaller fraction being extracted in order to heat up the near-BTES volume[134], see Figure 3.19.

The planned 3.6 GWh/year heat injection was reached in 2015, but the expected 2.6 GWh/year recovery (72%) still remains to be validated with recent production data.

The Emmaboda BTES is installed with open coaxial heat exchangers in bedrock like Luleå and in the first two years of operation circulation problems was encountered because of gas formation in the piping system as well as chemical reactions between the heat carrier fluid and the rock caused problems, but the system now works successfully[134]. As an increase of CO_2 is observed, which may lower the boiling point of the circulating fluid, it is considered to operate the BTES at a lower temperature to prevent a gas phase to form. The fluid chemistry is regularly monitored and no corrosion or scaling are anticipated for the long-term.

[133] Hellström G. 2012: UTES Experiences from Sweden, presentation from Lund University, Sweden and NeoEnergy Sweden Ltd.
[134] Nordell, B., Andersson, O., Rydell, L. & Liuzzo-Scorpo, A. 2015: Long-term Performance of the HTBTES in Emmaboda, Sweden, Proc. Greenstock 2015, Beijing, China.

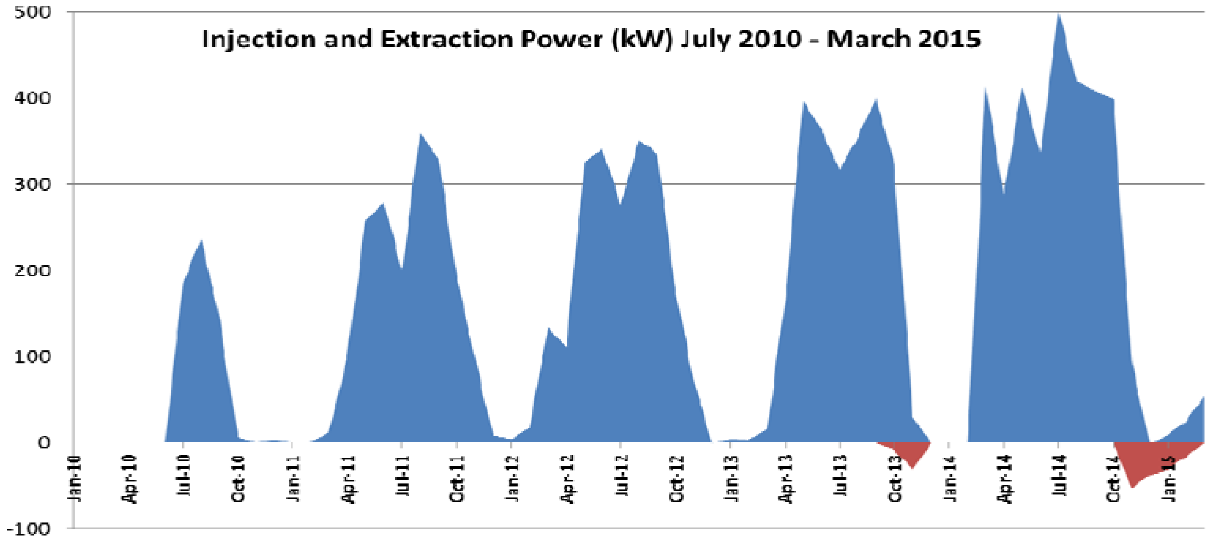

Figure 3.19 Monthly heat injection power (blue) and extraction power (red) from July 2010 until March 2015 in the Emmaboda BTES (from[135])

The monitoring temperature have been compared with the output of a numerical simulator and some discrepancies were observed. After analysis, it appears that the monitoring wells were not completely vertical leading to an effective closer distance from the heated area for GT3 than expected[135], see (Figure 3.20, right).

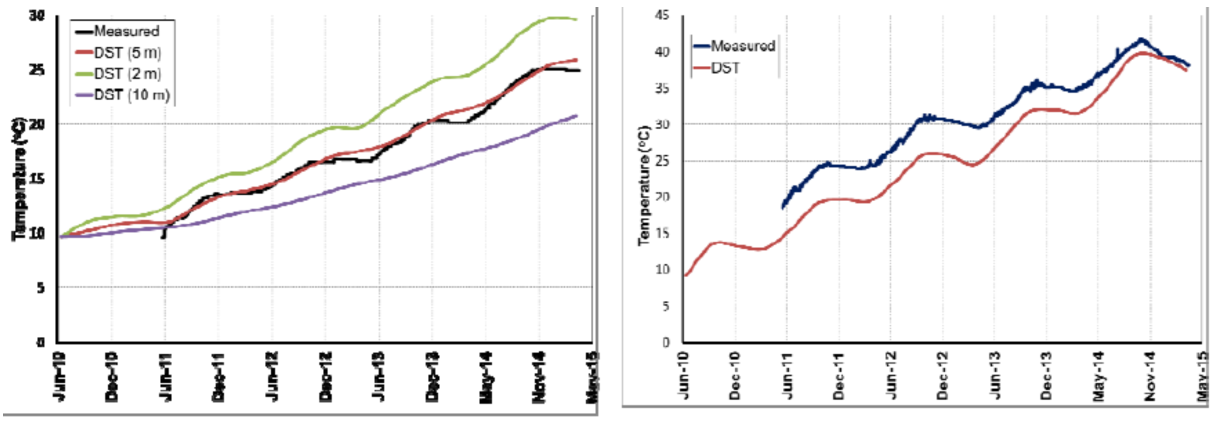

Figure 3.20 Comparison between the monitoring temperature evolution and the simulation at GT1 (left) and GT3 (right) for the Emmaboda BTES (from[135]), see also Figure 3.18

The design of the storage was based on simulations by the Duct Storage Model (DST). Later on, a three dimensional model has been developed using the finite-element commercial package COMSOL Multiphysics.

[135] Nordell, B., Andersson, O., Rydell, L. & Liuzzo-Scorpo, A. 2015: Long-term Performance of the HTBTES in Emmaboda, Sweden, Proc. Greenstock 2015, Beijing, China.

The design parameters for the Emmaboda BTES have been synthetized in Table 3.7 by Malmberg[136].

Table 3.7 Design parameters for Emmaboda (from[136])

HT-BTES in Emmaboda			
Start of operation	2010	Storage shape	Rectangular
Storage volume [m3]	323 000	Ground type	Rock
Number of boreholes	140	Thermal conductivity [W/(m*K)]	3
Borehole depth [m]	150	Volumetric heat capacity [MJ/(m3*K)]	2.34
Total borehole length [m]	21 000	Insulated [Yes/No]	Yes
Borehole spacing [m]	4	Insulation material	Foam glass
Borehole diameter [mm]	115	Insulation thickness [mm]	400
Collector type	Open Coaxial	Source of charge	Waste heat
Collector diameter [mm]	40/90	Injected energy/year (planned) [MWh]	3 271* (3 600)
Collector material	Polypropylene (PPE)	Extracted energy/year (planned) [MWh]	89* (2 700)
Collector temperature resistance	80	Charging temp [°C]	30-60
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	45
Number of boreholes in series	2	Storage minimum temp [°C]	Unknown
Total collector length in series [m]	300	HP for extraction [Yes/No]	Considered

* As of monitored operation in 2014 (Nordell, et al., 2016).

3.6.4 Anneberg, Sweden

This HT-BTES project was put in operation in 2002. It consists of 100 boreholes with 3 m spacing and a depth of 65 m. The heat source is solar from 2400 m^2 solar panels[137]. The configuration is square shaped and contains 2x10 parallel lines with 5 boreholes each (Figure 3.21, right). During charging, the storage is charged from the center and outwards. The whole system provides heat and domestic hot water for 50 residential units (Figure 3.21, left) and is supplemented with electrical boosters when the solar collectors and borehole storage is not sufficient.

A dedicated monitoring borehole enables to measure manually (on demand) the average storage temperature which shows a progressive increase up to 45°C (Figure 3.22, left) with injection and withdrawal temperatures in the order of 60°C and 30°C. Under the current steady state working conditions, the BTES efficiency is in the order of 46% but it does not include the heat loss in the distribution system that turn out to be very high (Figure 3.22, right). The monthly heat distribution appears also interesting since it illustrates the evolution of the BTES heat loss as a function of time. As expected, there is typically a factor 2 in the heat loss rate between the period at high temperature (end of summer) and low temperature (end of winter).

[136] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[137] Heier, J., Bales, C., Sotnikov, A. & Ponomarova, G. 2011: Evaluation of high temperature solar thermal seasonal borehole storage. In Proceedings of the ISES Solar World Congress, Kassel, Germany, 28 August–2 September.

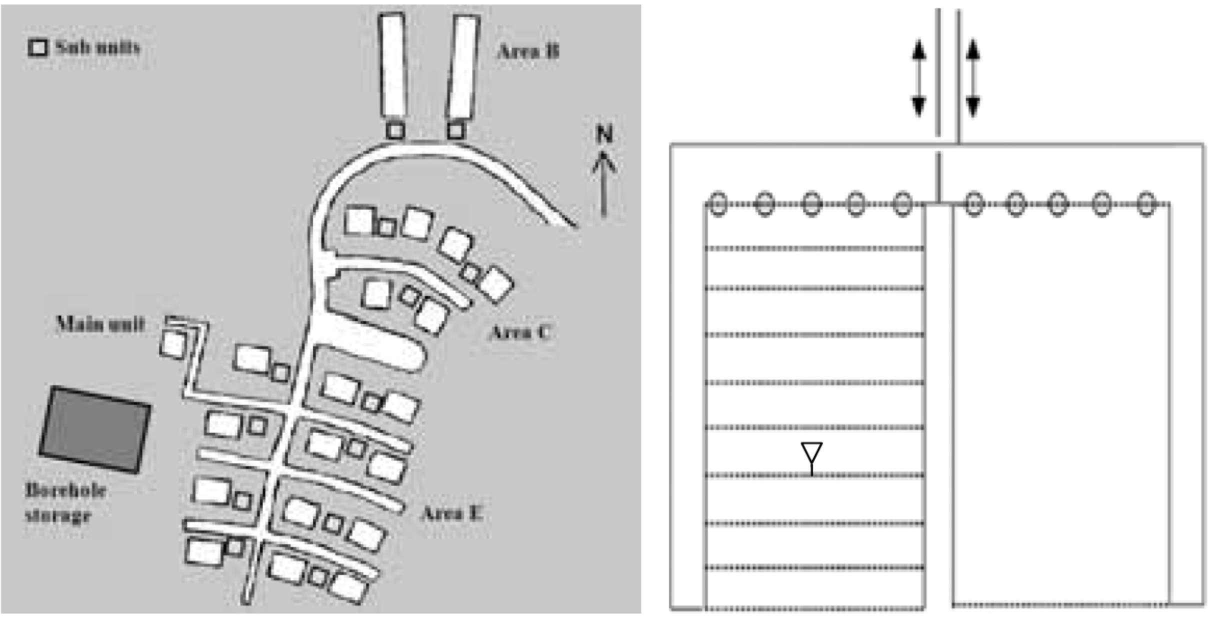

Figure 3.21 Overview of the Anneberg BTES residential area (left) including the borehole storage and details on the borehole field (right) which includes one borehole for a manual monitoring of the average BTES storage temperature (from[138])

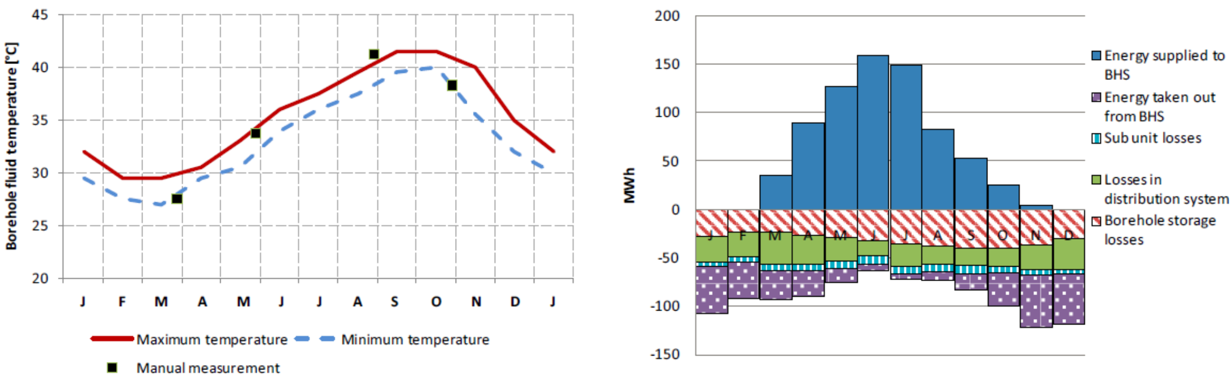

Figure 3.22 Left: estimated and calculated average storage temperature over one cycle and right: monthly energy supplies and losses in the HT-BTES over one cycle (from[138])

Although this HT-BTES installation now shows overall good performance[139], the efficiency still appears lower than the original expectations. It is described in Heier[76], that very disappointing results were obtained from the first cycles with residents complaining of a high use of electricity for domestic hot water and space heating and it is concluded from detailed analysis that the low efficiency was due to several factors:

- A need to ramp-up the system in order to reach steady-state behavior in the BTES
- The heat loss in the distribution system were significantly underestimated
- Lack of a buffer system to take fully benefit from the solar panel-BTES coupling
- Higher than planned indoor temperature setting

[138] Heier, J., Bales, C., Sotnikov, A. & Ponomarova, G. 2011: Evaluation of high temperature solar thermal seasonal borehole storage. In Proceedings of the ISES Solar World Congress, Kassel, Germany, 28 August–2 September.
[139] Malmberg, M., Mazzotti, W., Acuña, J., Lindståhl, H. & Lazzarotto, A. 2018: High temperature borehole thermal energy storage – A case study. IGSHPA Research Track, Stockholm, September 18-20.

The design parameters for the Anneberg BTES have been synthetized in Table 3.8.

Table 3.8 Design parameters for Anneberg

HT-BTES in Anneberg			
Start of operation	2002	Storage shape	Cylindrical
Storage volume [m3]	58500	Ground type	
Number of boreholes	100	Thermal conductivity [W/(m*K)]	
Borehole depth [m]	65	Volumetric heat capacity [MJ/(m3*K)]	
Total borehole length [m]	6500	Insulated [Yes/No]	
Borehole spacing [m]	3	Insulation material	
Borehole diameter [mm]		Insulation thickness [mm]	
Collector type		Source of charge	Solar panels
Collector diameter [mm]		Energy charged [MWh]*	720
Collector material		Energy discharged [MWh]*	333
Collector temperature resistance		Charging temp [°C]	55
Thermal stratification [Yes/No]		Storage maximum temp [°C]	45
Number of boreholes in series	5	Storage minimum temp [°C]	27
Total collector length in series [m]	1300	HP for extraction [Yes/No]	Y

**2010 figures (Heier et al., 2011)*

3.6.5 Paskov, Czech Republic

This HT-BTES project was put in operation in 2011. It consists of 16 boreholes with 2.5 m spacing and a depth of 60 m. The heat source is waste heat from a CHP unit. As the project was initiated and built exclusively as an experimental platform to gain more knowledge on HT-BTES, it is not connected to a heat distribution system[140]. The boreholes are divided in 8 loops with 2 boreholes coupled in series in each loop and 6 dedicated monitoring boreholes enable to measure the temperature evolution at various locations (laterally and at various depth)[141] as shown in Figure 3.23.

The HT-BTES was first charged during one year (February 2012 - February 2013) with a total of 2000 GJ (230 MWh). The initial ground temperature was 12°C and the maximum supply temperature was 97°C. The maximum storage temperature obtained was 75°C (Figure 3.24). After this period, the storage was left at rest for 189 days in order to monitor the temperature relaxation, followed by a second charging initiated with an increase of the temperature in the central part of the storage up to 78.5ºC. During the relaxation, the temperature in the central borehole dropped to 40°C and the fluid temperature from 60°C to 39°C[142]. As no withdrawal period was considered, the efficiency of this system cannot be qualified, but simulations showed that a top insulation would improve the performance and that the length of the injection and extraction cycles would have little or no impact on the performance as long as the BTES are not over exploited[143].

[140] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[141] Grycz, D., Hemza, P. & Rozehnal, Z. 2014: Charging of the experimental high temperature BTES via CHP unit - early results, Energy Procedia 48, pp. 355 – 360.
[142] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[143] Rapantova, N., Pospisil, P., Koziorek, J. Vojcinak, P., Grycz, D. & Rozehnal, Z. 2016. Optimisation of experimental operation of borehole thermal energy storage. Applied Energy, Volume 181, pp. 464-476.

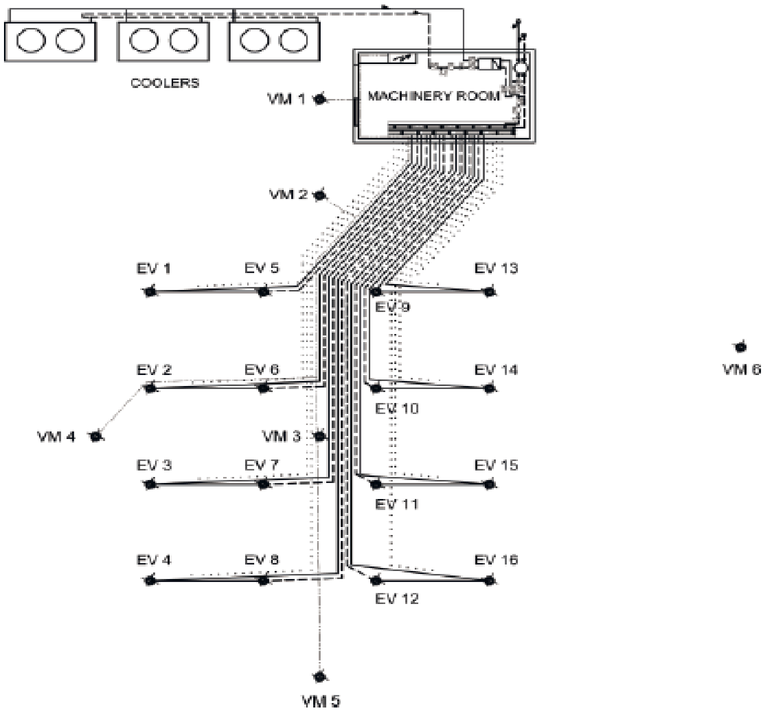

Figure 3.23 Scheme of the horizontal pipes and borehole positions (EV) for the Paskov BTES including the monitoring boreholes (VM) (reprinted from Energy Procedia, Vol 48, Grycz, D., Hemza, P. & Rozehnal, Z., Charging of the experimental high temperature BTES via CHP unit - early results, 355 – 360, Copyright (2014), with permission from Elsevier[144])

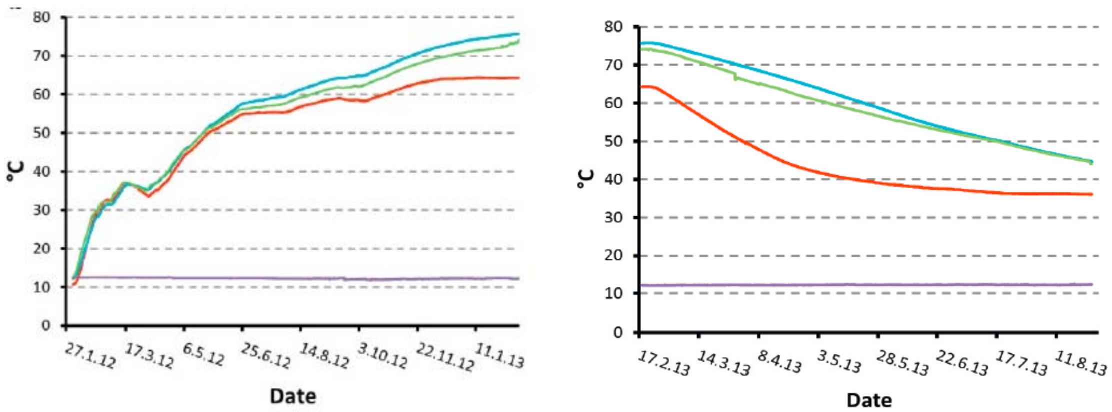

Figure 3.24 Temperature development in selected depth levels of the Paskov storage during the first charging and resting periods (reprinted from Energy Procedia, Vol 48, Grycz, D., Hemza, P. & Rozehnal, Z., Charging of the experimental high temperature BTES via CHP unit - early results, 355 – 360, Copyright (2014), with permission from Elsevier[144])

[144] Grycz, D., Hemza, P. & Rozehnal, Z. 2014: Charging of the experimental high temperature BTES via CHP unit - early results, Energy Procedia 48, pp. 355 – 360.

The design parameters for the Paskov BTES have been synthetized in Table 3.9 by Malmberg[145].

Table 3.9 Design parameters for Paskov (from[145])

HT-BTES in Paskov			
Start of operation	2011	Storage shape	Cylindrical
Storage volume [m3]	Not specified	Ground type	Clay/rock
Number of boreholes	16	Thermal conductivity [W/(m*K)]	2.17
Borehole depth [m]	60	Volumetric heat capacity [MJ/(m3*K)]	2.3
Total borehole length [m]	960	Insulated [Yes/No]	No
Borehole spacing [m]	2.5	Insulation material	-
Borehole diameter [mm]	120	Insulation thickness [mm]	-
Collector type	Double U-tube	Source of charge	CHP
Collector diameter [mm]	32	Injection power [GJ]	2000
Collector material	PE-RT	Extraction power [GJ]	-
Collector temperature resistance	Not specified	Charging temp [°C]	70-97
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	78
Number of boreholes in series	2	Storage minimum temp [°C]	39**
Total collector length in series [m]	240	HP for extraction [Yes/No]	No

* Optimum long-term operation from simulation (Rapantova, et al., 2016). **After resting phase of 189 days (without energy extraction) (Grycz, et al., 2014).

3.6.6 Neckarsulm, Germany

The Neckarsulm BTES was constructed in 1997 and is sourced by solar collectors. The total annual heating load of the community consisting of around 700 flats, a school and a shopping center is around 3 GWh. The BTES was extended in two phases, first in 1999 and later in 2002[145]. The BTES consists of 528 boreholes[146] to a depth of 30 m. This is about the half of the final size of what has been planned. A rectangular storage shape allows for future extension along with possible expansion of the residential area which is planned to be increased to around 1300 flats. Each borehole is equipped with double u-tubes made of Polybutene (PB). The boreholes are grouted with a mix of bentonite, sand cement and water. The thermal insulation is a 200 mm thick cover of polystyrene followed by 2-3 m top soil[147].

The district heating network is directly coupled to the storage system which also include two 100 m^3 buffer tanks used as short-term storage to balance peaks from the solar collectors charging the BTES. Depending on the temperature level heat is either supplied to the buildings through the

[145] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[146] Gehlin, S. E. A., Spitler, J. D. & Hellström, G., 2016. Deep Boreholes for Ground Source Heat Pump Systems - Scandinavian Experience and Future Prospects. Orlando, Florida. January 23-27.
[147] Nußbicker, J., Mangold, D., Heidemann, W. & Müller-Steinhagen, H., 2003. Solar assisted district heating system with duct heat store in Neckarsulm-Amorbach (Germany). Gothenburg. June 14-19, u.n.

BTES or the buffer tanks, while peak loads are covered by a gas condensing boiler. The goal has been to reach a solar fraction of 50% of the total space heating and hot water demand of the residential area[148]. In 2007 a solar fraction of approx. 45% were achieved with a total solar collector area of 5.670 m². However, the size of the community was smaller by that time and only around 300 flats. The approximate contribution from the solar collectors was around 1.850 MWh[149], but the fraction of this contribution that was charged to the BTES is unknown and the injection and extraction power rates of the BTES have not been identified either[150]. It has been considered to install a heat pump to increase the possible temperature level of the heat delivered from the BTES[148].

The design parameters for the Neckarsulm BTES have been synthetized in Table 3.10 by Malmberg[150].

Table 3.10 Design parameters for Neckarsulm (from[150])

HT-BTES in Neckarsulm			
Start of operation	1997/99/2002-	Storage shape	Rectangular
Storage volume [m3]	63 360	Ground type	Clay
Number of boreholes	528	Thermal conductivity [W/(m*K)]	2,2
Borehole depth [m]	30	Volumetric heat capacity [MJ/(m3*K)]	2,85
Total borehole length [m]	150 840	Insulated [Yes/No]	Yes
Borehole spacing [m]	2	Insulation material	Polystyrene
Borehole diameter [mm]	150	Insulation thickness [mm]	200
Collector type	Double U-tube	Source of charge	Solar thermal
Collector diameter [mm]	25	Injection power [GJ]	Not found
Collector material	Polybutene (PB)	Extraction power [GJ]	Not found
Collector temperature resistance	85	Charging temp [°C]	60 (66*)
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	65
Number of boreholes in series	6	Storage minimum temp [°C]	45
Total collector length in series [m]	360	HP for extraction [Yes/No]	No

* As of monitored operation in 2002 (Mangold, et al., 2003).

148 Nußbicker, J., Mangold, D., Heidemann, W. & Müller-Steinhagen, H., 2003. Solar assisted district heating system with duct heat store in Neckarsulm-Amorbach (Germany). Gothenburg. June 14-19, u.n.
149 Nußbicker-Lux, J., Bauer, D., Marx, R., Heidemann, W. & Müller-Steinhagen, H. 2009. Monitoring Results from German Central Solar Heating Plants with Seasonal Thermal Energy Storage. Stockholm. June 14-17, s.n.
150 Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

3.6.7 Crailsheim, Germany

The Crailsheim BTES was constructed in 2008 and is sourced by solar collectors to produce heat for a new residential area. The BTES consists of 80 boreholes to a depth of 55 m and can be doubled along with a planned expansion of the residential area. Each borehole is equipped with double u-tubes of high-pressure cross-linked polyethylene PEX (PEXa)[151]. The top of the storage is insulated with foam glass gravel and covered by water protecting foil and a drainage gravel layer. Significant groundwater flow were encountered in the upper 5 m of the storage volume and in order to avoid advective heat loss, a thermally reduced grout (a grout with lower thermal conductivity) was used in this zone while a thermally enhanced grout was used in the lower parts of the boreholes[152], see Figure 3.25.

Prior to building the residential area, simulations for long-term operation of the BTES and solar system were performed in TRNSYS[153]. A coverage of 50% of the heat demand in the residential area with solar thermal was expected, and this was almost achieved in the year of February 2012 - February 2013.

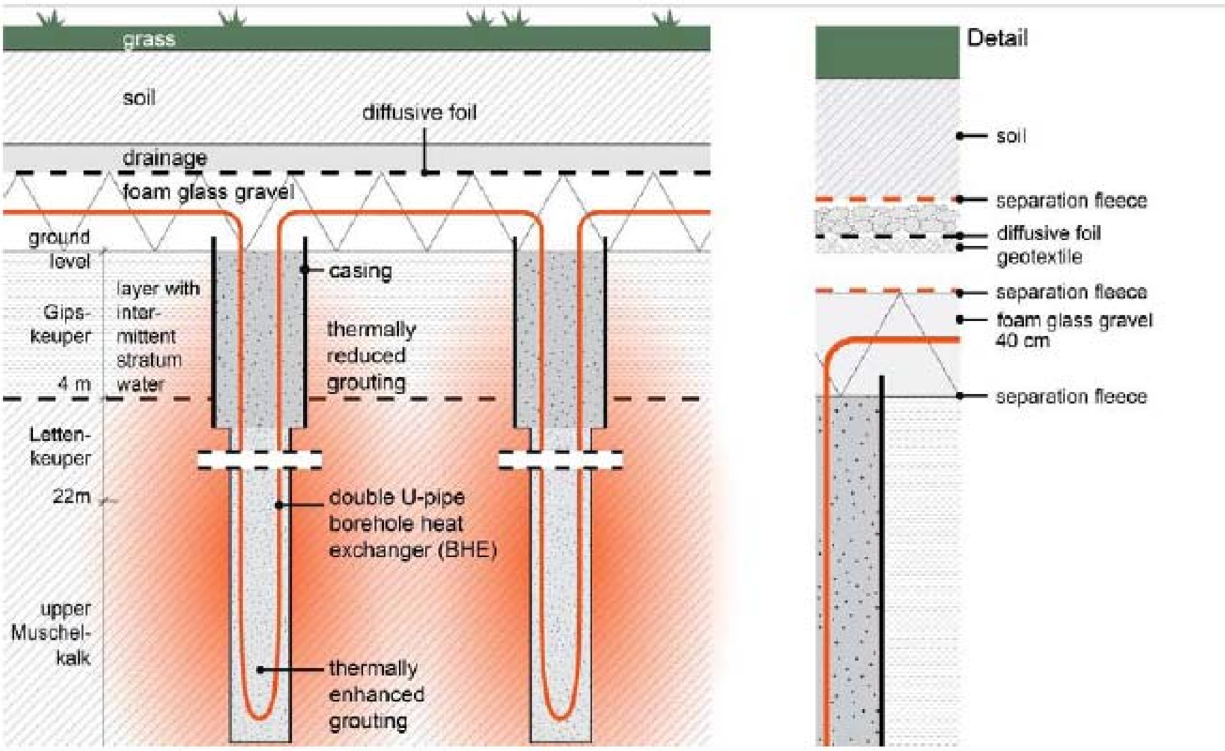

Figure 3.25 Cross section through the Crailsheim BTES, Germany (from[154])

[151] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.
[152] Mangold, D. & Schmidt, T., 2007. The next Generations of Seasonal Thermal Energy Storage in Germany, Stuttgart: Solites - Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems.
[153] Mangold, D., 2007. Seasonal storage - a German success story. Sun & Wind Energy, January, pp. 48-58.
[154] Mangold, D. & Deschaintre, L., 2015. Seasonal Thermal Energy Storage - Report on State of the Art and Necessary Further R+D, Stuttgart: International Energy Agency - Solar Heating & Cooling Programme (SHC), Task 45 Large Systems.

The solar collectors are divided in two parts; one diurnal part and one seasonal part connected to the BTES. As the BTES cannot directly support the large capacity of the solar collectors, a buffer water tank works as a short-term storage. Heat from the seasonal part can be transmitted through the district heating network to the diurnal part, either directly or via a 530 kW heat pump. The storage temperature can vary between 20-50°C, but the heat pump always supplies hot water of 60°C. With the use of the heat pump a lower storage temperature can be accepted and thereby the heat loss decreased[155].

The design parameters for the Crailsheim BTES have been synthetized in Table 3.11 by Malmberg[156].

Table 3.11 Design parameters for Crailsheim (from[156])

HT-BTES in Crailsheim			
Start of operation	2008	Storage shape	Cylindrical
Storage volume [m3]	37 500	Ground type	Soil
Number of boreholes	80	Thermal conductivity [W/(m*K)]	2.46
Borehole depth [m]	55	Volumetric heat capacity [MJ/(m3*K)]	2.4
Total borehole length [m]	4 400	Insulated [Yes/No]	Yes
Borehole spacing [m]	3	Insulation material	Foam glass
Borehole diameter [mm]	130	Insulation thickness [mm]	400
Collector type	Double U-tube	Source of charge	Solar thermal
Collector diameter [mm]	32	Charged heat [MWh]	780*
Collector material	RAUGEO PEXa	Charged heat [MWh]	382**
Collector temperature resistance	95	Charging temp [°C]	90***
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	65***
Number of boreholes in series	2	Storage minimum temp [°C]	20***
Total collector length in series [m]	220	HP for extraction [Yes/No]	Yes

*Mean value between 2009-2012 (Schneider, 2013). **Value for year 2012 (Schneider, 2013). ***From long-term simulations performed in TRNSYS (Mangold, 2007).

3.6.8 Brædstrup, Denmark

The Brædstrup BTES was constructed in 2012 and is sourced by solar collectors to produce heat for a district heating network. The BTES consists of 48 boreholes to a depth of 45 m, see also Figure 3.7 in section 3.4.5. Each borehole is equipped with double u-tubes of high-pressure cross-linked polyethylene PEX (PEXa). The boreholes are connected in 16 parallel flow lines with 6 boreholes in series and a pressure drop of approx. 2.0 bars in each line. The boreholes are grouted with HDG Thermo HS with a thermal conductivity around 1.44 W/mK. The storage is insulated with mussel shells, see also Figure 3.6 in section 3.4.4.

[155] Schneider, B., 2013. Storing Solar Energy in the Ground, Eggenstein-Leopoldshafen: FIZ Karlsruhe - Leibniz Institute for Information Infrastructure.
[156] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

The system is also equipped with a 5.000 m^3 buffer tank, a 1 MW heat pump and a 10 MW electric boiler. The system is planned with a possibility to expand further with additional boreholes placed around the pilot storage but with separate transmission lines.

A 1.2 MW ammonium heat pump of industrial SABROE® type (delivered by Johnson Controls) and based on a high pressure screw compressor is used in the system during heat extraction. The heat pump can deliver an outgoing temperature of up to 90°C for direct use in the district heating network[157]. Johnson Controls also deliver large non-standard SABROE® heat pumps of larger capacities up to 13 MW[158].

The designed storage temperature of the BTES varies between 70°C during charging period (summer) and 10°C during extraction period (winter). In February 2013 the BTES delivered heat at a temperature of 20°C to the heat pump which in turn delivered heat at a temperature of 80°C to the DH system[157]. The storage efficiency from May 2012 to February 2013 was 37%. In Figure 3.26 is shown the heat flow diagram for the Brædstrup BTES according to monitoring data for 2014 and in Figure 3.27 the heat balance for the period 2014-2017. The average storage efficiency in the period 2014-2017 was 61% calculated as the discharged energy plus the internal energy change and divided by the charged amount of energy.

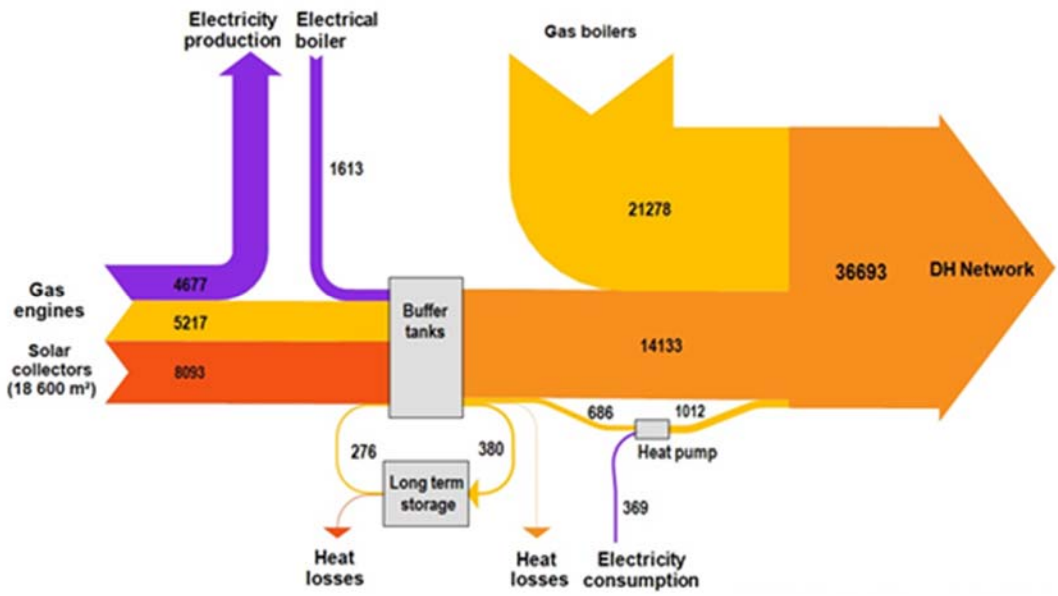

Figure 3.26 Heat flow diagram for Brædstrup according to monitoring data for 2014, numbers in MWh (SOLITES)

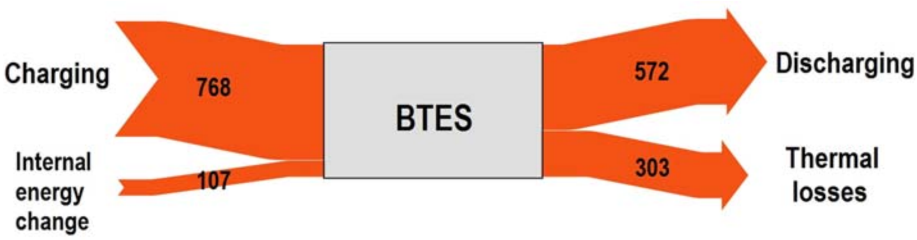

Figure 3.27 Heat balance for Brædstrup in MWh for the period 2014-2017 (SOLITES)

157 Sørensen, Per Alex et al. (2013). Boreholes in Brædstrup. Final report.
158 Johnson Controls, 2017. SABROE® Products 2017, s.l.: pp. 52.

The Brædstrup BTES was, however, still in a start-up phase in this period and it is expected from simulations that it may take 3-5 years to heat up the storage and the surroundings and furthermore the storage was not fully charged every year.

During operation, the Brædstrup BTES has realized a limited charge and discharge capacity. The maximum power of the solar collectors in the system is more than 7 MW, but the borehole storage can be charged with only 600 kW in the beginning of the season and down to 300 kW in the end of the season. Discharging has similar values, so even if charge and discharge could take place 24 hours per day, the borehole storage is very slow compared to water storages.

The design parameters for the Brædstrup BTES have been synthetized in Table 3.12 by Malmberg[159].

Table 3.12 Design parameters for Brædstrup (from[159])

HT-BTES in Brædstrup			
Start of operation	2012-	Storage shape	Cylindrical
Storage volume [m3]	19 000	Ground type	Clay
Number of boreholes	48	Thermal conductivity [W/(m*K)]	1.42
Borehole depth [m]	45	Volumetric heat capacity [MJ/(m3*K)]	1.9
Total borehole length [m]	2 160	Insulated [Yes/No]	Yes
Borehole spacing [m]	3	Insulation material	Cockles
Borehole diameter [mm]	150	Insulation thickness [mm]	500
Collector type	Double U-tube	Source of charge	Solar thermal
Collector diameter [mm]	32	Energy charged [MWh]	444*
Collector material	RAUGEO PEXa	Energy discharged [MWh]	163*
Collector temperature resistance	95	Charging temp [°C]	80
Thermal stratification [Yes/No]	Yes	Storage maximum temp [°C]	60
Number of boreholes in series	6	Storage minimum temp [°C]	20
Total collector length in series [m]	540	HP for extraction [Yes/No]	Yes

* As of operation between May 2012 to February 2013 (PlanEnergi, 2013). **Heat loss estimated as 24% (Gehlin, 2016).

[159] Malmberg, M. 2017: Transient modeling of a high temperature borehole thermal energy storage coupled with a combined heat and power plant. Master of Science Thesis EGI 2017: 0106 MSC, KTH Industrial Engineering and Management.

3.6.9 Other BTES systems

A number of other BTES systems have also been identified, however with less available information for most of them.

3.6.9.1 Attenkirchen, Germany

In Attenkirchen in Germany a combined solar district heating and BTES seasonal storage system was established in 2002[160]. It was designed to supply a new settlement of 30 homes and an indoor tennis court with heat for domestic hot water and space heating. The buildings are designed with an improved insulation standard which results in a planned total heat demand for space heating (385 MWh/a) and domestic hot water (102 MWh/a) of 487 MWh/a.

The BTES is a hybrid storage consisting of a 500 m³ underground concrete water tank acting as a short term buffer storage and surrounded by 90 boreholes to a depth of 30 m. The boreholes are installed in three rings around the water tank and adding a ground volume of 9.350 m³ to the storage[98], see Figure 3.28. The average volumetric heat capacity of the underground measured at this location is 2.7 MJ/m³/K and the borehole storage volume corresponds to 6.800 m³ water equivalent and thus the total hybrid storage represents 7.300 m³ water equivalent.

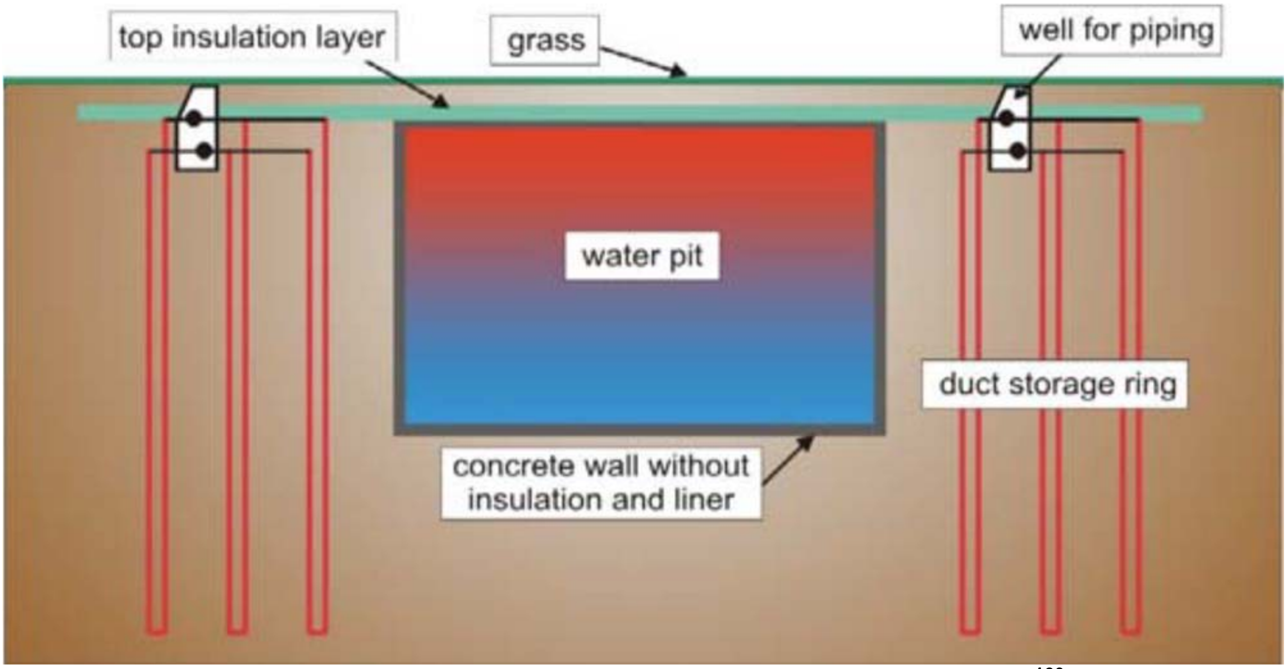

Figure 3.28 Combined water pit and BTES in Attenkirchen, Germany (from[160])

The borehole heat exchangers are constructed as double u-tubes made of Polybuten pipes (20x2.3 mm) with spacers every two meters. They are mounted in grouted boreholes of 150 mm in diameter. For investigation of the long-term performance of thermal grouts, two different materials were used. Half of the boreholes is grouted with a bentonite/cement/quartz-sand/water suspension while for the other half the convenience blend ThermoCem was used.

The system in Attenkirchen is equipped with an extended monitoring system which will allow detailed performance measurements for analysis of components, operation and optimization of control strategies. Reuss[98] reports that major research topics are detailed analysis of all energy flows in the system to investigate system behaviour and thermal performance as well as

[160] Reuss, M., Beuth, W., Schmidt, M. & Schoelkopf, W. 2015: Solar District Heating with Seasonal Storage in Attenkirchen; Bavarian Center of Applied Energy Research: Garching, Germany.

verification of the predicted yield of useful solar energy and solar fraction calculated in a feasibility study before construction. Operational features like storage management (parallel or serial charging of water and borehole storage) or cost optimized heat pump operation using cheap night electricity to discharge the BTES using the water tank as a buffer is also planned to be analysed.

During the first two seasons of operation only a small part of the planned buildings were connected to the district heating and a representative measured energy balance was not possible. Furthermore, problems was encountered both with the overall system performance due to a poorly working automatic control program and with the monitoring system. However, the amount of available monitoring data gradually increased from spring 2004 to almost 100% in 2005. Based on the analysis of the results of the monitoring it was possible to provide heat to the consumers all year round without affecting their comfort.

A detailed scheme of the energy fluxes in the system (2004/2005) is shown in Figure 3.29. In this period the temperature in the water tank was permanently kept on a temperature level above 50°C. The heat was directly transferred to the district heating and the heat pump was used only for experimentation. The specific solar fraction delivered to the district heating was 373 kWh/m² (aperture)[161].

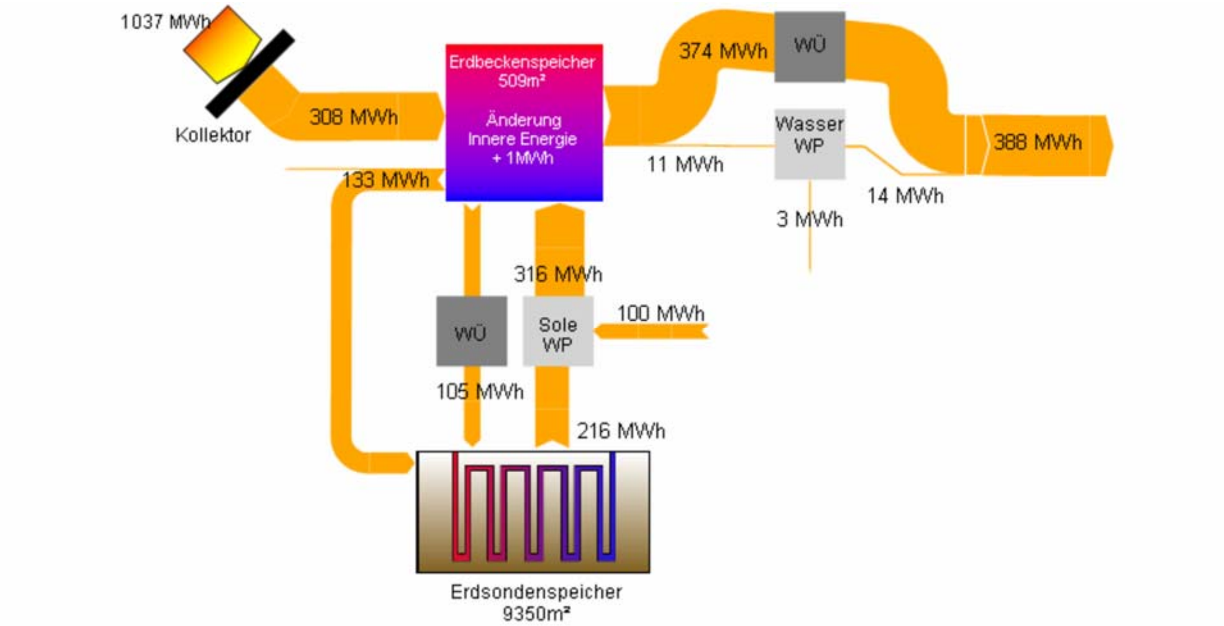

Figure 3.29 Energy balance for the Attenkirchen hybrid storage for the period April 2004 – March 2005 (from[161])

In the summer of 2005 modifications were included in the control program and in the autumn two new houses were connected to the district heating. Furthermore, one of the two heat pumps connected to the BTES was set to supply heat directly to the district heating while the other one was still feeding the water tank. The energy balance of the system in the next evaluation period, which was only 11 months[161] (see Figure 3.30), shows the improvements obtained by the changes. Heat losses of the water tank were reduced by lowering the temperature in winter below 15°C.

[161] Reuss, M., Beuth, W., Schmidt, M. & Schoelkopf, W. 2015: Solar District Heating with Seasonal Storage in Attenkirchen; Bavarian Center of Applied Energy Research: Garching, Germany.

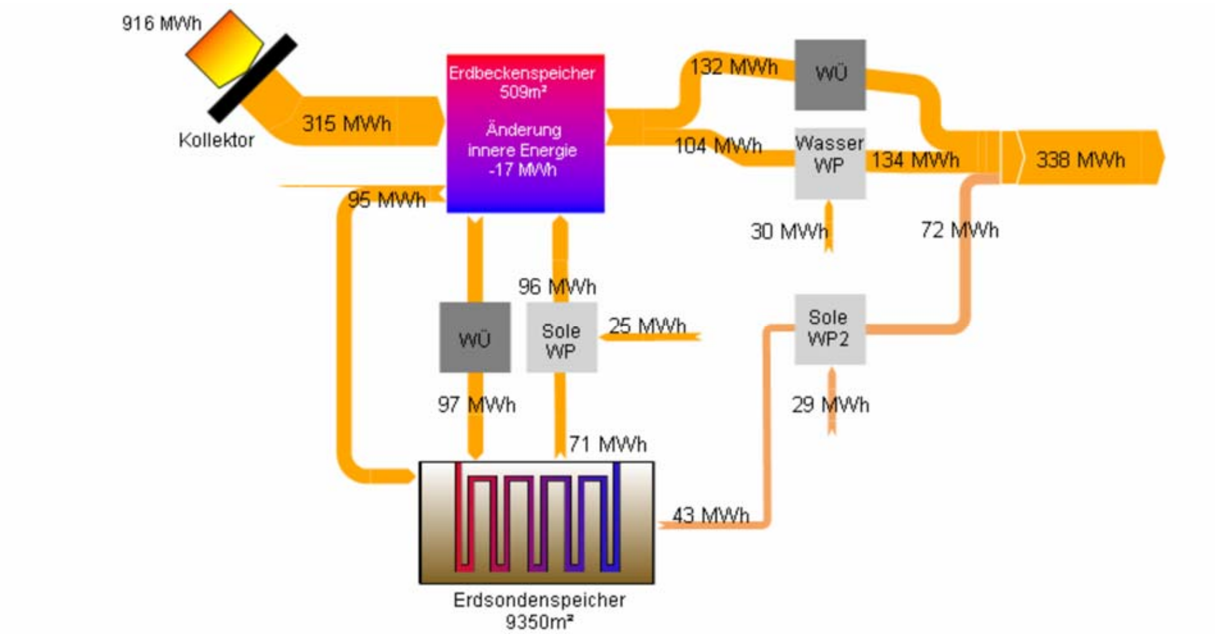

Figure 3.30 Energy balance for the Attenkirchen hybrid storage for the period April 2005 – February 2006 (from[162])

3.6.9.2 TESSAS Project in Mol, Belgium

The TESSAS project in Mol, Belgium is a high-temperature BTES project, established in 2002 and aiming at demonstrating and evaluating BTES in a water saturated sand layer[163]. Waste heat from a power plant is stored at 90°C during summer time. During winter, the stored heat is discharged and used directly for heating a building of 3700 m^2 floor area. The BTES comprise 144 boreholes to a depth of 30 m in a hexagonal shape and the total storage volume is 16,000 m^3. The spacing between individual boreholes is 2 m and the diameter of the storage is 26 m and thus the diameter/depth ratio is close to 1. Each borehole is installed with single u-tubes and the storage has a top insulation of 20 cm XPS (extruded polystyrene) covered with a PE (polyethylene) foil followed by soil. The boreholes are connected in series of three from the center and outwards. Temperature sensors are placed in 66 different locations and depths in order to be able to monitor the 3D temperature development.

During the first year of operation, the maximum temperature in the storage was 70°C and during discharging the temperature dropped to 30°C at the end of the heating season, but the overall storage efficiency was very low. In the second year of operation the storage efficiency was approx. 30% and expected to increase when steady state heat flow is reached.

3.6.9.3 Groningen, the Netherlands

In Groningen, the Netherlands a low-temperature BTES was established in 1985 for 96 houses in combination with solar heating[164]. The heat storage is cylindrical with a diameter of 39 m and a depth of 20 m. The storage volume is 23,000 m^3 and the estimated storage capacity is 595 MWh. In the center of the storage is a 100 m^3 water tank for short term storage. The heat is exchanged

[162] Reuss, M., Beuth, W., Schmidt, M. & Schoelkopf, W. 2015: Solar District Heating with Seasonal Storage in Attenkirchen; Bavarian Center of Applied Energy Research: Garching, Germany.
[163] Hoes, H., Reuss, M. & Staudacher, L. 2005: The TESSAS Project in Mol: High Temperature Thermal Energy Storage in Saturated Sand Layers with Vertical Heat Exchangers. Proceedings, World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.
[164] Wijsman, A. J. TH. M. & Havings, J. 1985: The Groningen project: 96 solar houses with seasonal heat storage in the soil. Proceedings “Intersol 85” Congress, Montreal, Canada.

with the storage volume through flexible polybutene tubes inserted vertically into the soil (it is not known if the tubes are installed in boreholes or using another technique) and covered by a top insulation.

The storage was monitored from February 1985 to January 1987. In the first year of operation, 470 MWh was charged to the storage, the heat loss was 288 MWh, 108 MWh was used for heating and 74 MWh was kept in the store. In the second year of operation, 546 MWh was charged to the storage, the heat loss was 354 MWh, 122 MWh was used for heating and 70 MWh was kept in the store.

3.6.9.4 Kerava, Finland

The Kerava Solar Village in Finland was built as a pilot project in 1983 with solar heating of 44 apartments combined with BTES[165]. The BTES system is a hybrid storage in hard rock formations with 54 boreholes surrounding a 1500 m^3 water filled cavity in the rock to a depth of 20 m. The boreholes are drilled in two circles around the cavity. The inner circle consists of 18 boreholes to a depth of 22 m and at an angle from vertical of 12°. The outer circle has 36 boreholes to a depth of 24 m and at an angle from vertical of 24°. The rock storage volume is 11,000 m^3 and the operating temperatures are 21-49°C.

3.6.9.5 Wollerau, Switzerland

The Wollerau BTES consists of 36 boreholes to a depth of 120 m. It is a low-temperature system designed to provide both heat and cold. It was established in 1998 and designed after accurate thermal and dynamic modelling according to the following assumptions:

- Supply of heat: 350 MWh/year
- Supply of cold 85 MWh/year

This case emphasized the importance of an integrated dynamic modelling of the parameters of the subsoil, the circulation in the wells, the GSHPs and the consumption parameters. The operational power and specific energy values recorded are[166]:

60 kWh/m of well/year and 40 W/m average heat extraction (winter) by the heat pump;

- 20-35 kWh/m of well/year and 10-13 W/m average heat injection (summer), with a peak value of 40-50 W/m, this in the case of direct cooling, without the use of a refrigerating machine (the storage must therefore remain "cold" to meet demand all summer),
- 54 kWh/m of well/year and 16 W/m average heat injection (summer), with a peak value of 60 W/m, this in the case of direct cooling with additional boosting by a refrigerating machine.

3.6.9.6 Root Lucerne, Switzerland

This BTES installation was built in 2001 and consists of 49 boreholes to a depth of 160 m over a volume of approx. 360,000 m^3. It is a combined solar and low-temperature BTES system, but the BTES is primarily used for producing heat and with a minor fraction of solar recharging. Energy savings of around 500 MWh and optimization of the GSHPs system were targeted and the project was supported by the Swiss Federal Office of Energy SFOE P&D funding program. In Figure 3.31 is an aerial photo of the construction work.

[165] Dalenbäck, J. O. 1990: IEA, Solar heating and cooling programme, Task VII. In: Central solar heating plants with seasonal storage - status report. Stockholm, Sweden: Swedish Council for Building Research.

[166] Hadorn, J-C. 2004: Rapport annuel 2003 du Programme ”Solaire actif – Chaleur et stockage de chaleur” - Activités et projets en 2002. OFEN, 24 janvier 2003.

Figure 3.31 Aerial view of the Technopark de Root site, Switzerland, during the GSHPs connection operations (foto from Vinard, P. 2015. Pré-étude comparative de projets et réalisations de systèmes de stockage saisonnier. Report Etat de Geneve, Office cantonal de l'Energie (OCEN) and Office federal de l'energie (OFEN))

The facility has been operating since the summer of 2003. The operational results show that the peripheral zone is affected more quickly than the boreholes located in the inner part. The outer zone faced a temperature decrease of about 1˚C at a depth of 40 m during the first 2 months of operations whereas the inner zone was only affected by 0.5˚C temperature reduction.

During the initial phase (1st year of measurements), the buildings were fed either by the geothermal heat pump, or by the solar, or by a booster boiler. The requirements reached 1,672 MWh. The GSHP supplied 74% of this energy, while the direct solar contributed with only 2%. In one year, the central part of the storage volume lost 2˚C (14.5˚C to 12.5˚C) with a minimum temperature of 12˚C. Solar recharge compensated for 0.6˚C. Balance in the system has been gradually reached by gradually adapting the production and injections operations.

3.6.9.7 Suurstoffi, Switzerland

This BTES project is located in Central Switzerland, a few kilometres from the village of Root. The heat storage system consists of 220 boreholes to a depth of 150 m deep. The main goal of this project is to operate a new district with renewable energy and zero emissions. The waste heat source is generated by cooling the buildings during summer season and transport the heat via the local district heating network to the BTES boreholes where it is stored. In winter, the stored heat is then used by means of heat pumps. PV panels generate the electric power needed to run the heat pumps. The temperature of the water varies between 5°C in the winter and about 25°C in the summer.

This low-temperature system has experienced various initial problems that are being optimized, including addition of solar thermal input not originally planned. Compared to the Root project, this is a more complex system given the size of the neighbourhood and the energy network that feeds it. At the moment monitoring of the whole energy system performance is ongoing.

3.6.9.8 Blatten Belalp, Switzerland

This project was established in 2014 and demonstrates that the concept of a combination between solar thermal and a low-temperature BTES composed of a series of 31 boreholes to a depth of 120 m is a stable and well-working solution, even in an Alpine region as where the Belalp village is located at 2.034 m a.s.l.

The originality of this project is constituted by the use of hybrid solar panels, which limits the amount of waste heat to store in summer, making the whole system operating temperatures significantly lower. However, this type of panels remains relatively expensive.

3.6.9.9 Oberfeld, Switzerland

The magazine "Wohnen" reported in October 2013 an original concept setup based on a floor heating system at very low temperature (30˚C). A set of five residential houses with 100 apartments are equipped with photovoltaic hybrid solar panels and thermal, which are connected to 40 BTES boreholes to a depth of 125 m, serving as seasonal storage. The originality of the concept is that properly glazed stairwells act as buffers of thermal energy.

3.6.10 Recovery efficiency

In general, the maximum and minimum storage temperatures, respectively, during charging and discharging are ranging between 30˚C and 60˚C and sometimes up to 70-80˚C in the 17 identified HT-BTES systems. It has only been possible to obtain a measure of the storage efficiency from 4 of these (Drake Landing, Luleå, Anneberg and Brædstrup) and here the efficiency is ranging between 45% and 60% and is often lower than expected.

This can be caused by several factors. Often the observed heat losses are higher than originally planned/modelled. This can be due to the construction method or in some cases groundwater flow. It can also be due to inadequate storage design or choosing parameters in the modelling that does not reflect the actual conditions. With regards to modelling the entire system, Lanahan & Tabares-Velasco[167] states, that some studies are coupling BTES at the component model with a system level simulation, but most previous studies have not bridged the modelling gap between the two levels of modelling.

Specifically for Anneberg, Malmberg et al.[168] states that a start-up period is needed to heat up the storage and the surroundings to reach steady-state behaviour in the BTES. Furthermore Malmberg et al.[168] states, that a higher heat loss in the distribution system and higher indoor temperatures on the demand side than expected as well as lack of a short term buffer system to take fully benefit from the solar panel-BTES coupling all together reduces the overall system efficiency compared to the expectations.

In Drake Landing the storage efficiency is approx. 50%, but the overall system efficiency is very high with solar supplying approx. 90% of the total energy consumption.

[167] Lanahan, M. & Tabares-Velasco, P. C. 2017: Seasonal Thermal-Energy Storage: A Critical Review on BTES Systems, Modeling, and System Design for Higher System Efficiency. Energies 2017, 10, 743; doi:10.3390/en10060743.
[168] Malmberg, M., Mazzotti, W., Acuña, J., Lindståhl, H. & Lazzarotto, A. 2018: High temperature borehole thermal energy storage – A case study. IGSHPA Research Track, Stockholm, September 18-20.

Table 3.13 Summary of identified and described BTES systems

Country	Location	Energy source	Application	Start of operation	No. of boreholes	Borehole depth (m)	Max. Temp. (°C)	Tubes	Storage volume (1000 m^3)	Estimated capacity (MWh)	Storage efficiency	Soil type
Canada	Drake Landing	Solar	Domestic (52 homes)	2006	144	35	80	U-tubes	34	780	0,5	Sand silty, clayey
Sweden	Luleå	Industrial	n/a	1983	120	65	65	Open	115	2000	45-55%	Crystalline rock
	Emmaboda	Industrial	Office buildings	2010	141	149	45	Coaxial	323	3800	n/a	Crystalline rock
	Anneberg	Solar	Domestic (50 homes)	2002	99	65	45	n/a	59	1467	0,46	Crystalline rock
Czech Republic	Paskov	CHP	Test site	2011	16	60	78	Double U-tubes	n/a	555	n/a	Clay/miocene rocks
Germany	Neckarsulm	Solar	Domestic (300 homes, shops)	1997	528	30	65	Double U-tubes	63	1000	n/a	Clay
	Crailsheim	Solar	School buildings	2008	80	55	65	Double U-tubes	38	1135	n/a	Mudstone/ Limestone
	Attenkirchen	Solar+ hybrid	Domestic (30 homes)	2002	90	30	n/a	Double U-tubes	10	77	n/a	n/a
Denmark	Brædstrup	Solar	District heating	2013	48	45	70	U-tubes	19	616	0,61	Clay/till
Belgium	Mol	Wast heat	Building	2002	144	30	82	U-tubes	16	130	n/a	Sand saturated
Netherlands	Groningen	Solar	Domestic (96 homes)	1985	20	20	50	U-tubes	23	595	n/a	Sand, clayey
Finland	Kerava	Solar+ hybrid	Domestic (44 homes)	1983	54	25	50	U-tubes	11	n/a	n/a	Soil and bedrock
Switzerland	Wollerau	Heat pump-Gas	Office buildings	1998	36	120	n/a	n/a	40	350	n/a	n/a
	Root Lucerne	LTN-heatpumps	Office buildings	2003	49	160	n/a	U-tubes	360	n/a	n/a	Sandstone
	Suurstoffi	Building cooling	District heating and cooling	2012	220	150	n/a	n/a	n/a	n/a	n/a	n/a
	Oberfeld	PVT	Domestic (100 homes)	2012	40	125	n/a	n/a	n/a	n/a	n/a	n/a
	Blatten Belalp	Solar	Residential	2014	31	120	n/a	n/a	n/a	n/a	n/a	n/a

3.7 Economics

Only a limited amount of cost data is available for the implementation of BTES, but Figure 3.32 shows the specific cost for some BTES that have been implemented as well as for some that are only conceptual[169]. It is clear that like other large storages, the specific cost drops significantly as the size increases. The curve shown is a fit to the Drake Landing data only.

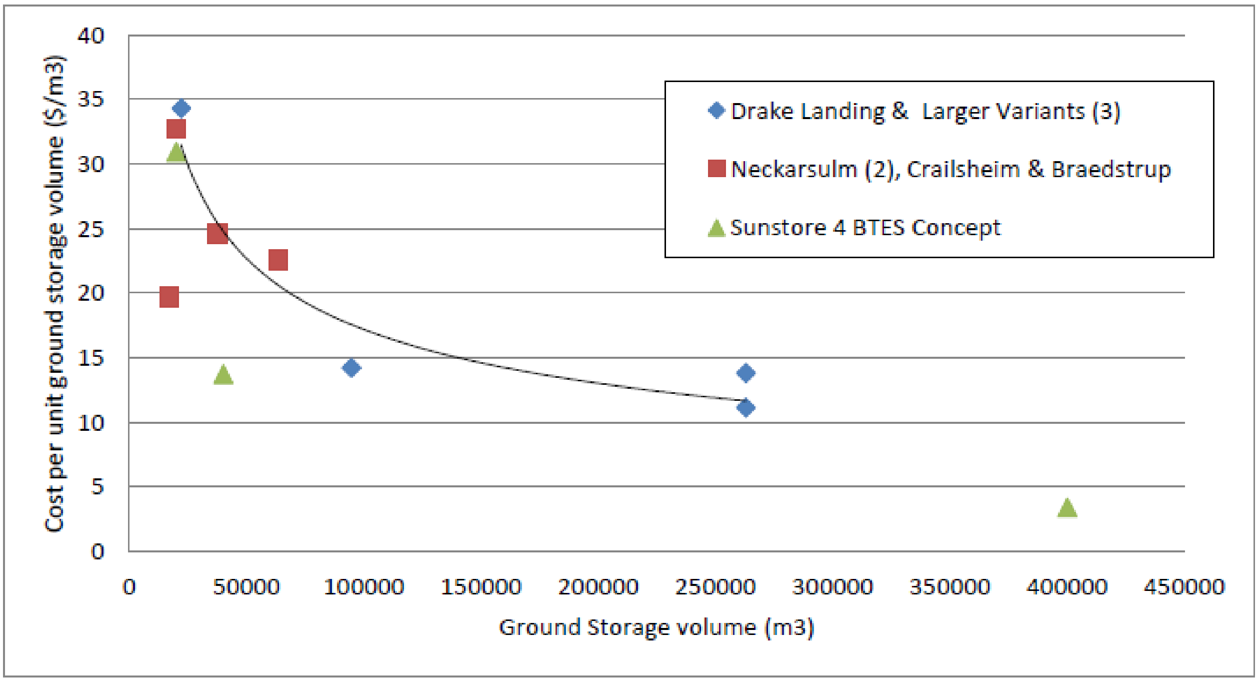

Figure 3.32 Specific installed costs for actual and conceptual BTES systems (from[169])

For any heat storage, including BTES, to work well within a system it is important to find the best or optimum sizing for the individual parts of the system. This can be done by systematically running a series of simulations to identify the best (generally the least cost) combination of major component sizes to achieve the design objectives. Since the goal is often to minimize the cost of achieving a particular outcome, optimization can sometimes make the difference between a profitable and an unprofitable investment. A generic optimization program like GenOpt® may be used with the TRNSYS system model to automatically perform numerous runs with varied parameters to minimize a specific target function.

Much of the cost of a BTES is related to drilling and completing the Borehole Heat Exchangers and to the top insulation of the store. For smaller storage demands (up to 5.000 m^3) typically an insulated steel tank is used but for larger storage demands a BTES can be considerably cheaper per unit volume of water-equivalent storage[169]. However, the size of the storage has to be between 3-5 times larger than that of a tank storage to obtain the same heat capacity due to the different heat capacity of soil (saturated/unsaturated)/rock and water and a BTES storage should have a minimum volume of 20.000 m^3 of underground volume to be energetically and financially interesting[170].

[169] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.
[170] Mangold, D. & Deschaintre, L., 2015. Seasonal Thermal Energy Storage - Report on State of the Art and Necessary Further R+D, Stuttgart: International Energy Agency - Solar Heating & Cooling Programme (SHC), Task 45 Large Systems.

Advantages specifically for BTES is that they can be subject to a modular design, where it is possible to add additional boreholes and extent the storage volume/capacity if needed. Furthermore, the area above the BTES is available for almost any use. It may be covered with grass for a park or a playing field or paved for a parking lot, tennis court etc. It is also possible that small structures can be built over it, depending on the load and construction of course[171].

3.7.1 Waste heat potential – feasibility study in France

According to the Agency for the Environment and Energy Management (ADEME) in France, the industrial sector is a larger potential of waste heat. This potential is estimated to be 109,5 TWh, including 52,9 TWh at a temperature exceeding 100°C. This heat is mostly produced continuously.

BRGM (Geological survey of France) carried out a preliminary analysis of economic and energetic sustainability of building a BTES to store this waste heat (report BRGM- RP-67592-FR). The study is based on hourly time-step dynamic simulations of the system over several years of operation. The annual heat demand of the network is assumed to be equal to the annual waste heat production, but only 66% of the waste heat is valorised directly because of time gap between production and consumption. The remaining part is provided by a gas boiler. The waste heat source and network temperatures are estimated to be 80ºC and 30ºC respectively. The economic indicator considered is the heat production cost calculated over 20 years. The economic viability of integrating a BTES increases with the amount of available waste heat. If the waste heat is available for free, the integration of BTES is economically relevant as soon as the available heat is more than 5.000 MWh/y. The BTES increases the waste heat fraction in the district heating network from 66% to about 87%. For a waste heat annual production of 10.000 MWh/y, the integration of a BTES remains competitive as long as the heat is bought below 14 €/MWh (considering a discount rate of 4.18%/y and a gas cost increase of 0.9%/y). Moreover, the integration of BTES has the advantage of stable production costs in the event of a significant variation in the natural gas cost.

[171] Sibbitt B. & McClenahan D.: Seasonal Borehole Thermal Energy Storage – Guidelines for design & construction, IEA-Solar Heating & Cooling TECH SHEET 45.B.3.1, page 1-15, April 2015.

4 PTES (Pit Thermal Energy Storage)

4.1 The PTES system

The principle of PTES is simple and works by storing hot water in very large excavated basins with an insulated lid. Sides and bottom are typically covered by a polymer-liner, but can also be made of concrete. Temperatures up to approx. 90°C can be stored and PTES offers the same flexibility to e.g. district heating energy systems as BTES.

Among current and needed research topics are lifetime of different materials for liners and improving insulating lid constructions with respect to ventilation and rain water drainage. In Denmark there are 5 plants (one was first developed as a pilot and a sixth is planned in 2019) connected to district heating networks:

- 10,000 m^3 pilot storage in Marstal on the island Ærø in 2003
- 75,000 m^3 full scale storage in Marstal in 2011-12
- 60,000 m^3 full scale storage in Dronninglund in Northern Jutland in 2013 (see Figure 4.1)
- 122,000 m^3 full scale storage in Gram in Southern Jutland in 2014
- 203,000 m^3 full scale storage in Vojens in Southern Jutland in 2015
- 85,000 m^3 full scale storage in Toftlund in Southern Jutland in 2017
- 70,000 m^3 full scale storage in Høje Taastrup near Copenhagen, planned 2019.

Figure 4.1 Picture of Dronninglund Pit Storage under construction. Dronninglund District heating; 37,573 m^2 of solar collectors and a 62,000 m^3 water in pit heat storage (PlanEnergi)

The main advantages of the PTES concept are the possibility for quick charging or discharging, short heat storage periods and the fact that water is ideal as storage medium due to high thermal capacity. Also, inherent stratification in the water column introduce storage water in different temperature intervals. If the ground conditions are optimal, the construction costs are low.

Some of the disadvantages to keep in mind are that the system is space demanding. The storage requires large areas without infrastructure, which makes it less feasible in urban areas. The lifetime of liners and the lid construction is still partly unknown. High groundwater levels and poor soil conditions directly affects the construction costs.

4.2 Lessons learned line – up

In Table 4.1 below, the lessons learned from existing Pit Storage systems are lined up. The table summarises the important messages from the more thorough report text in the linked sections.

Table 4.1 Line up on important lessons learned from PTES

PTES systems – Lessons learned		
Pre-investigation (feasibility study)	• Check for groundwater flow (4.3.1) • Check soil: The excavated soil must be of a quality that can be utilized as banks. Too much silt in the soil can be a problem and a geotechnical investigation must confirm that the excavated soil can be utilized as banks (4.3.1) • Secondary groundwater levels: Careful geotechnical investigations will localize the groundwater level and secondary groundwater levels. If secondary groundwater levels are localized it is important to get an estimate of the costs for drainage measures from the excavating entrepreneur (4.3.1) • Space demands (available areas for storage and potential solar collectors)	*External factors (political, legislation):* (see also chapter 6) **Environmental restrictions:** Environmental Impact Assessment - Screening is required. **Permissions which can be required:** Permission for seepage of groundwater drainage.

PTES systems – Lessons learned		
Construction	**Excavation (4.4.1)** • Compression of excavated soil: When soil is rebuilt into the banks it has to be compressed to a certain standard defined in the tender documents. To be proved by taking out samples for laboratory testing. • Stones on the banks: Before the liner contractor begins the liner installation, stones have to be removed from the banks and a geotextile with high penetration resistance must be placed to protect the polymer liner. • The top of the banks has to be in the same level: Since the water level is 100% equal it is important that the elevation of the banks is at same level. A maximum deviation of 2 cm is tolerated in order not to lose storage capacity. **Lid (4.4.2.2)** • When the liner for the lid construction is floated on the water, waves can easily cause water on the liner. This must be avoided. Rain during the lid construction cannot be avoided but must be removed before the roof foil is implemented. Care to be taken with tightness, draining rain water, avoiding air pockets under lid. **Liners (4.4.2.3)** • Care to be taken with liner material with respect to life time (temperature resistance) and vapour permeability. So far, good experience with HDPE[172] • Test of welds: The liner welds must be properly pressure tested. But not all weldings are double. Electrical tracer detection of the total area of liner and welds is recommended after the liner work has been completed. **Insulation (4.4.2.3)** • Insulation of sides and bottom normally not necessary • Examples of suitable materials: LEC[173], PUR[174], Nomalén (PE/PEX[175] mats) *Recommendations for general specifications and design of PTES are presented in the HEATSTORE deliverable D1.2 report “General specifications and design for UTES systems”*	Permission for seepage of water from pit top. Permission for seepage / drainage of (salty) return water from softening unit when filling storage Permission for new water supply drillings for water to fill storage. Groundwater should not be heated. New environmental permission or change in the environmental permission for the energy production plant. **Planning restrictions:** Change of status of land use. Changes needed for District plans and Municipality plans.

[172] HDPE: High density Polyethylene
[173] LECA: Small balls of burned/expanded clay
[174] PUR: Polyurethane
[175] PE: Polyethylene, PEX: Cross-bound Polyethylene

PTES systems – Lessons learned		
System integration	PTES is well suited for: • Seasonal storage (e.g.: solar, waste heat, etc.) • Short term storage (e.g.: CHP[176] optimization) To be used with (combinations of): • Solar heating • CHP • Heat pump • Industrial waste heat • Geothermal heat? Enables: • Flexible operation of CHP plants • Grid balancing e.g. with excess renewable electricity using electrical boilers and heat pumps • Integration of high shares of renewable energy • Can be used for heating and cooling • High charge and discharge capacity	
Operations feedback	**Monitoring (4.6.1)** • Temperatures from bottom to top in the storage (around the centerline) should be monitored • Measurements should be in general agreement with calculations **Maintenance (4.6.1)** During operation and maintenance it is important to: • Clean the filters protecting the heat exchangers • Check the water quality at least yearly (pH, oxygen content) • Check the construction under the water yearly (diver inspection) • Check for leakage: Be aware of how much water that has to be added and check expected level of the water in the PTES continuously. Leakage in liners can be repaired under water by diver (when the storage is not too hot) • Be aware of spoiled stratification if the PTES is connected to solar thermal because a too hot bottom temperature might cause boiling in the solar system. • Check daily that everything works normally (rain water pumps, water puddles on the lid etc.) • Check regularly for wet insulation	
Conclusions	• Care to be taken with respect to materials and construction • Efficiency of large PTES storages depends strongly on the whole system. Important are: • Usable temperature differences in the storage • Heat “turnover” – number of annual storage cycles • Utilising heat pumps for discharging • Temperatures in the district heating network	

[176] CHP: Combined Heat and Power

4.3 (Pre-)investigation and feasibility studies

4.3.1 Screening process

In a first feasibility study, the following parameters are important to investigate to find out if the construction of a Pit Storage is feasible:

- The geotechnical conditions has to be investigated
- Evaluation of the local soil properties and upper geological conditions is important (the excavated soil must be of a quality that can be utilized as banks of the storage)
- High silt content in the soil are problematic
- Upper groundwater levels and flow are important to investigate (groundwater flow above bottom of pit is problematic due to excessive heat loss)
- Available areas for the storage site (and flat topography)

Normally the slopes of the Pit are constructed with a steepness of 25°, which requires soil types being stable at this angle.

4.3.1.1 Test drillings

Drilling investigations with a geotechnical perspective are necessary. Soil samples from the drillings should confirm that the excavated soil can be utilized as banks of the storage. It is important to determine clay and silt content.

Regarding the groundwater it is important to get information from boreholes on the upper groundwater levels and to conclude if there is a significant groundwater flow in layers above the planned elevation of the storage bottom. In the case of groundwater flow the stored heat can be transported away from the pit storage.

4.3.2 Geography and climate

Geography and climate will influence the dimensioning of the heat supply system including the storage. Especially when the storage is serving as a seasonal storage for a solar heating plant, the volume of the storage will depend on the annual solar radiation and the (distribution of) annual heating load.

4.4 Construction phase

4.4.1 Excavation and construction

During the implementation phase for PTES it is important to be aware of the following topics[177]:

Secondary groundwater levels: Thorough geotechnical investigations will localize the general groundwater level and any upper or secondary groundwater levels. If upper groundwater levels are localized it is important to get a precise estimate of the costs for drainage measures from the excavating entrepreneur.

Compression of excavated soil: When soil is rebuilt into the banks, it has to be compressed to a certain standard defined in the tender documents. This standard has to be proved by taking out samples and make laboratory tests.

Stones on the banks: Before the liner entrepreneur starts his work, stones have to be removed from the banks and a geotextile with high penetration resistance must be placed to protect the polymer liner.

[177] Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling”. Accessible from https://www.iea-dhc.org/index.php?id=293 (ANNEX XII Project 03).

Rain water under excavation: Rainwater will flow from the banks to the bottom areas. Especially if clays is present and this can cause problems during excavation. A drain in the bottom of the pit with drainage pumps is necessary during the construction until the liner work is finalized. Long term heavy rain can erode the banks and delay excavation.

Test of weldings: The liners are merged together with double weldings. These are normally all pressure tested, but it needs to be double checked by applying pressurized air to see if it is done properly. Not all weldings connecting the liners are double. Therefore electrical tracer detection of the total area of liner and weldings, when the liner work has been finalized, is recommended.

The top of the banks have to be in the same level: Since the water level is 100% equal it is important that the banks are in the same level. Maximum 2 cm deviation is tolerated in order not to lose storage capacity.

Water in the lid: When the liner for the lid construction is floated on the water, waves can easily cause water on the liner. This must be avoided. Rain during the lid construction cannot be avoided but must be removed before the roof foil is implemented.

4.4.2 Pit design and configuration

To minimize the cost of soil handling and transportation the excavation is made with soil balance which means that the soil excavated from the bottom part of the storage is used as embankments around the upper part of the storage. The necessary volume of the storage depends on the overall system it is connected to. It is necessary to make a calculation model of the overall system to find the optimal volume[178].

4.4.2.1 In and outlet pipes in pit storage

The advantage of letting the pipes enter the bottom of the storage is that the pipes enter the storage perpendicular to the liner. This makes the concrete construction below the liner and the flange connection simpler. The disadvantage compared to a pipe connection through the sides is that the pipes have to be buried deeper in the ground (below the storage).

4.4.2.2 Lid/cover of pit storage

Rainwater is a general challenge for the cover of a pit storage. The rainwater introduce a risk for puddles of water on the lid, which affect the bulk insulation. To solve this issue, the lid is constructed with a 2% slope towards the center of the cover. Thereby rainwater will add pressure at the center and press the lid further down consequently minimizing the risk of puddles of water around the cover.

Bulk Insulation: When using expanded clay in the lid construction there is a risk that the insulation will absorb moisture and thereby have a significant lower insulation value. Calculations have been carried out to prove that this can be avoided by introducing a relatively low degree of ventilation of the insulation, but it is not demonstrated in reality. Because there is limited cohesiveness in the bulk insulation there is also a risk that the insulation particles will not remain in the same place as when originally installed because of movements of the cover by weather impact, temperature expansion etc. To avoid clumping of the insulation and areas losing the insulation value this has to be considered in the design. To keep the water level as steady as possible it is also advised to counteract temperature expansion by pumping in and out water from the storage to a reservoir. A cover based on expanded clay insulation was implemented on pit heat storages in the Danish cities Gram and Vojens in 2015[178].

[178] Seasonal pit heat storages - Guidelines for materials & construction, IEA SHC TECH SHEET 45.B.3.2.

4.4.2.3 Lining materials - bottom and sides

Polymer liners: In the Danish PTES systems a polymer liner of High Density Polyethylen (HDPE) has been used because it is cheap and can be welded. The liner has been tested under high temperatures. The tests show that the degradation starts from the water side and is depending on temperature level and oxygen content of the water. Test results show liner lifetimes of 5-25 years at 90ºC depending on oxygen content. The lifetime can be extended by using a double liner construction if liner no. 2 is not in contact with water. Another possibility is to use a PolyPropylen (PP) liner because it's degradation in contact with water is less than for the HDPE-liner.

Metal lines: Material cost for a stainless steel liner or an aluminum liner are maybe approx. 3 times as high as for a HDPE liner. In addition to this the installation costs are estimated to be double as high.

4.4.2.4 Storage water

It has been seen that severe contamination of soil particles in the storage can lead to bacterial corrosion of steel parts and clogging of heat exchangers.

After filling of the storage the water can be treated to avoid corrosion depending on the steel quality used. Typically the pH-value is raised to a level around 9.8 to minimize corrosion of steel parts but it depends on the materials used. If aluminum parts are used, a pH value of more than 8 will cause corrosion of the aluminum parts[59].

4.5 System integration

PTES can be applied in all areas where large thermal storage capacities are required at temperature levels below 100°C. Large-scale TES can have different purposes in energy supply systems. The most common ones are[179]:

- Buffer storage for short-term heat storage or peak shifting
- Long-term or seasonal storage of e.g. solar thermal or surplus heat
- Energy management of multiple heat producers such as CHP, solar thermal, heat pumps, and industrial surplus heat
- Cold storage of e.g. ambient cold (air, surface water) or evaporator cold from heat pumps

A dedicated integration into the overall energy supply system is essential for an efficient operation of a large-scale TES. This includes a suitable hydraulic system layout as well as a careful design of not only the storage but also other system components like additional heat or cold producers, DH network, heat transfer substations etc., up to the point of building installations. In particular, the process control system must be configured to ensure that the storage services provides the greatest possible benefit, depending upon specific project objectives such as maximization of renewable energy share or CHP electricity production.

Storage temperature levels, quality of stratification and return temperatures of the heating network strongly influence the efficiency of a TES. Those parameters not only depend on the storage, but also to a large extent on the connected energy system. Hence, during storage design, an accurate prediction of the entire system characteristics is needed. Operation temperatures of the storage throughout the year and charging and discharging power rates have to be predicted, along with the DH network return temperatures, as they play a key role for the performances of the storage. Together with the maximum charging temperatures, they define the usable temperature difference, and, accordingly, the thermal capacity of a TES. For some storage concepts additional components such as short-term buffer tanks or heat pumps can also be economically reasonable supplements.

[179] Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling". Accessible from https://www.iea-dhc.org/index.php?id=293 (ANNEX XII Project 03).

A key advantage of large-scale TES are low specific heat losses. Most of the common storages accumulate thermal energy as sensible heat in a water volume. In general, the water is heated up to temperatures below 100ºC. The thermal losses of the storage are mainly influenced by the surface-to-volume ratio of the storage volume and the quality of the installed insulation material. Large storages have much lower surface-to-volume ratios than small storages, which is an important advantage in particular for long-term storage. For example, a small storage with a volume of 100 m³ has a surface-to-volume ratio that is about eight times higher than the ratio of a storage with 50,000 m³. Hence, the specific heat losses of the large storage are a factor of eight lower.

The energy efficiency of a storage device is further strongly influenced by the so-called number of storage cycles. This is an indicator for how often the storage is charged and discharged in a certain time period and for the energy turnover.

4.6 Existing operations feedback

4.6.1 Monitoring and maintenance

During operation and maintenance it is important to[180]:

- Clean the filters protecting the heat exchangers.
- Check the water quality at least yearly (pH, oxygen content)
- Check the construction under the water yearly (diver inspection)
- Be aware of how much water that has to be added and check expected level of the water in the PTES continuously
- Be aware of spoiled stratification if the PTES is connected to solar thermal because a too hot bottom temperature might cause boiling in the solar system
- Check daily that everything works normally (rain water pumps functions, water puddles on the lid etc.)

Normally it is sufficient to monitor the water stratification in the storage at only one location since the temperatures are the same everywhere in the storage in the same height.

Leakages in liners can be repaired under water by a diver when the temperatures in the storage are not too high.

4.6.2 Operational experience from two examples (Marstal and Dronninglund)

4.6.2.1 Marstal

The overall experience in the operation period from 2012 until 2017 is that the storage operates in a satisfying way. The minor problems that were identified during operations were[61]:

- After one year of operation, corrosion was found by a diver inspection of the storage. The problem was that galvanized metal was mixed with iron and that organic material in the water gave possibilities for bacterial corrosion. The pH value has now been changed from 7.4 to 9.8 and galvanized metal was replaced.
- The heat exchanger between the storage and the energy system was very ineffective. The reason was sludge from the storage water. The heat exchanger was cleaned and a filter had to be implemented in the heat exchanger inlet.
- Two holes in the liner have been observed during the yearly diver inspection. The holes have been patched by a diver.

[180] Design Aspects for Large-Scale Aquifer and Pit Thermal Energy Storage for District Heating and Cooling". Accessible from https://www.iea-dhc.org/index.php?id=293 (ANNEX XII Project 03).

The overall experience is that performance and operation of the storage is nearly as expected. The technology seems to be reliable, but lifetime for liner and insulation has to be further investigated.

4.6.2.2 Dronninglund

During the operation period from 2014 and onwards, no major problems have turned up. Water ponds are regularly removed from the lid and water can occur in the insulation. This may be due to water from water puddles on the lid transported through the ventilation valves. A yearly diver inspection shows no corrosion signs and clear water.

Performance and operation of the storage is as expected. The technology seems to be reliable but the lifetime for liner and insulation has to be further investigated.

4.6.3 Storage efficiency

Two examples of Danish PTES efficiencies are shown – a good one, and a not so good one. The large difference in efficiency shows that it is important to do things thoroughly. From the feasibility screening, construction, system integration to operation, maintenance and monitoring.

4.6.3.1 Dronninglund – good efficiency

The district heating production plant in Dronninglund comprise the following main production units:

- 37,600 m^2 solar collectors
- 2.1 MW cooling absorption heat pump
- Bio oil boilers
- Gas engines

And a PTES storage:

- Volume: 60,000 m^3
- Capacity: 5,400 MWh (T_{max} 89ºC and T_{min} 12ºC)
- Max charge/discharge capacity: 27 MW

The energy balance of the Dronninglund PTES for the period 2014-16 is shown in Figure 4.2. Using the numbers from the figure and defining the storage efficiency as:

EFF = (output + internal change)/input

gives an efficiency of:

EFF = (33038+1056)/ 38093 = 89.5%

The storage heat losses are only 10.5%

The number of storage cycles defined as charging / capacity is:

N_C =(38093/3)/5400 = 2.0.

The very good heat storage efficiency is mainly due to low storage temperatures (powerful heat pump) and well-functioning lid insulation - but also to some extent due to good utilisation of the storage, showing up in the value of the number of storage cycles = 2.

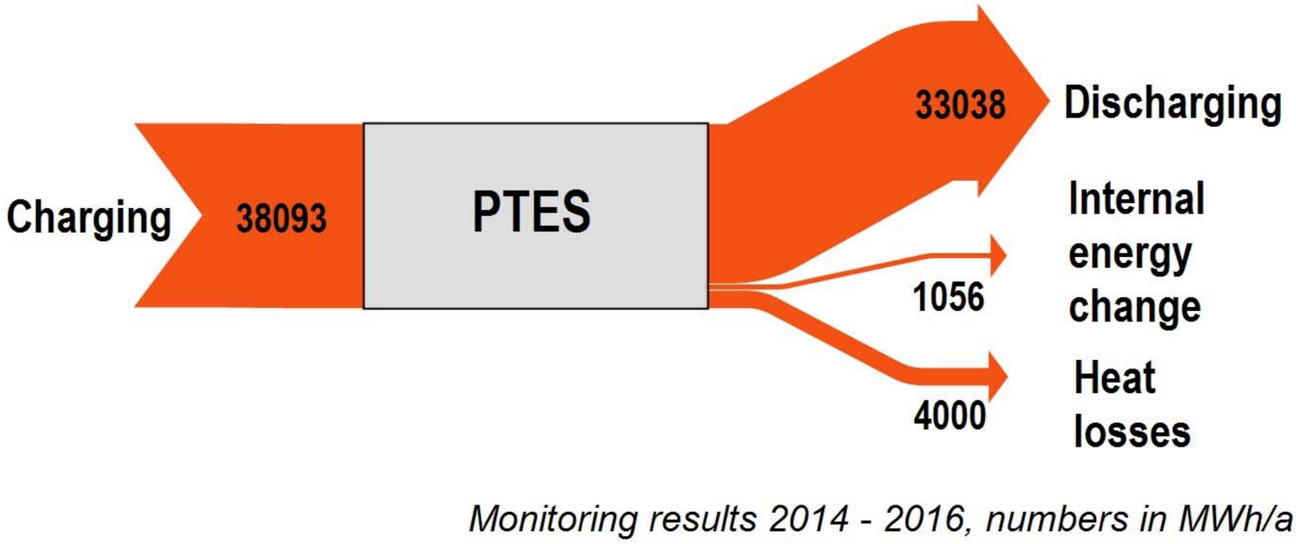

Figure 4.2 Energy balance for Dronninglund PTES, 2014-2016 (SOLITES)

4.6.3.2 Gram – not so good efficiency

The district heating production plant in Gram comprise the following main production units:

- 44,800 m^2 solar collectors
- 0.9 MW electrical heat pump
- 10 MW electric boiler
- 6.5 MW$_{th}$ CHP
- 10 MW Gas boilers

And a PTES storage:

- Volume:122,000 m^3
- Capacity: 8,630 MWh (61 K)

The energy balance of the Gram PTES in 2017 is shown in Figure 4.3.

The efficiency is calculated in the same way as above:

EFF = (2083+3868+583)/12997 = 50.3%

The storage losses are here massive 49.7%

The number of storage cycles defined as charging / capacity is:

N_C =12997/8630 = 1.5.

The massive storage losses are due to wet insulation in the lid. When this has been fixed, it is expected that the losses will be much lower.

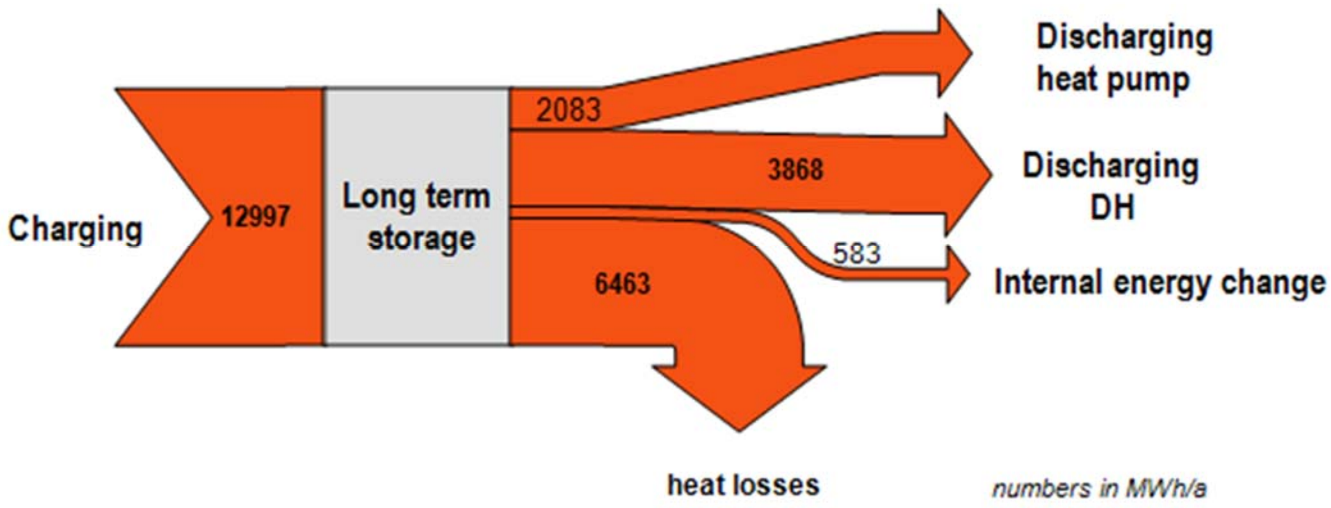

Figure 4.3 Energy balance for Gram PTES, 2017 (SOLITES)

4.7 Economics

In Figure 4.4 are shown investment cost data of realized large-scale UTES pilot, demonstration and full scale plants. For comparing different storage concepts and storage materials, the specific storage costs are related to the water equivalent storage volume. The listed storages are operated at maximum storage temperatures between 50ºC and 95ºC and are integrated into solar district heating plants with seasonal storage. Six of them are additionally used for CHP optimization and/or power-to-heat applications.

The graph illustrates that the cost decrease with increasing storage volumes. It is seen that Large-scale PTES are relatively cheap – down to approx. 25 €/m³.

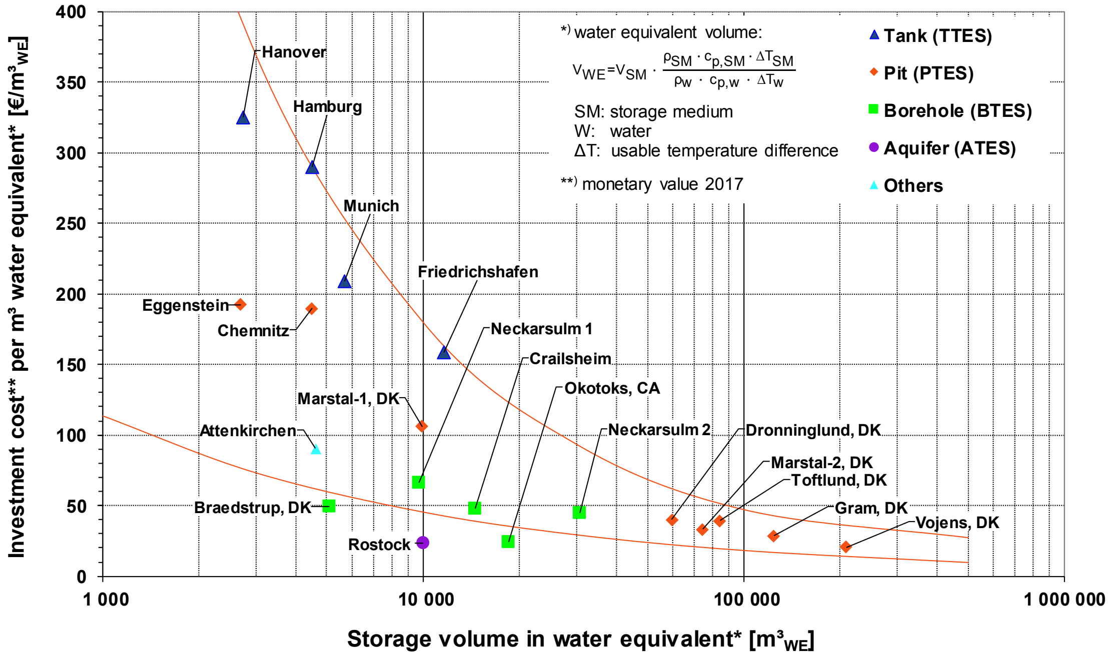

Figure 4.4 Specific investment cost for large-scale thermal energy storages (including all necessary cost for building the storage device, without design, without connecting pipes and equipment in the heating plant and without VAT) (SOLITES)

In Table 4.2 an example of the distribution of costs for the different parts/phases of establishing a PTES storage is shown.

Table 4.2 Cost of the storage in Marstal (SUNSTORE 4), 75,000 m³

Marstal (75,000 m³)		
	1000 €	**€/m³**
Excavation	601	8.0
Side and bottom liners	180	2.4
Lid	1,069	14.3
In- and outlet	172	2.3
Water and water treatment	195	2.6
Pipes and heat exchanger	413	5.5
Total	**2,630**	**35.1**

From the table it is seen that the lid in the Marstal case represents almost half of the total construction costs. The costs for design and consultancy are not included.

4.8 Conclusive remarks – PTES

Large scale PTES are so far[181] mainly used in Denmark - and in connection with solar district heating. Cost reduction has been the main driver for developing the Danish PTES concept with soil balance shaped as a truncated pyramid placed upside down.

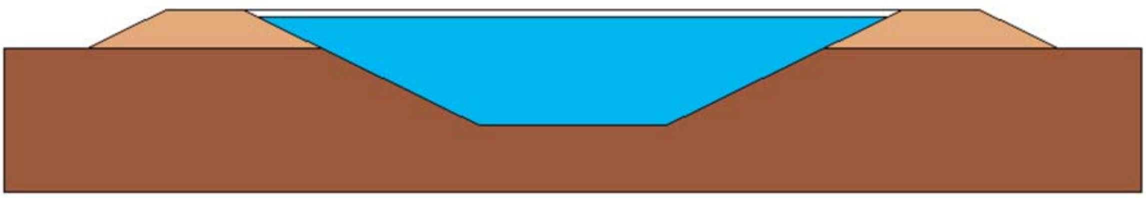

Figure 4.5 Danish PTES concept with soil balance shaped as a truncated pyramid placed upside down.

The status is that water is used as storage medium, welded polymer liners are used for tightening, the lid is floating on the water, and insulation materials in the lid are expanded clay or (PE/PEX) mats. Storages are uninsulated to the earth. Maximum temperatures are 90ºC.

Construction cost of large PTES storages are relatively cheap. A number of large-scale PTES were built in Denmark with investment costs of 20 – 40 €/m³

[181] China has now established the first large scale PTES – and many more are expected in the near future.

5 MTES (Mine Thermal Energy Storage)

Mine water of abandoned and flooded mines is used as a low-temperature energy source for heating buildings and a few plants exist in Germany and the Netherlands.

Up to this point a pilot plant has not been established, in which the possibility of thermal energy storage in a former coal mine has been considered.

5.1 Ongoing case studies

5.1.1 Overall objective

The aim of the German HEATSTORE sub-project is to create a technically and fully functional seasonal Mine Thermal Energy Storage (MTES) pilot plant for the energetic reuse of the abandoned coal mine Markgraf II in Bochum, with the emphasis on a two year operating and monitoring phase during the project lifetime. The generated data can be exploited for the implementation and dissemination of future deep geothermal storage systems. The conceptual idea is based on storage of seasonal unutilized surplus heat during the summer from solar thermal collectors within the mine layout and to use the stored heat during the winter for heating purposes of the institute buildings of the International Geothermal Centre (GZB).

5.1.2 MTES demo site in the HEATSTORE Project

This pilot plant aims at utilizing the abandoned coal mine Markgraf II, which is directly located under the premises of the International Geothermal Centre (GZB) in Bochum, as a seasonal MTES. This area also includes the drilling and test facility site (see Figure 5.1 below), on which the Bo.REX (Bochum Research and Exploration Drilling Rig) is currently located.

Figure 5.1 Location of the coal mine Markgraf II below the GZB well site (GZB)

This leads the way of a very cost effective exploration of the flooded Markgraf II mine in a depth of approx. 63 m below ground. The injection and production well and the additional monitoring wells will be drilled with the GZB drilling rig. The Markgraf II mine produced 37.043 tons of coal during 1953 to 1958. Based on a calculation with a coal density of 1,35 g/cm³, we can assume a void volume of approx. 27.439 m³. This volume does not include any drifts and shafts, which need to be analysed based on the mine layout. Considering the effect of mine subsidence, the remaining void volume will most likely be in the range of approx. 10%. Utilizing a Δt of 50°C within the mine water, a heat capacity of approx. 165 MWh, which resembles the yearly heat demand of the GZB compound, could be stored within dedicated drifts and former mining areas of Markgraf II, for the heating season. Based on this first evaluation the yearly GZB heat demand could be substituted by emission free solar thermal energy. After the two year pilot phase is concluded the integration of the Markgraf II MTES into the district heating network of the “unique Wärme GmbH” could be tackled, as two CHP plants (7,2 MW_{th}) are going to be put in operation by 7/2018 in a very close proximity of approx. 350 m to the GZB pilot plant.

5.1.3 MTES current state of technology

The idea of obtaining thermal energy from an inoperative colliery has already been pursued for a long time, although to a comparatively limited extent. Up to this point a pilot plant has not been established, in which the possibility of thermal energy storage in a former colliery has been considered. Well-known executed projects concerning the utilization of mine water include:

- The Mijnwater-project in Heerlen (Netherlands), whereby an already completely flooded and no longer accessible mine layout was accessed through directional drilling technology.
- The building of the School of Design at the Zeche Zollverein in Essen (Germany), which is heated by 28°C warm mine water, originating from the mine drainage of the RAG AG.
- The utilization of mine water of the former Robert Müser colliery in Bochum (Germany) as an energy source for the heat supply of two schools and the mine drainage station in Bochum. Within this pilot plant the 20°C warm mine water, which originates from the mine drainage of the RAG AG from a depth of -570 m NHN[182], is being used.
- Seven operational mine water utilization plants in Saxony (Germany), which can be categorized as shallow geothermal reservoirs. A deep mine water project is currently being implemented at the West Saxon University of Zwickau, where mine water from a depth of 625 m below ground with a temperature of 26°C is planned to be extracted.

The thermal utilization of the mine water from existing mine drainage stations, as they are realized in Essen or Bochum (Germany), show the highest economic efficiency, as no additional pumping costs are being generated. Due to the lack of suitable customers and a not yet existing final planning security concerning the future locations of mine drainage stations after the end of active coal mining (end of 2018) and the renaturation of the Emscher, a further expansion currently only takes place to a limited extent. The “open” utilisation plan of the Mijnwater-project could be realized in the Netherlands, as the mine workings are already flooded after being closed down. In case of a mine water table <80 m below ground, the proportion between the thermal energy obtained and the input energy (pumping energy) is to be assessed as positive, despite the low temperature of the mine water of about 28°C. Nevertheless, the mine water must be brought to a higher temperature level with the use of heat pumps.

In contrast to the Mijnwater-project in the Netherlands, the mine water table in the majority of the central and northern Ruhr area, with a depth of approx. −600 m NHN below the surface[183] is

[182] Normalhöhennull ("standard elevation zero") or NHN is a vertical datum used in Germany.
[183] RAG AG (2015) Grubenwasserkonzept der RAG Aktiengesellschaft. http://www.energieagentur.nrw/content/anlagen/2015_03_12%20Grubenwasserkonzept%20der%20RAG%20Aktiengesellsca.pdf. Accessed 19 November 2017.

considerably deeper so that at water temperatures of up to 35°C, the energetic expense of the lifting is too high compared to the thermal energy obtained. One way of increasing the efficiency is to increase the temperature of the mine water through the storage of seasonal heat in the mine layout, which has not been realized yet.

5.2 MTES feasibility studies in Germany

5.2.1 GeoMTES Project

The last operative hard coal mine in North Rhine-Westphalia (Germany), Prosper-Haniel, has just been closed down, plugged and abandoned at the end of 2018. Large amounts of subsurface infrastructure, resembled mainly by open parts of former galleries and mining faces are going to be flooded after the mine closure and therefore have the potential of becoming an enormous geothermal reservoir for seasonal heat storage.

At the moment a seasonal heat storage within an abandoned hard coal mine has not yet been realized in Germany. Therefore the MTES project (feasibility study) of the International Geothermal Centre (in cooperation with RAG AG and delta h Ingenieurgesellschaft mbH) would lead the way within the sector of renewable energy storage systems. The R&D project is funded since 2014 by the German Federal Ministries BMWi, BMU and the BMBF "Initiative Energy Storage" program.

The aim of this project is to create a technically and economically feasible conceptual model of a MTES for the energetic reuse of the hard coal mine Prosper-Haniel, which is situated in Bottrop (Germany).

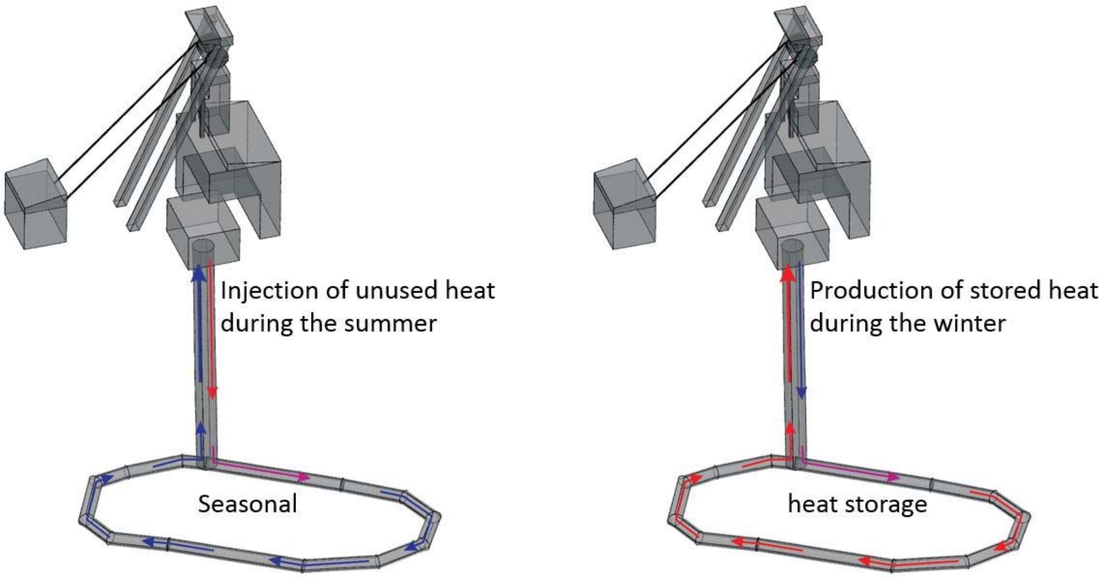

Figure 5.2 Conceptual model of seasonal underground heat storage in an abandoned coal mine (GZB)

The conceptual model (see Figure 5.2) is based on the storage of seasonal unutilized heat during the summer from solar thermal power plants, industrial production processes or CHP plants within the mine layout and to utilize the stored heat e.g. through distribution in a district heating grid during the winter, when there is a high heat demand. For the implementation of such a MTES within a former hard coal mine, the corresponding infrastructure measures and appropriate circulation applications would have to be modified, in order to establish a possible reutilization after the mine has been flooded. As a foundation for the implementation of a MTES, the undisturbed rock temperatures range between 30°C and 50°C[184] within the galleries and mining faces that are going to be flooded, after the mine is abandoned. The total mining area consists of 165 km^2 and the subsurface galleries have a total length of 141 km, at a maximum depth of 1159m NHN.

5.2.2 MTES Bochum

The aim of this project is to design a technically and economically feasible pilot plant for a MTES for the energetic reuse of the **abandoned** Dannenbaum colliery, which is located below the premises of the former Opel plant 1 in Bochum, Germany (see Figure 5.3). The abandoned Dannenbaum colliery was operated between 1859 and1958.

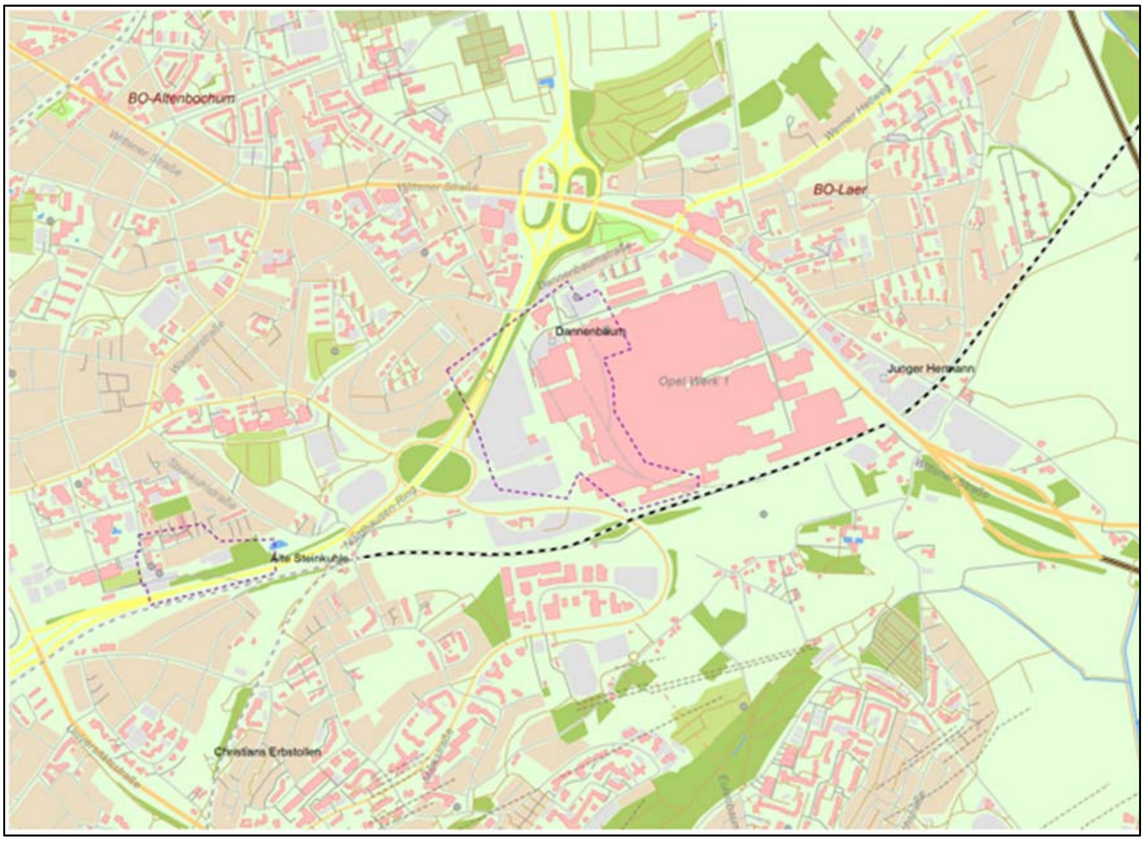

Figure 5.3 Location of the Dannenbaum colliery below the former Opel premises (www.ruhrkohlenrevier.de)

The conceptual model is based on the storage of seasonal unutilized surplus heat during the summer, supposedly from a CHP plant, within the mine layout and to utilize the stored heat through distribution in a newly established low ex district heating grid for this site.

The two main extraction shafts of the Dannenbaum colliery are located in the northwest of the former Opel plant in Bochum. The mine layout was developed down to a depth of -696 m NHN[185]. After the colliery was shut down, the two shafts were backfilled. Presently, the mine is flooded above the 4th level, up to -190 m NHN. It is assumed that within the mine building, an undisturbed temperature level of approx. 36°C[184] can be anticipated on the 8th level at a depth of -693 m NHN.

[184] Leonhardt, J. 1983: Die Gebirgstemperaturen im Ruhrrevier 90:218–230 RAG AG (2015).
[185] Huske, J. 2006: Die Steinkohlenzechen im Ruhrrevier. Daten und Fakten von den Anfängen bis 2005. 3., überarb. und erw. Aufl. Bochum: Dt. Bergbau-Museum (Veröffentlichungen aus dem Deutschen Bergbau-Museum Bochum, Nr. 144).

In a later test operation, the mine layout of the former Dannenbaum colliery is to be developed by a production and an injection well, using directional drilling technology. For this purpose, the production well should be drilled into the 8th level at -693 m NHN and the injection well into the 4th level at -227.6 m NHN. Once the feasibility study has been successfully completed, a pilot plant is planned to be implemented promptly. This would aim at the establishment of a central heating system with a CHP plant and a heat pump for the innovative heat supply of the new settlements on the former Opel premises, which is now marketed under the acronym Mark 51°7.

5.2.3 Requirements of a MTES

A MTES needs to have a large mine water volume, in order to store vast amounts of heat. At the same time, it has to be reliable, cost efficient and should be integrated into existing urban frameworks. In order to meet economical requirements, a MTES needs to be operative in the range of 40 to 50 years. Depending on the utilized heat source and its application, different heat capacities, mass flows and temperature levels would be encountered within the mine thermal energy storage.

All affected components need to be suitable for the intended operations and their possible resulting stresses. If the seasonal heat storage is operated by several different heat sources, a careful coordination of the specific heat amounts and loading cycles of the individual source needs to be taken into consideration.

5.2.4 Numerical modelling of MTES

Modelling hydraulic and thermal impacts on a regional scale for the MTES project presented many challenges, including appropriate discretization of mine drifts as well as accurate modelling of layered aquifer systems. To accommodate the complex underground heat reservoir and its interaction with the surrounding aquifers and fault systems, the finite element (FE) modelling code SPRING[186] was selected. SPRING includes a boundary condition specifically to describe mines or separate mining fields within a finite element mesh and to couple their hydraulic and thermal behaviour to the surrounding rock mass and aquifers. The software was first published in 1970 and has undergone a number of revisions. SPRING uses the finite-element approximation in solving the groundwater flow and -transport equations. Different model layers with varying thicknesses, including the pinching out of a layer, are possible. In order to predict the impacts of both historic mining operations and future thermal impacts, a detailed conceptual model of the aquifer systems and a three-dimensional model of the mine drifts were incorporated into a regional numerical heat and transport model. The model was used for dimensioning of the reservoir layout as well as for optimization of flow rates, dam positions and temperature profiles.

5.3 Outlook

The development of diversified storage capacities will have a great impact on the future promotion of renewable energy sources. Within the Ruhr area, unutilized mining infrastructures in combination with available unutilized surplus heat from power plants and industrial processes, resemble a vast potential for large heat storage capacities. Out of this reason, fundamental research in the field of seasonal heat storage in abandoned mines has to be conducted for further technology development and establishment of large scale storage systems.

In the case of a technical and economical implementation of the MTES, the design and operation results of the seasonal heat storage within an abandoned hard coal mine, would be scalable to other locations in Germany and worldwide.

[186] König, C. M. et. al. 2012: SPRING Manual, Vol.4.1, ISBN 978-3-00-040369-9, delta h Ingenieurgesellschaft mbH, Witten.

6 Existing barriers for (HT)-UTES

6.1 Introduction

The future development of High Temperature UTES systems are on a wide scale dependent on how existing barriers can be overcome or broken down. National legislation and regulation, (socio)-economic parameters and to some point technical issues are present existing barriers that are encountered both internationally and on a national scale.

In this "Lessons learned" report the main existing barriers are identified based on especially prior project studies focusing on barriers in shallow geothermal energy and heat storage. (e.g. *Regeocities* (regeocities.eu) and *E-USE(aq) Pathfinder*). Many of the known barriers are the same, or very much similar, across country borders. The European partnership in HEATSTORE is in this aspect a good platform to boost a successful development of HT-UTES in the years to come.

To overcome barriers the attractiveness of HT-ATES, BTES, PTES and MTES systems needs to be demonstrated and promoted. In Figure 6.1 is shown a general overview of the important advantages in the use of HT-UTES and the corresponding barriers discussed at the first HEATSTORE WP1 workshop in Bochum, Germany. Looking at the identified barriers from the discussion, they fall in the following categories:

Geographical parameters	Subsurface suitability Subsurface uncertainties (availability of existing data and information) Surface heat demand and infrastructure (developments) Optimal positioning/location choice in the thermal grid
Legislation and regulation	Unclear regulations for HT UTES systems Time consuming application and permit process No international guidelines for subsurface heat storage Regulatory framework for thermal grids and third party access
Public awareness and acceptance	Lack of knowledge in the public on technical HT-UTES solutions Low awareness in the public (politicians, stakeholders) Questionable business cases in the past (e.g. poor system integration) Awareness in urban/subsurface management Quality issues - system construction, water quality
Economic /socio economic	Large initial investment costs Heat demand and low marginal cost heat source (input source) Impact of ownership on business case for HT-ATES (heat source owner, grid owner, third party) Lack of district heating network in many urban areas
Technological parameters	Proven business case with newest technology Optimal system integration

The barriers are described in more detail in the following sections.

Advantages in the use of HT-UTES

- Clean energy
- Positive balance on CO_2 certifications (CO_2 savings and low CO_2 footprint)
- Contributes to Energy independency
- Contributes to Energy transition away from fossil fuels
- Use of waste heat
- Use of Solar heat and power
- Leveling out production/consumption
- Local source of energy → local commitment and engagement
- Storage → balance of heat surplus demand → good business case
- Storage of heat is becoming a known/hot topic in politics

Existing barriers

- No uniform international policies
- Missing national guidelines
- Missing regulations for HT systems
- Lack of district heating network in many countries (off grid)
- Still in need of proven business cases
- Dependent on local geology
- Uncertain effects on subsurface - how to assess this?
- Poor system integration → bad business case
- No SDE subsidies on HT-ATES
- Environmentally friendly technique to be developed for water treatment in ATES → use of CO_2
- Geochemistry and biology is site specific and partly unknown
- Many areas are not populated densely enough
- Conflicts with groundwater – public authorities

Figure 6.1 Discussed advantages in the use of HT-UTES, and existing barriers in the HEATSTORE partner countries (WP1 workshop discussion, Bochum 22nd of November 2018)

Fleuchaus et al.[187] has illustrated the important market barriers for ATES systems in a review study of existing systems worldwide, see Figure 6.2. The diagram/graph is divided in three phases: Emerging market, growth phase and maturity phase. The figure gives a good overview on what type of barriers that are challenging in different phases of technologic development and market breakthrough.

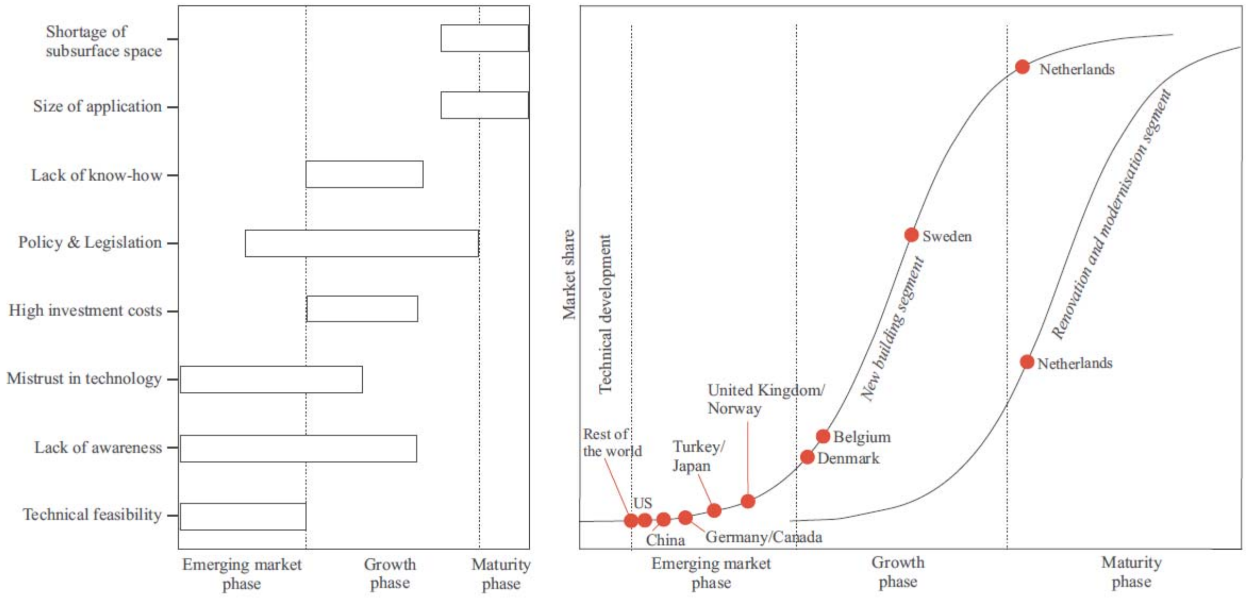

Figure 6.2 Left: market barriers limiting ATES development as a function of the market development level (suitable subsurface and climatic conditions are assumed) and right: market development of ATES in all relevant countries considering new building and renovation segments (reprinted from Renewable and Sustainable Energy Reviews, Vol 94, Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. Worldwide application of aquifer thermal energy storage – A review, 861–876, Copyright (2018), with permission from Elsevier[187])

Wesselink at al.[188] have developed a methodological framework to assess theoretical and technical potentials for HT-ATES (see Figure 6.3) and presenting a quick scan for identifying the feasibility of a HT-ATES case taking into account technical, economic and market conditions. The framework presented below defines research steps and key information that brings the researcher from technical potential towards market potential.

[187] Fleuchaus, P., Godschalk, B., Stobera, I. & Blum, P. 2018: Worldwide application of aquifer thermal energy storage – A review. Renewable and Sustainable Energy Reviews 94, 861–876.
[188] Wesselink, M. et al. 2018: Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands, Energy 147,477-489.

Theoretical storage potential				*Typical focus: local to national potential*
Critical information needed		**Research steps**		**Typical results**
• Depth of aquifers and aquitards • Net thickness of aquifers and aquitards • Permeability, porosity, transmissivity • Groundwater properties (flow, salinity, viscosity, temperature, density) • Hot well injection temperature • Cold well injection temperature	→	• Define boundary conditions for suitable aquifer segments • Create inventory of suitable aquifer segments • Calculate specific heat capacity of each aquifer segment • Calculate storage capacity of segments • Calculate cumulative subsurface aquifer heat storage capacity for area under study	→	• Thermal storage capacity (PJ/km^2) • Uncertainty attribution to Thermal Storage Capacity

↓

Technical storage potential				*Typical focus: local to national potential*
Critical information needed		**Research steps**		**Typical results**
• Technological drilling restrictions • Technological restrictions for temperature trajectory • Technological flow restrictions (well, pumps, aquifer stability)	→	• Correct available subsurface volume for drilling restrictions (e.g. impermeable rock formations) • Correct for injection and return temperatures • Assess temperature loss in subsurface (well, aquifer, aquitard) • Assess optimal well placement • Assess technical optimal annual injection and production profile	→	• Thermal storage capacity (PJ/km^2) • Thermal storage capacity ($PJ/year/km^2$) • Thermal storage production and injection power ($MWth/km^2$)

↓

Economic & market potential				*Typical focus: local / project specific*
Critical information needed		**Research steps**		**Typical results**
Economics • Time dependent (future) heat demand and supply profile (GJ/day or GJ/week) • Specific investment costs (euro/MW) • Fixed and variable operation & maintenance cost (eur/GJ; eur/MW) • Economic life time (year) • Marginal costs of heat sources (euro/GJ) • Financial and fiscal parameters (equity share, discount rate, tax rates, subsidies) • Cost of competitive heat sources *Local implementation* • Stakeholder acceptance • Spatial planning restrictions: subsurface competition and surface restrictions (e.g. nature areas, drinking water areas) • Regulatory framework	→	• Assess local implementation drivers and barriers • Calculate optimal annual injection and production profile over lifetime of ATES • Assess economical optimal well configuration and sizing of system • Assess business case of ATES configuration in local (district) heat system • Assess business case of alternative heat sources	→	• Thermal storage capacity (PJ) • Thermal storage production and injection power (MWth) • Stored thermal energy (PJ/yr) • Net present value (Eur) • Levelized cost of energy (eur/GJ) • Internal rate of return (IRR)

Figure 6.3 Methodological framework of assessing theoretical, technical and economic & market potential of HT-ATES (reused from https://doi.org/10.1016/j.energy.2018.01.072 with permission by Elsevier Ltd. under Creative Commons license CC-BY-NC-ND https://creativecommons.org/licenses/by-nc-nd/4.0/[189])

[189] Wesselink, M. et al. 2018: Conceptual market potential framework of high temperature aquifer thermal energy storage - A case study in the Netherlands, Energy 147,477-489.

6.2 Geographical barriers

The geological and hydrogeological conditions are the first prerequisites defining the potential of HT-ATES or BTES. Screening for suitable areas on a national scale for aquifer and borehole heat storage is therefore a first step in the initial phase to guide the decision makers. This overview is presently available in several countries as e.g. mentioned in the E-USE(aq) Pathfinder project[190].

Pit Thermal Energy Storage (PTES) is less dependent on the subsurface characteristics, but are more space demanding at the surface. This can pose a barrier in dense populated areas/urban areas where space for a large pit storage and potential solar collectors is limited. Mine storage (MTES) is limited to suitable areas with abandoned mineshafts in applicable depths such as the Ruhr district (see section 5.1.2).

The requirements on the surface such as heat demand, heating infrastructure, water protection zones etc. are geographical obstacles as well. A thorough feasibility study should be able to identify these potential barriers.

6.3 Legislation and regulation

The national legislative framework is generally described as a main barrier to overcome regarding development and implementation of HT-UTES in many countries in Europe. Even though technologies as HT-ATES and BTES are not new, only very few systems have been established due to e.g. limitations in the legislation and poor business cases. The legislation is currently generally not adapted to HT-UTES systems, and as a consequence the permit procedures can be long, uncertain and expensive. Also missing or lacking common standards for quality schemes can pose a barrier in regard to confidence in the HT-UTES technologies[191].

The legislation defines the ownership of the heat storage/geothermal energy resource and should therefore identify the relevant authority responsible for licensing and regulating HT-UTES systems at regional/municipal/local level. Clear regulatory definitions are necessary in the implementation of successful legislation for Shallow Geothermal Energy (SGE) or HT-UTES. In the Regeocities EU project[192] the following definitions are considered important in establishing a clear regulatory framework for shallow geothermal resources:

- System Size (small scale and large scale systems)
- System Use – heating, heat storage and/or cooling requirements
- Geological and groundwater aquifer characteristics & sensitivity
- Borehole construction standards
- Thermal effects of long term operation
- Hydrogeological effects
- Mandatory monitoring
- Subsurface users (stakeholders)
- Depth (especially HT-ATES)
- Storage temperatures

The depth of the reservoir/storage aquifer and limitations in storage temperatures are important definitions regarding the legislation of HT-UTES. E.g. depth limits in the legislation can determine if the HT-UTES application is considered as deep geothermal energy resources. These broad

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[190] Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; "*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*", Technical report, January 2016.
[191] Jaudin, F. et al. 2013: Regeocities. General Report of the current situation of the regulative framework for the SGE systems, Deliverable 2.2, September 2013 (www.regeocities.eu).
[192] Pasquali, R. & O'Neill, N. 2015: Regeocities. Recommendation guidelines for a common European regulatory framework, Deliverable 3.4, June 2015 (www.regeocities.eu).

definitions are required to provide a common background to guide the local regulatory process that can vary between member states/regions/municipalities/local authorities. If the regional regulations appear heterogeneous it is difficult for UTES professionals to plan and manage the permission process. In different countries local authorities can be more or less involved in the regulative procedures for SGE/UTES systems.

6.3.1 National level

There are significant differences between the various countries regarding legislation for Shallow Geothermal Energy (SGE) systems. In general, permits are required for UTES and other SGE systems. An administrative approval can therefore be quite a significant and time consuming process. Over-regulation and regulation regarding the use of surplus heat are mentioned as country specific barriers. In the following sections a short description of relevant legal and regulative practices in the HEATSTORE partner countries regarding UTES are given. The national information are primarily compiled from the country reports in the Regeocities project (http://regeocities.eu/results/) and *the E-USE(aq) Pathfinder* project.

6.3.1.1 The Netherlands

In the Netherlands, both the national legislation and the legislation in the provinces are adapted to UTES – especially ATES systems. Bloemendal et al.[193] gives an overview on this topic: Permit conditions for utilizing aquifers for geothermal resources are described clearly. ATES systems are regulated in the Water law. This law regulates the management of surface water and groundwater on a national level. It is forbidden to extract groundwater for the use of ATES without a permit from the provincial government.

The law also states that each province has to describe its water policy in a so-called Provincial Water Plan. Each province has described a policy for ATES systems. The policy describes the provincial vision on ATES and what conditions an ATES system has to meet in order to obtain a permit. E.g. rules on maximum infiltration temperature, energy balance, use of aquifers, water quality etc. These rules are province based.

An ATES system is not allowed to have negative influence on other interests. These interests are (inter alia) drinking water extracting plants, nature, archaeology, ground (water) pollutions, infrastructure and other ATES systems.

The Decree on Shallow Geothermal Energy (SGE) effectuated July 1th 2013 proclaim:
- The municipality will become the authority for GCHP systems.
- New GCHP (Ground-Coupled Heat Pump) systems have to be reported to the authorities.
- For systems with a capacity below 70 kW, only a declaration is needed.
- If a system has a capacity that is higher than 70 kW, a permit is needed. This permit will be issued by the municipality as well. The municipality decides if they allow the system or not. There are no permit requirements attached to the permit, like for ATES systems.
- For the application of a permit, a description of the expected effects of the intended system has to be included.
- For GCHP systems that are already constructed, it is not compulsory to register.

Furthermore, the decree foresees the implementation of geothermal energy systems in spatial planning. This is done by creating the possibility to designate the so-called 'areas of interference'. In these areas the interference between different systems is in focus and can be prevented. The municipality is allowed to designate these 'areas of interference'. These are zones where the

[193] Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; "*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*", Technical report, January 2016.

number of SGE systems is, or is expected to be, high in a way that the application of SGE systems is, or will be, problematic due to a lack of space. Spatial planning of the subsurface in these zones is necessary. In these ‘zones of interference’, all BTES systems require a permit. The reason for this is to prevent smaller and energetically less favorable BTES systems from “disturbing” the use of big ATES systems[194].

For HT-ATES systems there are some hurdles related to the current regulatory framework. The regulatory framework most relevant for HT-ATES is summarized in Table 6.1 below. Important aspects to consider for HT-ATES with influence on the applicable framework and specific guidelines are the temperature and the depth of injection/production. The depth determines whether the Mining act and related regulations are applicable or whether it is the Water act and related regulations. It also determines the competent authority for the permitting procedure.

The current HT-ATES projects are executed or being developed to be at shallower depth than 500 m. This results in some important restrictions for ATES projects. The most important restrictions are the maximum allowed injection temperature of 25°C, limitations on the effect of heating the subsurface and the requirement to achieve net energy equilibrium every 5 years.

Table 6.1 Summary of regulatory framework for HT-ATES in the Netherlands

Depth of storage	**<500 m**	**>500 m**
Applicable regulatory framework	• Waterwet • Waterbesluit (AMvB Wijzigingsbesluit bodemenergiesystemen) • Waterregeling • Besluitvormingsuitvoeringsmethode (BUM) provinciale taken en Hand-havingsuitvoeringsmethode (HUM) provinciale taken,	• Mijnbouwwet • Mijnbouwbesluit • Mijnbouwregeling
Most important restrictions	• Infiltration temperature <25°C • No heating of the subsurface • Net energy equilibrium every 5 years	*No specific limitations set for HT-ATES*
Competent authority	Province	Ministry of Economic affairs
Procedure duration	~5 months (minimally)	6-9 months
Permit	Watervergunning (artikel 6.4 Waterwet) Water act permit	Opslagvergunning (art. 25 Mijnbouwwet) Storage permit Mining act

The projects in the Netherlands entails the injection of hot water to be well above 25°C. According to Dutch law[195] injecting water with a temperature above 25°C is only allowed if the project is considered to be a pilot R&D project. Pilot projects for injection of water with temperatures above 25°C have previously been permitted and realised in the Netherlands[196], but not at temperatures as proposed in the HEATSTORE project. Important lessons have been learned, but the regulatory framework has not yet fully materialised.

194 Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; “*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*”, Technical report, January 2016.
195 https://zoek.officielebekendmakingen.nl/stb-2013-112.html
196 Thermisch rendement hoge & middelhoge, temperatuur warmteopslag in de bodem, IF Technology 2014. https://www.kasalsenergiebron.nl/content/user_upload/MTO_en_HTO.pdf

In Koornneef et al. (2015)[197] the lessons learned from a recent permitted HT-ATES in the province of South Holland have been reported (in Dutch). Further details are there included on the provincial guidelines that indicate the set of boundary conditions for (HT-)ATES design and operation and set guidelines for monitoring.

The most important aspects to take into account in the permitting procedure are:

- The effects of the injection of high temperature reservoir water, including hydrothermal effects, geo-chemical effects and effects on microbiological populations in the subsurface.
- The amount of heat stored, the surplus of heat stored and the possible effect of surplus heat in the subsurface.
- The expected energy efficiency and its related environmental benefits (e.g. emission reduction).

To assess, minimize and monitor these effects careful procedures have been developed in earlier (pilot) projects and implemented to assess and monitor the effects over the full life cycle of the projects. These procedures have been laid down in permitting procedures. To minimise the environmental effects due to the proposed project these procedures can be followed and be improved/adapted as necessary. Careful further discussions with the competent authorities (and other stakeholders) are thus important to set the boundary conditions for design and operation of the ATES.

Permit requirements
A summary of the most important permit requirements that could be expected for the HT-ATES is presented below (see also Figure 6.4 for outline) based on experience with HT-ATES permitting in the province of South Holland. This does not necessarily mean that permitting the project under study would follow the same requirements.

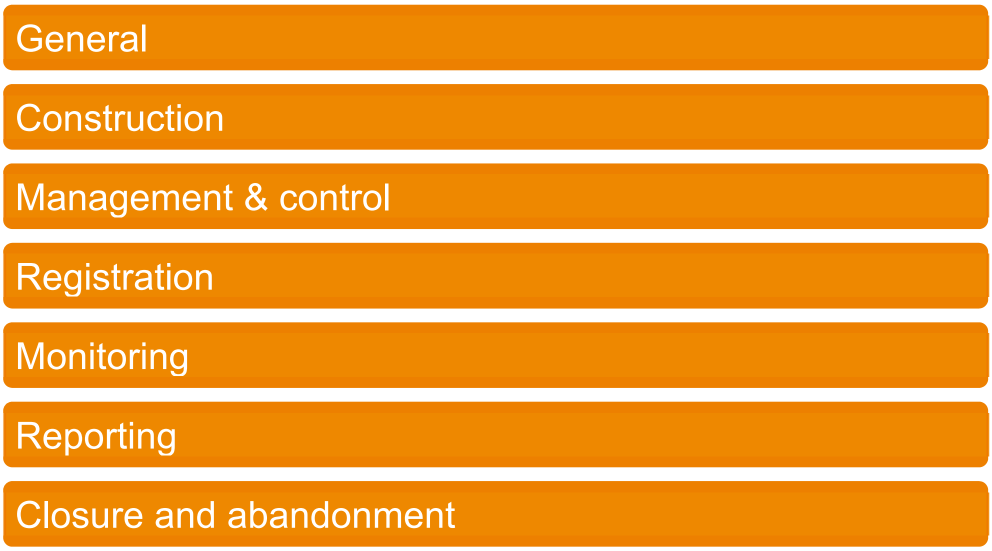

Figure 6.4 Outline of Permit procedure

[197] TNO 2015 Technical and juridical challenges for High Temperature Aquifer Storage (in Dutch)

General
This part of the permitting requirements defines the total amount of groundwater volumes that can be extracted and injected. This section also describes whether groundwater extraction and injections needs to be balanced on an annual basis depending of what exceptions are allowed (e.g. excess water from well test and well workover).

Construction
The permit sets requirements on the design and construction standards (NEN/ISO/BRL) of the ATES. The workflow of detailed designing (and later constructing) the ATES should be done according to the workflow prescribed in defined guidelines (SIKB BRL). This includes a test drilling for the design and permit phase[198]. It will be performed up to 500 m by a certified drilling company. The test drilling can later be used as a monitoring well. This results in local geohydrological description and a monitoring well for groundwater sampling and temperature measurements.

Management & control
The permit sets important boundary conditions related to maximum injection temperature (both cold and warm well) and in the ATES in South Holland the permit has set conditions to the maximum temperature in the first water bearing layer (aquifer) at 25°C. It sets boundary conditions to water treatment (e.g. conditioning with low concentration of hydrochloric acid) on the pH and calcium carbonate saturation index and prescribes how well workover should be carried out and how to report on such activities.

Registration
The most important items that need to be registered are mentioned in the permit. One of them is the registration of the extracted and injected volumes of groundwater and how these are to be measured.

Monitoring
The focus regarding monitoring is on the following aspects:
- Temperature.
- Energy equilibrium.
- Geohydrological effects.
- Groundwater quality.
- Microbiological effects.

The monitoring package for a recently permitted HT-ATES includes the prescription to perform a baseline assessment of groundwater quality (chemistry/microbiology) and the geohydrological state. Furthermore, to assess the effect of the ATES several multi-annual monitoring packages are included in the permit requirements to measure chemicals, metal ions, heavy metals, gasses and the microbiological state. Monitoring wells (3 in total) are prescribed to allow for these measurements to take place at different coordinates in the temperature influenced area. In the permit it is also mentioned that deviations from expected values for monitored items should be reported within one month.

Reporting
The permit sets requirements for the content and frequency of reporting. A yearly report is requested showing the most important parameters to measure the performance of the ATES, e.g.: temperature, energy and groundwater flow. After three years a detailed report was prescribed to evaluate the chemical, microbiological, thermal effects in the subsurface of the ATES site.

[198] During drilling, cuttings are collected and borehole logging will be performed. After drilling ground water samples are taken and analyzed by a BRL 2000-approved sampling company.

When relevant this report should include proposals for improvement to minimize or mitigate adverse effects.

Closure and abandonment
Important provisions for the end-of-life of the ATES are:

- The operator needs to assess together with the competent authority if and how the surplus of heat that remains in the subsurface after closure can have a useful function.
- (Monitoring) wells need to be closed (filled) within one month after ending operation.
- The initial subsurface profile needs to be restored.

6.3.1.2 Germany

For any intrusion into the underground (drilling or digging), permission is required from a certain depth. A general rule is that permission is needed whenever the intrusion into the underground reaches the groundwater level. A license (Erlaubnis as to WHG § 8) from the relevant water authorities is required, and this is the case for both open and closed loop geothermal systems.

For boreholes penetrating more than 100 m into the underground (100 m of drilling length, not necessarily vertical depth), the application has to go to the mining authorities as to BBergG § 127, and the mining authorities will carry out the licensing process and include the water authorities into the procedures. Another requirement is that all “drillings driven by mechanical power” have to be reported to the Geological Survey of the respective state.

Generally, geothermal energy including shallow geothermal energy is subject to the regulations of the Federal Mining Law, hence the right to use the energy available from the soil space beneath a particular property does not belong to the property owner. But, in the case that geothermal energy is only used for the energy supply in context with the use of the own property and, the geothermal facility does not exceed a depth of 100 m, the exploitation of the geothermal energy can be regulated by a permit process within the Water Household Act (WHG)[199].

6.3.1.3 France

In France, a legal framework exists to manage SGE/UTES. The framework is described in general by Jaudin et al.[200] and essentially consists of a mining code and an environment code. Realization of drillings is legally supervised by the mining code and, groundwater exploitation by the environment code. These codes plan procedures of authorization (licenses) or declaration (notifications) according to the Heat Capacity, and the depth of the drilling(s) of the SGE project and its technical characteristics (power, depth, water flow, temperature, quality of the rejected water).The management of the files of declaration (notifications) / authorization (licenses) is managed at regional level (Prefecture of Region and Regional direction for environment, DREAL) via: a) water police departments for files with pumping / injection of water, b) mine police department for the purely thermal files (without pumping / injection of water).

The environment code also plans regulations answering local problems. Purely local regulations can also exist (prefectural or municipal orders). In densely built urban environment, some additional requirements are also to be fulfilled, for instance, minimum distances with regards to pipelines, electric networks, roads or buildings etc.

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[199] Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; “*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*”, Technical report, January 2016.
[200] Jaudin, F., Bezelgues-Corurtade, S. & Poux, A. 2013: “French regulative framework”, Regeocities, Deliverable 2.1, National report WP2, June 2013, (www.regeocities.eu).

For new buildings or strong refurbishment projects, with a total useful floor area >1,000 m², it is mandatory to investigate the technical, environmental and economic feasibility of alternative energy supply systems (for heating, cooling, ventilation, refreshing, hot water production and lighting (decree n° 2007-363 du 19 March 2007). This study has to be joined to the construction license request.

6.3.1.4 Belgium

The utilization of shallow geothermal energy in Flanders is regulated by the 6 February 1991 Order of the Flemish Government concerning Environmental Licences (VLAREM I). VILAREM I, divided into sections, determines when an environmental permit must be requested. Depending on the level of nuisance, the project is classified in one of the three classes:

- Class 3: no permit, but only a notice to the Municipality;
- Class 2: a municipal permit;
- Class 1: a provincial permit.

Specific guidelines are applicable for the use of heat pumps (VLAREM, chapter 16.3: installations for the physical threat of gases). Furthermore, the installation of the ground source system is governed by VLAREM, chapter 55.6. For groundwater systems, it is obliged to have a reinjection well that returns groundwater in the same aquifer as the extraction well. For vertical loop systems, it is obliged to have an announcing at the local government for shallow loops (< 50 m) and to submit a permit demand to the provincial government (> 50 m)[201,202].

6.3.1.5 Switzerland

The Suisse legal framework is based on the water protection Federal law (OEaux, annexe 2 chapitre 21 alinéa 3) which states that the heat production or injection in groundwater must not change the natural groundwater temperature more than 3˚C. In the Swiss Federal Office of Environment guidelines, it is prescribed that this maximal temperature variation (ΔT_{max}) has to be considered outside a 100 m radius from the exploitation point. Within a 100 m radius larger temperature fluctuations are allowed. (OFEV, 2009).

Similar prescriptions are also applied by the law SIA 384/7 which regulates the heat use from groundwater. This law introduces also the concept of reinjection. Therefore the mentioned 3˚C limit is applied to the injection well, which allow larger temperature variations within a 100 m radius from the injection point. Furthermore, this law states that if the temperature difference between production point and injection point exceed 10˚C, the groundwater nature has to be studied in details. This means that a ΔT_{max} of 10˚C is possible in respect of the 100 m radius on a seasonal basis (SIA, 2015).

Additionally, prescriptions concerning chemical and biological processes are described in annex E2 (SIA, 2015). In the case of pumping wells, no minimal distance is imposed. In some cantons, as Zurich, some differences in the authorization process are applied for heating or cooling uses. For groundwater cooling, local differences of 7˚C for heating buildings is accepted (OFEN, 2017).

The SIA 384/7 law, excludes seasonal thermal energy storage targeting groundwater at temperatures higher than 25˚C from its scope of application (part 0 scope of application SIA, 2015). The current legal framework suffer from lack of clarity regarding groundwater with temperatures higher than 25˚C, which corresponds to about 400 m in depth.

[201] Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; "*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*", Technical report, January 2016.
[202] Fallon, G. & Croufer, M. 2012: "Belgian regulative framework", Regeocities, Deliverable 2.1, National report WP2, April 2013, (www.regeocities.eu).

The Swiss Federal Office of Environment guidelines (2004), recommend that the feasibility of exploitation of geothermal energy from deep wells, has to be considered case by case to define the prescription to apply. The term "deep wells" is not defined in details.

6.3.1.6 Denmark

The regulation of SGE/UTES in Denmark is national and the steps and procedures to follow for establishing ground source heating and cooling are the same for the whole country. However, the permitting authority is the local municipality, which can introduce differences in the administration of the regulation.

Ground Source Heating and Cooling is regulated pursuant to the Danish environmental protection act and permissions are issued by the municipalities. There are different regulations for closed and open loop systems, respectively. The municipalities and the Danish Energy Agency have agreed, that if planned boreholes for geothermal energy are deeper than 250 m, the Energy Agency must be consulted to clarify whether the installation are subject to the subsoil act or not[203].

Closed loop systems

Permissions for closed loop systems are administrated pursuant to the statutory order “BEK nr 1019 af 25/10/2009”. The purpose of the order is to prevent contamination of the groundwater, soil or underground, by setting up rules for construction, operation and inspection of ground source heating and cooling installations. Below is a summary of the most important content of the order:

- Ground source heating systems must not be established or changed without a permit.
- Horizontal installations must be placed at least 50 m from drinking water wells and at least 5 m from other water wells.
- Borehole heat exchangers must be placed at least 300 m from drinking water wells and at least 50 m from other water wells.
- Horizontal installations with direct expansion must be placed at least 10 m from drinking water wells supplying 10 or more households and at least 5 m from drinking water wells supplying less than 10 households.
- The municipality can increase the required safety distance to drinking water wells and stipulate special conditions in the permit regarding e.g. the construction of the installation, in order to protect a water catchment against contamination.
- The distance between boreholes for borehole heat exchanger systems must be at least 20 m.
- The order specifies the type of plastic pipes that can be used for horizontal and borehole systems, respectively.
- A specific statutory order for the execution of boreholes also applies for boreholes for closed loop systems (“BEK nr 1000 af 26/07/2007”).
- If the void between plastic pipes and borehole wall in borehole heat exchangers is not entirely filled with sealing material, the system must be designed to ensure that the inlet temperature for the heat pump is always above 2ºC.
- A ground source heating system must be tight and equipped with a pressure-drop alarm and auto-stop device in case of leakage.
- Before start-up of a ground source heating system, a leakage test must be performed. The leakage test must be performed using clean water at 1.5 times the working pressure.
- A yearly inspection of the ground source heating system must be performed by a professional.

[203] Vangkilde-Pedersen, T. & Nielsen, A. M. 2012: ”Denmark – National Report”, Regeocities, Deliverable 2.1, National report WP2, December 2012, (www.regeocities.eu).

Open loop systems

Permissions for open loop groundwater based systems are administrated pursuant to the statutory order “BEK nr 1206 af 24/11/2006”. By setting up rules for construction, operation and inspection of installations, the purpose of the order is to ensure that the aquifer groundwater quality is preserved and that no water catchments are contaminated. Below is a summary of the most important content of the order:

- Open loop groundwater systems must not be established or used without a permit.
- The applicant must document that groundwater will be produced from and re-injected into the same aquifer.
- The applicant must document that investigations have been performed that provides the following information about the aquifer:
    - The geology, hydrogeology and spatial extent
    - The hydraulic properties including connectivity to other aquifers
    - The hydrothermal properties
    - The chemistry and microbiology
- An application must include information documenting that:
    - There is no risk for groundwater contamination by agents used in the heating circuit
    - There is no risk for soil failure caused by the re-injection of produced groundwater
    - The installation is a closed system, with no possibility of invasion of atmospheric air and with no water treatment
- Numerical modelling is required in order to show that:
    - The temperature of the groundwater in existing water catchments will not increase more than 0.5ºC
    - The groundwater resource in “areas of specific drinking water interests” will be exploitable again 10 years after closing the installation
- No mixing of groundwater with other fluids must take place in the consumer circuit.
- The installation must be equipped with a pressure-drop alarm and auto-stop device in case of leakage.
- The monthly average outlet temperature of the groundwater for re-injection must not be lower than 2ºC
- The outlet temperature of the groundwater for re-injection must not exceed 25ºC and the monthly average outlet temperature must not exceed 20ºC.
- Before start-up, the owner must provide a chemical analysis of the water in the aquifer used for production and re-injection, including temperature measurements.
- Three months after start-up, and then on a yearly basis, the owner must analyze the outlet water for agents that could potentially be dissolved from the system.
- An open loop installation must be equipped with temperature sensors measuring the inlet and outlet temperature of the groundwater.
- The re-injection well must be equipped with temperature sensors connected to an automatic data-logging system and the logged outlet temperatures must be reported on a yearly basis to the municipality.
- The extraction and re-injection of groundwater must be monitored and reported on a yearly basis to the municipality.
- A yearly inspection of the open loop system must be performed by a professional.

The statutory order for execution of boreholes (“BEK nr 1000 af 26/07/2007”) also applies to boreholes for open loop groundwater based systems. This is not specifically stipulated in the order for open loop systems, but implicitly understood from the wording of the order for boreholes.

An owner has to fill in an application to the municipality or alternatively give power of attorney to e.g. a consultant to apply for permit. The application evaluation procedure for open loop systems is more complicated than for closed loop systems and the time for obtaining a permit or rejection is in the order of months rather than weeks[204].

PTES – Danish regulation practice
For the PTES systems in Denmark an environmental impact assessment is required. To obtain approval for constructing a pit storage, permission for seepage of drainage water from groundwater or secondary groundwater layers, permission for seepage of water from the pit top, and permission for seepage / drainage of (salty) return water from the softening unit when filling the storage is needed. If new water supply wells are needed to fill up the storage, permission is required for this as well.

6.4 Public awareness and acceptance of SGE

Public awareness and acceptance of especially small SGE (Shallow Geothermal Energy) systems is widely mentioned as a barrier to overcome in the national reports in the Regeocities[205] project and in the conclusions in Bloemendal et al.[206]. The typical reasons for this are a general lack of knowledge and experience within SGE technologies and possibilities, a potentially low acceptance due to bad references, and a lack of common standards ensuring high quality systems.

Lack of knowledge and experience
SGE systems are complicated systems and several fields of expertise are necessary for a good realisation of a sustainable system (geological and hydrogeological knowledge, knowhow on construction, well drilling and completion, system integration etc.). Compared to e.g. gas boilers, HVAC installers consider ground source heat pumps (SGE systems) as a difficult technology where contact to e.g. a specialized drilling company to perform the drilling activities is needed. Low knowledge on the interaction and cooperation between the technologies coupled with disappointing experiences in the past for small systems therefore makes this a challenging barrier to overcome[206].

Acceptance
Geothermal resources/shallow geothermal energy (SGE) can appear as a complicated subject in the public. It is difficult to visualize the underground and therefore also a challenges to disseminate SGE systems in an easy and understandable way. Shifting opinions on the negative impact from SGE systems on groundwater quality has been acknowledged in e.g. Regeocities[205]. Combined with bad references on smaller SGE system as a result of systems installed by incompetent installers, this contributes to a needless negative image. Regarding the large HT-UTES systems studied in HEATSTORE, these systems have a different scope than smaller SGE application, but still, the poor small systems can potentially have a negative impact on geothermal installations in general.

Common quality levels – certification and standards
Missing common quality standards and no obligatory certification is also mentioned as important potential barriers[206] towards the use of SGE in the Regeocities project. The efficiency of a SGE system involves a good design and operational control for the entire system. Unfortunately unqualified companies have been seen to realize small ATES or BTES SGE systems in the past. The result has been low quality and an operating system that do not match the expected efficiency.

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[204] Vangkilde-Pedersen, T. & Nielsen, A. M. 2012: "Denmark – National Report", Regeocities, Deliverable 2.1, National report WP2, December 2012, (www.regeocities.eu).
[205] Jaudin, F. et al. 2013: Regeocities. General Report of the current situation of the regulative framework for the SGE systems, Deliverable 2.2, September 2013 (www.regeocities.eu).
[206] Bloemendal, M. et al. 2016: E-USE(aq) – European Use of Sustainable Energy from aquifers; "*Europe-wide Use of Sustainable Energy from aquifers. Barrier assessment*", Technical report, January 2016.

Training and certification is a mean to improve the standards of SGE systems and the development of HT-UTES would benefit directly from this. Also mandatory monitoring and yearly inspections by authorized professionals of existing systems can help to improve and optimize system operations.

6.5 Economic barriers

The investment costs are often mentioned as an economic barrier for implementing SGE and HT-UTES systems. Comparing e.g. HT-ATES or BTES with other more conventional energy systems, the initial investments cost are relatively high. However the payback time of the system are potentially low - the break-even point is often within 10 years. Test drillings and additional field data necessary in the feasibility study can deter project developers and there is not full certainty for a successful outcome.

Potential savings in the operational phase (financial and CO_2 reduction) needs to be disseminated and published as a positive response to the initial investments (a higher degree of user feedback focusing on operational savings).

On the macroeconomic scale, one of the challenges for UTES/SGE is to find its place in the European heat market. Gas and home heating oil prices are often fixed by national authorities by means of social tariffs. The main consequence of these measures is that the final price of conventional sources of energy is below its real cost. The general political trend moving the energy supply away from fossil fuels (e.g. tax on CO_2) makes renewable heating such as SGE and HT-UTES more and more competitive[207].

Exploitation of surplus heat from e.g. waste incineration plants or data centres/server centres through HT-UTES is very important. If prices for utilising the surplus heat is too high or imposed with taxes, this becomes a barrier that can jeopardize the economy of a HT-UTES system.

6.6 Technological parameters

Awareness of the technological aspects in the (HT)-UTES methods are a common barrier. Regarding SGE systems in general, this is most widespread in the emerging market. For HT-UTES the technology mistrust or low awareness is more or less worldwide. As mentioned in this report and relevant literature the business cases are few. Lessons learned from prior systems and technological progress are, however, strongly believed to give better proven business cases in the coming years like e.g. the Reichstag[208] project in Berlin. Also available information sources both on the building and the ground side are becoming more and better which improve an optimal system integration.

[207] Jaudin, F. et al. 2013: Regeocities. General Report of the current situation of the regulative framework for the SGE systems, Deliverable 2.2, September 2013 (www.regeocities.eu).
[208] Sanner, B., Kabus, F., Seibt P. & Bartels, J. 2005: Underground Thermal Energy Storage for the German Parliament in Berlin, System Concept and Operational Experiences. Proceedings World Geothermal Congress 2005, Antalya, Turkey, 24-29 April.

Appendices

I: *HEATSTORE – State of the art HT-ATES in the Netherlands – Evaluation of thermal performance and design considerations for future projects*

II: *HEATSTORE – Design considerations for high temperature storage in Dutch aquifers*

Appendix I

HEATSTORE – State of the art HT-ATES in the Netherlands – Evaluation of thermal performance and design considerations for future projects

HEATSTORE

State of the art HT-ATES in the Netherlands

Evaluation of thermal performance and design considerations for future projects

Prepared by: Guido Bakema, IF Technology
Benno Drijver, IF Technology

Checked by: IF Technology: Hetty Mathijssen

Approved by: GEUS: Thomas Vangkilde-Pedersen
TNO: Holger Cremer,
HEATSTORE coordinator

HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority - 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage, which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2019.04.26	Ver. 0 Final report

Table of Content

1 Summary

In the Netherlands over 3,000 (licensed) ATES systems have been installed since 1985. For more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in six projects. The first relevant HT-UTES project in the Netherlands was installed in the Beijum district in Groningen (1985: storage of 60 ºC solar heat using BTES). The first HT-ATES projects were made at Utrecht University (1991: storage of 90 ºC heat from a CHP installation using ATES) and a health care institution in Zwammerdam in the late nineties (storage of 90 ºC heat from a CHP installation using ATES). Furthermore, four medium (< 50 °C) temperature storage systems were build the last 15 years.

The measured recovery efficiency for all the HT-ATES is lower than designed. The main reasons are:

- The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in the building was not adapted to the extraction temperatures from the heat store.
- The storage volumes of the projects are lower than designed. This makes them extra vulnerable for high thermal losses;
- Some low temperature projects (Harderwijk and Eindhoven) are made in formations with very course sand. Buoyancy flow will decrease efficiency;

All the projects were evaluated with the HSTWIN-3D-software. The modelled recovery efficiency and temperature fields show good similarity with the measured values.

In general more than 50 % of the stored energy in the HT-ATES projects was not used for heating. Besides the negative influence on the profitability of the HT-ATES project, also the authorities and other subsurface stakeholders will have their concerns about thermal and environmental impact of HT-ATES. For future projects the recovery efficient will have to be increased to at least 70 %.

For future HT-ATES the next design rules for high thermal efficiency (> 70 %) must be considered:

<u>Underground:</u>

- <u>Design HT-ATES with a sufficient size</u>
  For the Dutch target formations (Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis) the following design considerations could be defined based on the following assumption: Screen length 50 m (to get economical feasible projects), K horizontal < 10 m/d, minimal recovery rate: 70 %, Anistropie 2-5:
  - A HT-ATES with a temperature of 90 °C needs a <u>minimum</u> storage volume between 250.000 and 500.000 m^3/season.
  - A HT-ATES with a temperature of 50 °C needs a <u>minimum</u> storage volume between 35.000 and 180.000 m^3/season.
- <u>Always use a test drilling</u>.
  The aquifers that are suitable for heat storage are often subject to limited research. This is mainly because these aquifers have never been attractive for drinking water extraction or low temperature cold / heat storage. Research through a test drilling is necessary to show where layers are located and which water quality they have. It is also desirable to perform a pumping test because the estimation of permeabilities based on grain sizes in such fine-sand packages (this usually concerns permeability <5 m/d) is too inaccurate.

- Calculate the recovery efficiency with a 3D thermal model.
  The model schematization is also important. For example, a 3-dimensional thermal transport model is required to correctly calculate the effects of density-driven groundwater flow (e.g. HSTWIN-3D, Modflow/SEAWAT, FEFLOW).
  The reliability of the predicted effects depends on the reliability of the input in the model. This concerns the usage pattern of the system (pumped water quantities, extraction and infiltration temperatures and variation over time), the properties of the system (locations of wells, screen lengths and screen depths) and the subsurface (heterogeneity, permeability).

System Integration

- Ensure that the usable (cut-off) temperature from the store is as low as possible;
  The recovery efficiency of the storage is determined not only by the heat loss in the subsurface, but also by the minimum usable extraction temperature from the hot well. This is referred to as the "cut-off temperature". At this cut-off temperature the maximum required heating power can be supplied under design conditions. The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency. Lowering the cut-off temperature with 10 º can increase the recovery efficiency significantly (e.g. by 10 to 15 %).

- Use star-shapes well configurations;
  The HT-ATES well configuration normally consists of a doublet (one cold and one warm well). If more capacity is required more doublets were used. In a star-shape; warm wells in the middle and a ring of cold wells. In this configuration the cold wells will insulated the heat around the warm wells and efficiency will increase up to 10 %.

- Put the heat storage system at base load in winter time.
  The heat storage is a slow-reacting system because the heat must come from a large depth (e.g. 150-300 mbgl) and because pipe systems must be heated up. To minimize start-up losses and heating losses, it is recommended to use the heat storage as the base load of the heating system. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat.

2 Introduction

In this report an overview of high (> 30 ºC) temperature aquifer thermal energy storage experience in the Netherlands is presented. It is part of Task 1.1 in Work Package 1 of the HEATSTORE project and serves as starting of the engineering in the Dutch pilot in Heatstore of a new HT-ATES at ECW Middenmeer.

Different technologies for underground thermal energy storage (UTES) exist. ATES (Aquifer Thermal Energy Storage), BTES (Borehole Thermal Energy Storage), PTES (Pit thermal Energy Storage), TTES (Tank Thermal Energy Storage) and MTES (Mine Thermal Energy Storage). In the Netherlands the main applications for high temperature storage are in ATES; other technologies are very rare (BTES and MTES) or do not exist yet (TTES and PTES).

This report describes the existing or former HT-ATES projects and focusses on recovery efficiency, system integration and thermal effects in the subsurface. The microbiology and chemical impact of the temperature changes in the underground is intensively studied and reported in the research program “Meer met Bodemenergie” (IF Technology, 2012). In Work Package 6 of HEATSTORE on environmental assessment this research will be summarized.

The engineering aspects of the HT-ATES projects are addressed in a separate report for Task 1.2 of Work Package 1.

The information on the performance of the existing/former HT-ATES projects is taken out of existing evaluation reports:

- **Drijver, 2012**. More with underground energy storage, high temperature storage, report nr. 6 (in Dutch), knowledge overview and experiences. IF Technology, Bioclear, Wageningen University and Deltares. Arnhem. Overview of the biological and chemical impact of high (> 30 °C) temperature aquifer thermal energy storage based on modelling and measurement at existing projects. This report is part of the large research program MMB (Meer met Bodemenergie www.meermetbodemenergie.nl) between 2008 and 2012.

- **IF Technology, 2014**. Thermal efficiency of High and medium temperature storage in the Underground (in Dutch). 63112/BP/20141002. Arnhem. Overview of the experience with all the Dutch high (> 30 °C) temperature aquifer thermal energy storage projects over the last 20 years.

This report starts with a general description of the application of HT-ATES. Followed by a more detailed description of the well documented HT-ATES projects which are still in operation and of abandoned projects. Finally, the lessons learned and some design criteria with respect to aquifer selection and system integration are described.

3 High temperature aquifer thermal energy storage technology

Within the HEATSTORE project HT-ATES is defined as storing of water between 30 and 95 °. Based on complexity (water treatment and material selection) of the technology a subdivision is made in the Netherlands for HT-ATES projects between 30 and 60 °C (for the Dutch situation called medium temperature MT-ATES) and 70- 90 °C.

3.1 High temperature aquifer thermal energy storage 70- 90 °C

HT-ATES is a storage technique in which surplus heat with a high temperature (around 70 to 90 ºC) is temporarily stored in an aquifer (in the Netherlands it concerns aquifers consisting of fine-sand). To limit heat losses to overlying layers (and the associated thermal impact in overlying layers) the aquifer has to be confined. The stored heat is withdrawn in a later period and used directly for heating buildings and greenhouses. The temperature of the extracted groundwater typically drops significantly during the recovery period (typically the winter season).
It is therefore important to take this temperature drop into account in the design of the heating system. This means that a relatively low extraction temperature (for example 50 ºC) should still be sufficient/usefull for the heating system.

The high storage temperatures result in change of the chemical composition of the groundwater, therefore chemical treatment of the groundwater is needed to prevent the precipitation of minerals in the system (wells, heat exchanger and pipes).

The most important application for HT-ATES lies in the large-scale storage of residual heat from the industry, waste incineration, power plants or CHPs (Combined Heat and Power). HT-ATES has large potential in district heating networks and geothermal energy. An important condition for HT-ATES is that the residual heat is available at low marginal costs, otherwise it will be difficult to complete the business case (in the current (2018) energy mix in the Netherlands). Furthermore, as this report will demonstrate, the size of the system must be sufficiently large, since small systems have relatively low recovery efficiencies.

HT-ATES is a technique that was developed and researched in the eighties of the last century and of which some pilots have been installed. The first relevant projects in the Netherlands were installed in the Beijum district in Groningen (1985: storage of 60 ºC solar heat using BTES) and at Utrecht University (1991: storage of 90 ºC heat from a CHP installation using ATES). In addition, a project was installed at a health care institution in Zwammerdam in the late nineties (storage of 90 ºC heat from a CHP installation using ATES). The project in Beijum is still running; the Zwammerdam project was stopped since it was not economically profitable to run. The project in Utrecht was stopped due to well problems and a mismatch between the temperature level required for the building heating system and the temperature level that the storage could provide.

The applications of HT-ATES has been limited in the past 20 years. Mainly caused by legal limitations, the poor business case because of the competition with natural gas and the decline of the application of CHP installations. In the future, the use of natural gas is expected to be strongly reduced in the Netherlands. More and more new residential areas are made without a natural gas grid. As a consequence, the interest in alternatives (like HT-ATES) is expected to increase significantly.

3.2 High temperature aquifer thermal energy storage 30- 60 °C

Excess heat with a medium-high temperature (30 to 60 ºC), for example coming from a greenhouse, CHP, cooling machine or solar panels, is temporarily stored in an aquifer. The stored heat can be extracted in a later period and used for heating of buildings or greenhouses. A heat pump can be used to raise the temperature to the desired level. HT-ATES at this temperature level is pre-eminently a technique that is applied locally and in which the residual heat of the user is stored.

An advantage over higher temperature storage is that, due to the lower storage temperatures, there are far fewer thermal losses in the subsurface. Because the storage temperature is lower, there is usually no need for water treatment to prevent precipitation of minerals (in the heat exchanger, pipes and wells). Furthermore, the density difference between the stored warm water and the surrounding (colder) groundwater is less, making the density-driven groundwater flow less strong. This means that aquifers with a higher permeability can be used (there is more experience with these aquifers and the flow rate that can be achieved per well is higher). Another advantage is that at lower temperatures, less stringent requirements are applicable on the materials used (temperature resistance).
A disadvantage of the medium-high temperature storage is that the recovered heat has a lower temperature and therefore has fewer possible applications. Furthermore larger volumes of groundwater must be pumped to provide the same amount of heat.

Medium-high temperature storage is not a new technique. In the early nineties of the last century, the first project was developed at the Heuvelgalerie Shopping Mall in Eindhoven (storage of heat that is released during cooling in the summer period). Projects were also installed at the Dolfinarium in Harderwijk (1998: heat from a CHP installation), 2MW in Haarlem (2002: storage of heat from solar collectors) and NIOO in Wageningen (2012: storage of heat from solar collectors), van Duin in Steenbergen (2016) and Koppert Cress in Monster (2017).

The choice for medium-high temperature is often made for projects that only need low-value heat and that can produce low-value heat themselves. In most cases, it concerns relatively small projects (300 - 1,000 kWt), (50 - 200 houses or 1 hectare of greenhouse).

The applications have been very limited in recent years. This is largely caused by the fact that a higher infiltration temperature than 25 ˚C is, in principle, not permitted from a legal point of view. Furthermore, it has to compete with the low prices of gas fired boilers.

4 The projects

4.1 General overview

If heat supply and heat demand are not simultaneous, (temporary) storage of heat can be used. This for example applies for the heating of buildings or greenhouses. The duration of the heat storage can roughly be divided into short-term storage (day / night) and long-term storage (summer / winter). The latter is also called "seasonal storage". A heat surplus (usually in summer) is stored for use in a period with a heat deficit (usually in winter). In the Netherlands the subsurface is the most used medium for seasonal thermal energy storage.

The heat can be stored and extracted through closed tubes systems or by groundwater wells. A system with closed tubes in the subsurface is also called a borehole heat exchanger system (BTES). In the Netherlands, one project was installed where heat is stored in the subsurface using vertical borehole heat exchangers. In the Beijum in Groningen project, since 1983 heat of 60 ºC has been stored in the ground via 360 borehole heat exchangers of 20 m depth.

To limit heat losses to the atmosphere, an insulation layer has been installed on top of the borehole heat exchanger field. The heat is collected with solar collectors and used for the heating of 100 houses (Wijsman, 1983).
All other (known) heat storage projects installed in the Netherlands use groundwater wells (also known as “open loop systems”). These systems extract and infiltrate groundwater into aquifers (ATES).

In the Netherlands more than 3,000 (licensed) ATES systems have been installed since 1985 (Bakema, 2016). In more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in nine projects.
The main characteristics of these heat storage projects are summarized in Table 1 and are briefly described below. The size of the heat storage varies between approx. 400 MWht and 8,000 MWht; the heating power varies between 6 and 1,5 MW.

In this evaluation the main focus is on recovery efficiency. Recovery efficiency is the recovered heat (recovered volume* (temperature warm well – temperature cold well)) divided by stored heat (stored volume * (temperature warm cold – temperature warm well))

Table 1 Overview of MT-ATES and HT-ATES Projects in the Netherlands (>25 °C)

Project	year of installation	Storage temperature [°C]	Storage capacity [MWh_t]	Heat power [MW_t]
Office complex, Bunnik	1985	25-30	370 (?)	unknown
Utrecht University	1991	90	6.000	6,0
Heuvelgalerie Shopping Mall Eindhoven	1992	32	3.300	1,8
Dolfinarium Harderwijk	1997	40	7.650	4,7
Hooge Burch Zwammerdam	1998	88	2.250	1,45
2 MW, Haarlem	2002	43	1.650	2,0
NIOO, Wageningen	2011	45	1.280	1,5
Van Duin, Steenbergen	2016	40	2000	2
Koppert Cress, Monster	2017	40		

4.2 Medium-high temperature aquifer thermal energy storage

4.2.1 Office complex Bunnik (1985-1994)

In 1985 the first aquifer storage project in the Netherlands was installed in Bunnik. This system was set up for space heating of the Bredero office complex. The heat was supplied by solar collectors and residual heat from cooling. The average storage temperature was 25 to 30 ºC. In the winter, the warm water was extracted from the aquifer and upgraded with a heatpump to a maximum temperature of 42 ºC. The well screens of the storage are placed in a moderately coarse to coarse aquifer between 17 and 50 mbgl.

Evaluation of the performance of the storage in the first 5 years shows that a great deal of knowledge has been gained regarding the design and management of heat storage (Heidemij and Bredero Energy Systems, 1990). The project was less successful regarding the functioning of the energy system because the new technologies, such as solar collectors and heat pump, did not function properly yet. The storage itself has functioned well technically. Around 1994 the heat storage was converted to a cold storage system.

4.2.2 Heuvelgalerie Eindhoven (1992)

Heuvelgalerie is a shopping mall in the centre of Eindhoven (Figure 1). At the end of 1992, a medium temperature heat storage system (30 ºC) was established and is in use since spring of 1993. The system consists of one cold well and one warm well. In addition, four monitoring wells have been placed. To limit the heat losses due to regional groundwater flow, the cold well is located downstream of the warm well. The locations of the wells and monitoring wells are shown in Figure 2.

Figure 1 Shopping mall Heuvelgalerie Eindhoven (in 2015 the name Heuvelgalerie was changed in Heuvel)

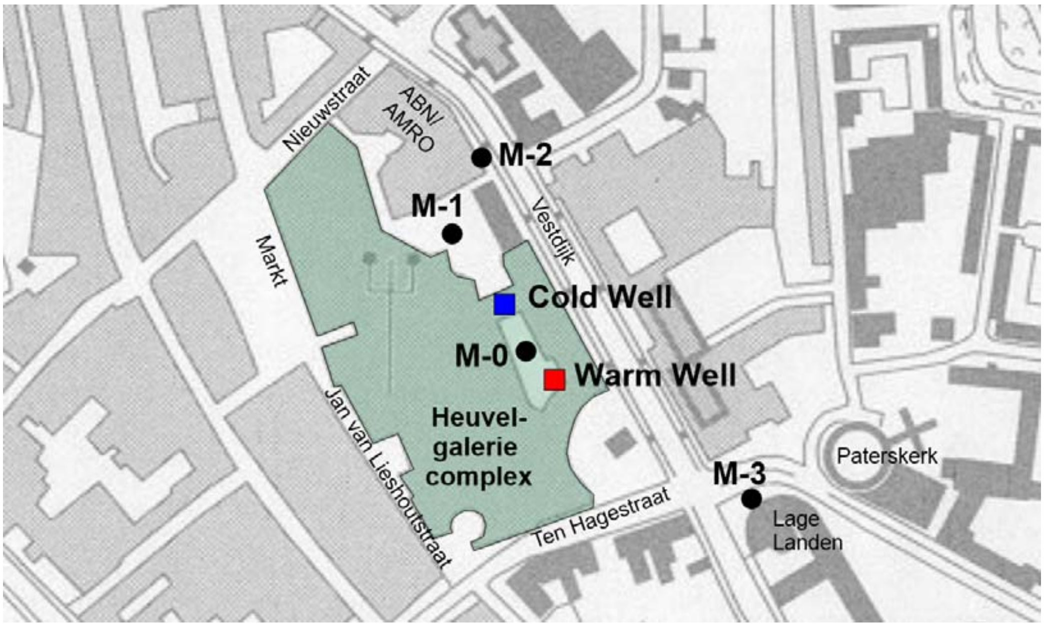

Figure 2 Position of wells and monitoring wells Heuvelgalerie Eindhoven

Recovery efficiency

The storage was designed for storage of 200,000 m³ (and a maximum of 275,000 m³) of groundwater of 32 ºC in the warm well in the summer period. In the winter the warm water is extracted and used for heating the ventilation air. Use of the heat is possible as long as the temperature of the extracted groundwater is at least 24 ºC (cut-off temperature = 24 ºC). After use for heating, the cooled groundwater is infiltrated at 18 ºC in the cold well.

When applying for the license in 1990, a storage efficiency of 50- 55 % was calculated in the fourth year (Table 2). During the period 2006 and 2011 the average storage efficiency is comparable with this number. Large differences over the years occur due to climate differences and occupancy rate of the mall.

Table 2 Recovery efficiency Heuvelgalerie Eindhoven

Year	Stored volume m^3	Recovered volume m^3	Stored heat MWh_t	Recovered heat MWh_t	Recovery Efficiency %
Design	200.000	150.000	3.250	1.740	54
2006	46.000	168.700	1.554	398	26
2007	48.300	115.200	1.027	299	29
2008	124.200	101.900	832	501	60
2009	95.700	128.000	1.354	488	36
2010	213.100	233.500	1.046	1.431	136
2011	57.600	79.700	667	318	48
Average	97.500	137.800	1.080	573	53

Temperature measurements

The heat storage system was installed at the end of 1992 and is in operation since the spring of 1993. In the first 5 years there was a pilot permit and monitoring of the groundwater composition (chemical and microbiological) and the subsurface temperature (measured in the warm and cold well and the four monitoring wells around the site).

The results of the subsurface temperature measurements in the cold and hot well and in the monitoring wells M0 and M1 are shown in Figure 3 (no changes were measured in the monitoring wells M2 and M3). Several graphs have also been made for monitoring well M0, in which several successive measurements have been added, so that it is clearer which changes have been measured successively.

The warm well and M0 show lower temperatures between 30 and 45 m-mv at the end of 1993 - early 1994. The reason for this is the interruption of the screen in the warm well of 35-40 mbgl because of the presence of a clay layer (also visible at M0, but not at the cold well). In the first quarter of 1994, the subsurface temperature in M0 is clearly higher than that in the warm well (on average about 22 °C and 15 °C respectively); this is possibly due to infiltration of warm water with different temperature levels during the summer period.

In the last quarter of 1994 both M0 and the warm well showed higher subsurface temperatures than in the first quarter of 1994. This is a logical consequence of the storage of heat in the previous summer period.

In the graphs of M0 and M1 the heat concentrates in the upper part (at less than 65 m depth at M0 and less than 55 m depth at M1). This can be explained by the occurrence of density-driven groundwater flow because of the increased storage temperatures. The screen of the warm well is between 24 and 81 m-mv, so at the warm well the heat will be injected in this depth interval. The groundwater takes some time to reach monitoring well M0 and even more time to reach monitoring well M1. In time, the warmer groundwater can flow in the upward direction because of the lower density, which explains the heat is shallower at monitoring well M1 than at M0 and at M0 shallower than at the warm well.

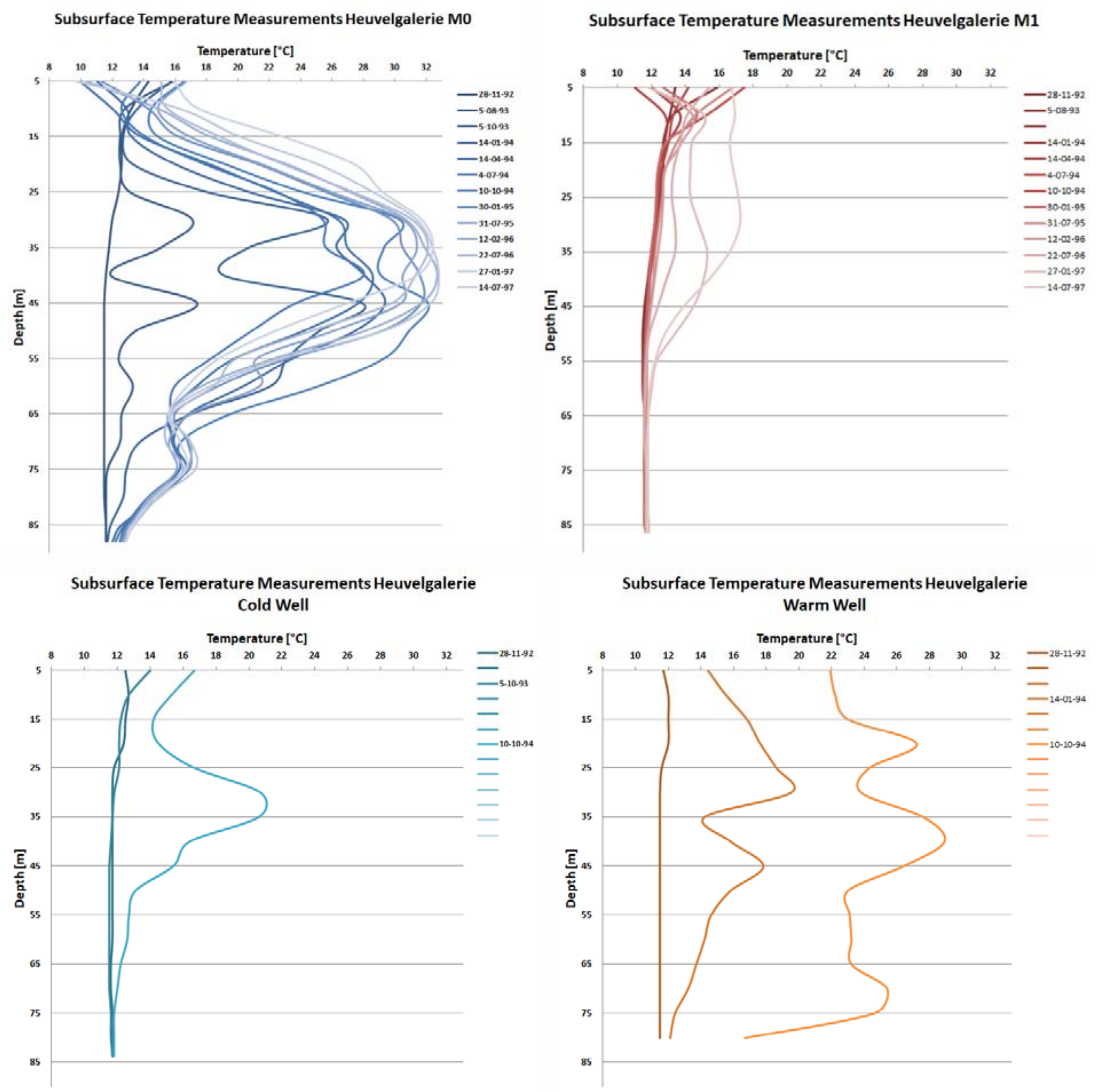

Figure 3 Results of subsurface temperature measurements Heuvelgalerie Eindhoven

4.2.3 Dolfinarium Harderwijk (1997)

At the sea animal park Harderwijk (Dolfinarium Harderwijk) combined heat and power units (CHP units) are used for generating electricity and supplying heat for space heating of offices, buildings (at a high temperature) and basins (at a low temperature) (Figure 6). In the summer period, in which the visitor's peak traditionally falls, the CHP units produce a large surplus of heat, while the demand for heat is concentrated in the winter months.
In the summer situation, the excess heat from the CHP units is therefore stored in the subsurface using an ATES system.

In the summer season, on average 244,000 m³ of water is stored with a maximum temperature level of 40 ºC. During the winter season, on average 366,000 m³ of groundwater is extracted from the warm well and infiltrated at a temperature of 13 ºC in the cold well. This recovered heat is used for the heating of the basins (which are suitable for this because of the low temperature heating). The extracted groundwater can be used for heating when the extraction temperature is at least 17 ºC (cut-off temperature = 17 ºC).

The locations of the wells and the monitoring wells are shown in Figure 4. The screens of the wells are placed in the combined 1st, 2nd and 3rd aquifer between 75 and 125 mbgl.

The calculated extraction temperatures show that approximately 55% of the heat, that is stored in the warm well during the summer period, is recovered during the winter period. This storage efficiency hardly increases over the years due to the relatively large thermal losses caused by the natural groundwater flow and the influence of density-driven groundwater flow.

Table 3 shows the measurement data for the period 1997-2010 (pumped water quantities and stored and recovered amounts of energy for each year). These data apply to calendar years (heat supply in the first months and the last months of the year and in the interim period heat storage takes place).

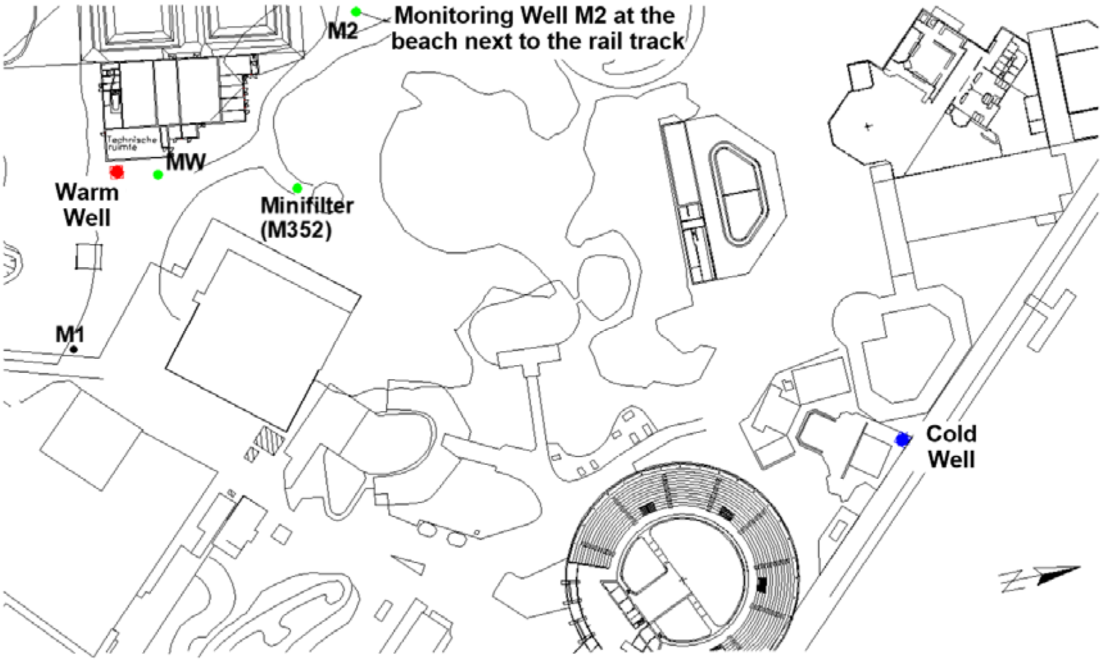

Figure 4 Locations of the wells and the monitoring wells at the Dolfinarium in Harderwijk

The long-term average efficiency is about 40%. The most important explanation for this relatively low average efficiency (compared to the 55% that was calculated in the design phase) is that on average significantly more water is pumped for heat storage than is withdrawn for heat supply, while in the design phase the opposite was assumed (system integration issue).

Table 3 Measured water and energy volumes Dolfinarium Harderwijk

	Recovered water volume [m³]	Stored water volume [m³]	Recovered heat [GJ]	Stored heat [GJ]	Recovery Efficiency
1998	237.606	108.118	9.244	13.224	70%
1999	65.076	277.755	3.012	34.097	9%
2000	108.192	139.317	3.670	15.712	23%*
2001	295.478	305.810	17.896	34.724	52%
2002	223.685	324.488	17.110	38.018	45%
2003	254.765	268.448	14.494	27.659	52%
2004	185.296	240.732	12.433	23.643	53%
2005	182.564	286.988	11.072	33.417	33%
2006	188.496	319.085	17.553	37.875	46%
2007	126.066	203.239	3.079	6.729	46%
2008	175.286	405.693	14.902	45.912	32%
2009	178.092	365.741	12.741	40.099	32%
2010	226.371	334.721	16.974	38.585	44%
average	188.229	275.395	11.860	29.976	40%

Temperature measurements

In the measurement wells MW (near the warm wells) and M2 (downstream of the warm well), subsurface temperature measurements are performed twice a year. The results of the measurements performed in both wells are shown in Figure 5.

At monitoring well MW, which is a short distance from the warm well, the temperature increases are concentrated in the depth range of the screen of the warm well (75-125 mbgl).
At monitoring well M2, located downstream of the warm well, there is a more gradual temperature gradient in the depth, with the highest temperatures occurring between approximately 50 and 90 mbgl. The centre of the heat bubble is thus shifted from 100 mbgl at the warm well (corresponds to the centre of the well screen) to 70 mbgl. Apparently upward transport of the heated groundwater occurs between the warm well and monitoring well M2, which can be attributed to density-driven groundwater flow as a result of the elevated temperature. In this case, density-driven groundwater flow has little impact on the storage efficiency (at the warm well the heat remains concentrated at the depth of the well screen) but is important for the spatial distribution of the heat in the long term (downstream of the heat store).

In monitoring well M2 it is also striking that the oldest measurements show warming at about 85 mbgl and that the warmest zone gradually spreads to more shallow depths in the successive measurements. Approximately 5 years after commissioning (from 2002), a virtually stable situation is reached: all temperature profiles that have been measured afterwards show a very similar pattern and further heating does not occur or only to a limited extent.

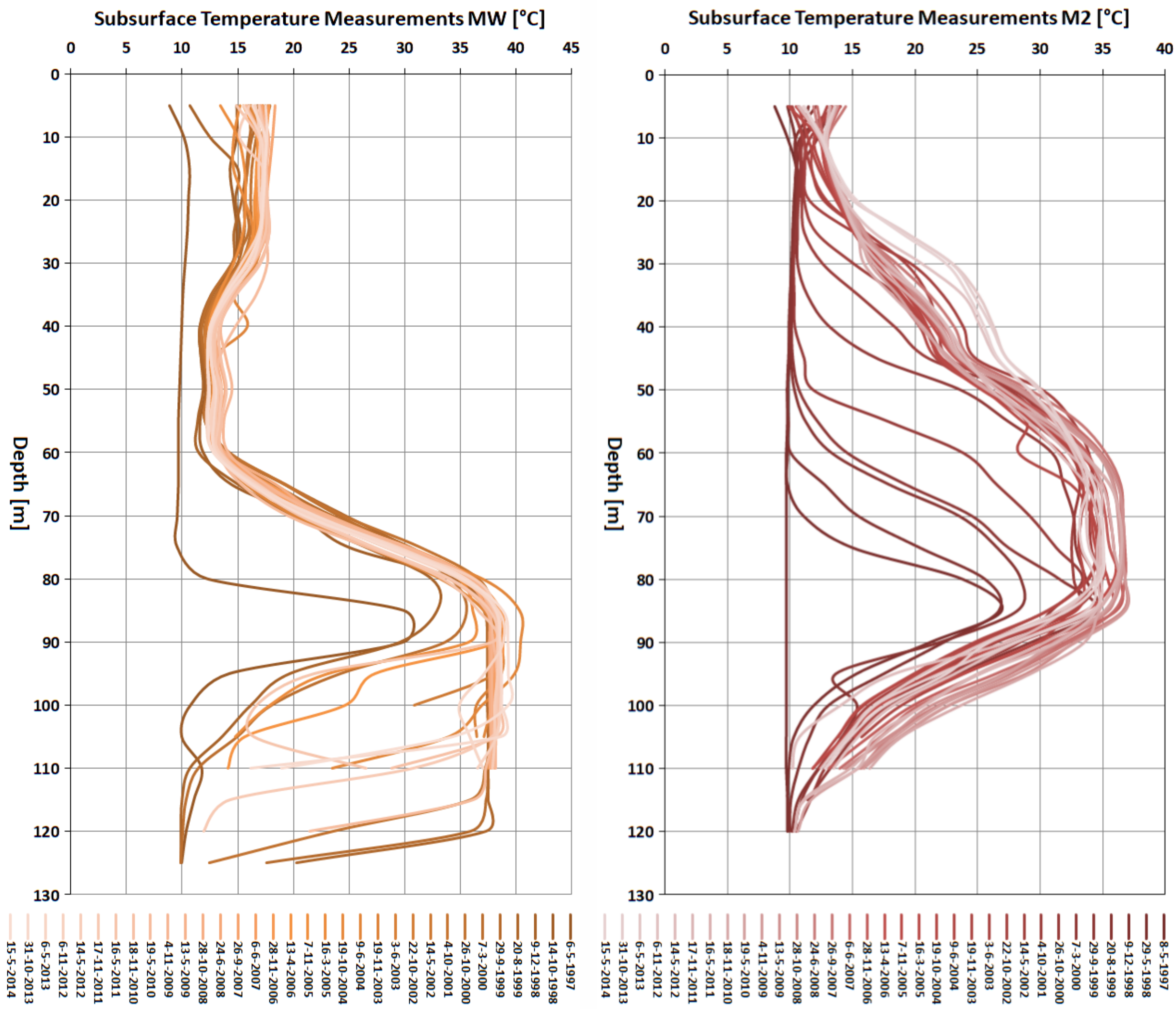

Figure 5 Results of subsurface temperature measurements monitoring wells MW and M2 Dolfinarium Harderwijk

4.2.4 NIOO Wageningen (2011)

The headquarters of the Netherlands Institute of Ecology of the Royal Netherlands Academy of Sciences (NIOO-KNAW) in Wageningen has a high sustainability level (Figure 6).

To enable a sustainable climate control system, two ATES systems have been installed. The first (shallow) groundwater system is a regular (low temperature) ATES system in a coarse sand aquifer. The second (deep) ATES system is a medium-temperature heat storage system in a low permeability aquifer. The medium temperature heat storage system of NIOO consists of a cold and a warm well with infiltration temperatures of respectively 26 ºC and 45 ºC. Figure 7 shows the locations of the wells. The well screens are placed in the depth range of 220 to 295 mbgl.

Figure 6 NIOO Wageningen

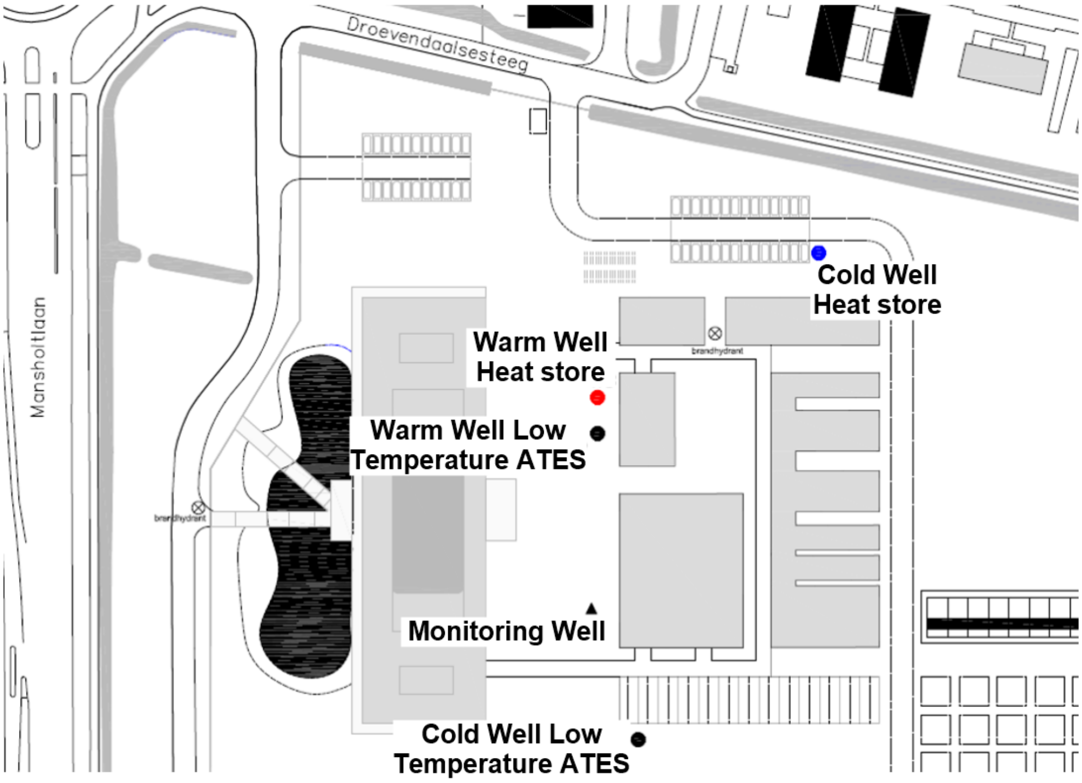

Figure 7 Positions of the wells and monitoring wells NIOO Wageningen

Recovery efficiency
The system was designed with a recovery efficiency of 45 % (Table 4). Untill now the efficiency is between 10 and 20 % and the recovered heat is only 5 % of what was expected (Table 4). The latter is mainly caused by the installation of less solar collectors and the lower capacity of the groundwater system. The recovery efficiency is negatively influenced by:

- The subsurface temperature at storage depth is lower (14 °C) than assumed in the design (18 °C).
- The stored water temperature (45 °C) is too close to the cut-off temperature (40 °C). In 2016 the cut-off temperature is lowered to 30 °C)
- A much smaller stored volume.

Table 4 Amounts of energy displaced per year

	Recovered heat [MWht]	Stored heat [MWht]	Recovery efficiency [%]
designed	**578**	**1.283**	**45 %**
2011	18,5	100,4	18%
2012	0,0	182,7	0%
2013	0,6	305,6	0%
2014	34,3	271,4	13%
2015	7,9	232,1	3%
2016	55,5	320,4	17%
average	19,5	235,4	8%

Temperature measurements
The subsurface temperature was measured in the monitoring wells every five meters. Figure 8 shows the results for the warm and the cold wells up to 2016. In the subsurface temperature measurements, the effects of both the regular ATES (up to about 65 mbgl) and the medium-temperature heat storage system (from around 220 mbgl) are visible.

The temperature in the warm well has been increased to approximately 36 ºC due to the storage of heat in 2016 (was 30 ºC in 2013). The deepest measurement was measured at 220 meters. Currently, the monitoring well is obstructed, and measuring is no longer possible. The temperature in the cold well is comparable with the measurements in 2013 (relatively warm in autumn). In the monitoring well (Figure 8) the seasonal influence of the shallow ATES is clearly visible: the temperature decreases in the spring (after injection of cold in the winter period), and in the autumn (after injection of heat in the summer period). The monitoring well lies outside the thermal influence area of the medium-temperature heat storage

Extensive analyses of the NIOO project is made in Work Package 5 of the HEATSTORE project.

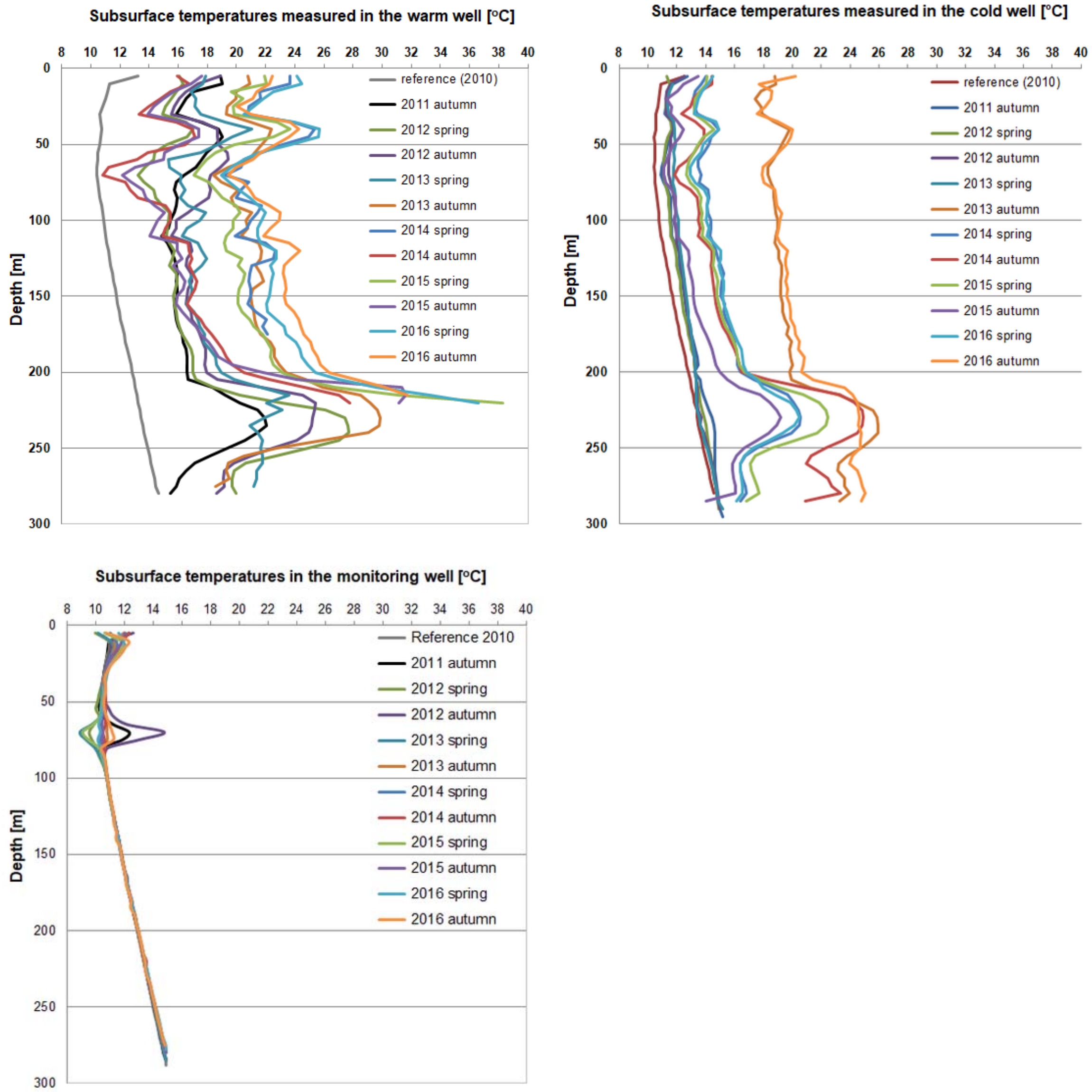

Figure 8 Results of subsurface temperature measurements NIOO Wageningen

4.3 High temperature aquifer thermal energy storage

4.3.1 Utrecht University (1991-1999)

Figure 9 Campus Utrecht University

The heat storage at Utrecht University has been unique in the world as the only high temperature ATES system. The heat storage was commissioned in 1991. In 1999 the warm well was damaged, and the storage was taken out of service. The functioning of the heat storage has been extensively evaluated (IF Technology, 2001)

The ATES stored residual heat from the university's combined heat and power (CHP) plants in the summer period. The heat storage consisted of a cold and a warm well, both in the third aquifer at a depth of 220 to 260 mbgl (Figure 10). The storage was designed for a storage capacity of 6 MW_t and a storage quantity of 6,000 MWh/year (21,600 GJ); the predicted recovery efficiency was 59 %.

Recovery efficiency

The measured average recovery efficiency of the storage was 33 % during the nine years the system operated (see Table 5). In the period 1994-1997 efficiency was 53 %. The low recovery efficiency was partly caused by failures of the CHPs (less heat stored). More importantly, the return temperature (= cut-off temperature) from the building was far too high. As a consequence, the heat storage could add little heat to the central heating system the cut-off temperature was reached after extraction of a limited amount of water. As a result, the storage still contained a lot of heat at the end of the winter. Conclusion is that the low average recovery efficiency of 33 % was mainly caused by the high return temperatures from the building and not by losses in the subsurface.

Table 5 Recovery efficiency University Utrecht

year	Stored heat GJ	Recovered heat GJ	Recovery Efficiency %
design	21.600	12.660	59
1991	18.979	1.927	10
1992	9.836	3.503	37
1993	19.380	3.350	17
1994	15.225	6.301	41
1995	20.792	4.765	23
1996	8.330	5.670	68
1997	4.648	3.729	80
1998	2.903	435	15
1999	13.079	765	6
average			33

Temperature measurements

After the first storage cycle the measured temperatures were use the calibrate the hydrothermal model HST-3D (see Figure 11) (Heidemij, 1996). This calibrated model was used to predict the thermal efficiency and thermal impact after the fourth cycles (see Figure 12)

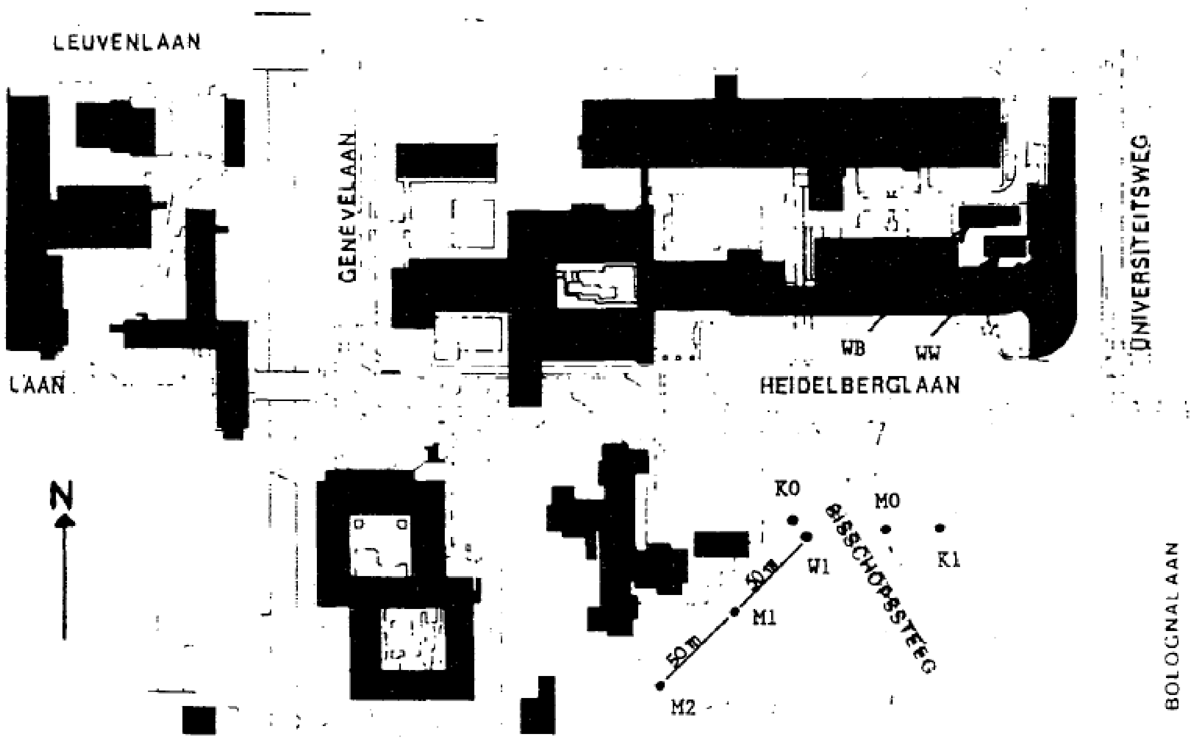

Figure 10 Location of wells and monitoring wells at HT-ATES University Utrecht

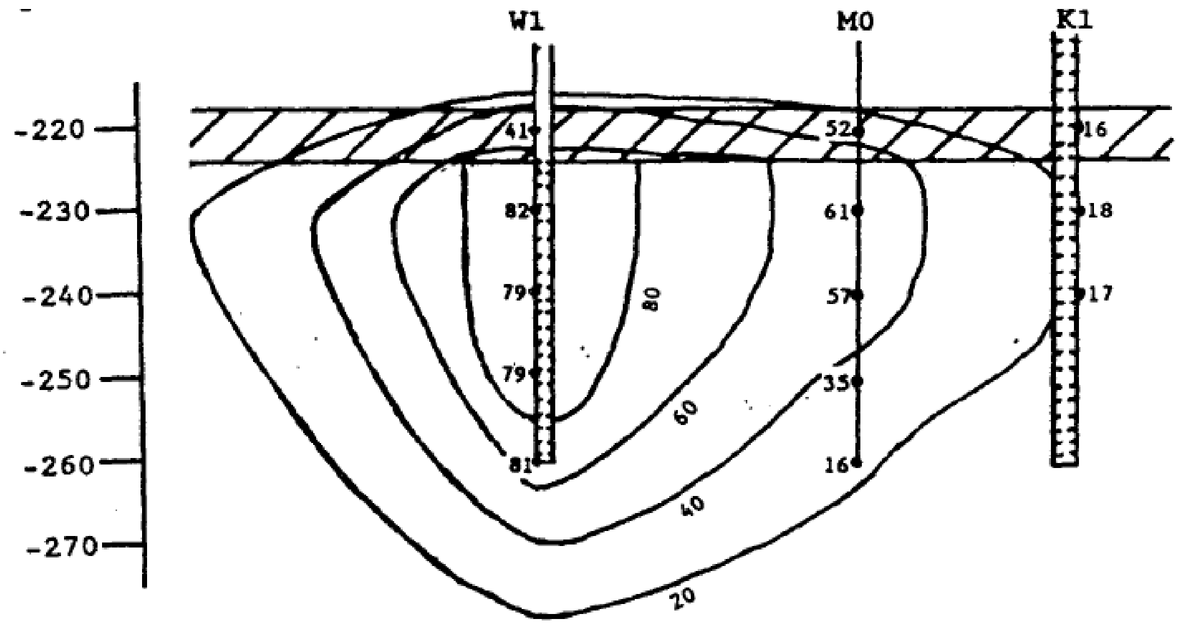

Figure 21 Measured and calculated temperatures after the first storages cycle at HT-ATES University Utrecht

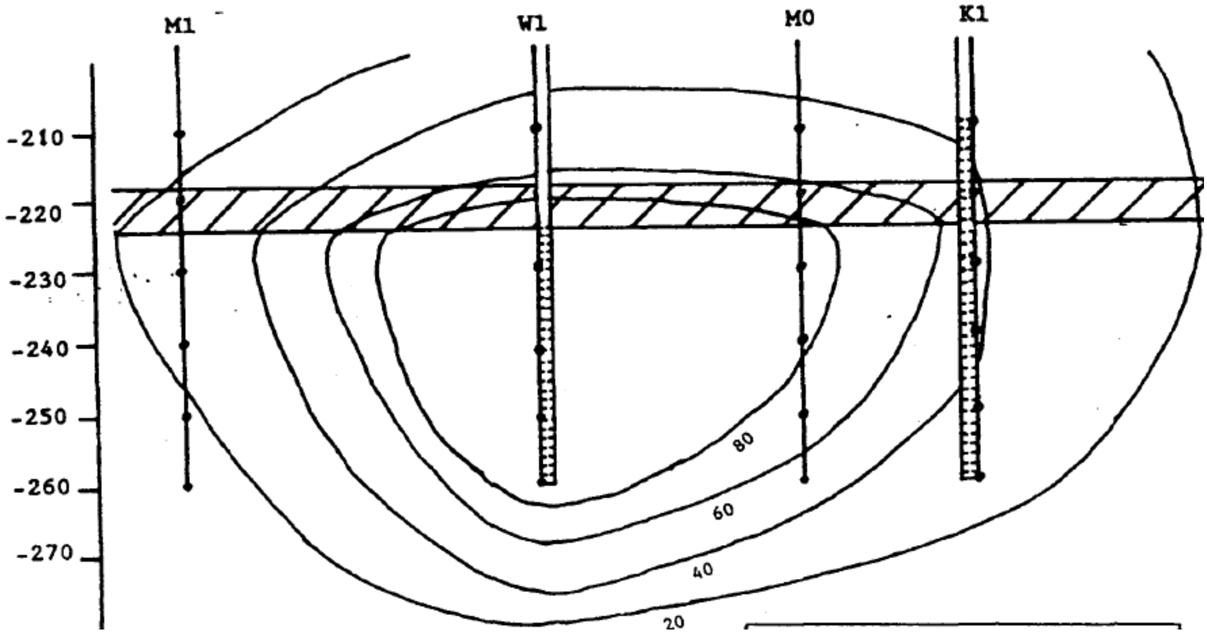

Figure 32 Modelled temperatures profile after the fourth cycle at HT-ATES University Utrecht

4.3.2 Hooge Burgh Zwammerdam (1998-2009)

The Hooge Burgh health care institution in Zwammerdam has a combined heat power plant (CHP) for electricity production and heating. The installation was also equipped with a high temperature heat storage system at a depth of approximately 180 mbgl. Heat is stored at 90 ºC when the CHP runs for electricity production and the heat demand is smaller than the heat production. The stored heat can be used later for heat supply to the health care institution. The heat storage consists of a cold and a warm well, both in an aquifer at a depth of 135 to 151 mbgl. The distance between the cold and the warm well is approximately 67 m. The storage was designed for storage of 2,250 MWh_t of heat per year. The expected recovery efficiency was 49 %.

The heat storage has been carefully managed for 5 years. After that, the heat storage has been taken out of operation for financial reasons. The reason was that the CHP is the main source of heat. The CHP is controlled by electricity demand. The electricity is then returned to the grid at a favourable rate. Monitoring data have shown that the feed-in fee for electricity production and heat storage profits were financially unattainable. It was decided to reduce the CHP in operating hours and not to use the heat storage anymore.

The system was put into operation in 1998. In 2003, hardly any water was pumped and in the following years the system was no longer used. In 2009, the license was withdrawn on request. Three monitoring wells are present at the heat store system. Figure 13 shows the locations of the wells and monitoring wells. As prescribed in the Groundwater Act license, measurements were performed on chemistry, microbiology, hydraulic head and subsurface temperature.

Recovery efficiency
The expected recovery efficiency is determined for the initial situation in which an average of 41,000 m^3 of groundwater is pumped in summer and winter; this is therefore 82,000 m^3 per year (see Table 6). The measurement data shows that less groundwater is pumped than expected: for the years 1999 to 2001, an average of approx. 47,500 m^3 per year has been pumped; this is 58% of the expected quantity.

The expected amount of energy stored in the summer period was 2,250 MWh (charging) and the amount of heat to be recovered in the winter period was 1,100 MWh in winter (discharging). In the period 1999-2001, an average of 1,561 MWh per year was charged and 167 MWh discharged. So 69% of the expected amount of energy was charged, and only 15% of the expected amount of energy was discharged (IF Technology,2002).

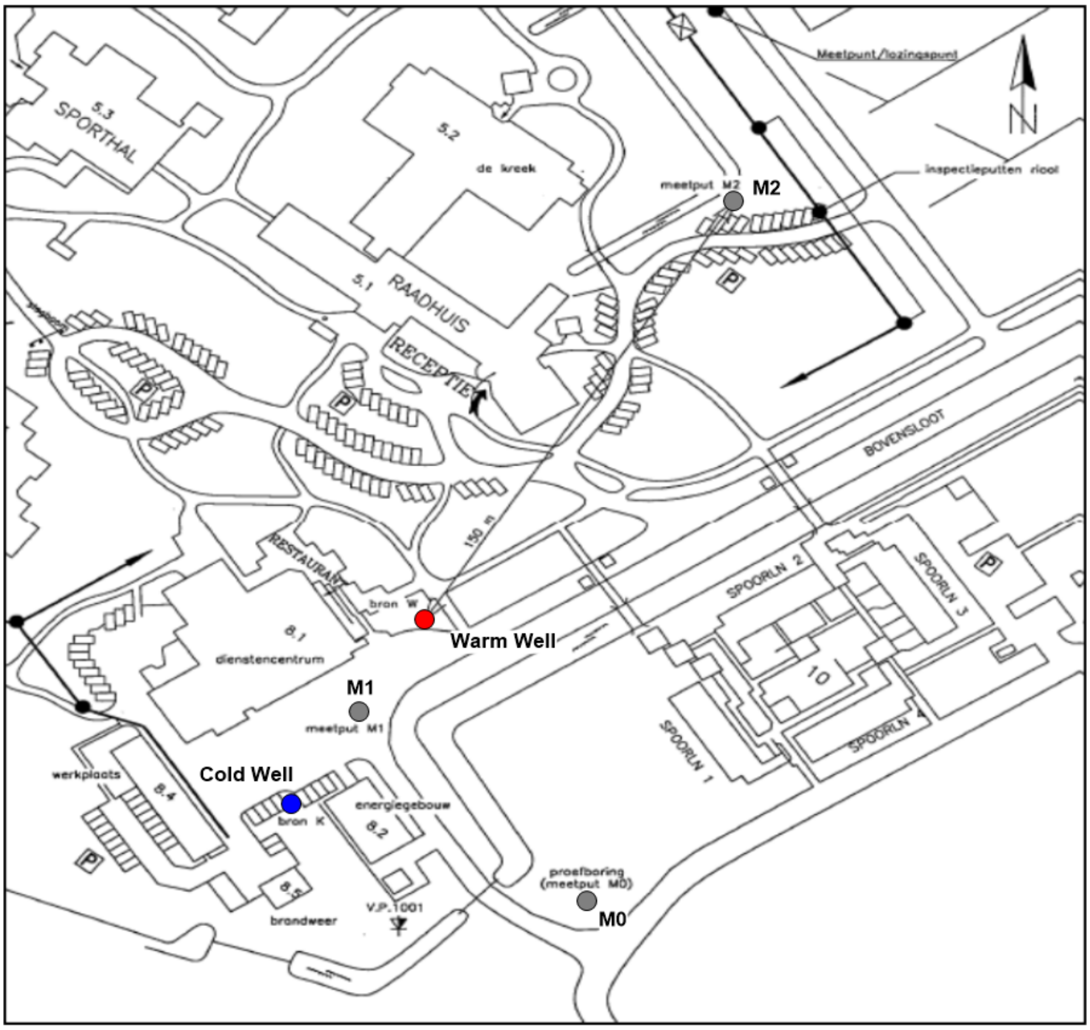

Figure 43 Wells Hooge Burch Zwammerdam

Table 6 shows the pumped water and energy quantities and the average extraction and infiltration temperatures.

Table 7 shows that the expected recovery efficiency has not been achieved. This can be explained by the fact that annually less groundwater is pumped than expected (58% of the expected amount) and from the high cut-off temperature combined with the rapid decrease of the extraction temperature during discharging (resulting in a small temperature difference during heat supply and only a small amount of heat supplied to the building).

Table 6 Water and energy volumes Hooge Burch Zwammerdam

year	Charging (heat storage)			Discharging (heat recovery)		
	pumped water volume [m³]	average extraction temperature [ºC]	average infiltration temperature [ºC]	pumped water volume [m³]	average extraction temperature [ºC]	average infiltration temperature [ºC]
1998	19,226	13	71	2,513	54	44
1999	18,923	25	81	4,944	72	62
2000	24,662	37	86	21,097	59	55
2001	22,424	44	82	21,162	58	54

Table 7 Recovery efficiency Hooge Burch Zwammerdam

Year	1998	1999	2000	2001
Recovery efficiency	3,45%	10,3%	11,3%	10,4%

Temperature measurements
During the “Meer met Bodemenergie” research project, this HT-ATES system has been hydrothermally modelled (Drijver, 2012).

The calculation of the thermal effects of the heat storage was carried out with the program HstWin-3D. With the HstWin-3D program heat and solute transport can be simulated in a saturated 3-dimensional groundwater system.

Based on the extraction / infiltration pattern shown in Table 6, the groundwater system was modelled. The calculations assumed that the storage was stopped after 2001 (insufficient data available for 2002). Subsequently another 96 years were simulated (so 100 years has been calculated) to see how the thermal effects develop in time after stopping the HT-ATES.

Figure 14 shows cross sections of the calculated temperatures after the first and fourth heat storage season.

After stopping the heat storage (in the model after 2001), the residual heat will spread gradually and at the same time the temperature level will decrease. The calculated temperatures in 2005, 2011, 2020 and 2038 are shown in cross sections in Figure 15. The temperature in the subsurface does not deviate more than 2 ºC from the natural groundwater temperature approximately 35 years after storage has ceased. From the calculations it follows that about 70 years after the storage is stopped the temperature in the subsurface does not deviate by more than 0.5 ºC from the natural groundwater temperature. It has to be noted, that in this project relatively small amounts of heat have been stored. Therefore, the residual heat “dilutes” relatively rapid. For a larger scale HT-ATES, the thermal effects are expected to be much more pronounced and last much longer after ending the project.

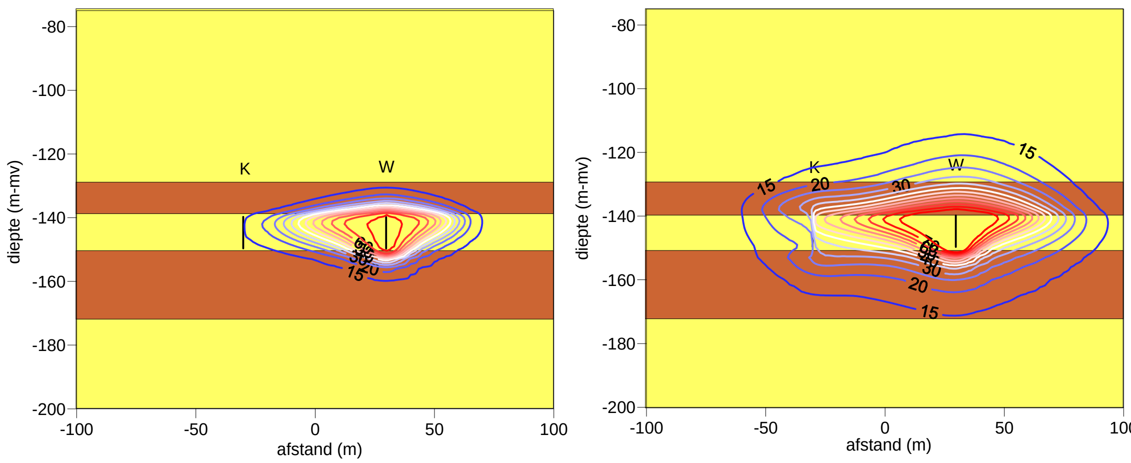

Figure 14 Calculated temperature first and fourth storage season

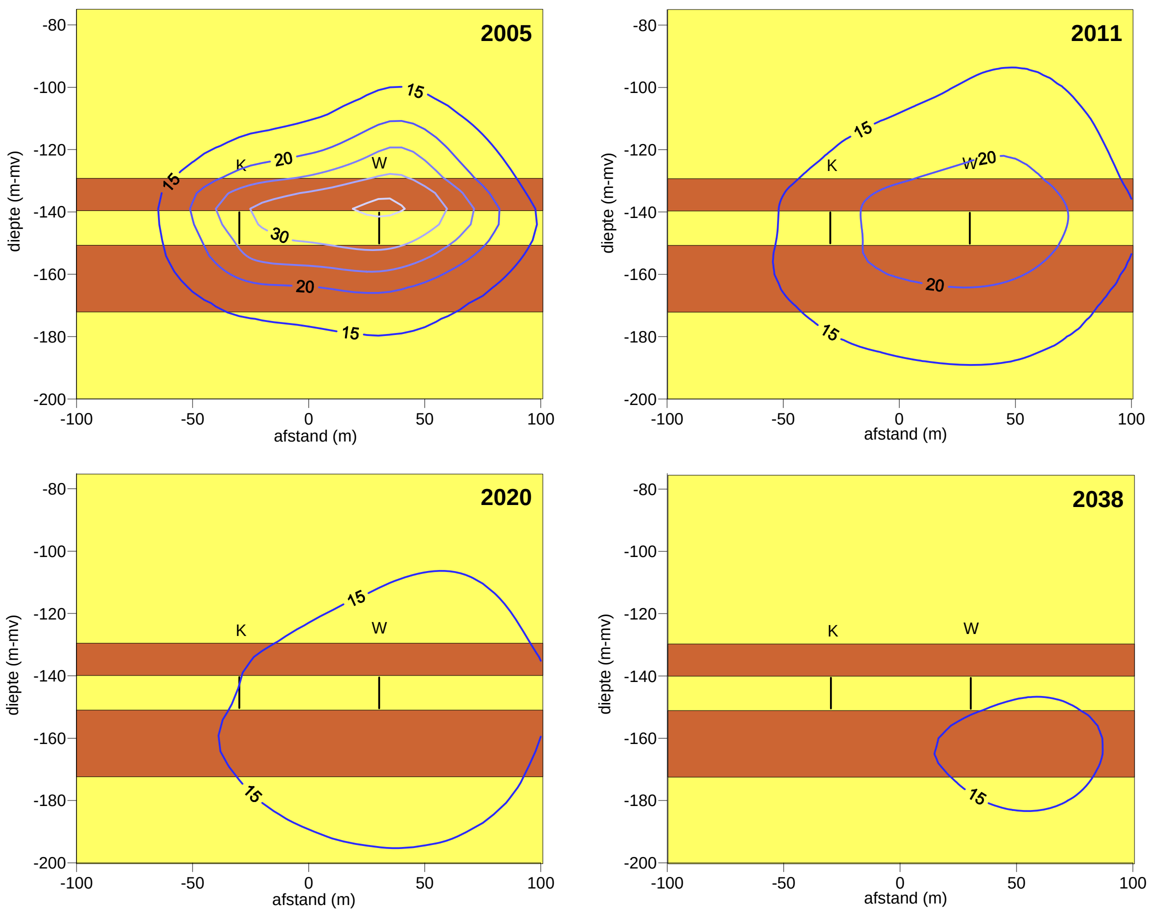

Figure 15 Calculated temperature after stopping the heat storage

4.4 Conclusions on project experiences

The measured recovery efficiency for all the HT-ATES is lower than designed (Table 8). The main reasons are:

- The storage volumes of the projects are lower than designed. This makes them extra vulnerable for high thermal losses;
- Some low temperature projects (Harderwijk and Eindhoven) are made in formations with very course sand. Buoyancy flow will decrease efficiency;
- The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system or the other way around: the heating system in the building was not adapted to the extraction temperatures from the heat store.

Table 8 Recovery efficiency (designed versus measured)

Project	Year of installing	Storage temperature [°C]	Design recovery efficiency (%)	Measured Recovery efficiency (%)
Utrecht University	1991	90	59	33
Heuvelgalerie Shopping Mall Eindhoven	1992	32	60	55
Dolfinarium Harderwijk	1997	40	55	40
Hooge Burch Zwammerdam	1998	88	49	10
NIOO, Wageningen	2011	45	45	15

All the projects were evaluated with the HSTWIN-3D-software. The modelled recovery efficiency and temperature fields show good similarity with the measured values.

5 Design criteria on recovery efficiency for future HT-ATES projects

In general more than 50 % of the stored energy in the existing HT-ATES projects was not used for heating. Besides the negative influence on the profitability of the HT-ATES project, also the authorities and other subsurface stakeholders will have their concerns about thermal and environmental impact of HT-ATES. For future projects the recovery efficient will have to be increased. In this chapter some suggestions based on validated models are made for improving recovery efficiency.

5.1 Subsurface design rules

<u>Make HT-ATES of sufficient size.</u>

Because water with a high temperature has a lower density than the ambient groundwater in the used aquifers, the warm water tends to flow to the upper part of the aquifer. This process can have major negative consequences for the storage efficiency. For high-temperature heat storage systems (seasonal storage), based on a large number of model calculations, a relationship has been derived (IF Technology/SKB, 2012 ; Schout et al., 2014) between the recovery efficiency and the following parameters:

- the stored volume of hot groundwater (V);
- the well screen length / thickness of the aquifer (H) used;
- the temperatures of the natural groundwater in the storage aquifer (Ta) and the stored water (Ti);
- the horizontal and vertical permeability (kh and kv) of the aquifer used.

Figure 56 shows the recovery efficiencies that were calculated with this relationship as a function of the storage volume at different hydraulic conductivities, storage temperatures and well screen lengths. These tables are based on a number of assumptions:

1) the volumes of water that are pumped during storage and recovery are equal;
2) the cold well temperature of the is equal to the ambient groundwater temperature in the storage aquifer (assumed to be 12 ºC);
3) the efficiency is given for the fourth year;
4) interaction between the warm and cold well is insignificant;
5) heat losses by regional groundwater flow are negligible.

Since at least some of these assumptions will not be true in a real case, the recovery efficiency in practice may differ. The derived relation is especially useful to make a selection of the best aquifer for storage. For a proper assessment of the recovery efficiency in practice, numerical simulations are required.

Storage Temperature 30°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	75%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%
10	2	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	2	70%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
20	2	67%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
30	2	62%	64%	66%	68%	69%	71%	72%	73%	73%	74%	74%	74%
40	2	57%	60%	62%	65%	66%	68%	70%	71%	71%	72%	73%	73%
50	2	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%
5	5	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
10	5	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%
15	5	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%	78%	78%
20	5	74%	74%	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%
30	5	71%	72%	73%	74%	75%	75%	76%	76%	76%	76%	77%	77%
40	5	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
50	5	67%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
5	10	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
10	10	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%	78%	78%
15	10	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%	78%	78%
20	10	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%	78%
30	10	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%	78%	78%
40	10	74%	74%	75%	75%	76%	76%	77%	77%	77%	77%	77%	77%
50	10	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%

Storage Temperature 30°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
10	2	70%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
15	2	66%	68%	70%	71%	73%	74%	75%	75%	76%	76%	77%	77%
20	2	62%	64%	67%	69%	70%	72%	73%	74%	74%	75%	75%	76%
30	2	54%	57%	61%	63%	66%	68%	69%	71%	72%	72%	73%	74%
40	2	47%	51%	55%	59%	61%	64%	66%	68%	69%	70%	71%	71%
50	2	41%	46%	50%	54%	57%	60%	63%	65%	66%	68%	69%	69%
5	5	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%	80%	80%
10	5	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%	79%
15	5	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%
20	5	72%	74%	75%	75%	76%	77%	77%	78%	78%	78%	78%	79%
30	5	69%	70%	72%	73%	74%	75%	76%	76%	77%	77%	77%	78%
40	5	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
50	5	62%	64%	67%	69%	70%	72%	73%	74%	74%	75%	75%	76%
5	10	79%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%	80%
10	10	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%	80%	80%
15	10	77%	78%	78%	79%	79%	79%	79%	79%	80%	80%	80%	80%
20	10	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%	79%
30	10	74%	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%
40	10	72%	74%	75%	75%	76%	77%	77%	78%	78%	78%	78%	79%
50	10	70%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%

Storage Temperature 50°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%	77%
10	2	63%	66%	68%	69%	70%	71%	72%	73%	74%	74%	75%	75%
15	2	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
20	2	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	71%	71%
30	2	42%	46%	50%	54%	57%	59%	62%	64%	65%	66%	67%	68%
40	2	34%	38%	43%	47%	51%	54%	57%	60%	61%	63%	64%	65%
50	2	27%	32%	37%	42%	46%	49%	53%	56%	58%	59%	61%	62%
5	5	75%	76%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%
10	5	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	5	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
20	5	66%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
30	5	61%	63%	66%	67%	69%	70%	71%	72%	73%	73%	74%	74%
40	5	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%	72%	73%
50	5	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	71%	71%
5	10	77%	77%	77%	77%	78%	78%	78%	78%	78%	78%	78%	78%
10	10	75%	76%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%
15	10	74%	74%	75%	76%	76%	76%	77%	77%	77%	77%	77%	77%
20	10	72%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
30	10	69%	70%	72%	73%	73%	74%	75%	75%	76%	76%	76%	76%
40	10	66%	68%	70%	71%	72%	73%	74%	74%	75%	75%	75%	76%
50	10	63%	66%	68%	69%	70%	71%	72%	73%	74%	74%	75%	75%

Storage Temperature 50°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	68%	69%	71%	72%	74%	75%	75%	76%	76%	77%	77%	77%
10	2	57%	60%	63%	65%	67%	69%	71%	72%	73%	73%	74%	74%
15	2	48%	52%	55%	59%	61%	64%	66%	68%	69%	70%	71%	72%
20	2	40%	45%	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%
30	2	28%	33%	38%	43%	47%	51%	54%	57%	59%	61%	62%	64%
40	2	20%	25%	30%	35%	39%	44%	48%	51%	54%	56%	57%	59%
50	2	14%	18%	23%	28%	33%	37%	42%	46%	49%	51%	53%	54%
5	5	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
10	5	70%	71%	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%
15	5	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
20	5	61%	63%	66%	68%	70%	71%	72%	73%	74%	75%	75%	76%
30	5	53%	56%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
40	5	46%	50%	54%	58%	60%	63%	65%	67%	68%	69%	70%	71%
50	5	40%	45%	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%
5	10	78%	78%	78%	79%	79%	79%	79%	80%	80%	80%	80%	80%
10	10	75%	76%	77%	77%	78%	78%	78%	79%	79%	79%	79%	79%
15	10	72%	74%	75%	76%	76%	77%	77%	78%	78%	78%	78%	79%
20	10	70%	71%	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%
30	10	65%	67%	69%	71%	72%	73%	74%	75%	76%	76%	76%	77%
40	10	61%	63%	66%	68%	70%	71%	72%	73%	74%	75%	75%	76%
50	10	57%	60%	63%	65%	67%	69%	71%	72%	73%	73%	74%	74%

Storage Temperature 70°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	64%	66%	68%	70%	71%	72%	73%	74%	74%	74%	75%	75%
10	2	53%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%
15	2	44%	48%	52%	55%	58%	61%	63%	65%	66%	67%	68%	69%
20	2	36%	40%	45%	49%	52%	56%	59%	61%	63%	64%	65%	66%
30	2	24%	29%	34%	39%	43%	47%	51%	54%	56%	58%	59%	60%
40	2	16%	21%	26%	31%	35%	39%	44%	47%	50%	52%	54%	55%
50	2	11%	15%	20%	24%	29%	33%	38%	42%	45%	47%	49%	51%
5	5	73%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
10	5	67%	69%	70%	71%	72%	73%	74%	75%	75%	75%	76%	76%
15	5	62%	64%	66%	68%	70%	71%	72%	73%	73%	74%	74%	74%
20	5	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
30	5	49%	53%	56%	59%	62%	64%	66%	67%	68%	69%	70%	71%
40	5	42%	46%	50%	54%	57%	60%	62%	64%	65%	66%	67%	68%
50	5	36%	40%	45%	49%	52%	56%	59%	61%	63%	64%	65%	66%
5	10	75%	76%	76%	77%	77%	77%	77%	77%	78%	78%	78%	78%
10	10	73%	73%	74%	75%	75%	76%	76%	76%	77%	77%	77%	77%
15	10	70%	71%	72%	73%	74%	74%	75%	76%	76%	76%	76%	76%
20	10	67%	69%	70%	71%	72%	73%	74%	75%	75%	75%	76%	76%
30	10	62%	64%	66%	68%	70%	71%	72%	73%	73%	74%	74%	74%
40	10	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
50	10	53%	56%	59%	62%	64%	66%	68%	69%	70%	71%	71%	72%

Storage Temperature 70°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	58%	61%	64%	66%	68%	70%	71%	72%	73%	74%	74%	75%
10	2	42%	47%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%
15	2	30%	35%	40%	45%	49%	53%	56%	59%	61%	62%	64%	65%
20	2	22%	27%	32%	37%	41%	46%	50%	53%	55%	57%	59%	60%
30	2	12%	16%	20%	25%	30%	34%	39%	43%	46%	48%	50%	52%
40	2	6%	9%	13%	17%	21%	26%	31%	35%	38%	41%	43%	45%
50	2	3%	5%	9%	12%	15%	19%	24%	28%	32%	34%	37%	39%
5	5	71%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
10	5	62%	65%	67%	69%	70%	72%	73%	74%	75%	75%	76%	76%
15	5	55%	58%	61%	64%	66%	68%	70%	71%	72%	73%	73%	74%
20	5	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
30	5	37%	42%	46%	51%	54%	57%	60%	63%	64%	66%	67%	68%
40	5	29%	34%	38%	43%	47%	51%	55%	58%	60%	61%	63%	64%
50	5	22%	27%	32%	37%	41%	46%	50%	53%	55%	57%	59%	60%
5	10	75%	76%	77%	77%	78%	78%	79%	79%	79%	79%	79%	79%
10	10	71%	72%	73%	74%	75%	76%	77%	77%	77%	78%	78%	78%
15	10	66%	68%	70%	72%	73%	74%	75%	76%	76%	76%	77%	77%
20	10	62%	65%	67%	69%	70%	72%	73%	74%	75%	75%	76%	76%
30	10	55%	58%	61%	64%	66%	68%	70%	71%	72%	73%	73%	74%
40	10	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
50	10	42%	47%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%

Storage Temperature 90°C ; Screen Length 25m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	57%	60%	63%	65%	67%	68%	70%	71%	72%	72%	73%	73%
10	2	42%	46%	50%	54%	57%	60%	62%	64%	65%	67%	67%	68%
15	2	31%	36%	40%	45%	49%	52%	55%	58%	60%	61%	63%	64%
20	2	23%	27%	32%	37%	41%	45%	49%	52%	55%	56%	58%	59%
30	2	12%	16%	21%	26%	30%	35%	39%	43%	46%	48%	50%	52%
40	2	6%	10%	13%	18%	22%	26%	31%	35%	38%	41%	43%	45%
50	2	3%	6%	9%	12%	16%	20%	25%	29%	32%	34%	37%	39%
5	5	69%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
10	5	61%	64%	66%	68%	69%	70%	71%	72%	73%	73%	74%	74%
15	5	54%	57%	60%	63%	65%	67%	68%	69%	70%	71%	72%	72%
20	5	48%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	70%
30	5	37%	42%	46%	50%	53%	56%	59%	62%	63%	64%	65%	66%
40	5	29%	34%	39%	43%	47%	51%	54%	57%	59%	60%	62%	63%
50	5	23%	27%	32%	37%	41%	45%	49%	52%	55%	56%	58%	59%
5	10	74%	74%	75%	76%	76%	76%	77%	77%	77%	77%	77%	77%
10	10	69%	71%	72%	73%	74%	74%	75%	75%	76%	76%	76%	76%
15	10	65%	67%	69%	70%	71%	72%	73%	74%	74%	75%	75%	75%
20	10	61%	64%	66%	68%	69%	70%	71%	72%	73%	73%	74%	74%
30	10	54%	57%	60%	63%	65%	67%	68%	69%	70%	71%	72%	72%
40	10	48%	51%	55%	58%	61%	63%	65%	67%	68%	69%	70%	70%
50	10	42%	46%	50%	54%	57%	60%	62%	64%	65%	67%	67%	68%

Storage Temperature 90°C ; Screen Length 50m

k_h [m/d]	k_h / k_v	25.000	35.000	50.000	70.000	95.000	130.000	180.000	240.000	300.000	360.000	430.000	500.000
5	2	48%	52%	56%	59%	62%	64%	66%	68%	69%	70%	71%	72%
10	2	29%	34%	39%	43%	47%	51%	55%	58%	60%	61%	63%	64%
15	2	17%	22%	27%	32%	36%	41%	45%	49%	51%	54%	55%	57%
20	2	10%	14%	19%	23%	28%	33%	37%	41%	44%	47%	49%	51%
30	2	4%	6%	9%	13%	16%	21%	25%	30%	33%	36%	38%	40%
40	2	1%	2%	4%	7%	10%	13%	17%	21%	24%	27%	30%	32%
50	2	0%	1%	2%	4%	6%	8%	12%	15%	18%	21%	23%	25%
5	5	65%	68%	70%	71%	72%	73%	74%	75%	76%	76%	77%	77%
10	5	53%	57%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
15	5	43%	48%	52%	56%	59%	61%	64%	66%	67%	68%	69%	70%
20	5	35%	40%	45%	49%	53%	56%	59%	62%	63%	65%	66%	67%
30	5	23%	28%	34%	38%	43%	47%	51%	54%	56%	58%	60%	61%
40	5	15%	20%	25%	30%	34%	39%	43%	47%	50%	52%	54%	56%
50	5	10%	14%	19%	23%	28%	33%	37%	41%	44%	47%	49%	51%
5	10	73%	74%	75%	76%	76%	77%	77%	78%	78%	78%	78%	79%
10	10	65%	68%	70%	71%	72%	73%	74%	75%	76%	76%	77%	77%
15	10	59%	62%	65%	67%	69%	70%	72%	73%	74%	74%	75%	75%
20	10	53%	57%	60%	63%	65%	67%	69%	70%	71%	72%	73%	73%
30	10	43%	48%	52%	56%	59%	61%	64%	66%	67%	68%	69%	70%
40	10	35%	40%	45%	49%	53%	56%	59%	62%	63%	65%	66%	67%
50	10	29%	34%	39%	43%	47%	51%	55%	58%	60%	61%	63%	64%

Figure 56 Estimated recovery efficiency for different storage temperatures, aquifer thickness values and vertical anisotropy (k_h/k_v) values

Some observation from Figure 5:

- The recovery efficiency is never higher than 80%. This is explained by heat losses caused by heat conduction and dispersion, that also occur at low temperatures.
- The recovery efficiency at low storage temperatures is higher than at high temperatures. At high temperatures, heat losses caused by density driven flow increase (the higher the storage temperature, the bigger the density difference between the ambient groundwater and the stored water).
- When higher temperatures are stored, the recovery efficiency significantly increases with decreasing hydraulic conductivity of the storage aquifer and/or increasing vertical anisotropy. This is because density driven flow is suppressed in less permeable aquifers.
- A small well screen length results in a higher recovery efficiency for the same storage volume, because the relative impact of density driven flow is smaller. A drawback of a small well screen length is that the capacity per well is also smaller (resulting in higher investment costs).
- The recovery efficiency significantly improves when the storage volume is increased, especially at high storage temperatures. When large volumes are stored, the tilting of the thermal front occurs further away from the well and therefore the impact on the recovery efficiency becomes smaller. Furthermore, the surface area/volume ratio of the hot bubble becomes smaller, reducing the relative heat losses by conduction.

When high temperatures are stored (70 and 90 °C), the tendency for density driven flow is strong. As a result, small storage volumes usually lead to low recovery efficiencies. Furthermore, layers of lower hydraulic conductivity and/or higher anisotropy are required to suppress density driven flow. In the Netherlands the Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis formations are the most interesting aquifers for storage of high temperature heat. At most locations these layers are located at a depth of more than 150 mbgl. Although the permeability of these layers is usually not well known, the permeabilities are relatively low compared to the shallower aquifers. The disadvantage of these moderately permeable aquifers is that the current design standards indicate low flow rates per well, which adversely affects the economic feasibility of projects in these aquifers. It is therefore key to find an optimum between recovery efficiency (a lower permeability is favourable to reduce thermal losses by density driven flow) and investment costs (an aquifer with a higher permeability is favourable, since higher flow rates per well can be achieved, which reduces the amount of wells that are required). For each location a consideration has to be made, based on the local hydrogeological conditions (number of aquifers present with associated depths and properties) (e.g. Drijver et al., 2012).

When relatively low temperature heat is stored (30 and 50 °C), the decrease in density is smaller. In that case storage volume is less important and the recovery efficiency can be acceptable in layers with a relatively high hydraulic conductivity. It is important here to also consider any additional losses under the influence of the regional groundwater flow (for the same hydraulic gradient a higher permeability results in a higher groundwater flow velocity).

For the Dutch target formations (Sand of Brussels and the Formations of Breda, Oosterhout and Maassluis) the following design considerations could be defined based on the following assumption: Screen length 50 m (to get economical feasible projects), K horizontal < 10 m/d, minimal recovery rate: 70 %, Anistropie 2-5:

- A HT-ATES with a temperature of 90 °C needs a minimum storage volume between 250.000 and 500.000 m^3/season.
- A HT-ATES with a temperature of 50 °C needs a minimum storage volume between 35.000 and 180.000 m^3/season

Test drilling is always necessary

The aquifers that are suitable for heat storage are often subject to limited research. This is mainly because these aquifers have never been attractive for drinking water extraction or low temperature cold / heat storage. Research through a test drilling is necessary to show where layers are located and which water quality they have. It is also desirable to perform a pumping test because the estimation of permeabilities based on grain sizes in such fine-sand packages (this usually concerns permeability <5 m/d) is too inaccurate. To reduce costs, a test drilling can be used later as a monitoring well (which is usually a requirement in the permit for a heat storage project).

Use 3-D Modelling, with accurate subsurface and time schematization

Reliability predicted effects
The reliability of the predicted effects depends on the reliability of the input in the model. This concerns the usage pattern of the system (pumped water quantities, extraction and infiltration temperatures and variation over time), the properties of the system (locations of wells, screen lengths and screen depths) and the subsurface (heterogeneity, permeability).

The model schematization is also important. For example, a 3-dimensional thermal transport model is required to correctly calculate the effects of density-driven groundwater flow (e.g. HSTWIN-3D, Modflow/SEAWAT, FEFLOW).

Heterogeneity
In groundwater models it is usually assumed that the storage aquifer is homogeneous: this means that it is assumed that the permeability in the entire aquifer is constant. This is not the case in reality, but there is often no good information about the heterogeneity at the location. Heterogeneity affects the distribution of the stored heat in the subsurface. When infiltrating the heated groundwater, a relatively large part of the water will flow into the coarsest sand layers, because they have the highest permeability. In case of groundwater extraction, however, a relatively large proportion of the extracted water is also produced from the same coarse sand layers. As a result, heterogeneity does influence the distribution of the heat in the subsurface, but the influence on the storage efficiency is usually limited. If, however, there is strong heterogeneity or if the cold and warm wells are close to each other, the influence of heterogeneity can be important.

Time scheme
When modelling heat storage in the subsurface, it is usually assumed that there is one period in which heat is stored continuously and one period in which heat is continuously supplied (for example two periods of six months). The average time that the supplied heat is stored is in that case about half a year. Realistically the system is controlled by the supply and the demand for heat, which varies over time. As a result, the flow rate and the pump direction of the heat storage system also varies over time. Due to the fluctuating pump regime (mainly pumped back and forth in the mid-season) the average storage period will in reality be somewhat shorter than half a year. Because heat losses due to processes such as heat conduction, regional groundwater flow and density-driven flow are time-consuming, a somewhat shorter average storage time will result in a somewhat higher average extraction temperature. The modelling therefore gives a slightly less favourable picture. When the cut-off temperature is reached during the winter season, the average storage time is also somewhat shorter. Generally this is favourable for the storage efficiency, but the fact that the cut-off temperature is reached is (obviously) detrimental to the storage efficiency.

Perform a sensitivity analysis for the recovery efficiency

The projects presented in this report indicate that there is a clear difference between the predicted recovery efficiency and the actual recovery efficiency. This can often be explained by the fact that the recovery efficiency of MT-ATES / HT-ATES is sensitive to variations in the storage volume, the storage temperature, the cut-off temperature and the permeability of the aquifer. In the preliminary phase it is therefore important to address the uncertainties in these parameters and the consequences of these uncertainties for the feasibility of the project. For example, the project can be feasible with a large storage volume and a high storage temperature, but not feasible in case of a smaller storage volume and / or a lower storage temperature. In certain cases, it may be useful to carry out additional research to reduce the uncertainties in the key parameters and thus to obtain more certainty about the feasibility in practice.

5.2 System integration design rules

Based on the experience with the current projects, the following design rules have been compiled for the integration with the building system.

Ensure that the usable temperature is as low as possible

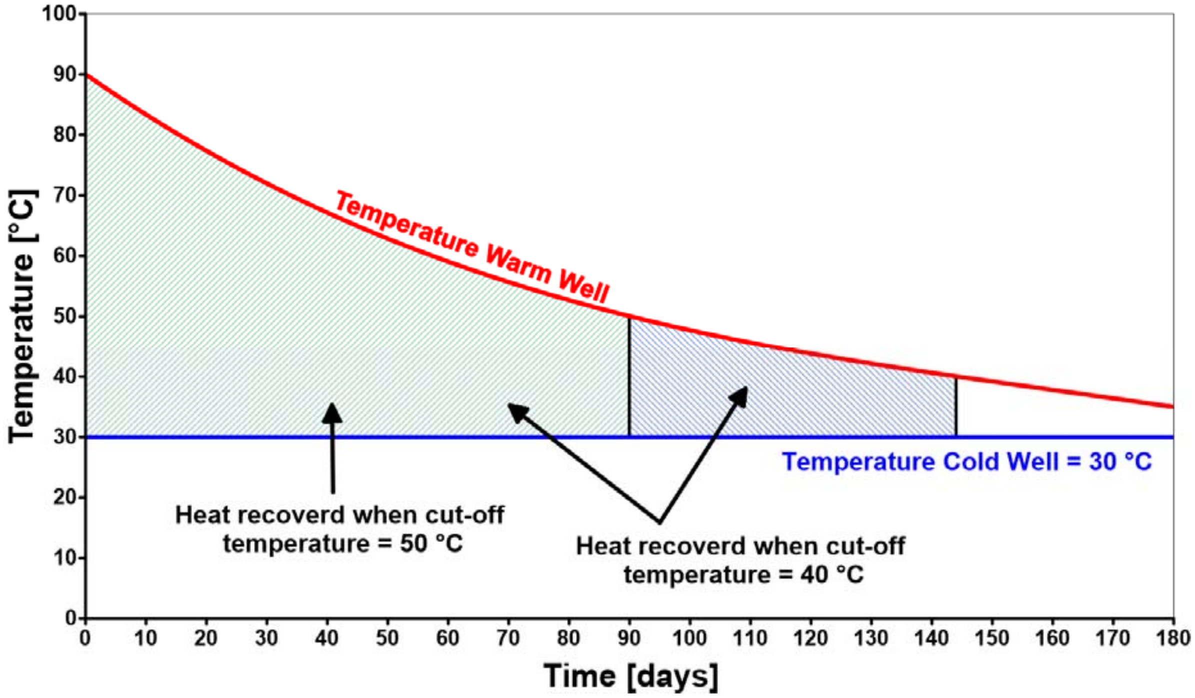

Figure 6 Example of the impact of different cut-off temperatures on the amount of heat that can be extracted

The recovery efficiency of the storage is determined not only by the heat loss in the subsurface, but also by the minimum usable extraction temperature from the hot well. This is referred to as the "cut-off temperature". At this cut-off temperature the maximum required heating power can be supplied under design conditions. The lower the cut-off temperature, the more stored heat can be recovered, which will improve the recovery efficiency. Figure 17 shows the relationship between cut-off temperature and the amount of heat that can be extracted from the subsurface with heat storage at 90 ºC. Lowering the cut-off temperature with 10 º can increase the recovery efficiency significantly (e.g. by 10 to 15 %).

Use STAR well configurations.

The HT-ATES well configuration normally consists of a doublet (one cold and one warm well). If more capacity is required more doublets were used. During the design of the HT-ATES at GEOMEC-4-P (IF technology, 2013) the wells were configurated in a star-shape; warm wells in the middle and a ring of cold wells. In this configuration the cold wells will insulated the heat around the warm wells (see Figure 18) and efficiency will increase up to 10 % (Drijver 2012).

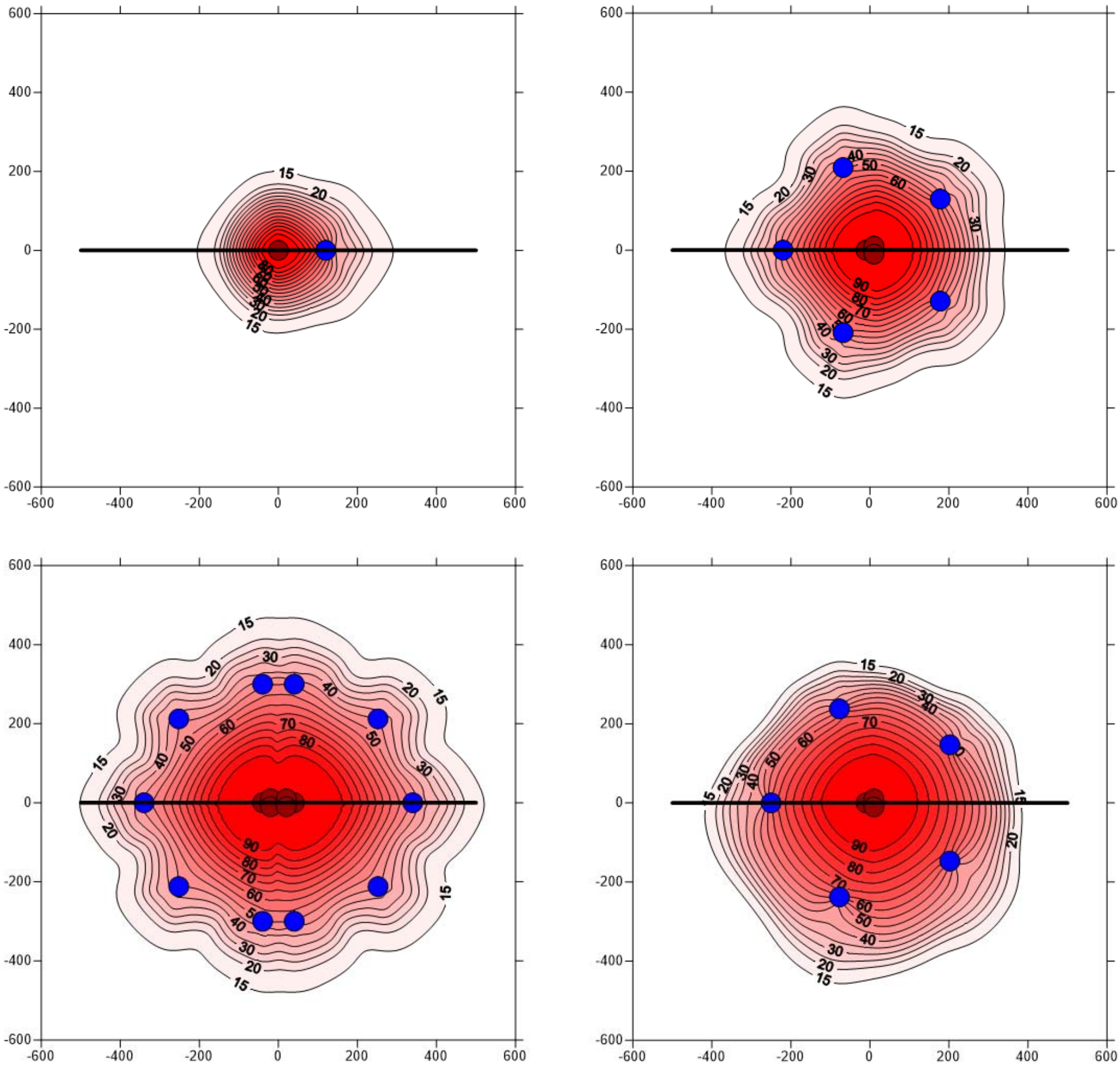

Figure 7 Different star-shape well configurations in comparison with a doublet-shape configuration (up left)

MT-ATES (50 °C) is technically less complicated than HT-ATES (90 °C)

MT-ATES (storing heat up to 50 °C) has significant technical advantages over HT-ATES (less density-driven groundwater flow, it can be used in aquifers with a higher permeability, no special high temperature resistant materials needed, no water treatment required and environmental (temperature) effects are smaller. Disadvantages of MT-ATES are that heat from a lower temperature level is suitable for less applications and a higher flow rates (and larger volumes of water) are needed for the same heating power.

Use heat storage systems in base load

The heat storage is a slow-reacting system because the heat must come from a large depth (e.g. 150-300 mbgl) and because pipe systems must be heated up. To minimize start-up losses and heating losses, it is recommended to use the heat storage as the base load of the heating system. This allows the heat storage to run almost continuously. Furthermore, the recovery efficiency can be increased by extracting as much heat as possible in the period immediately after storing the heat. Day/night storage could also increase seasonal recovery efficiency.

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Appendix II

HEATSTORE – Design considerations for high temperature storage in Dutch aquifers

HEATSTORE

DESIGN CONSIDERATIONS FOR HIGH TEMPERATURE STORAGE IN DUTCH AQUIFERS

Prepared by: Guido Bakema, IF Technology
Bas Pittens, IF Technology
Nick Buik, IF Technology
Benno Drijver, IF Technology

Checked by: IF Technology: Hetty Mathijssen

Approved by: GEUS: Thomas Vangkilde-Pedersen
TNO: Holger Cremer,
HEATSTORE coordinator

HEATSTORE (170153-4401) is one of nine projects under the GEOTHERMICA – ERA NET Cofund aimed at accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximise geothermal heat production and optimise the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe.

This project has been subsidized through the ERANET cofund GEOTHERMICA (Project n. 731117), from the European Commission, RVO (the Netherlands), DETEC (Switzerland), FZJ-PtJ (Germany), ADEME (France), EUDP (Denmark), Rannis (Iceland), VEA (Belgium), FRCT (Portugal), and MINECO (Spain).

About HEATSTORE

High Temperature Underground Thermal Energy Storage

The heating and cooling sector is vitally important for the transition to a low-carbon and sustainable energy system. Heating and cooling is responsible for half of all consumed final energy in Europe. The vast majority - 85% - of the demand is fulfilled by fossil fuels, most notably natural gas. Low carbon heat sources (e.g. geothermal, biomass, solar and waste-heat) need to be deployed and heat storage plays a pivotal role in this development. Storage provides the flexibility to manage the variations in supply and demand of heat at different scales, but especially the seasonal dips and peaks in heat demand. Underground Thermal Energy Storage (UTES) technologies need to be further developed and need to become an integral component in the future energy system infrastructure to meet variations in both the availability and demand of energy.

The main objectives of the HEATSTORE project are to lower the cost, reduce risks, improve the performance of high temperature (~25°C to ~90°C) underground thermal energy storage (HT-UTES) technologies and to optimize heat network demand side management (DSM). This is primarily achieved by 6 new demonstration pilots and 8 case studies of existing systems with distinct configurations of heat sources, heat storage and heat utilization. This will advance the commercial viability of HT-UTES technologies and, through an optimized balance between supply, transport, storage and demand, enable that geothermal energy production can reach its maximum deployment potential in the European energy transition.

Furthermore, HEATSTORE also learns from existing UTES facilities and geothermal pilot sites from which the design, operating and monitoring information will be made available to the project by consortium partners.

HEATSTORE is one of nine projects under the GEOTHERMICA - ERA NET Cofund and has the objective of accelerating the uptake of geothermal energy by 1) advancing and integrating different types of underground thermal energy storage (UTES) in the energy system, 2) providing a means to maximize geothermal heat production and optimize the business case of geothermal heat production doublets, 3) addressing technical, economic, environmental, regulatory and policy aspects that are necessary to support efficient and cost-effective deployment of UTES technologies in Europe. The three-year project will stimulate a fast-track market uptake in Europe, promoting development from demonstration phase to commercial deployment within 2 to 5 years, and provide an outlook for utilization potential towards 2030 and 2050.

The 23 contributing partners from 9 countries in HEATSTORE have complementary expertise and roles. The consortium is composed of a mix of scientific research institutes and private companies. The industrial participation is considered a very strong and relevant advantage, which is instrumental for success. The combination of leading European research institutes together with small, medium and large industrial enterprises, will ensure that the tested technologies can be brought to market and valorised by the relevant stakeholders.

Document Change Record

This section shows the historical versions, with a short description of the updates.

Version	Short description of change
2019.04.26	Ver. 0 Final report

Table of Content

1 INTRODUCTION

This report present design considerations for high temperature aquifer storage (HT-ATES). It is part of Task 1.1 and 1.2 in Work Package 1 of the HEATSTORE project.

The design considerations are based on the experience with the HT-ATES project (> 30 °) of the last 25 years in the Netherlands for sedimentary unconsolidated aquifers. In addition to the project experience use as been made of (inter)national scientific research on clogging, scaling and water treatment.

The considerations are given for the key component of HT-ATES like wells, submersible pumps, heat exchangers and water treatment. Furthermore, there will be some more general considerations on corrosion, scaling and well clogging. Thermal efficiency, aquifer selection and well configuration for HT-ATES are outside the scope of this report and dealt with in the State of the art report on HT-ATES (IF Technology, 2018b).

2 EXPERIENCES

In the Netherlands more than 3,000 (licensed) ATES systems have been realized since 1985 (Bakema, 2016). In more than 99% of these storage systems, the seasonal average of the infiltration temperature in the warm wells is below 25 ºC. ATES with storage temperatures > 30 °C has only been implemented in nine projects.
The main characteristics of these heat storage projects are summarized in Table 1. With exception of the NIOO project all the mid-temperature (< 50 °C) are made in coarse sandy fresh water aquifers. These projects are made under the same design consideration as those for low (< 25 °C) temperature storage (NVOE, 2006). Except from low thermal efficiency no problems where recorded for the main components at these mid-temperature projects. Because of the low thermal efficiency it's advised not to use these coarse sandy aquifer (Permeability > 10 m/d) for future HT-UTES projects (IF Technology, 2018).
In this evaluation, the focus will be on the project NIOO, University Utrecht and Hooge Burgh, Zwammerdam, which are made in medium fine to fine sandy aquifers (mostly salt water). Also the GEOMEC-4P HT-ATES project in Brielle is part of the evaluation although it hasn't been realised so far.

Table 1 Realised HT-ATES

Project	Realization	Flow (m^3/h)	Storage temperature [°C]	Aquifer depth [m bs]	Formation material	Water quality
Office complex, Bunnik	1985	40 (?)	25-30	20 – 50	Coarse sand	Fresh water
Utrecht University	1991	100 charge, 50 discharge	90	220 - 260	Medium fine sand	Brackish water
Heuvelgalerie Shopping Mall Eindhoven	1992	100	32	25 -80	Coarse sand	Fresh water
Dolfinarium Harderwijk	1997	Charge 90, discharge 150	40	75- 125	Coarse sand	Fresh water
Hooge Burch Zwammerdam	1998	Charge 20, discharge 25	88	130 - 150	Medium fine sand	Salt water
2 MW, Haarlem	2002	50	45	90 -120	Coarse sand	Fresh water
NIOO, Wageningen	2011	40	45	225 - 295	Fine sands	Brackish/salt water
Van Duin, Steenbergen	2016	60	40	45-80	Coarse sand	fresh
Koppert-Cress Monster	2017	40	45			
GEOMEC-4P	Only design	450	78	80-190	Medium fine sand	salt

2.1 NIOO Wageningen 2011

The headquarters of the Netherlands Institute of Ecology of the Royal Netherlands Academy of Sciences (NIOO-KNAW) in Wageningen has a high sustainability level.

To enable a sustainable climate control system, two ATES systems have been installed. The first (shallow) groundwater system is a regular (low temperature) ATES system in a coarse sand aquifer. The second (deep) ATES system is a medium-temperature heat storage system in a low permeability aquifer. The medium temperature heat storage system of NIOO consists of a cold and a warm well with infiltration temperatures of respectively 26 ºC and 45 ºC.

Table 3 gives an overview of the key design and construction items. The wells have screens at the Oosterhout formation at a depth of 220 – 290 m bs (Figure 1). Stainless steel screens have been used because of the very fine sand layers. Due to the fact that temperatures remains under the 50 °C, the casing is made of standard PVC-pipe. A submersible pump was selected that is normally used in wells of low temperature aquifer energy storage systems.

The average permeability of the top 40 m is about 0.5 m/d. The lower 30 m has a permeability of less than 0.02 m/d; mainly caused by the high content of fines (< 63 µm) and clay (Table 2).

Table 2 Sieve analyses warm well NIOO

Parameter/depth (m bs)	225	240	256	266
sand > 125 µm (%)	30.7	31.8	27.4	15.8
sand 63 -125 µm (%)	66.3	64.1	69.0	74.5
M 63 Cijfer (µm)	96	95	93	92
Silt (<63 µm) (%)	3.0	4.1	3.6	9.7
Clay (<2 µm) (%)	0.5	0.5	0.5	3.6
permeability (m/d)	0.52	0.54	0.36	0.01

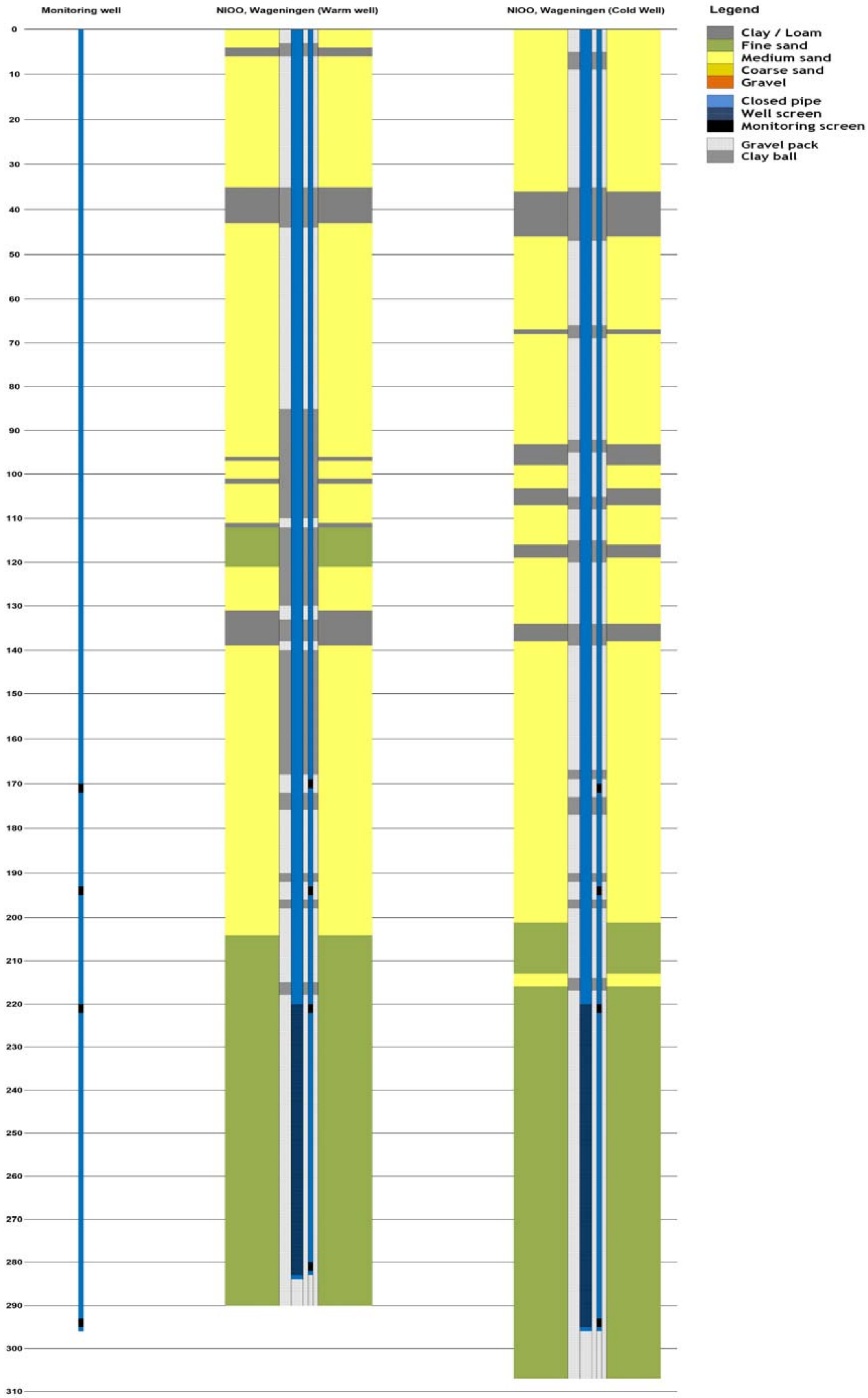

Figure 1 Well data NIOO HT-ATES project

From the different evaluation reports (DWA, 2014, IF Technology 2011 and IF Technology 2018b) the following conclusions can be drawn:

- A test drilling should have been done to verify the hydrogeologic starting points of the design.
- The capacity of the wells is more than 50 % less than expected from the geohydrological design. Mainly caused by the low permeability of the aquifer and skin. Intensive well development hasn't brought sufficient improvement. Maybe the fine sorted gravel pack and small slot size of the screen has negative impact on the productivity;
- The lower part of the screen has a low productivity (see Figure 2). The lower screen between 247-283 m bs (57%) produces 10% of the flow the upper part of the screen 220-247 m bs (43%) produces 90%. Low permeability of the deeper part of the aquifer is one of the main reasons. Also the drilling process might have negative effect on the permeability. It's suggested that during the back-fill process drilling fluids have sunk to the lower part of the wells. Also clay swelling due the intrusion of fresh water (drilling fluids) in a salt water aquifer was mentioned as cause for the low permeability.
- During the period 2011-2018 no decline of well capacity was found.
- With the exception of some broke tubes (PVC) in the monitoring and warm well no problems occurred in the rest of the groundwater systems

Table 3 Design parameters key-components

Drilling method	Reverse rotary with air-lift 600 mm
Well development methods	Sectional cleaning, air surge, chemical treatment (hydrogen peroxide)
Screen	Stainless Steel slotsize 0,1 mm, open screen surface 9,5 %
Casing pipe	PVC
Gravel pack	grainsize 0,2 to 0,63 mm
Back-fill material	Mikolite 300 (strong swell clay pellets), gravel 2 -3 mm. No insulation.
Pumps	Submersible pumps
Water treatment	no

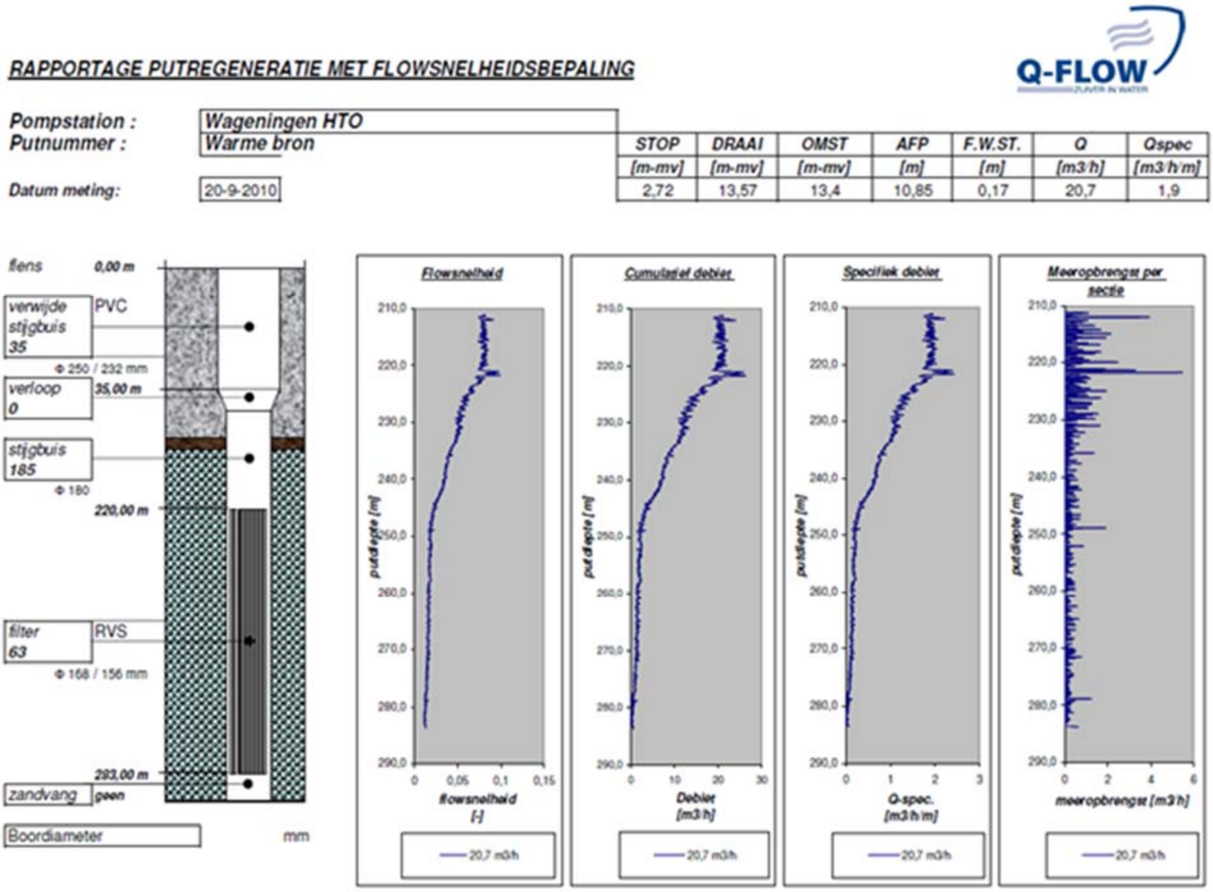

Figure 2 Flow speed measurements

Figure 3 Drilling process NIOO

2.2 University of Utrecht

The heat storage at Utrecht University has been unique in the world as the only high temperature ATES system. The heat storage was put into operation in 1991. In 1999 the warm well was damaged and the storage was taken out of service.

The ATES stored residual heat from the university's combined heat and power plants in the summer period. The heat storage consisted of a cold and a warm well, both in the third aquifer (formation of Oosterhout) at a depth of 220 to 260 mbgl.
In the design phase a test drilling was performed (Heidemij, 1988). The aquifer consist of coarse till medium fine sands with a permeability between 25 and 3 m/d (Figure 4). Because of potential high thermal losses the upper high permeable part of the aquifer was not used. The upper part of the aquifer consists of fresh water (Cl^{-}< 50 mg/l); the deeper part of brackish water (500 mg/l Cl^{-}).

The high storage temperature forces to use glass fiber reinforced epoxy (GRE) or composite casing GRE; because slotting a GRE with small size slots is impossible a stainless steel screen has been used. Suitable and payable high temperature submersible pumps were not at the market in 1991. A line shaft pump (LSP) with the motor on the surface has been used (see Table 4).

The technique of ion-exchange has been put into practice at Utrecht University. The groundwater passes an ion exchanger and calcium from the ground water is absorbed by the resin where it is exchanged by sodium. This reduces (among other things) the calcium concentration in the groundwater and the calcium carbonate saturation degree. In this way, the precipitation of calcium carbonates can be prevented.

After some time, the resin becomes saturated and has to be regenerated with sodium. After regeneration the resin can be reused.

Table 4 Design parameters key components

Drilling method	Reverse rotary with air lift 600 mm
Well development methods	Sectional cleaning and air lifting
Screen	Houston, Well Screen stainless steel RVS 316L Houston Free 114.3 x 103 mm, wirewrapped slotsize 0.3 mm, open surface 12%
Casing	Wavin, Wavistrong GRE pipe EST 25, Glass fiber reinforced epoxy
Gravel pack	0.5 – 0.8 mm
Back-fill material	Spherlite-cement thermal conductivity of 0.12 W/mK
Pumps	Line Shafts pumps (LSP)
Water treatment	Ca/Na ion-exchanges

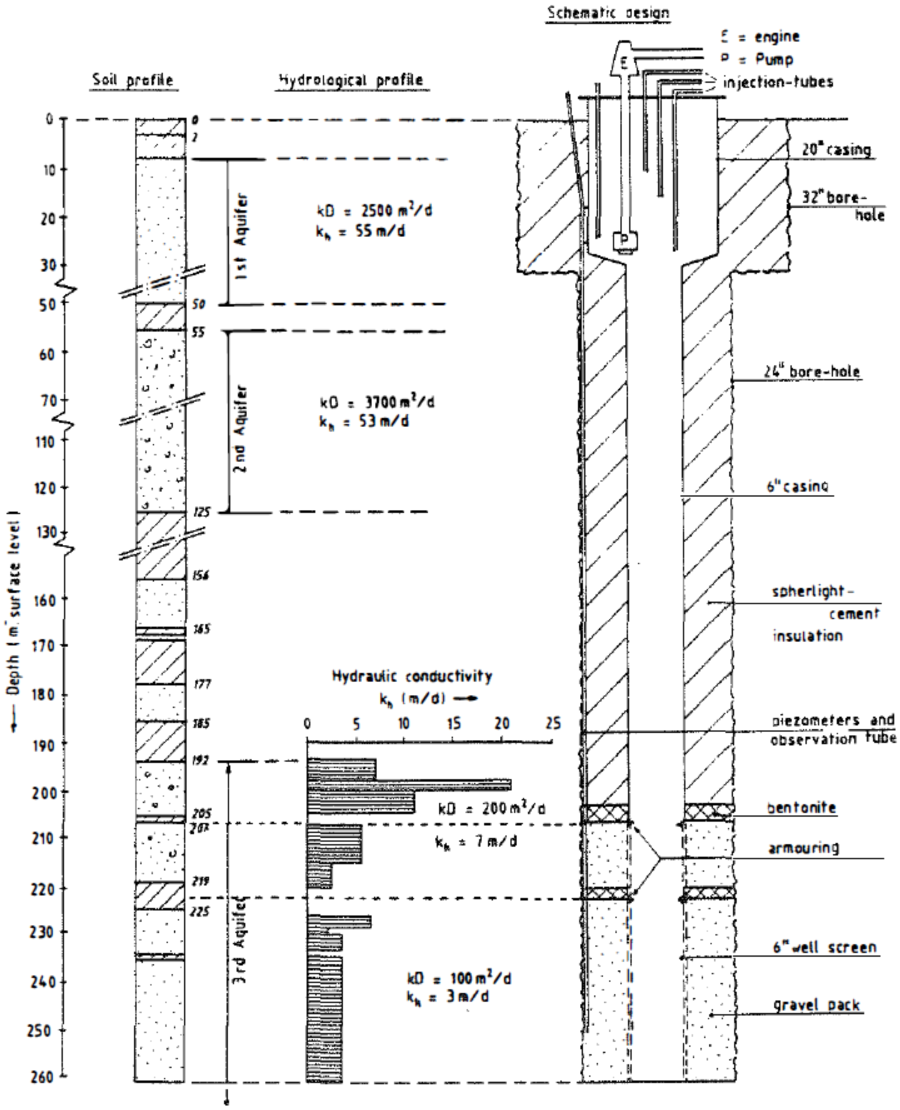

Figure 4 Geohydrological profile and well design HT-ATES University Utrecht

The HT-ATES was abandoned in 1997 due to well problems and low thermal efficiency. The project was extensive evaluated in 2001 (IF Technology, 2001). From this evaluation the main conclusions are listed:

- No corrosion was noticed. The well construction (screens, casing, well head etc) functioned without any problem.
- The warm well got serious (reduction of 85%) clogged after two years of operation. The clogging might have been caused by the water treatment (clay swelling or calcite precipitation). Regeneration of the well with HCl and hypochlorite was effective but the well never reached more than 50 % of its original capacity. During regeneration no fines (clay, sand, slit) were found.
- Due to clogging and misfunctioning of the control system the warm well cracked (1999) and injected warm water flowed to surface. The well wasn't restored.
- The Ca/Na ion-exchanges was very critical in respect to the risk of clay swelling. Manual adjustments had to be made on a regular bases and the installation was out of order during periods in 1994. Clay swelling because of the ion-exchange system has caused clogging of the warm well. Furthermore the ion-exchanges uses large amount of salt (NaCl) for

regeneration. It's was concluded that Ca/Na ion exchanges should not have been used for HT-ATES in Dutch aquifers.

- The shaft-pumps of the warm well functioned well although maintenance was very complicated and expensive. The shaft pump of the cold well broke after five years and has been replaced by a submersible pump. For future project it is advised to use submersible pumps for all wells.
- To prevent thermal losses insulation of wells and terrain piping is necessary. The wells were insulated by using concrete with spherlite around the casings. The production lines within the wells where not insulated.
- HT-ATES is mainly used in aquifers with shallow groundwater level. Water levels in the warm well can raise far beyond surface level causing practical problems during maintenance jobs at wells and pump.

2.3 Hooge Burch Zwammerdam

The Hooge Burch care institution in Zwammerdam has a cogeneration plant (CHP) for electricity production, the generated heat is used for heating. The installation was also equipped with a high temperature heat storage. Heat is stored at 90 ºC when the CHP runs for electricity production and the heat demand is smaller than the heat production. The stored heat can be used later for heat supply to the health care institution. The heat storage consists of a cold and a hot well, both in an aquifer at a depth of 135 to 151 mbgl (Figure 5). The distance between the cold and the hot well is approximately 67 m. The aquifer consists of medium fine sand with a hydraulic conductivity of 5 m/d. The aquifer contains salt water (4,000 mg/l Cl^-).
Because of the high storage temperature, the use of PVC pipes was not possible and glass fiber reinforced epoxy (GRE) was used; because slotting a GRE pipe with small size slots is impossible, a stainless steel screen has been used (see Table 5). The project was designed with line shaft pumps (LSP); during the construction phase the shafts proved to be non-resistant for salt ground water (Timmermans, 2018). Therefore these LSPs have not been installed though submersible pumps were used. Besides some issues with the cables (rubber was affected by the HCL-watertreatment) the pumps functioned well.

The solubility of carbonates is not only dependent on the temperature, but also on the pH. Addition of acid lowers the pH and provides a higher solubility of carbonates. By reducing the pH of the groundwater before the temperature is increased, carbonate precipitation can be prevented. For reducing the pH several acids can be selected. At Hooge Burch hydrochloric acid (HCl) has been used.

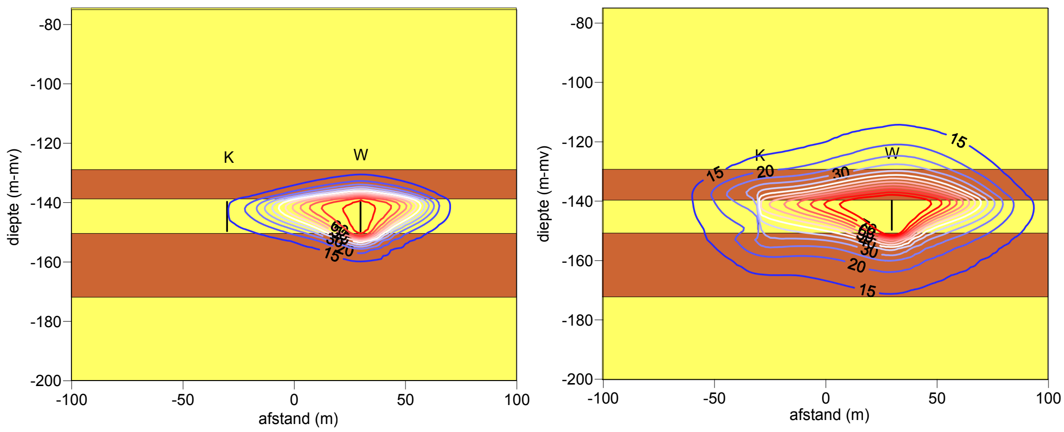

Figure 5 Temperature profile HT-ATES Zwammerdam

Table 5 Design parameters key components

Drilling method	Reverse rotary, 500 mm
Well development methods	Sectional cleaning, air surge and twin pumping.
Screen	Houston, Well Screen RVS 316L Houston Free 114.3 x 103 mm, wirewrapped, Slot size 0.3 mm, open surface 12%
Casing	Wavistrong GRE tube EST 25, DN 100, FB/FS
Gravel pack	Grain size 0.5 to 0.8 mm
Back-fill material	54% spherlite, G-cement Thermal conductivity 0.43 W/m.K
Pumps	Submersible pumps
Water treatment	HCl treatment

The HT-ATES was abandoned in 2003 due to bad economics. The water treatment was extensively evaluated and modelled (IF Technology, 2002a and 2002b, and Drijver, 2012).

In practice, about 50% of the dosage was used that would have been required based on calculations and - after four years of operation – there were no indications for clogging of the wells. It has to be noted, that no mixing of water was encorporated in the calculations, resulting in a higher dosage than predicted based on the calculation method that was used. In 1998-2001 an average acid dosage (30% HCl) of 4,0 ; 3,6 ; 2,9 and 3,2 ml/kWh was used. Although this is only for 4 years, there does not seem to be an increasing dosage. The relatively low dosage in Zwammerdam was based on the measured pH of the extracted water. It has to be noted, that the reliability of the pH-meters was limited. When the measured pH is lower than the value that is expected in case of calcite equilibrium, this indicates some degree of undersaturation. In fact, part of the acid that was added during the previous heat storage period has not been used. As a consequence, a lower dosage is sufficient.

Apparently, in practice less calcite dissolves than was expected based on model calculations. Possible explanations are the presence of layers without calcite (so no calcite can dissolve), natural inhibitors (no precipitation occurs despite some degree of oversaturation), slowness of the dissolution reaction (equilibrium conditions are not reached) and/or mixing of calcite saturated water of different temperatures which leads to undersaturation (this process is known as mixing corrosion, a phenomenon leading to karst features/cave formation, especially in coastal areas). Although the results of the Zwammerdam HT-ATES suggest that a lower dosage may be sufficient, this is not necessarily the case for other projects. Based on measurements in practice, a more accurate dosage can be worked out.

Other experience in the project were:

- The level transmitters in the wells broke down several times due to the high temperatures. No trends of pressure build-up could be measured in the wells. The maintenance firm claimed however no clogging in the wells occurred.
- The cables of the submersible pump in the warm well was affected due to the water treatment with HCl (Timmermans 2018)

2.4 Reichstag Berlin (water treatment)

At the German Parliament building (Reichstag building) two aquifers at different depth are used to store cold (ca. 60 m) and heat (ca. 300 m). The underground storage is operational since 1999, however, the full capacity of the total system and the final operational strategy could not be tested before completion of the energy network and all buildings involved in 2003. Both storage systems, after minor teething problems, performed to satisfaction (Sanner et al., 2005).
The design temperature at the warm well is 70°C while charging. No water treatment is used at the Reichstag building heat store (Sanner, 1999). According to Kranz and Bartels (2010), the storage temperature is limited to 70 °C because of geochemical aspects. They state that the solubility of silicates at higher temperatures is the limiting factor, but this probably should have been carbonates (instead of silicates). Based on the groundwater composition data, the natural groundwater seems to be calcite saturated. Apparently, in this case heating to 70 °C is possible without the necessity of water treatment.

2.5 GEOMEC-4P 2013 (design phase)

In 2013 a HT-ATES was designed for the GEOMEC-4P project. GEOMEC-4P intended to store surplus heat of a geothermal plant to be used in winter time for heating horticulture. Due to economical set-back the system wasn’t built so far. The HT-ATES design of GEOMEC-4p combined all the lessons learned from the former Dutch and international HT-ATES project.

Test drilling proved there was suitable aquifer between 80 and 190 m-bs (Figure 7). The aquifer consists of medium fine sand of the Maassluis formation with a permeability of 8 m/d. The ground water in the aquifer is salty (10.000 mg/l CL^-).

In comparison to the older HT-ATES sytems the GEOMEC-4P was significant larger in volume. It was meant to store approximately 800.000 m^3 with a configuration of three warm wells surrounded by a “ring” of three cold wells (see Figure 6).

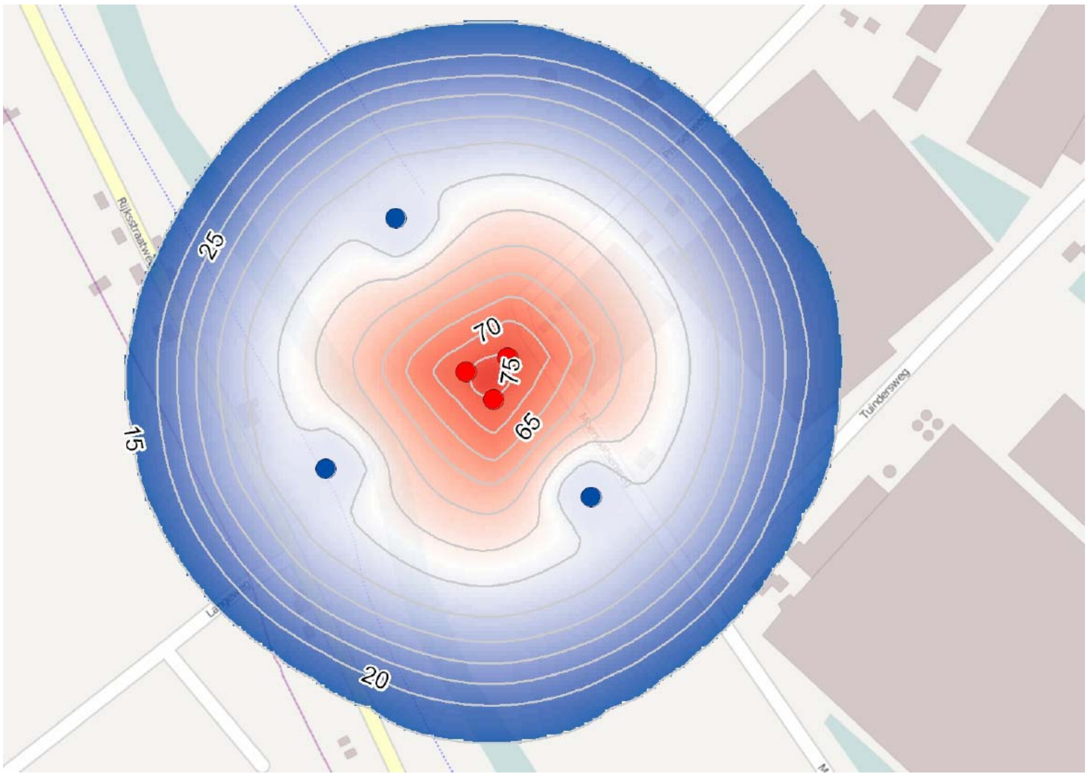

Figure 6 Well configuration HT-ATES GEOMEC

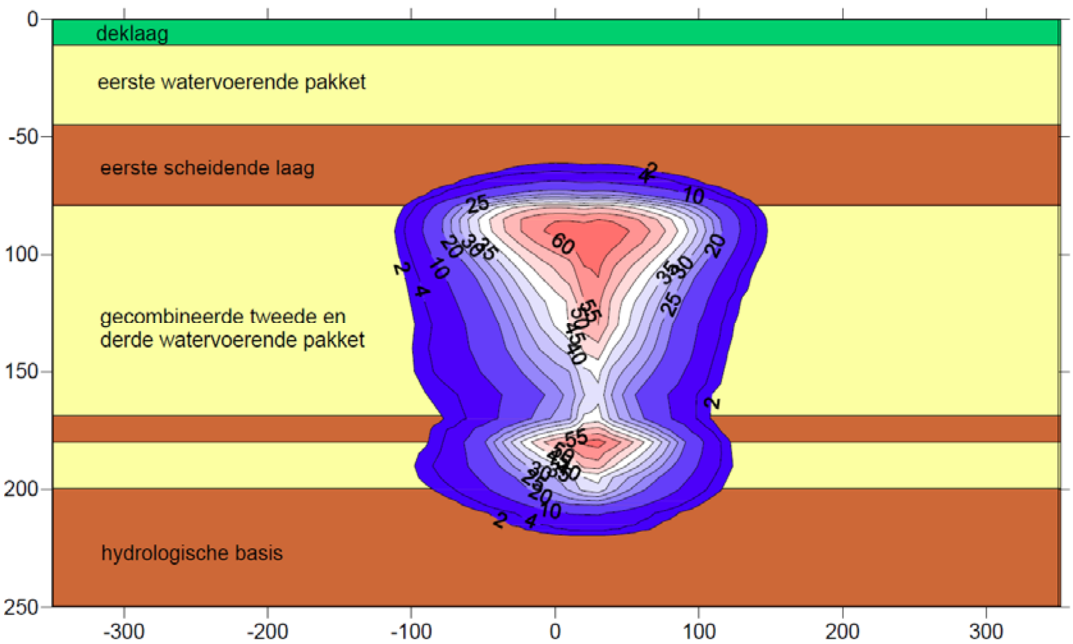

Figure 7 Cross section with HT-ATES after discharging period

Table 6 Design parameters key components

Drilling method	Reverse rotary air lift 700 mm cold well, 500 mm warm well.
Well development methods	Sectional cleaning, air lift and twin pumping.
Screen	Cold wells: PVC slotted 0,4 mm Warm wells: stainless steel, wire wrapped screen, slotsize 0,4 mm
Casing	Cold wells: PVC Warm wells: Wavistrong GRE casing
Gravel pack	Grain size 0,5 tot 0,8 mm
Back-fill material	Mikolite 300 (clay pellets with extra swelling properties), gravel 2 -3 mm. No insulation.
Pumps	Cold wells: standard submersible pumps ,Melotte Warm wells: ESP from oil&gas industry, Schlumberger
Injection valves in wells	Melotte
Water treatment	HCl treatment

The main design consideration of the GEOMEC-4P projects were:

- The cold wells were constructed with PVC screens and casings; the temperature wasn't expected to exceed 60 °C. Cost savings per well up to 70 k€
- The submersible pumps in the cold wells are standard low temperature submersible pumps; in the warm wells specific ESP were to be installed suitable for high temperatures. These ESP's are commonly used in oil&gas or geothermal applications.

2.6 Design considerations form existing projects

The experiences with former or existing HT-ATES leads to the following design considerations:

- HT-ATES systems with a warm well temperature lower than 45 °C can be designed with the same design criteria as for LT-ATES (8 – 25 °C).
- A test drilling should always be applied when designing a HT-ATES.
- Water treatment with ion-exchanges should not be used. HCl-treatment is proven to be a reliable technique to prevent clogging. High HCl consumption is major disadvantage in respect to public acceptance and high operational costs.
- Shaft-pump should not be used. Submersible pumps proved to be reliable and well adjustable to low flows; temperature level and groundwater quality should be considered when selecting a submersible pump.
- As long as oxygen accession is prevented, RVS 316 quality stainless can be used for the main components (pipes, valves, heat exchangers). However instead of RVS, the use of GRE can be a better or comparable solution for some components.
- Insulation of the well casing can minimize heat losses of the store and prevent heating up shallow (fresh water) aquifers.

3 General design aspects.

3.1 Scope of considerations

The design recommendations are concentrating on HT-ATES with temperature levels between 45 and 95 °C. Below 45 °C a standard low temperature ATES design can be used. Systems above 95 °C are considered as highly experimental (TRL below 6) and need different design considerations. The focus is on sedimentary **unconsolidated** aquifers. For the Dutch situation these are the formations of Maassluis, Oosterhout, Breda and Brussel. The standard wells for HT-ATES are vertical; horizontal and radial wells are considered experimental (TRL below 7) and need further development. and demonstration.

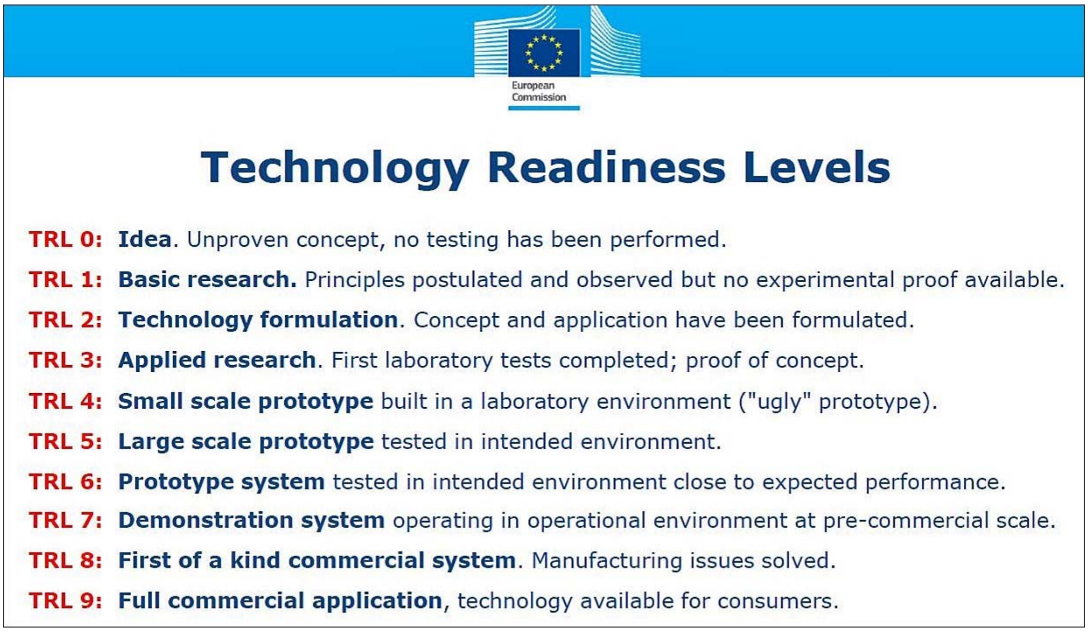

Figure 8 Technical readiness levels

3.1.1 Legal framework

The design considerations need to fit in Dutch regulation on Energy storage in the Underground (ATES). For drilling it's the regulation on mechanical drilling BRL-SIKB 2100 (SIKB 2015) and for design and construction of underground systems the BRL-SIKB 11000 (SIKB 2014). The BRL's consist of process rules and guide lines. Also the BRL demands for certified companies to construct and design ATES systems.

3.1.2 General design criteria

There is limited experience in realization of HT-ATES systems. Therefore the considerations for the designs and realizations of the existing and new HT-ATES systems are mainly based on experiences of many regular ATES systems and on deep geothermal systems. The learning curve will be very steep in the years to come. It is of great importance that before designing new HT-

ATES systems, the experiences of the latest HT-ATES systems should be studied. This information could be very valuable to adjust the design considerations as stated below.

For designing HT-ATES the same design criteria as for LT-ATES will apply. It has to apply the next design criteria:

- Minimum Lifespan of the different component:
    - Wells; 30 years; every five year mechanical (or sometimes chemical) cleaning;
    - Submersible pumps: 5 years;
    - Piping and cables : 30 years;
    - Water treatment: 10 years;
    - Heat exchangers: 10 years;
    - Pumps and valves: 10 years.
- Reliability
    - 97,5 % (one week out of order for maintenance)
    - Number of disturbances (1 hour or more): 10
- Safety
    - Regulations according to:
        - ARBOWET (Dutch law on working conditions)
        - NEN standards
        - CE/PED directives

More specific technical design criteria are:
- No corrosion of piping, heat exchangers, pumps and valves. Use stainless steel of RVS 316L quality or plastics (if possible);
- No erosion and limited pollution/clogging of wells, pumps, heat exchangers etc. The produced water should contain a minimum of non-dissolved particles: silt (MFI < 2.0) and fines (less than 0,01 mg/l);
- No oxide in the water that is produced from the aquifer. Ingress of oxygen/air needs to be prevented by using gas tight systems and by maintaining an overpressure in the system;
- No degassing of the produced water that will be injected again; system pressure is always above gas bubble point (check gasses in produced water during testing the exploration well and take into account possible high gas pressures because of CO_2 treatment);
- No scaling in wells, pumps and heat exchangers. Check water quality during testing the exploration well. Consider water treatment for every project above 50 °C, especially for preventing $CaCO_3$ scaling while heating.

3.2 Design main components

3.2.1 Test drilling

Limited data about the potential formations to be used for HT-ATES (Maassluis, Oosterhout, Breda and Brussel) is available. These formations are not used for drinking water or industrial cooling due to the high salt content and standard ATES applications are mostly applied in less deep aquifers. Therefore drilling and testing an exploration well to obtain more data is highly recommended for all HT-ATES project. In most cases the test drilling can be completed as a monitoring well that will be used during operation.

The key parameters to be investigated during drilling and testing the exploration well are:

- Groundwater composition for designing water treatment and environmental assessment study;
- Horizontal and vertical permeability of the target aquifer for calculating potential flow and thermal efficiency;
- Grain size of the sand of the target aquifer to design slot size of the screen and gravel pack
- Geohydrological structure and characteristics of the top layer (a consistent clay layer is needed) for calculating thermal efficiency and environmental assessment study.
- Drilling issues and risks (for example clay balling, mud/water losses, hard layers etc.) for designing the final wells and determine the best drilling procedures and mud.

Design considerations for drilling and testing the exploration well are:

- Reversed rotary air drilling to get good samples for accurate stratification interpretation.
- Well logging (Gamma and SP) are necessary for information on clay content and coarseness of the sand.
- Sieve analyses on some soil samples in the target aquifer for coarseness of the sand and clay-content. Correlation with the well log.
- Construction of a screen (minimal 200 mm) in the target aquifer to be able to perform a well test.
- A step draw-down test should be performed, followed by a shut in or recovery test. Well testing results will be used to determine the aquifer transmissivity and to predict production capacity of the future wells and model the thermal efficiency of the heat storage. Construct monitoring pipes in the gravel pack to be able to perform water sampling and analyses. Pipes and screens should be of GRE or stainless steel if the test well is made in the > 60 °C influence zone of the future HT system.
- During well testing the produced water will be sampled and analyzed on:
    - bubble pressure of the dissolved gas, dissolved gas quality and quantity;
    - chemical water composition.
- flow velocity measurements in the screen sections.

3.2.2 Maximum production and injection rate

For ATES systems two criteria exist to calculate the maximum allowable well entering velocity (production) and the maximum aquifer infiltration velocity. The idea behind the maximum velocity is for production avoiding sand mobilization and infiltration it is a maximum allowable clogging rate.

In the existing criteria the temperature is assumed to be fairly constant (around 12°C). It is thought that the criteria can be used in the temperature range between 6 and 20°C. The temperature effect in this range is neglectable (+/- 15%). At higher temperatures the effect of the viscosity will be of greater importance and must therefore be taken into account. In the equation below the temperature effect is incorporated into the existing production criterium:

$$v_e = 7200 * \frac{\rho_f * g}{\mu} * K_i$$

v_e maximum extraction velocity [m/h]
7200 a constant [-]
ρ_f density of produced water [kg/m³]
G gravitational acceleration [m/s²]
μ viscosity of produced water [kg/(m·s)]
K_i intrinsic permeability [m²]

The existing Infiltration criterium is based on the following equation:

$$v_{clog} = \frac{2\, MFI_{mea}\, p\, A_f^2}{\rho_w\, g} \frac{t}{t_0} \frac{\mu}{\mu_0} \frac{d_p^2\; 6^2}{D_{50}^2}\, v_{inf}^2$$

p standard pressure, 2E-5 [Pa]
t_0 running hours per year, 8760 [h]
A_f Area of filter, 1.38E-3 [m²]
μ_0 viscosity of water @10°C, 1.3e-3 [kg/(m·s)]
μ viscosity of water [kg/(m·s)]

t_0 number of hours per year [h]
t full load running hours [h]
g gravitational acceleration velocity [m/s²]
ρ_w density of water [kg/m³]
MFI_{mea} measured MFI [s/l²]
d_p diameter filter pore [m]
D_{50} average grain size [m]
V_{inf} injection velocity [m/h]
v_{clog} clogging velocity [m/a]

$$v_{clog} = \frac{2\, MFI_{mea}\, 2\, 10^5\, (1.38\, 10^{-3})^2}{\rho_w\, g} \frac{t}{8760} \frac{\mu}{1.3\, 10^{-3}} \frac{(0.45\, 10^{-6})^2 6^2}{D50^2} {v_{inj}}^2\; 3600\; 8760\; 10^6$$

$$v_{clog} = 1.6\, 10^{-9}\, MFI_{mea}\, t\, \mu \frac{1}{{D_{50}}^2}\, {v_{inj}}^2$$

When Sheperd (1989) is used to replace D_{50} by a permeability, k in [m/d] the equation changes to:

$$v_{clog} = 1.6\, 10^{-3}\, MFI_{mea}\, t\, \mu \frac{1}{(\frac{k}{150})^{1.2}}\, {v_{inj}}^2$$

This can be rewritten as:

$$v_{inj} = \sqrt{\frac{v_{clog}}{1.6\, 10^{-3}\, MFI_{mea}\, t\, \mu} \left(\frac{k}{150}\right)^{1.2}}$$

The idea behind this criteria is that the pore throat size (see Figure 9) defines the clogging potential of the aquifer and the MFI defines the clogging potential of the water to be infiltrated. When a tetrahedral arrangement of the grains is assumed, the pore throat size is about a sixth of the grainsize.

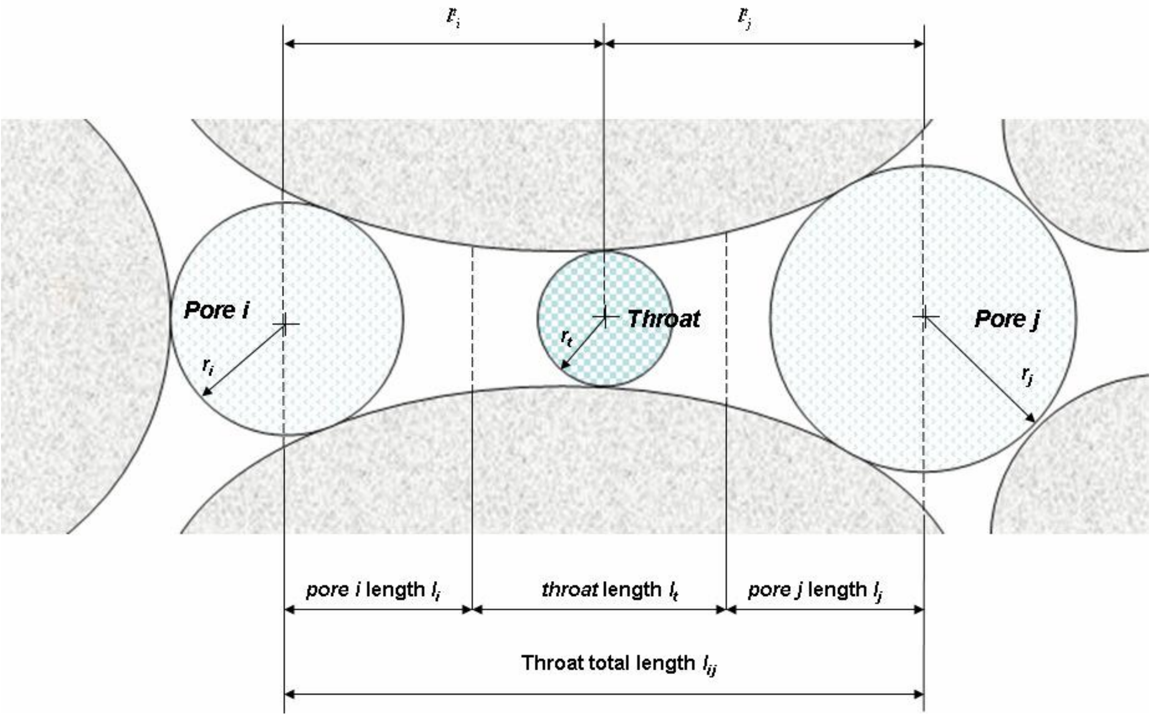

Figure 9 Schematic representation of pore throat

In Figure 10 the workflow of how the pore throat size is determined is shown.

Figure 10 Workflow for relating permeability to pore throat size

The current workflow is a bit cumbersome, also because the permeability in [m/d] depends on the temperature and the salinity of the water. It seems to be better to relate the pore throat size directly to the matrix permeability in [m^2]. In Figure 11 an example of this relation is given. The given relation below is for consolidated sediments. The question is how this relation looks like for unconsolidated sediments.

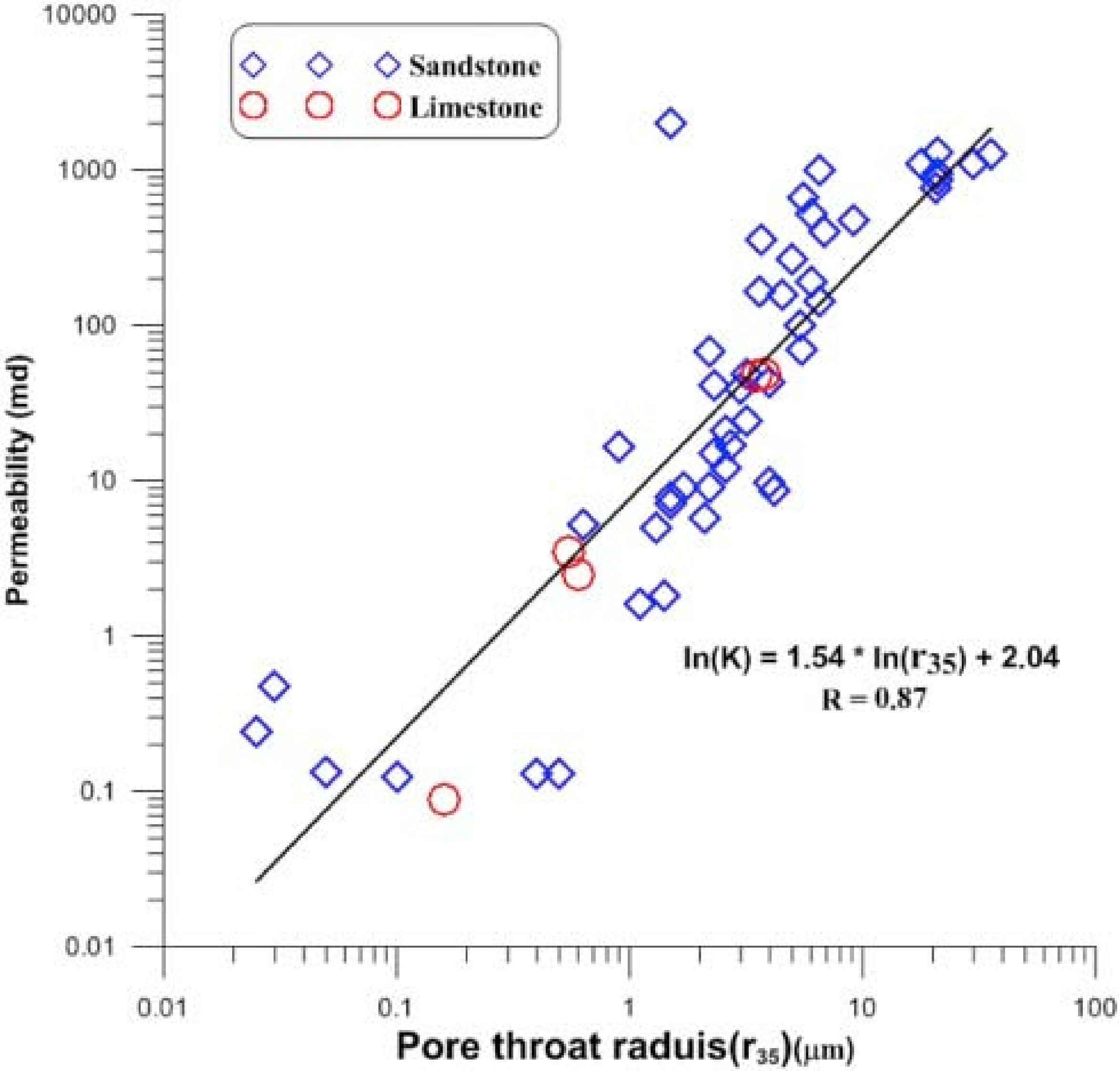

Figure 11 Example of relation between pore throat radius and permeability

Another important aspect is grain size distribution. The more unsorted (large variation in grain sizes) the reservoir the higher the risk on sand production. In reservoirs with a small variation in grain sizes, the risk on sand production is much less. How to incorporate this into design criteria is not clear yet.

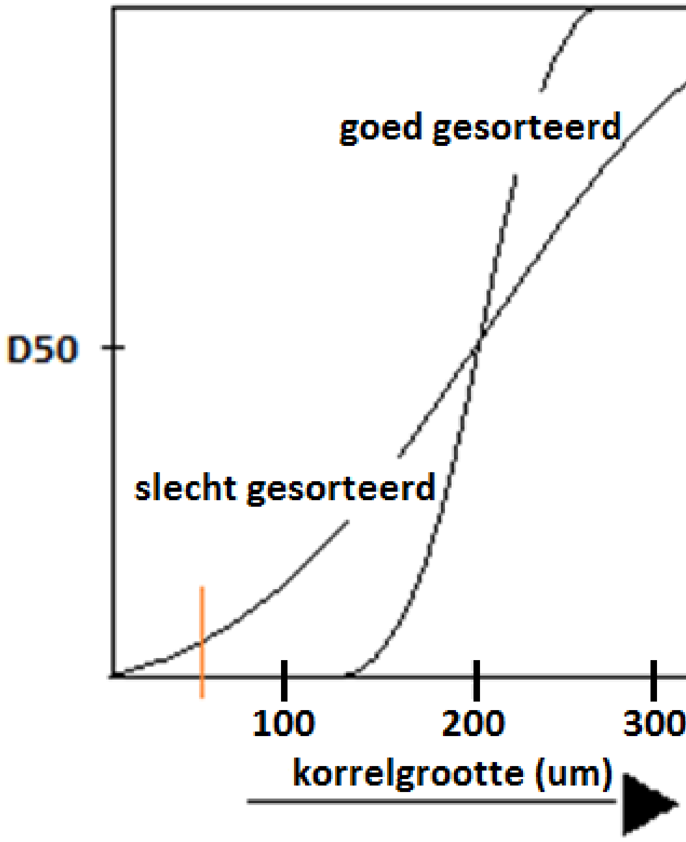

Figure 12 Schematic presentation of grains size distribution

3.3 Realisation of wells in low permeable aquifers

Considerations for realization procedures and methods are divided in: installation of well materials (casing, screen, backfill/cementing), drilling technique and process, and the well development process.

3.3.1 Casing selection

Casings for HT-ATES up to 95°C need to withstand collapse and burst pressures. In most NL HT-ATES projects GRE is and can be used. GRE is also non-corrosive and the risk for scaling is minimal.

Typical ATES wells as described in the BRL are being drilled in one stage from surface to end depth and production casing and screen are installed in one stage in this borehole. HT-ATES wells will be drilled deeper. Drilling risks (as can be experienced during drilling the exploration well, see 4.3) could increase significantly, which could affect the design.

Design consideration:

- For high temperature wells up to 95°C GRE is preferred above steal or stainless steel.
- For temperatures < 45°C, standard PVC can be considered but special attention should be given to decreased collapse and burst pressures because of these high temperatures (40% decrease @ 45°C). PVC could be considered for the cold wells as the injected water is cooled down. Restrictions: HEX needs to be operational and no possibility for bypassing the HEX (f.e. for maintenance or testing operations)
- Good experiences have been experienced using stainless steel wirewrapped screens. Special attention should be given to high load weights during installation (tensile strength on couplings and crossover to steel).
- It is preferred to use a one-stage-approach for drilling the well and installing the casing and screen: first drill the hole to end depth in the target reservoir and then install the total casing, screen and backfill in one stage. In the Netherlands this has been proven to be doable up to depths of more than 500m. Important advantages: 1. it will maximize the borehole diameter at target aquifer and 2. reduce costs significantly.
  The other approach is a telescopic approach. This approach is more common for deep geothermal wells (>1000m): first drill to the sealing clay layer above the target reservoir, then install the casing and cement it. After this first stage, the target reservoir will be drilled into with a smaller diameter. This is a two stage approach, but it could be done in even more stages.
  This telescopic approach could be considered when drilling in complex geohydrological systems. Advantage is that drilling risks can be reduced. After installing a first casing the overlying formations above the aquifer will not influence the drilling in the aquifer anymore (no clay swelling, water losses, borehole collapse). Furthermore different muds can be used for overlying formations and for the target aquifer, as the mud specifications for the target aquifer are not only important for stabilizing the borehole but also for minimizing borehole damage after drilling. The need for a more expensive telescopic approach can be concluded after a test drilling has been performed.
- Wells will be heated during operation and cool down during non-operating periods. With the high temperatures the expansion and shrinkage of the casing and wellhead need to be taken into account in the design to prevent damage during operation. This also accounts for monitoring pipes in or nearby the well. Damage can be prevented to provide enough space for expansion/shrinkage and to use special piping constructions or install compensators that will decrease expansion effects between wellhead and piping connections.

3.3.2 Screen and gravelpack selection

In the HT-ATES wells that have been build sofar wire wrapped screens of stainless steel (SS 316L) with gravel pack are used. No fines production or corrosion is reported in these wells.
There are suppliers for GRE piping that can deliver slotted GRE screens. The percentage of open area of these GRE screens is lower than for RVS wire wrapped screens, however quite similar to PVC applications in low temperature ATES systems in non-consolidated aquifers. In the Netherlands there is no experience with these slotted GRE screens and it could be interesting to investigate this option in more detail.

The Dutch BRL 11001 prescribes:Filter sand should be used as back fill material in the borehole next to the screen. Standard industrial filter sand is heterogenous and classified between a lower and upper grainsize fraction (grainsize distribution curve). The lower grainsize fraction of the filter sand should be maximal factor 4 bigger than the M50 of the sand in the aquifer.

The slot size of the screen should be at least 0.1 mm smaller than the lower grainsize fraction of the filter sand.

Design consideration:

- For the slotsizes the best option in the typical Dutch aquifers and water quality is to use wire wrapped screens of stainless steel 316L. Suppliers of GRE and/or SS 316L wire wrapped screens can deliver crossovers for connecting casing and screen. A SS 316L pipe joint for coupling the screens is laminated in the GRE pipe joint.
- Use filtersand as backfill around the screens to prevent production of fines;
- Use filtersand with a grainsizes fraction less than four times bigger than the M50 of the finest sandlayers in the aquifer. If the aquifer is considered to be very heterogenic, it can be considered to use different filtersand grainsizes.
- Well development is considered more important than risk of sand delivery. The coarser the gravel pack, the better wells can be cleaned and developed, though the more risk on sand delivery.
- Check the manufacturers deviations of slot size and gravel pack grainsizes as this can be very relevant for the small grainsizes to be used for HT-ATES.

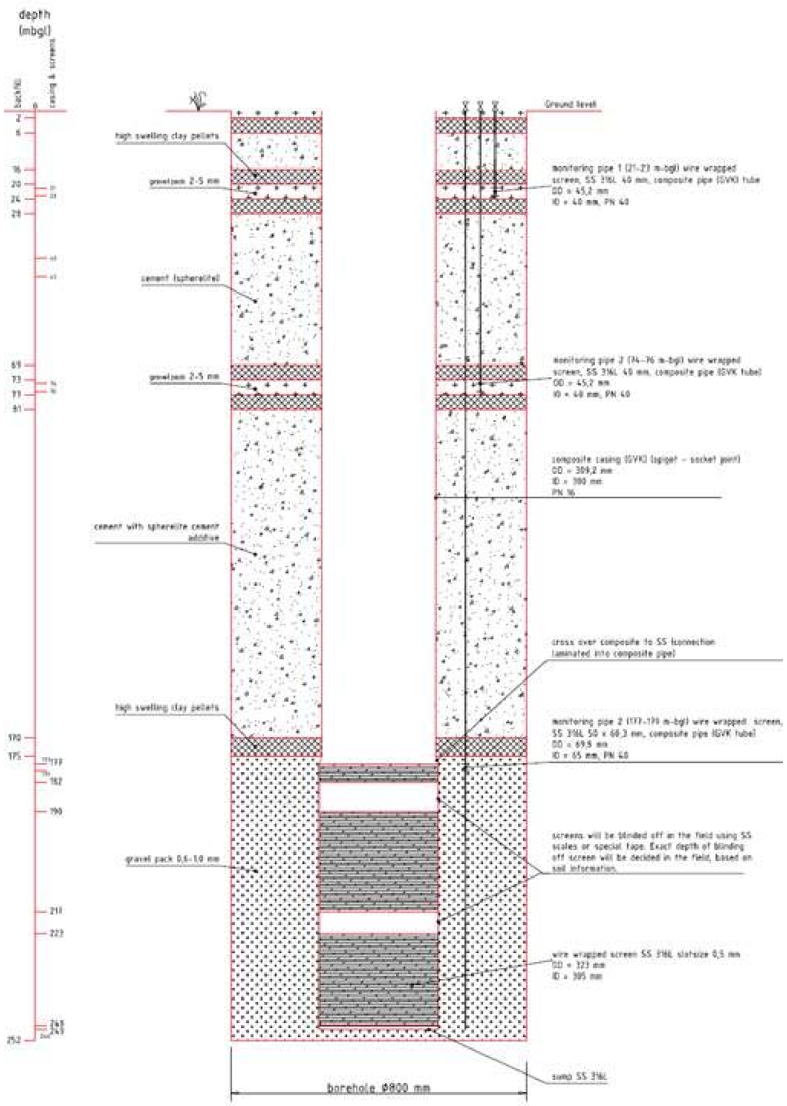

Figure 13 Typical design for an HT-ATES well

3.3.3 Back-fill material (insulation)

Not only the temperature of the target aquifer will be influenced by HT-ATES, but also the formations at more shallow depths surrounding the wells will be affected because of heat radiation from the hot casings. In the Netherlands there is no clear environmental legislation for the need of casing insulation to prevent warming up the direct surroundings of the well. The absolute effect of heat radiation depends on the water temperature that is injected in the well. At high temperatures it has been concluded that the absolute temperature effect on the surroundings of the well can be high, however, it is not expected that this will lead to environmental impact (see AVR 66146/GB for thermal calculations on effect of insulation).

The only insulation used for HT-ATES projects is a special light weight cement (Spherelite). This special cement can reduce heat losses compared to clay pellets as backfill. Spherelite minerals (hollow, fused, pressure-resistant mineral) can be mixed up with cement in different quantities. Most common and practical Spherelite cements at densities of 1.2-1.4 ton/m³ have average thermal conductivities of 0.4-0.5 W/Km. This is circa three times as low as a backfill of clay pellets.

Design considerations are:

- Use of cement with insulating properties should be considered. (e.g. Spherelite). Work out thermal calculations to determine the effect of extra insulationon the impact on temperatures around the wells and to determine the economic advantages during exploitation because of decreased heat loss. These advantages should be outweighed to the disadvantages of using special cement, which leads to extra costs and technical complications compared to standard ATES backfill of clay and sand.
- For insulation of wells Spherelite Cement is proven to be installed successful. However other light-weight cements have not been used before for HT-ATES wells in the Netherlands. Research on costs and technical impact can be considered.

3.3.4 Monitoring lines in HT-ATES wells

In common LT ATES wells monitoring lines (OD/ID of 32/28 mm) are installed in the borehole next to the well casing/screen. These monitoring lines are installed at different depths with screens at different formations in and above the target aquifer. In these monitoring lines groundwater can be sampled to analyse the water quality, gas quality and gas quantity at these depths. But also temperature and water pressure is monitored in these monitoring lines. With this data any possible effect of the target aquifer to the shallower formations can be evaluated (requirement of Dutch legislation).

For monitoring HT-ATES wells the following considerations need to be taken into account:

- Because of heat radiation from the hot well casing to its surroundings, in most cases it is of no use to monitor the temperature in monitoring lines in the same borehole next to the well casing.
- If monitoring pipes are installed in the HT-ATES well, it should be considered to use GRE pipes and GRE or SS316 screens when temperatures in the well exceed 40 C.
- To monitor the heat and water quality in the aquifer, it is advised to install a separate monitoring well at a certain distance to the hot well of the HT-ATES system. Depending on the expected temperatures, it should be considered to use GRE pipes and GRE/SS316 screens in this monitoring well. If a test drilling is done, this borehole could be completed as monitoring well.

- In case the HT ATES well is cemented, monitoring lines above the target aquifer cannot be installed anymore in the annulus between borehole and well casing. These monitoring lines should be installed in a separate nearby monitoring well.
- For monitoring temperature it can be considered to use glasfiber techniques instead of measuring temperatures in the wells or monitoring lines using temperature sensors that are installed from above. Reasons to do so:
    - temperature over depth in the monitoring lines can be influenced by heat convection in these lines (hot water going up);
    - Using a glasfiber cable gives more detailed information (continues measurement over the whole length of the well);
    - Measuring temperatures by hanging in T-sensors in the monitoring pipes is time-consuming especially at great well depths.

3.3.5 Drilling technique and process

Reverse rotary with air-lift is considerate standard technology for HT-ATES because of well diameter and a clean drilling process (see also NVOE, 2006 and SIKB 2015). In addition to the SIKB mechanical drilling protocol the considerations below for realizing HT-ATES wells focus on drilling to large depths (200 – 500 m.bs) and in heterogeneous fine sandy aquifers.
By definition deeper wells will lead to higher drilling risks as drilling to end depth will take longer and more different formations will be drilled through. Both the chance and impact of typical risks are higher when drilling deeper wells, like losing a borehole or stuck pipe after having water losses in highly permeable formations or because of swelling clays .
Furthermore the reservoirs will be less permeable: sandy reservoir with fine to very fine sands. This makes that borehole damage prevention is more important (good quality mud that prevents deep infiltration of fines in the reservoir) and de-sanding during drilling is more important as these fines are more difficult to separate from the mud.

In addition to the Dutch SIKB protocols 2101 and 11001 the following aspects need special attention:

- Check suitability of drilling rig: higher loads, more pressure needed etc.
- Do use heavy weight drilling pipes.
- The salt content will increase at these depths and therefore water levels in deep reservoirs will most likely be lower than less deep reservoirs of <200mbgl. However the reservoir pressures should be evaluated for each case as some deep reservoirs can be pressurized (Artesian) because of former geological processes.
- In the upper North Sea group it is not expected to pass zones with significant shallow gas, though this should always be evaluated before drilling.
- Gasses
- Special attention should be given to drilling mud to prevent typical drilling issues like borehole collapse and stuck-pipe. In most cases a combination of CMC (Antisol) and bentonite will be needed. Concentrations should be limited to prevent too much skin on the borehole wall in the target reservoir. Max. CMC of 0.3 kg/m³ and 1,0 kg/m³ for exceptional cases (Oasen, 2006). Bentonite?50 kg/m³? KCL??
- The mud should be pre-hydrated for at least 24 hours before start drilling. This will ensure a proper aggregation of the bentonite-clay particles.
- It is necessary to use a solid control installation to remove fines from the mud: shakers and/or hydrocyclones (desanders/desilters).
- Mud quality monitoring should be more intensive compared to regular shallow drillings. Consider to use separate mud specialist for making, maintaining and monitoring the

mud. The following parameters should be monitoord: pH (??), viscosity, density, concentration of sand/clay after the solids control installation.

- Mud should be in perfect shape before entering the reservoir. If too much sand/silt is in the mud, it should be circulated and treated until it is improved, or it should be changed out with new clean mud.
- As long as no gravel pack and backfill is being installed, the mud in the annular zone should be circulated to prevent the settling of the mud.

3.3.6 Mechanical engineering considerations

The most important design considerations will be discussed by using a global diagram (Figure 14). For the specific projects the global diagram gives a rough idea of the system layout. This diagram have to be agreed by the involved designers of the backbone installations as well as the designers of the district heating network.

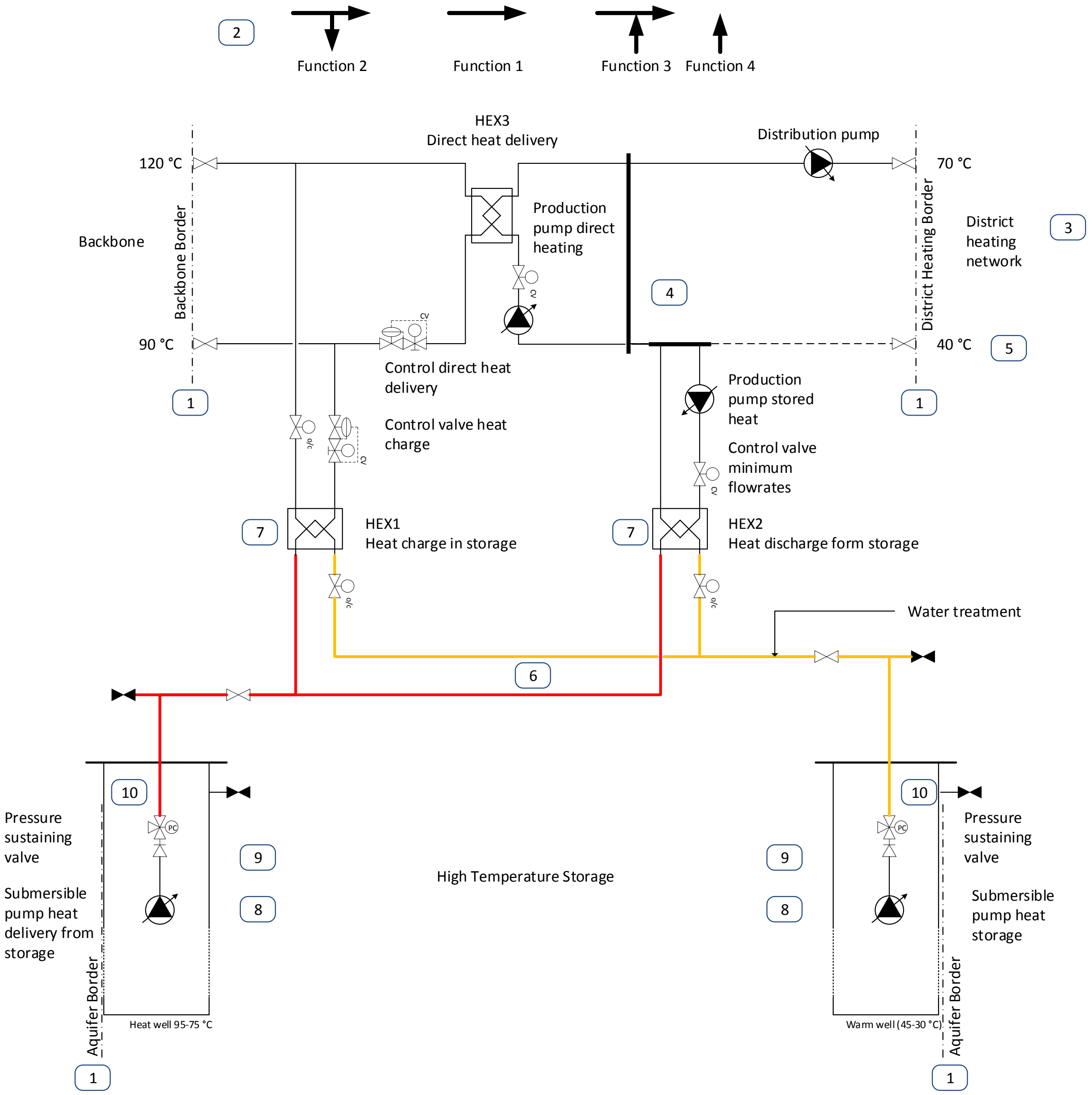

Figure 14 System integration of a HT-ATES

1. System borders

First step is to define the system borders and the design starting points and limitations at that borders: pressures, temperatures, flow's, water levels, water amounts, energy amount, power and other system requirements. In the scope of the High Temperatures Aquifer Thermal Energy Storage (HT-ATES) three borders are relevant: the back bone, which is the source of high temperature energy, the district heating network side which is the demand side of the system and the aquifer which is the location energy will be stored. In between these three borders the energy is exchanged in several ways.

2. Defining the functionality

Regarding the requirements as mentioned above and the global diagram, the functions of the energy system have to be defined. For example:

Function 1 Direct delivery: energy is delivered from the back bone to the district heating network

Function 2 Direct delivery and heat charge: energy is delivered from the backbone to the district heating network and charged in the high temperature storage at the same time

Function 3 Direct delivery and heat discharge: energy is delivered from the backbone to the district heating network and discharged from the high temperature storage at the same time

Function 4 Heat discharge: energy is discharged from the storage and delivered to the district heating network, the back bone connection is not in operation

3. Embedding HT-ATES in the energy system

In contrast to the regular used production units for heating, the HT-ATES will not be able to deliver a constant temperature during winter time (see Figure 15, displayed is the 10th year of system operation). This is of great influence in the choice where the HT-ATES will play its role in the installation.

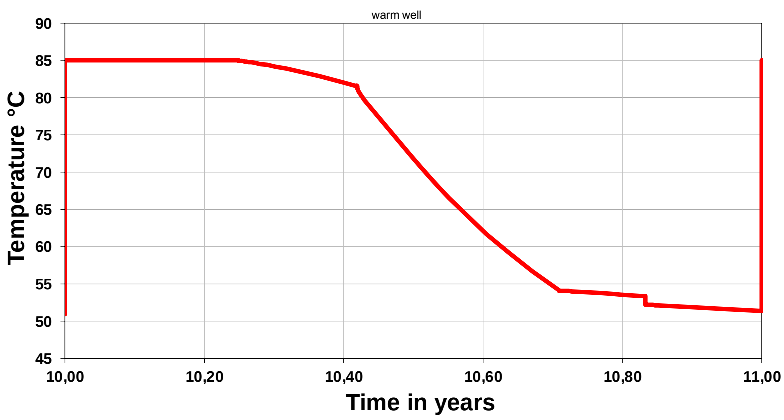

Figure 15 Temperature groundwater from warm well

Usually production units are placed in parallel while producing all the same temperature to fulfil the heating demand (see picture below). The delivery side of the installation frequently split up in several energy consumers with their one required temperature levels. By producing a high temperature at the energy power station, all temperatures can be generated by mixing valves at the delivery level.

In this kind of systems there is a big chance for a relatively small share of the HT-ATES in the energy production because the supply temperature will decrease quickly throughout the winter season and the return temperature may be too high because of the mixed high and low temperature delivery systems.

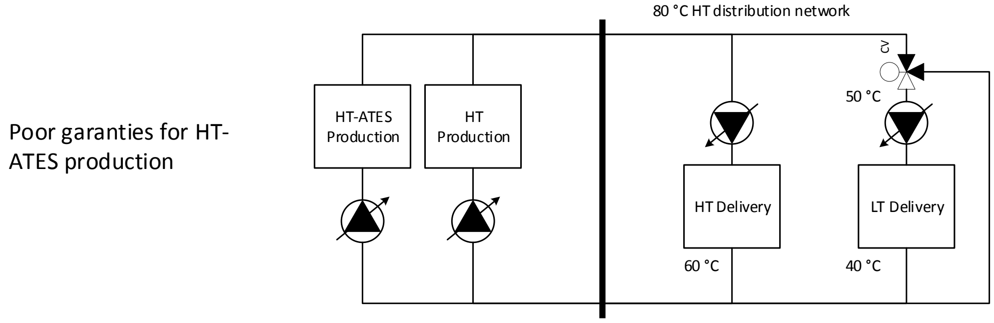

Figure 16 Poor guaranties for HT-ATES production

This situation can be improved by placing the HT-ATES production in serial with the HT production. The chance for a high return temperature form the delivery side is still there, but the possibility of HT-ATES production is improved because it is now possible to heat up the return in two steps. Where the first step is on behalf of the HT-ATES. Important point of attention is the maximum allowed entrance temperature in the HT production.

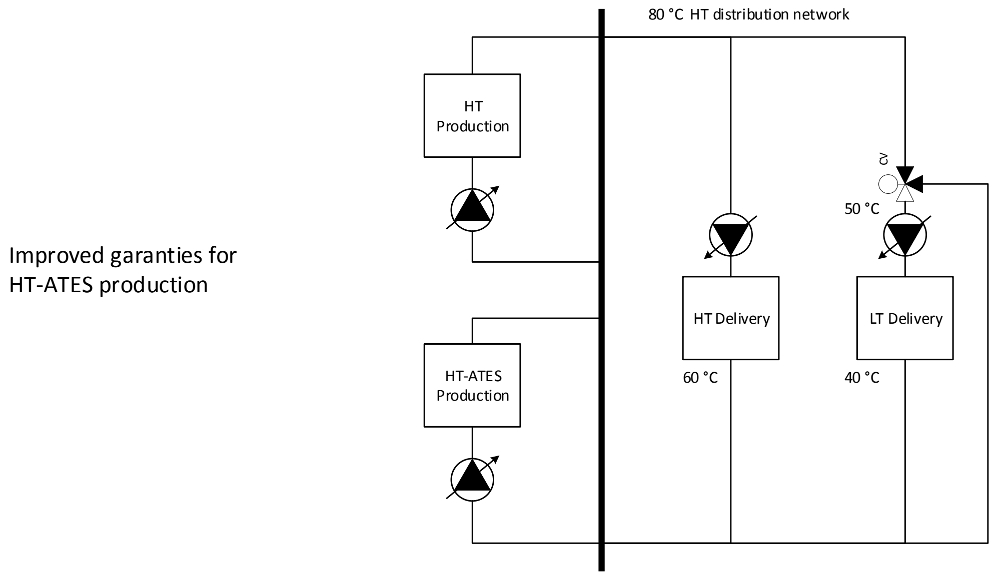

Figure 17 Improved guaranties for HT-ATES production

Better results can be achieved by splitting up the delivery distribution network in a high temperature network and a low temperature network. The HT production contributes to the HT network and the HT-ATES will produce on the LT network.

Best garanties for HT-ATES production

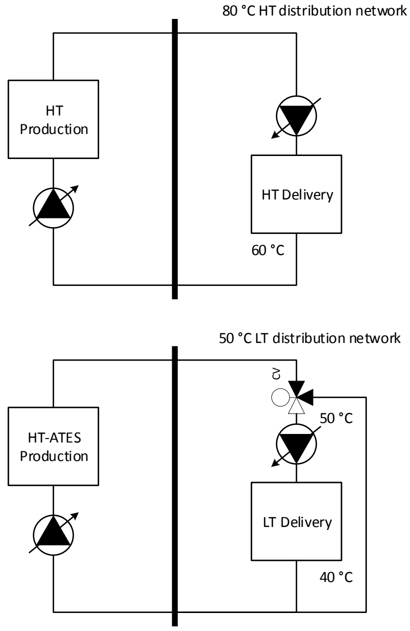

Figure 18 Best guaranties for HT-ATES production

Off course only a low temperature network will suits the best for HT-ATES production.

4. Production configuration

As mentioned above, for having a great share of the energy delivered by the HT-ATES, it is important that the HT-ATES production can be placed in serial with the direct delivery with the back bone. When a high temperature is available the HT-ATES will be able to generate the desired supply temperature. When the temperature from the warm well is decreasing, the HT-ATES is still able to take its part in the power generation in addition to the delivery from the backbone. Important point of attention is the return temperature in the Backbone circuit when HEX2 and HEX3 are placed in serial. Also the minimum capacity of the direct heating is a point of attention.

5. Return temperature

The return temperature from the district heating network is of great influence on the HT-ATES share in the energy production. The measures which are necessary to guarantee these good return temperatures lays at the other side of the border in the district heating network. So this is an important risk which cannot be controlled in the design of the HT-ATES itself, but have to be guaranteed by other parties.

High return temperatures are often caused by short cuts between supply and return pipes in the district heating network. These short cuts are necessary due to the short response times in domestic hot water production. This have to be an important discussion between the engineers of the HT-ATES and the engineers of the district heating network with low return temperatures as the final goal and meeting the requirement with regard to response times.
In each delivery set on the end users location a temperature limitation have to be implemented.

6. Temperature split.

Splitting up de system in two temperature levels might have some advantages in system cost when the low part of the system becomes beneath about 50 °C. At the low temperature side cheaper and more regular components can be selected. Important point of attention is the risk of higher temperatures at the low temperature side with possible component failure as a result. The most of the risks can be eliminated by good system alarming. However in situations with thermal break through between the warm well and the cold well, nothing can be done to protect the warm well for being exposed to high temperatures.

7. Heat exchanger

In all of the Dutch HT-ATES projects plate heat exchangers are used for the energy exchange between groundwater and other circuits. Frequently expansion and shrink of the heat exchanger due to temperature differences gives a risk for leakage at the sealings. For that reason a temperature hold function can be added to the heat exchanger.
Stainless Steel 316L is the commonly used material for the plates (important requirement is the absence of oxygen in the system). Final material choice depends on the water quality and water treatment.
Heat exchanger fouling can be of great influence on the temperatures at both sides of the heat exchanger. An important measure to avoid fouling is the water treatment (described in the next chapter) an the use of strainers in the pipework. Good monitoring with match paired temperature transmitters in combination with reliable flow transmitters (magnetic inductive or ultrasonic) and pressure transmitters makes early detection of heat exchanger fouling possible.

8. HT-ATES Pump

In the past deep shaft pumps were placed at some of the Dutch HT-ATES projects but they have all been replaced by Electrical Submersible Pumps (ESP).
Distinction can be made between de cold and the warm well of the HT-ATES. Normal ATES ESP's (also used for domestic water wells) are suitable up to a temperatures of about 60 °C during pump operation and about 85 °C when not in operation (to be confirmed by the supplier). For motor cooling a water/glycol mixture is used.
At the warm well a pump can be used from the oil and gas industry. These type of ESP's are oil filled and often equipped with down hole monitoring to measure the performance of the pump but also the monitoring for the well. A so called “food-grade” oil is available to avoid environmental damage in case of oil leakage.
Cooling of the motor is always an important issue due to the fact that the motor cooling is performed by the flow of the groundwater.

9. Injection valve

Degassing of groundwater have to be avoided because it may clog the wells very fast. Several types of pressure sustaining options have been practised in ATES-history. At the beginning of ATES injection lines where used. These injection lines consist of several pipes in the pump chamber which generates enough pressure drop at certain flowrates. A big disadvantage of this type is that the flowrate can only be adjusted in fixed values (not stepless). For that reason now a days only back pressure valves are used as pressure sustaining valve. These back pressure valves can be split up in to types: the inline version which is placed in the pump chamber and the normal version which is placed in the well house. The normal ATES versions are suitable for temperatures up to 85 °C (this have to be confirmed by the specific supplier of the valve). Extra point of attention is the control circuit of the valve, especially when this may come in contact with the hot groundwater.

10. Components in pump chamber
The high temperatures in the wells have some consequences for the pump chamber design which have to be taken in to account:

a. Wells will be heated during operation and cool down during non-operating periods. With the high temperatures the expansion and shrinkage of the casing and wellhead need to be taken into account in the design. This also accounts for piping that is connected to the wellhead.
b. Because of heating up the well, the water level in the well will rise significantly. Special attention is needed on pressures (can become artesian when heated), on safety measures to prevent exposure to hot water and on special constructions on the wellhead and procedures for maintenance purposes when wellheads need to be opened (for example regeneration operations or changing pumps etc.).
c. All components have to be suitable for the maximum temperatures which might occur in the pump chamber (even at the cold side of the HT-ATES).
d. Due to degassing of the groundwater, at the top of the pump chamber gas may accumulate just beneath the well head. This is the naturally dissolved gas in the groundwater combined with the gas which might be introduced by the water treatment. It is recommended to place the cables for pumps and transmitters in a stainless steel casing filled with domestic water. Depending on the quality of the gas a safety risk may be introduced in the well house due to small gas leakages at the well head.

3.3.7 Water treatment

One of the main problems that were encountered in TH-ATES projects in the past is mineral precipitation, especially precipitation of carbonates. For most minerals the solubility increases when the temperature rises, but for carbonates this is not the case. The result is well known from daily practice: scaling in kettles or at heating elements in washing machines. In theory a limited rise in temperature of water that is initially saturated with calcite, the most common carbonate ($CaCO_3$), leads to oversaturation and should result in calcite precipitation. In practice however, calcite precipitation does not occur when the temperature rise is limited. In literature different critical temperatures are mentioned, varying from 50 °C (Heidemij, 1987), 40-60 °C (Snijders, 1991, 1994) and 60 to 70 °C (Knoche et. al, 2003). The fact that no precipitation occurs despite significant oversaturation is attributed to the presence of natural inhibitors like phosphate and organic acids (Griffioen and Appelo, 1993; Griffioen, 1992). At the Reichstag Building (storage of 70 °C heat) no water treatment is used (Sanner, 1999). Apparently, the groundwater composition is favorable at this site.

Conclusion is that the risk of carbonate precipitation depends on the degree of carbonate saturation of the original groundwater, the temperature increase and the presence and concentrations of inhibitors. If groundwater is used that is/has been in contact with carbonates (which is likely to be saturated with carbonates), precipitation of calcite is likely in case of HT-ATES if no countermeasures are taken. The necessity to avoid calcite precipitation is illustrated by the initial experiences at the University of Minnesota in St. Paul (USA), where the heat exchanger of an experimental HT-ATES plant had to be cleaned with acid after every 40 hours of operation (Miller and Delin, 2002).

Methods

Precipitation of carbonates occurs because of (significant) oversaturation. For calcite, the degree of saturation is assessed by calculating the calcite Saturation Index (SI_{cc}):

$SI_{cc} = \log [Ca^{2+}][CO_3^{2-}]/k$

Here $[Ca^{2+}]$ and $[CO_3^{2-}]$ are the concentrations (or more accurately: the activities) of Calcium (Ca^{2+}) and Carbonate (CO_3^{2-}), and k is the equilibrium constant for calcite. The equilibrium constant is temperature dependent and decreases for increasing temperatures. When $SI_{cc} = 0$, the water is calcite saturated (in equilibrium with calcite: no calcite will dissolve or precipitate). When the Saturation Index is negative the water is undersaturated, which means that more calcite can be dissolved in the water. When the Saturation Index is positive, the water is oversaturated and there is a tendency for calcite to precipitate. However, in practice it appears that some degree of oversaturation is possible without calcite precipitation, which is attributed to the presence of inhibitors.

Based on the above theory, several strategies are possible to prevent clogging by precipitation:

<u>1. Lowering of the temperatures that the water experiences (increases the value of the equilibrium constant);</u>

The most straightforward way is to reduce the storage temperature. However, this option has large consequences for the temperature level of the heat that is recovered. Since storage of high temperatures is the starting point of this project, lowering the storage temperature is not considered as an option.
However, lowering the temperature of the hot water that is used to heat the groundwater will help to minimize scaling potential. When high temperatures are fed into the plate heat exchanger, this will increase the scaling tendency. Using a lower feed temperature reduces the risk of scaling (and/or reduces the required degree of water treatment), but increases the required size of the heat exchanger.

<u>2. Lowering the calcium concentration (reduces the saturation index);</u>

An option to reduce the calcium concentration is the application of ion exchange. This method was used in the Utrecht University HT-ATES plant, but had too many drawbacks (more details in Drijver, 2011).
Another option that reduces the calcium concentration is the use of a complexing agent, that binds part of the dissolved calcium. Because the saturation index is reduced, this may lead to dissolution of carbonates from the storage aquifer (when present) so that treatment may be required each heat storage cycle.

<u>3. Lowering the Carbonate concentration (reduces the saturation index);</u>

A standard technique to reduce the carbonate concentration is lowering the pH by adding acid:

$H^+ + CO_3^{2-} \Rightarrow HCO_3^-$

Since the saturation index is reduced, dissolution of carbonates (when present) may occur in the storage aquifer. As a consequence, treatment may be required each heat storage cycle.

Treatment with hydrochloric acid (HCl) can be considered proven technology, since this was successfully used at the Zwammerdam HT-ATES plant. The main disadvantage of HCl is that it is a hazardous fluid and large volumes of HCl are needed in large scale HT-ATES plants. The necessity of frequent transport movements of trucks with HCl is considered undesirable. Another disadvantage is that the salinity of the groundwater will increase. In aquifers that contain carbonates, the addition of HCl will be necessary each cycle, which will eventually result in a significant increase in salinity: in Zwammerdam a rise in chloride concentration from 3900 to 4100 mg/l was calculated for 20 years of operation (Drijver, 2011). For brackish and salt groundwater this rise may not be a problem, but for initially fresh water this will usually not be acceptable.

Another acid that was considered in the past is CO_2. Addition of CO_2 was tested successfully in experiments, but has not been used in full scale plants (Sanner, 2004; Sanner, 1999; Koch and Ruck, 1992). In water treatment systems using membranes (e.g. Reverse Osmosis systems), CO_2-treatment is also known for scaling prevention in other

4. Adding inhibitors

Inhibitors effectively hinder the precipitation process. The presence of inhibitors explains why some degree of oversaturation is possible without precipitation. The idea of adding inhibitors is to further increase the degree of oversaturation that is possible without precipitation. So far, this method has not been used in HT-ATES plants. However, positive experience is available in deep geothermal plants.

5. Controlled precipitation

In the past, experiments have been performed with controlled precipitation of carbonates that are subsequently removed from the system. In 1989, a fluidized bed heat exchanger was installed in the HT-ATES pilot plant SPEOS in Dorigny (Switzerland). This solved the scaling problems in the heat exchanger, but clogging in the drains was still found (Sanner, 1999).

Scaling tests

Satisfying prediction of scaling behavior in heat exchangers by means of conventional geochemical modelling software is not possible. This makes it difficult to assess the necessity of water treatment and the required degree of treatment. Within the Implementing Agreement "Energy Conservation by Energy Storage" Annex 12 "High Temperature Underground Thermal Energy Storage" of the International Energy Agency a mobile test rig (MTR) has been constructed for preliminary investigations on groundwater in respect to troublesome scale formation in above-surface HT-ATES installations, e.g. heat exchangers (Knoche et al., 2003). This mobile test rig has been used on groundwater from eight different locations to find the temperature where scaling starts to occur when no water treatment is used. The same device was also used to perform tests with CO_2 treatment. These tests show that water treatment with CO_2 works to prevent carbonate scaling and can also be used to dissolve scaling that has already formed in a heat exchanger (Sanner, 2004). Unfortunately, the test device has been dismantled and is therefore not available any more (Sanner, personal communication).

For new HT-ATES projects, a first indication of the required degree of water treatment can be obtained by performing geochemical modelling. In these calculations, a certain critical value for the saturation index must be assumed (saturation index above which scaling in the heat exchanger occurs). The right value can be obtained from in-situ tests with the local groundwater from the HT-ATES site (after construction of a test drilling or at least one of the HT-ATES wells). These tests can be extended with water treatment, to find the required dosage. When no tests are done, this may result in overtreatment, with the associated unnecessary costs and environmental impact.

Scaling control system

When scaling occurs in the heat exchanger or in the wells, this can lead to failure of the system and/or irreversible damage to the wells. It is therefore essential to be able to timely register the start of a scaling problem and take the right measures. For the heat exchanger, deterioration of the heat transfer coefficient may be the best indicator. However, tests in practice were not yet successful (Sanner, 2004). For the wells, the specific capacity is usually used as an indicator. Complicating factor for HT-ATES is the influence of the temperature distribution around the well that is tested. It can be considered to lead part of the heated groundwater through a small-scale sand filter and monitor the pressure drop. Another option is the use of coupons.
A standard measure to prevent hydraulic fracturing (resulting in irreversible damage to the wells) is the use of a pressure limit during injection.

Summing up the design considerations for water treatment:

- Consider water treatment at temperatures above 50 °C
- Use of hydrochemical modelling for a first assessment of the necessity of water treatment. In-situ testing with local groundwater recommended.
- HCL treatment is proven technology. Main disadvantage is the use of large volumes of HCl
- CO_2 treatment is a promising technology. To be tested on full-scale
- Automated scaling detection/scaling control system is highly recommended to prevent irreversible damage to the system
- Inhibitors may be worth investigating

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