HEATSTORE
Underground Thermal Energy Storage (UTES) – general specifications and design

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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
2019.09.20	Ver. 0 Final report

Table of Content

1 Introduction

This report gives general specifications and design for different types of Underground Thermal Energy Storage Systems (UTES):

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

The report is based on the experiences and lessons learned described in the HEATSTORE report "Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned"[1].

[1] Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report, GEOTHERMICA – ERA NET Cofund Geothermal. 130 pp + appendices.

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

2.1 Introduction to HT-ATES systems

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 will be restricted to a few tens of degrees Celsius (Low Temperature storage, LT). Medium temperature (MT-ATES) systems are defined as heat storage at temperatures ranging from 30-60ºC[2].

Figure 2.1 illustrates the principles of seasonal heat storage by the use of ATES in district heating. In 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.

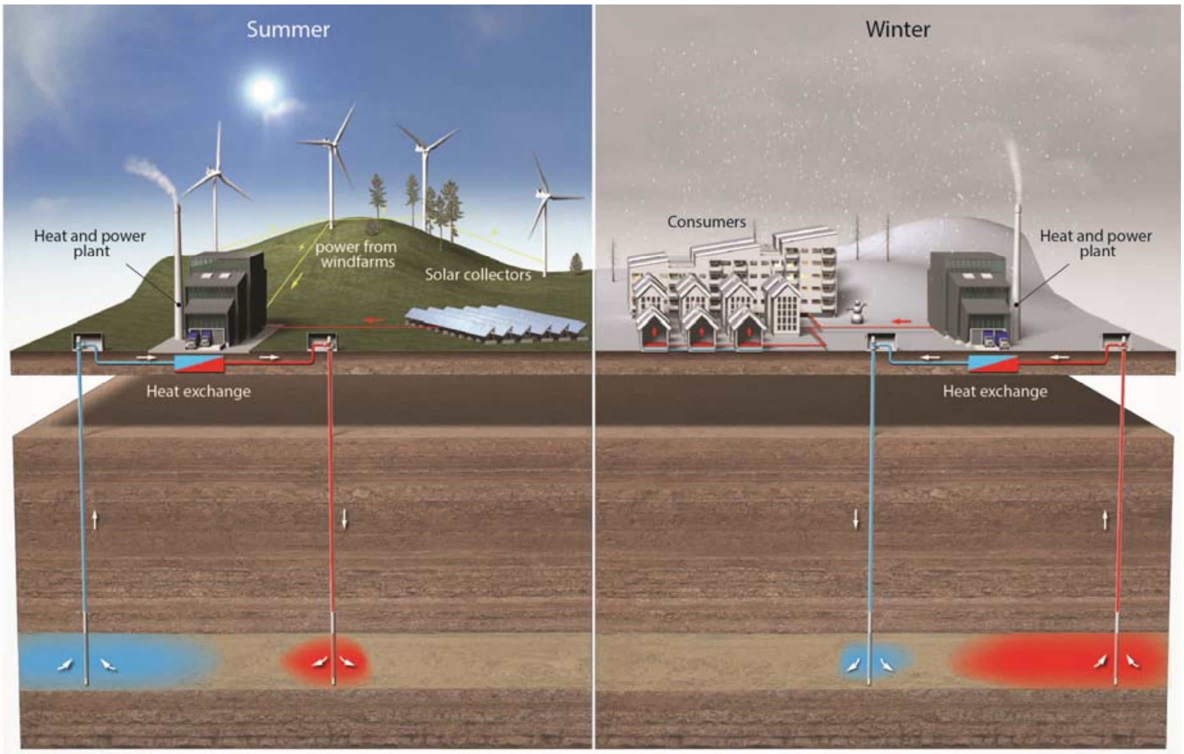

Figure 2.1 The principles of seasonal heat storage by the use of ATES in a district heating network (GEUS)

Low-temperature (<30°C) heat and cold ATES plants are the most common systems especially in the Netherlands with around 2,500 operating systems. When looking at systems with injection

[2] Whitebook - Energy storage technologies in a Danish and international perspective. DTU, Department of Energy Conversion and Storage, 2019.

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[3].

The advantages of ATES systems include very large storage potential, low operational costs and high long-term profitability. The known technical challenges include e.g. hydro-geochemical precipitation and scaling in wells and pipes, and possible weathering of the geological formation and other geochemical and rock mechanical effects resulting in formation damage. Besides the need of research and demonstration of technical issues, regulatory aspects are currently regarded as barriers for the deployment of HT-ATES.

Especially high storage temperatures >60°C may result in changes of the chemical composition of the groundwater and make chemical treatment of the groundwater necessary to prevent precipitation of minerals in the system (wells, heat exchanger and pipes). Another issue to take into consideration is that 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 the so-called cut-off temperature (the lowest applicable extraction temperature, for example 50ºC, useful in the heating system) should be as low as possible to ensure a positive business case.

Operating at lower temperatures, e.g. 30-60°C, benefits from lower thermal losses in the subsurface and usually no need for water treatment to prevent precipitation of minerals. Furthermore, the density difference between the stored warm water and the surrounding (colder) groundwater is smaller, making density-driven groundwater flow and the associated heat loss less significant. Another advantage of lower temperatures is less specific requirements for material selection for pipes, pumps and casings etc. A disadvantage of medium-temperature ATES is that the recovered heat has a lower temperature and therefore has fewer possible applications. Also, larger volumes of groundwater must be pumped to provide the same amount of heat.

2.2 General specifications for HT-ATES

The following sections are largely based on the HEATSTORE report “Design considerations for high temperature storage in Dutch aquifers”[4] produced by IF Technology.

2.2.1 Regulatory and environmental framework conditions

The national legislative framework can be a potential barrier towards HT-ATES in many countries in Europe. The permit procedures can be long, uncertain and expensive and the authority in charge can vary between e.g. member states, regions and municipalities or other local authorities.

The design considerations for HT-ATES typically need to fit several different regulations, e.g. regulation on mechanical drilling, water acts, environmental protection acts, mining acts/use of the subsurface underground acts, construction acts etc. The depth of the storage aquifer and limitations in storage temperatures are important definitions regarding the legislation of HT-ATES and e.g. depth limits in the legislation can determine which legislation is applicable. In practice, a higher infiltration temperature than 20-25 ˚C is, in principle, not permitted from a legal point of view in some countries and therefore HT-ATES will need exemption from current regulation in such cases.

[3] Fleuchaus P., Godschalk B., Stobera I. & Blum P. 2018: “Worldwide application of aquifer thermal energy storage – A review”, Renewable and Sustainable Energy Reviews 94 (2018) 861–876.
[4] Bakema, G., Pittens, B., Buik, N. & Drijver, B. 2018: Design considerations for high temperature storage in Dutch aquifers. IF Technology.

The environmental issues regarding HT-ATES are related to impact on the subsurface. The hydrogeological uncertainty will to a high degree define 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 systems 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.

All in all, the regulatory and environmental framework conditions will depend on national and local law/regulation - and on the design and operation conditions of the storage (materials, fluids, temperatures etc.). So, it is necessary to have a rough idea of the storage design and operation conditions before investigating the legal framework. And before applying for permissions, it is necessary to have a close to final version of the design and the operation conditions.

Below is given a basic check list (not to be regarded complete in all cases):

- ❒ Special regulation for the area
  - ➔ Check if it is a wildlife and botanical protected area (normally not a problem as the final above-ground space requirements for at least the HT-ATES system is normally rather small and as most of the area can be re-established after construction)
  - ➔ Check if it is a historically protected area
  - ➔ Check if there are special restrictions due to drinking water supply area
- ❒ Change of status of land use
  - ➔ Check if changes are needed for district plans and municipality plans
- ❒ Environmental Impact Assessment (EIA)
  - ➔ Check if full EIA or only EIA "screening" is required
- ❒ Groundwater should not be heated
  - ➔ Give evidence that groundwater will not be heated above limits in regulation
  - ➔ Check for the groundwater regulation, as it may set strict limitations
  - ➔ Check that the HT-ATES is not in a water abstraction area or the implications if it is
- ❒ Environmental permission issues for the energy production plant
  - ➔ Check if new/revised environmental permission for the associated energy production plant is needed

Note: Local and national specific regulations related to UTES will be screened in Task 6.2 of the HEATSTORE project.

2.2.2 Physical framework conditions

The geological and hydrogeological conditions are the first prerequisites defining the potential of HT-ATES and screening for suitable areas is therefore a first step in the initial phase to guide the decision makers. The requirements on the surface such as space requirements, heat demand, heating infrastructure, water protection zones etc. should, however, also be thoroughly investigated in a feasibility study.

The physical framework conditions to be investigated and considered before (and when) designing a HT-ATES is e.g.:

- Space requirements
- Groundwater conditions
- Ground/soil conditions
- Maximum temperature

Space requirements
The final above-ground space requirements for a HT-ATES system is normally rather small and as most of the area can be re-established after construction, but in the construction phase a larger area must be accessible for drilling rig etc. However, 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 therefore important at an early stage.

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 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[5].

Groundwater conditions
Without the availability of a suitable aquifer with favourable properties and dimensions it is not feasible to establish HT-ATES and the important parameters are:

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

[5] 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.

Ground/soil conditions
The important geological parameters are:
- 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

Important thermal properties are:
- 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

Maximum temperature
The maximum storage temperature influences the choice of material for piping, pumps and casing etc. (or the material chosen set limits to max. temperature).

2.3 Design of HT-ATES

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 the experience from many "regular" low-temperature (<30°C) ATES systems and from deep geothermal systems. The learning curve will be very steep in the years to come and 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 recommendations given below.

Minimum lifespan of the different components:
- 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

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 (Modified Fouling Index (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 of 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.

2.3.1 HT-ATES application

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) and solar thermal. HT-ATES has a 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 (2019) energy mix in most European countries.

In general, more than 50% of the stored energy in most known existing HT-ATES projects was not recovered/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 efficiency therefore will have to be increased.

HT-ATES can offer a buffer storage for short-term heat storage, for peak shifting or seasonal storage. 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)[6]. Also the charging period of the storage to the designed temperature levels needs to be included in the system integration.

2.3.2 HT-ATES construction

2.3.2.1 Mechanical engineering

The most important design considerations will be discussed by using a global diagram, see Figure 2.2. 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.

System borders

First step is to define the system borders and the design starting points and limitations at those borders: pressures, temperatures, flows, water levels, water amounts, energy amounts, power and other system requirements. In the scope of HT-ATES three borders are relevant: 1) the backbone, which is the source of high temperature energy, 2) the district heating network side which is the demand side of the system, and 3) the aquifer which is where the energy will be stored. In between these three borders the energy is exchanged in several ways.

[6] 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.

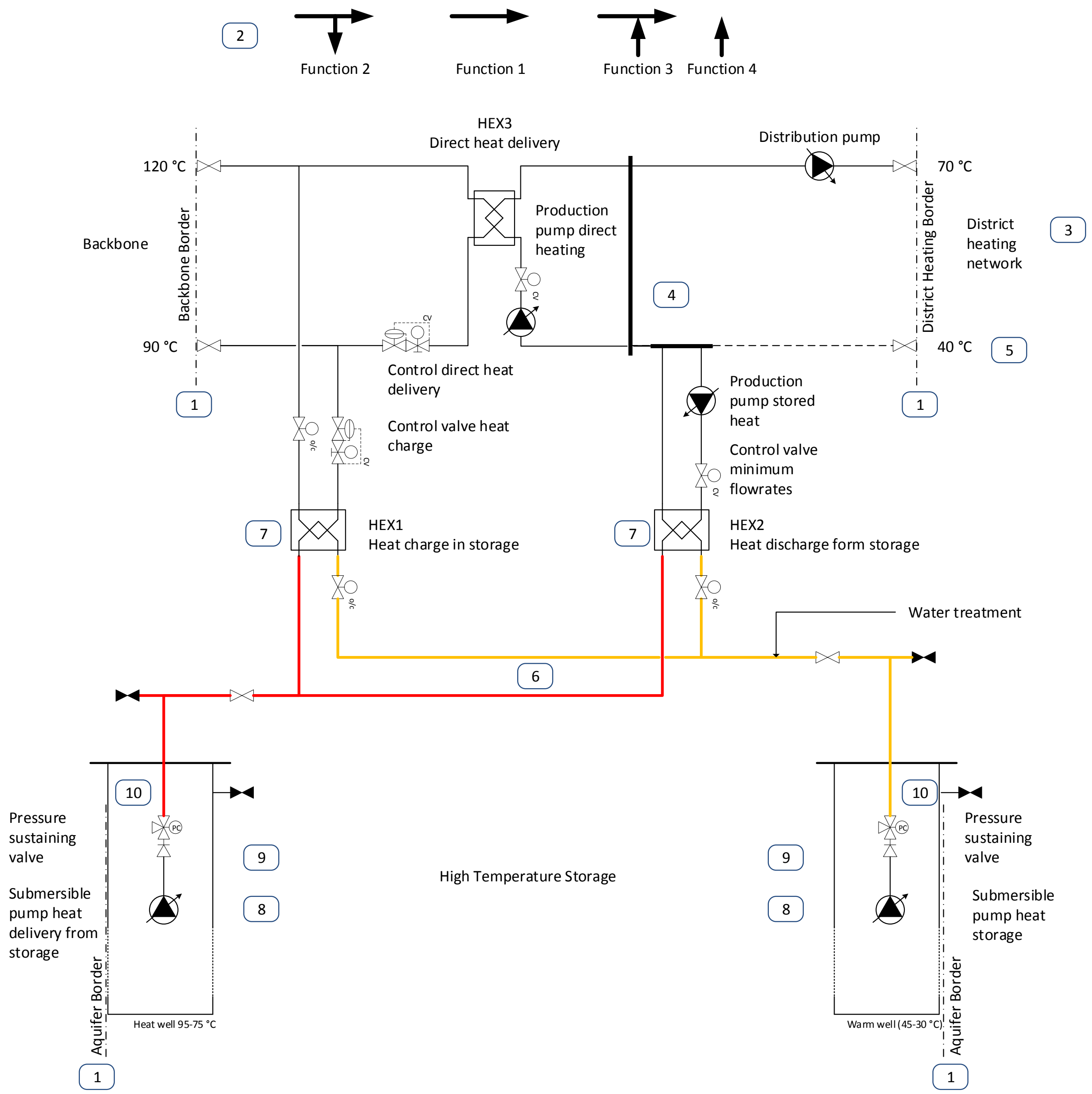

Figure 2.2 System integration of a HT-ATES

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 backbone 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 backbone connection is not in operation

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 2.3, displaying the 10th year of a system in operation). This is important in the choosing where the HT-ATES will play its role in the installation.

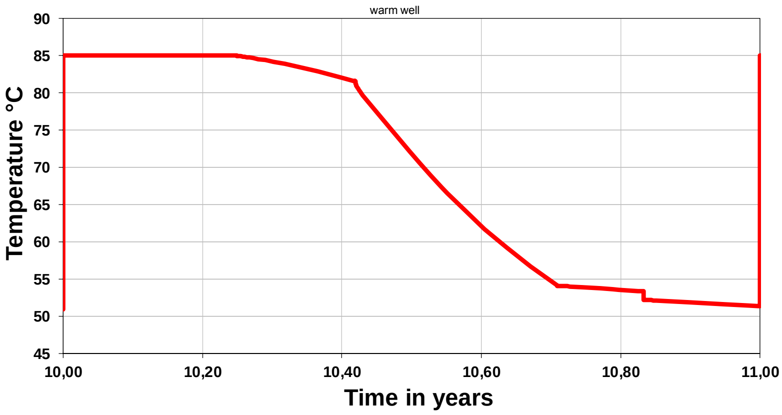

Figure 2.3 Groundwater temperature from warm well

Usually production units are placed in parallel while all producing the same temperature to fulfil the heating demand (see diagram in Figure 2.4). The delivery side of the installation is frequently split up in several energy consumers, each with their own 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 these kind of systems the potential for HT-ATES in the energy production is relatively small, 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 (HT and LT) delivery systems.

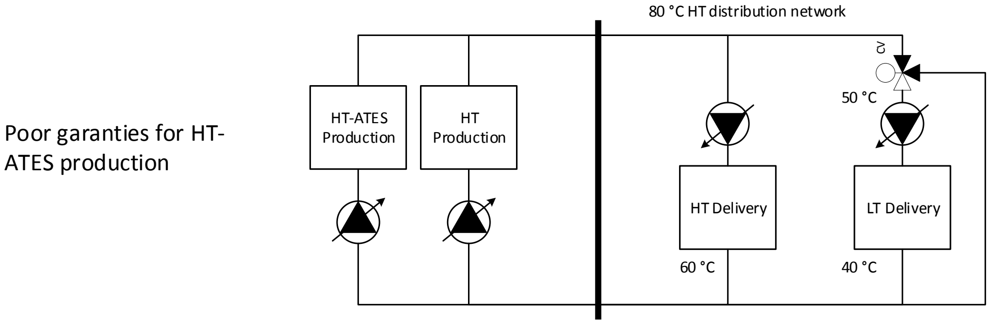

Figure 2.4 Poor guaranties for HT-ATES production

This situation can be improved by placing the HT-ATES production in serial with the HT production, see Figure 2.5. The chance for a high return temperature from 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. An important point of attention is the maximum allowed entrance temperature in the HT production.

Improved garanties for HT-ATES production

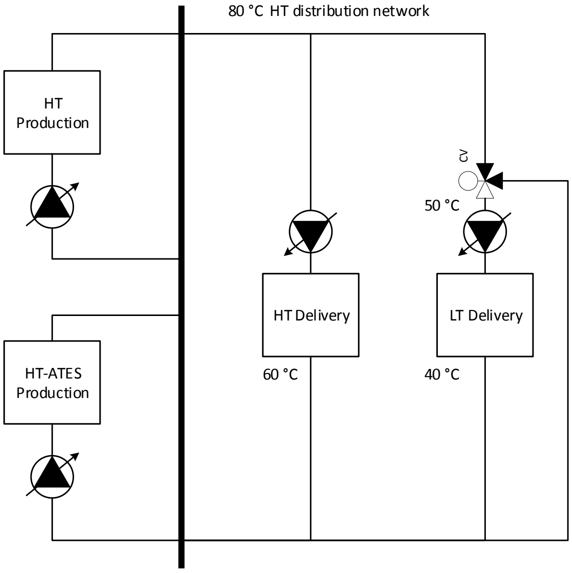

Figure 2.5 Improved guaranties for HT-ATES production

Even better results can be achieved by splitting up the delivery distribution network in a HT network and a LT network, see Figure 2.6. The HT production contributes to the HT network and the HT-ATES will produce on the LT network. In all cases, HT-ATES will always work best with a LT network.

Best garanties for HT-ATES production

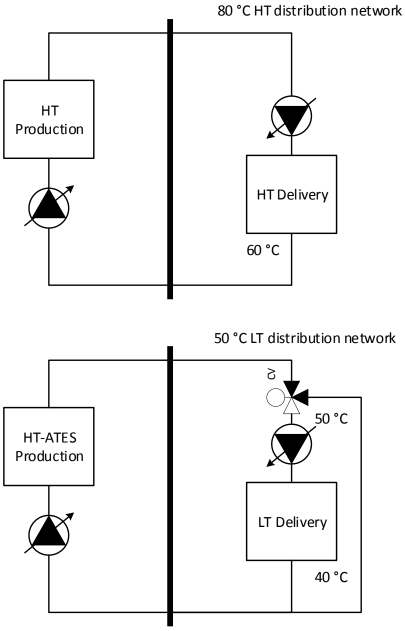

Figure 2.6 Best guaranties for HT-ATES production

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 in the backbone. 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 heat generation in addition to the delivery from the backbone. Important point of attention is the return temperature in the backbone circuit when the heat exchangers are placed in serial. Also the minimum capacity of the direct heating is a point of attention.

Return temperature
The return temperature from the district heating network has great influence on the HT-ATES share in the energy production. The measures which are necessary to guarantee optimal 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.

Temperature split
Splitting up the system in two temperature levels might have some advantages with regards to system costs when the LT part of the system is below about 50°C because cheaper and more regular components can be selected. Another important point of attention is the risk of higher temperatures than expected at the LT side with possible component failure as a result. This risk can, however, to some extent be eliminated by a good alarming system. But in situations with thermal breakthrough between the warm well and the cold well, nothing can be done to protect the cold well for being exposed to high temperatures.

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 section 2.3.3) and 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.

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 the cold and the warm well of the HT-ATES. Normal ATES ESP's (also used for domestic water wells) are suitable up to 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 types of ESP are oil filled and often equipped with downhole 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.

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 regular ATES projects. In early installations, 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, only back-pressure valves are used nowadays as pressure sustaining valve. These back-pressure valves can be split up in two 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). An extra point of attention is the control circuit of the valve, especially when this may come in contact with the hot groundwater.

Components in pump chamber
The high temperatures in the wells have some consequences for the pump chamber design, which have to be taken into account:

- 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.
- 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.).
- 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).
- 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.

2.3.2.2 Drilling technique and process

Reverse rotary drilling with air-lift is considered standard technology for HT-ATES because of well diameter and a clean drilling process. The considerations below for realizing HT-ATES wells focus on drilling to large depths (200 – 500 mbgl) and in heterogeneous fine sandy aquifers.

By definition deeper wells will lead to higher drilling risks as drilling to final 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 a 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. Therefore borehole damage prevention (good quality mud that prevents deep infiltration of fines into 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 with depth and therefore water levels in deep reservoirs will most likely be lower than less deep reservoirs (<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 in the Netherlands it is not expected to pass zones with significant shallow gas, though this should always be evaluated before drilling.
- 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.
- 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 monitored: 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 replaced by 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.

2.3.2.3 Casing selection

Casings for HT-ATES up to 95°C need to withstand collapse and burst pressures. In most HT-ATES projects in the Netherlands, Glass-Reinforced Epoxy (GRE) casings is, and can be, used. GRE is also non-corrosive and the risk for scaling is minimal.

Typically, regular ATES wells are being drilled in one stage from surface to final depth and production casing and screen are also installed in one stage. HT-ATES wells will be drilled deeper and as mentioned above, the associated drilling risks could increase significantly, which could also affect the design.

Design considerations:

- 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 high temperatures (40% decrease @ 45°C). PVC could be considered for the cold wells as the injected water is cooled down. Restrictions: the heat exchanger needs to be operational and there is no possibility for bypassing the heat exchanger (e.g. for maintenance or testing operations).
- Good experiences have been obtained using stainless steel wire wrapped 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 final 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 are: 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. The 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 (see section 2.3.4.1).
- 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 by providing enough space for expansion/shrinkage and to use special piping constructions or install compensators that will decrease expansion effects between wellhead and piping connections.

2.3.2.4 Screen and gravelpack selection

In the HT-ATES wells that have been built so far, 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, but 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.

The Dutch BRL 11001 regulation prescribes: filter sand should be used as back fill material in the borehole next to the screen. Standard industrial filter sand is heterogeneous and classified between a lower and upper grain size fraction (grain size distribution curve). The lower grain size fraction of the filter sand should be less than 4 times 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 grain size fraction of the filter sand.

Design considerations:

- For the slot sizes the best option in 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 filter sand as backfill around the screens to prevent production of fines.
- Use filter sand with a grain size fraction less than four times bigger than the M50 of the finest sand layers in the aquifer. If the aquifer is considered to be very heterogenic, it can be considered to use different filter sand grain sizes.
- 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 manufacturer's deviations of slot size and gravel pack grain sizes as this can be very relevant for the small grain sizes to be used for HT-ATES.

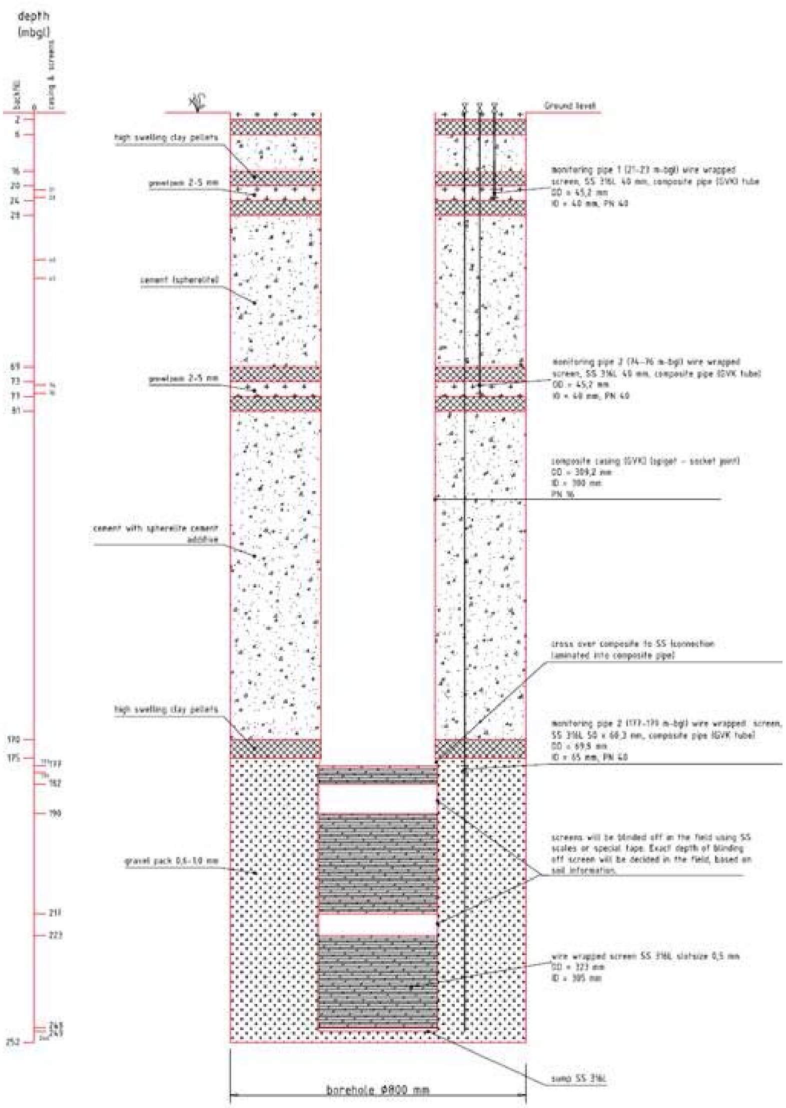

Figure 2.7 Typical design for a HT-ATES well

2.3.2.5 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, but it is not expected that this will lead to environmental impact (see the Dutch AVR 66146/GB regulation 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 often Spherelite cements at densities of 1.2-1.4 ton/m³ have average thermal conductivities of 0.4-0.5 W/(m K). This is approx. 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). Thermal calculations can estimate the effect of extra insulation, the impact on temperatures around the wells and the economic advantages during exploitation because of decreased heat loss. These advantages should outweigh the disadvantages of using special cement, e.g. extra costs and technical complications compared to standard ATES backfill of clay and sand.
- For insulation of wells Spherelite cement has proven to be successful. However, other light-weight cements have not been used before for HT-ATES wells in e.g. the Netherlands and further research on costs and technical impact can be considered.

2.3.2.6 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 in 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. With these data, any possible effect of the target aquifer to the shallower formations can be evaluated (requirement of e.g. 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 a 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 are:

- o Temperature over depth in the monitoring lines can be influenced by heat convection in these lines (hot water going up).
- o Using a glass fiber cable gives more detailed information (continues measurement over the whole length of the well).
- o Measuring temperatures by installing temperature sensors in the monitoring pipes is time-consuming especially at large depths.

2.3.2.7 Well configuration

The HT-ATES well configuration normally consists of a doublet (one cold and one warm well). If more capacity is required more doublets are used. During the design of the HT-ATES at GEOMEC-4-P[7], the wells were placed in a star-shape; warm wells in the middle and a ring of cold wells around them. With this configuration the cold wells will capture the heat from the warm wells (see Figure 2.8) and the efficiency will increase up to 10%[8].

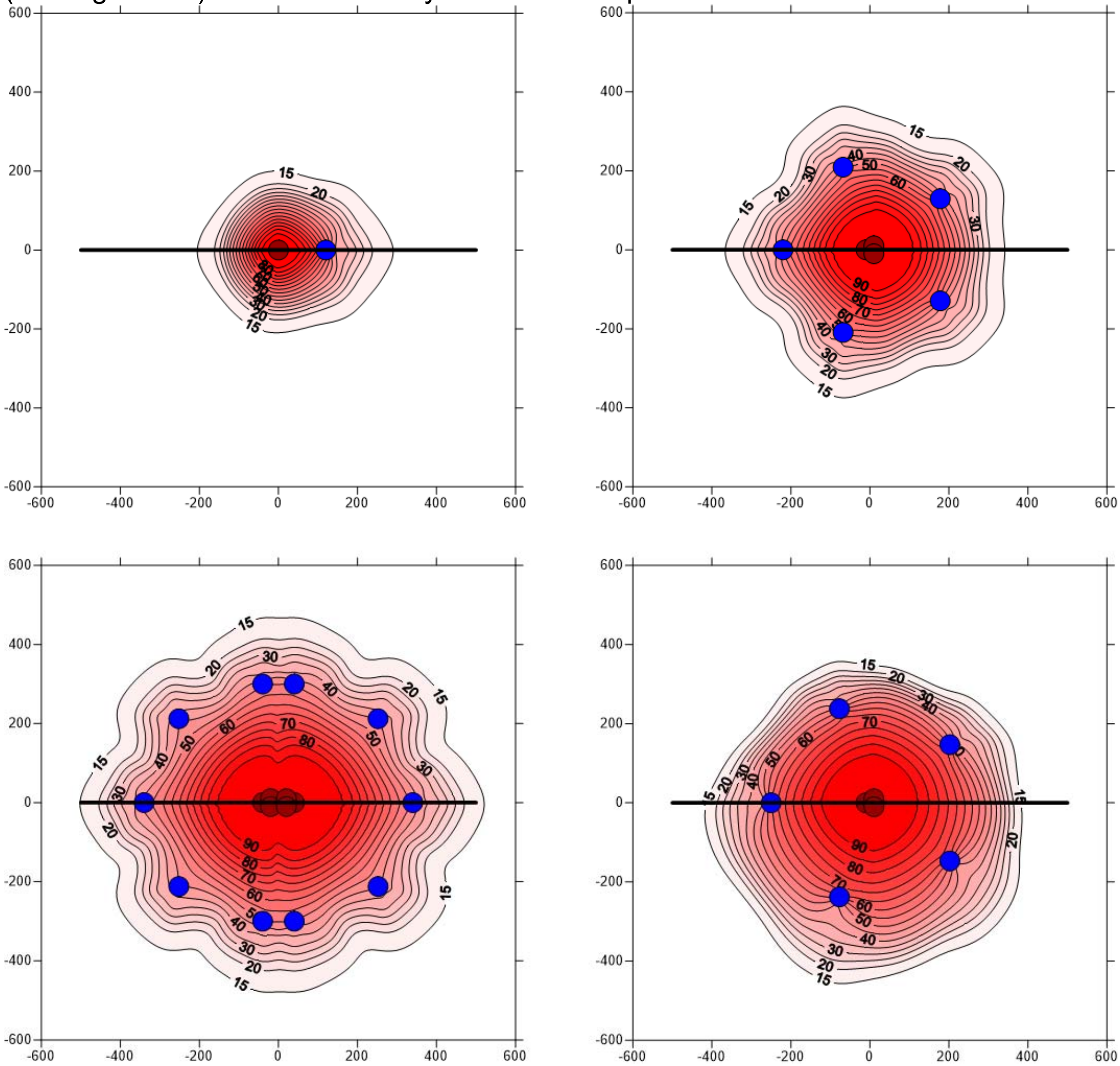

Figure 2.8 Different star-shape well configurations in comparison with a doublet-shape configuration (upper left)

[7] IF Technology. 2013: Design wells and water treatment for GEOMEC-4P (in Dutch). 2013044/58182/BP (confidential). Arnhem

[8] Drijver, B. 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.

2.3.3 Water treatment

One of the main problems that were encountered in HT-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 heating elements in e.g. washing machines. In theory, a limited rise in temperature of water that is initially saturated with calcite ($CaCO_3$, the most common carbonate), will lead to oversaturation and 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[9], 40-60°C[10,11] and 60-70°C[12]. The fact that no precipitation occurs, despite significant oversaturation, is attributed to the presence of natural inhibitors like phosphate and organic acids[13,14]. At the Reichstag Building (storage of 70°C heat) no water treatment is used[15]. Apparently, the groundwater composition is favourable at this site.

The 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[16].

2.3.3.1 Methods

Precipitation of carbonates occur 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 with increasing temperatures. When SI_{cc} = 0, the water is

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9 Heidemij. 1988: Seasonal storage university of Utrecht. Geohydrological research, results of test drilling 3the aquifer (in Dutch). 630-04426.1. Arnhem.
10 Snijders, A. 1991: IEA energy storage programme - Annex VI: "Environmental and chemical aspects of ATES and research and development of water treatment methods". Proceedings Thermastock '91, Scheveningen, the Netherlands.
11 Snijders, A. 1994: ATES: water treatment and environmental impacts. Proceedings Calorstock '94. Espoo, Finland.
12 Knoche, G., Koch, M. & Metzgeret, J.W. 2003: Scaling-tests on Groundwater for use in high-temperature-ATES in respect to calcite precipitates in heat exchangers. Proceedings Futurestock 2003, Warsaw, Poland.
13 Griffioen, J. & C.A.J. Appelo. 1993: Nature and extent of carbonate precipitation during aquifer thermal energy storage. Applied Geochemistry 8 (2): 161-176.
14 Griffioen, J. 1992: Cation-exchange and carbonate chemistry in aquifers following groundwater flow. PHD Thesis, VU Amsterdam.
15 Sanner, B. (ed.). 1999: High Temperature Underground Thermal Energy Storage, State-of-the-art and Prospects. Giessener Geologische Schriften, 67, 158 p.
16 Miller, R.T. & Delin, G.N. 2002: Cyclic injection, storage, and withdrawal of heated water in a sandstone aquifer at St. Paul, Minnesota - Analysis of thermal data and non-isothermal modeling of short-term test cycles. USGS Professional Paper, 1530-B, 66 p.

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:

1. Lowering the water temperatures (increases the value of the equilibrium constant):
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 and since storage of high temperatures is the focus point of this project, lowering the storage temperature may not be the most relevant 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.

2. Lowering the calcium concentration (reduces the saturation index):
A way 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 is described by Drijver[17]). 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 during each heat storage cycle.

3. Lowering the Carbonate concentration (reduces the saturation index):
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 during 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 in the Netherlands. 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 using 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 in 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[17]. For brackish and salt groundwater this rise may not be a problem, but for initially fresh water this will usually not be acceptable.

[17] Drijver, B. 2011: High Temperature Aquifer Thermal Energy Storage (HT-ATES): Water treatment in practice. First National Congress on Geothermal Energy, Utrecht, the Netherlands.

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[18,19]. In water treatment systems using membranes (e.g. Reverse Osmosis systems), CO_2-treatment is also known for scaling prevention.

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 exists from deep geothermal.

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[19].

2.3.3.2 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 IEA Technology Collaboration Programme "Energy Conservation by Energy Storage", Annex 12 "High Temperature Underground Thermal Energy Storage" 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[20]. This MTR 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[18]. Unfortunately, the test device has been dismantled and is therefore not available any more[21].

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.

2.3.3.3 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

[18] Sanner, B. 2004: Thermische Untergrundspeicherung auf höherem Temperaturniveau: Begleitforschung mit Messprogramm Aquiferspeicher Reichstag, Schlussbericht zum FuE-Vorhaben 0329809 B, Giessen.
[19] Sanner, B. (ed.). 1999: High Temperature Underground Thermal Energy Storage, State-of-the-art and Prospects. Giessener Geologische Schriften, 67, 158 p., 1999.
[20] Knoche, G., Koch, M. & Metzgeret, J.W. 2003: Scaling-tests on Groundwater for use in high-temperature-ATES in respect to calcite precipitates in heat exchangers. Proceedings Futurestock 2003, Warsaw, Poland.
[21] Sanner, B., personal communication

heat transfer coefficient may be the best indicator. However, testing this in practice has not yet been successful[22]. For the wells, the specific capacity is usually used as an indicator. A 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 test-coupons. A standard measure to prevent hydraulic fracturing (resulting in irreversible damage to the wells) is the use of a pressure limit during injection.

2.3.3.4 Summing up the design considerations for water treatment:

- Consider water treatment at temperatures above 50°C.
- Use hydrochemical modelling for a first assessment of the necessity of water treatment. In-situ testing with local groundwater is 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.

2.3.4 Specifications related to geological settings

2.3.4.1 Test drilling

In many cases only limited data about the potential formations to be used for HT-ATES is available as these formations are typically not used for drinking water or industrial cooling due to the high salt content and since LT-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 projects. In most cases, the test drilling can be completed as a monitoring well to 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 confining clay layer is needed) for calculating thermal efficiency and for 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 (minimum 200 mm) in the target aquifer to be able to perform a well test.

[22] Sanner, B. 2004: Thermische Untergrundspeicherung auf höherem Temperaturniveau: Begleitforschung mit Messprogramm Aquiferspeicher Reichstag, Schlussbericht zum FuE-Vorhaben 0329809 B, Giessen.

- 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 for:
    - Bubble pressure of the dissolved gas, dissolved gas quality and quantity.
    - Chemical water composition.
- Flow velocity measurements in the screen sections.

2.3.4.2 Maximum production and injection rate

For ATES systems two criteria exist to calculate the maximum allowable well production and aquifer infiltration velocity. The idea behind the maximum velocity is for production to avoid sand mobilization and for 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/m^3]
G gravitational acceleration [m/s^2]
μ viscosity of produced water [kg/(m·s)]
K_i intrinsic permeability [m^2]

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 [m^2]
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/s^2]
ρ_w density of water [kg/m^3]
MFI_{mea} measured MFI [s/l^2]
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:

$$v_{clog} = 1.6\,10^{-3}\,MFI_{mea}\,t\,\mu\frac{1}{\left(\frac{k}{150}\right)^{1.2}}\,{v_{inj}}^2$$

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 2.9) defines the clogging potential of the aquifer and the Modified Fouling Index (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 one sixth of the grain size.

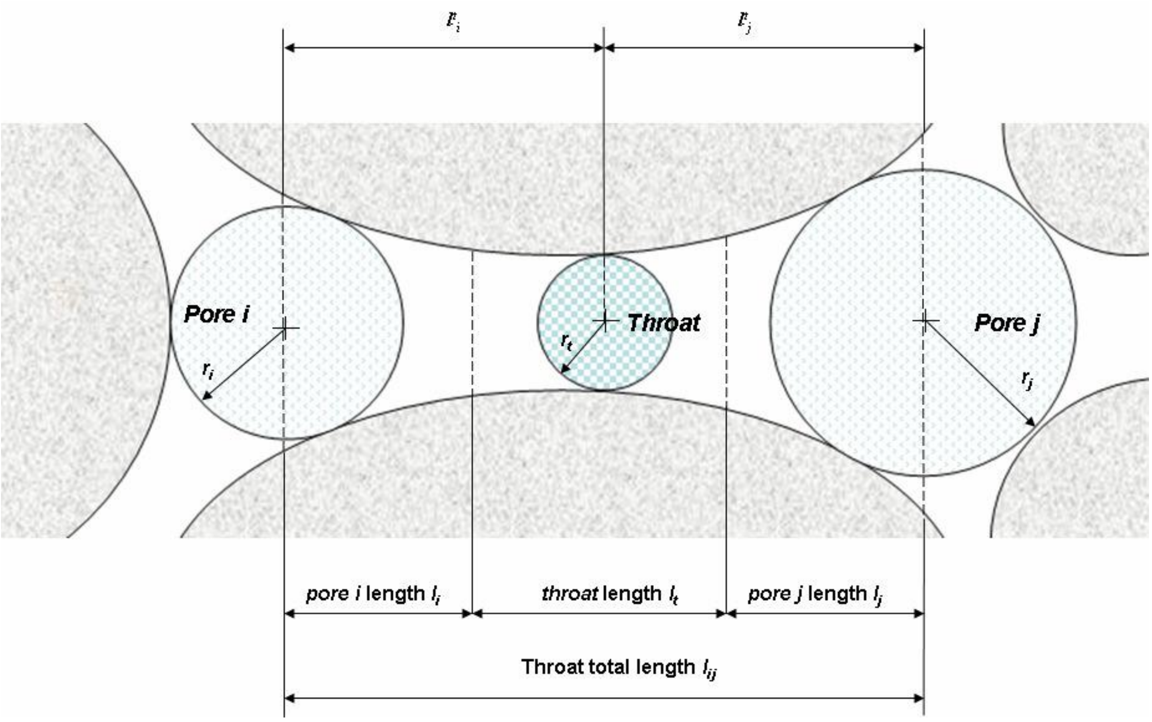

Figure 2.9 Schematic representation of pore throat

In Figure 2.10 the workflow of how the pore throat size is determined is shown.

Figure 2.10 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 2.11 an example of this relation is given for consolidated sediments. The question is how this relation looks like for unconsolidated sediments.

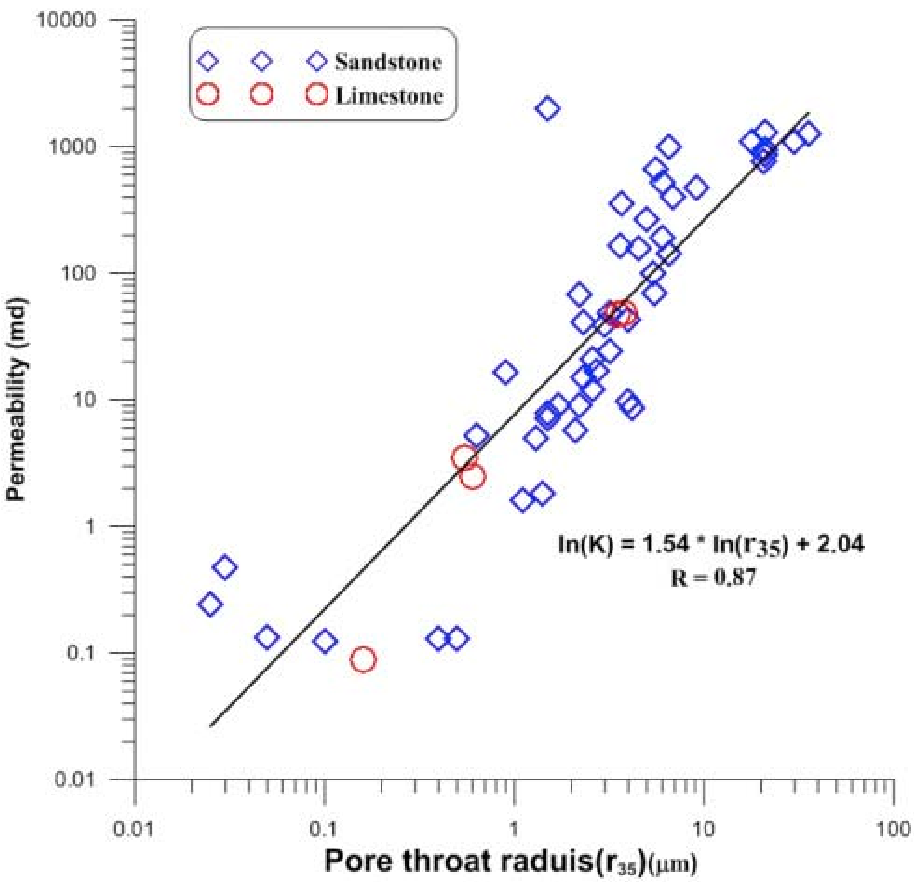

Figure 2.11 Example of relation between pore throat radius and permeability

Another important aspect is grain size distribution. The more unsorted (large variation in grain sizes) the reservoir, the higher the risk of sand production. In reservoirs with a small variation in grain sizes, the risk of sand production is much lower. How to incorporate this into design criteria is not clear yet.

2.3.4.3 Recovery efficiency

Because water with a high temperature has a lower density than the ambient groundwater in the storage 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 between the recovery efficiency and the following parameters[23,24]:

- 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 2.12 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 is equal to the ambient groundwater temperature in the storage aquifer (assumed to be 12ºC)
3) The efficiency is given for the fourth year of operation
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 for making a selection of the best aquifer for storage. For a proper assessment of the recovery efficiency in practice, numerical simulations are required.

[23] IF Technology/SKB. 2012: High temperature storage report 3 thermal efficiency (in Dutch), 25889/61335/RW, SKB, Gouda , IF Technology, Arnhem.
[24] Schout, G., Drijver, B., Gutierrez-Neri, M. & R. Schotting. 2014: Analysis of recovery efficiency in high-temperature aquifer thermal energy storage: a Rayleigh-based method. Hydrogeology Journal 22: 281–291.

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%	8%	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%	39%	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 2.12 Estimated recovery efficiency for different storage temperatures, aquifer thickness values and vertical anisotropy (k_h/k_v) values

Some observations from Figure 2.12:

- 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 (larger 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 a smaller capacity per well, 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 (e.g. 70-90°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 Brussels Sand Member and the sands of the 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)[25].

When relatively low temperature heat is stored (e.g. 30-50°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 (the Brussels Sand Member and the Breda, Oosterhout and Maassluis Formations) 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%, Anisotropy 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

[25] Drijver, B. 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.

2.3.4.4 3D geological, hydrological and thermal modelling

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.

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

Thus, the geological risk due to subsurface complexity can be minimized by thorough geological understanding and modelling. It can be necessary to obtain additional knowledge on the geology by more test drillings or geophysical investigations such as seismics or electromagnetic surveys. In urban areas, which are often the areas of interests for HT-ATES applications, collecting geophysical data can be very difficult.

The 3D geological will serve as input to hydrological and thermal modelling aiming to simulate and predict groundwater flow and expected heat transport in the aquifer and below is given some important considerations.

Reliability of 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 3D thermal transport model is required to correctly calculate the effects of density-driven groundwater flow (model tools can be 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 in the ground, 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.

Sensitivity analysis for the recovery efficiency
The current experience[26] 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.

2.3.5 Specifications related to thermal energy demands and heat sources

Based on the experience from existing projects, the following design rules have been compiled for the integration of ATES with the remaining part of the energy system.

2.3.5.1 Size of storage

Based on Dutch experiences Bakema & Drijver[26] 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. They also state that the thermal losses are less for medium storage temperatures (~50°C), than for high storage temperatures (~90°C).

Thus, 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 (LT-ATES) the capacity ranges between 0.1 and 0.3 MW for small-scale and between 5 and 30 MW for large-scale systems[27].

[26] 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.
[27] 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.

2.3.5.2 Cut-off temperature

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 2.13 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%)[28].

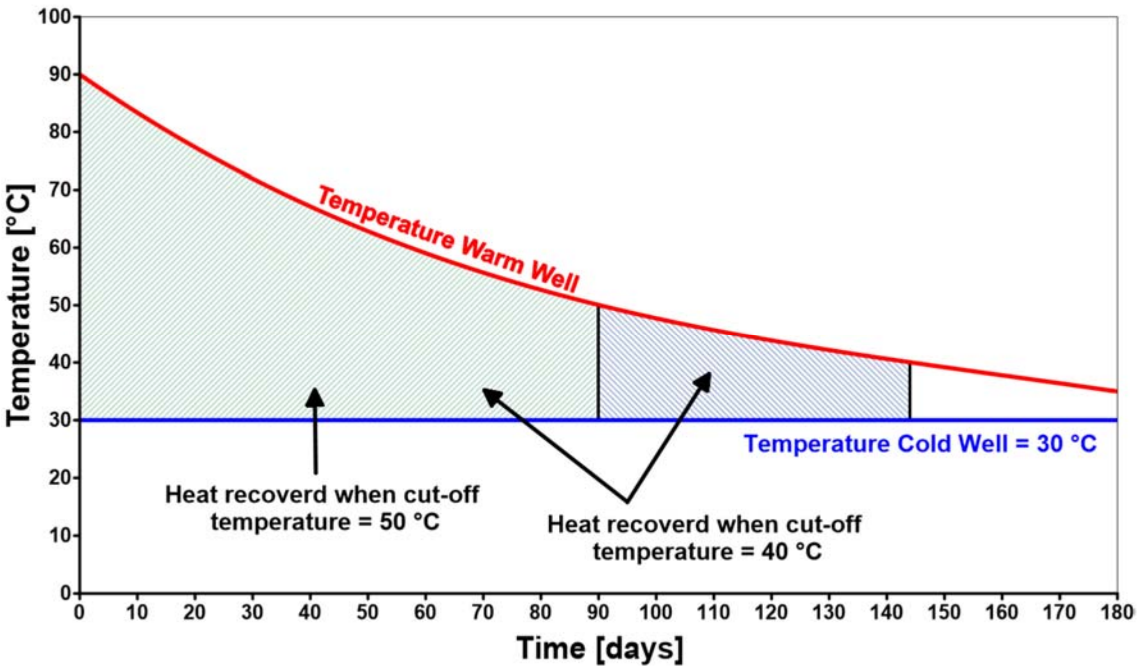

Figure 2.13 The relationship between cut-off temperature and the amount of heat that can be extracted from the subsurface with heat storage at 90ºC (IF Technology)

2.3.5.3 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[28].

[28] 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.

3 BTES (Borehole Thermal Energy Storage)

3.1 Introduction to BTES systems

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 2-5 m and BTES is normally limited to boreholes of c. 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 layout of the boreholes), regional groundwater flow (heat losses by advection) and heat losses to the surface.

Temperatures up to c. 90°C can be stored[29] 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[30].

Figure 3.1 Tube layout for borehole storage. Drake Landing BTES under construction (from[29])

[29] 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.
[30] Danish Energy Agency, 2014. Status and recommendations for RD&D on energy storage technologies in a Danish context.

3.2 General specifications for BTES

3.2.1 Regulatory and environmental framework conditions

The regulatory and environmental framework conditions will depend on national and local law/regulation - and on the design and operation conditions of the storage (materials, fluids, temperatures etc.).

So, it is necessary to have a rough idea of the storage design and operation conditions before investigating the legal framework. And before applying for permissions, it is necessary to have a close to final version of the design and the operation conditions.

Below is given a basic check list (not to be regarded complete in all cases):

- ❒ Special regulation for the area
  - ➔ Check if it is a wildlife and botanical protected area (normally not a problem as the area above the store can be re-established)
  - ➔ Check if it is a historically protected area
  - ➔ Check if there are special restrictions due to drinking water supply area
- ❒ Change of status of land use
  - ➔ Check if changes are needed for district plans and municipality plans
- ❒ Environmental Impact Assessment (EIA)
  - ➔ Check if full EIA or only EIA “screening” is required
- ❒ Groundwater should not be heated
  - ➔ Give evidence that groundwater will not be heated above limits in regulation
  - ➔ Check for the groundwater regulation, as it may set limitations to the borehole depth
  - ➔ Check that the BTES is not in a water abstraction area
- ❒ Use of anti-freeze fluid
  - ➔ If a glycol or any other anti-freeze fluid is to be used, check if any restrictions e.g. requirement for leakage control
- ❒ Environmental permission issues for the energy production plant
  - ➔ Check if new/revised environmental permission for the energy production plant is needed

Note: Local and national specific regulations related to UTES will be screened in Task 6.2 of the HEATSTORE project.

3.2.2 Physical framework conditions

Some physical framework conditions shall be investigated and considered before (and when) designing a BTES:

- Space requirements
- Groundwater conditions
- Ground/soil conditions
- Maximum temperature

Space requirements
The space on top of a BTES can be utilized for other purposes as the ground beneath is in principle normal ground, but in the construction phase the area much be accessible.

Groundwater conditions
Any moving groundwater should be at least some meters below the bottom of a BTES. If the groundwater level is above the bottom of the BTES then it should NOT be moving in order not to remove heat from the storage.

Ground/soil conditions
The thermal conductivity should be estimated/measured. A "thermal response test" (TRT) can be used for determination of the thermal conductivity/borehole resistance. A TRT is an indirect (in-situ) measurement method where heat at constant power is injected into (or extracted from) a borehole while the borehole mean temperature is measured.

Note (values taken from[31]): Thermal conductivity of soil is very depending on soil type and humidity:

- The thermal conductivity of water is approx. 0.63 W/(m K) at 40°C
- The thermal conductivity of different soil types:
    - Dense rock is approx. 3.5 W/(m K) (approx. 5.5 x higher than water)
    - Heavy saturated soil is approx. 2.4 W/(m K) (approx. 4 x higher than water)
    - Light dry soil is approx. 0.35 W/(m K) (approx. 1/2 of water)

Soil heat capacity should also be estimated/measured.

Note (values taken from[31]): Soil has lower heat capacity than water so storing a certain amount of heat will require a larger soil/rock volume than water volume:

- The heat capacity of water per m^3 is approx. 4200 J/(kg K)*1000 kg/m^3 = 4200 MJ/m^3
- The heat capacity of soil per m^3 vary depending on soil type:
    - Dense rock is approx. 840 J/(kg K)*3200 kg/m^3 = 2700 MJ/m^3 (2/3 of water)
    - Heavy damp soil is approx. 960 J/(kg K)*2100 kg/m^3 = 2000 MJ/m^3 (1/2 of water)
    - Light dry soil is approx. 840 J/(kg K)*1500 kg/m^3 = 1260 MJ/m^3 (1/3 of water)

Maximum temperature
The maximum storage temperature influences the choice of material for tubes (or the material chosen sets limits to max. temperature).

Note: 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.

[31] 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.

3.3 Design of BTES

The size and design of the BTES depends on the application, which is defining the needed storage volume and the temperatures in the storage. It will also depend on the geographical and geological conditions, which will e.g. define the specific layout of heat exchanging tubes and the depth of the piping.

3.3.1 Borehole storage application

The actual borehole storage application is given by the specific configuration of heat sources and heat demands working on the storage. Typically, a buffer storage is connected to the borehole storage to compensate for the slow thermal reaction of the boreholes (due to the heat exchange from the soil/rock to the water flowing in the tubes).

The specific application(s) and configuration sets the operation conditions for the storage. How much heat will be stored and extracted – and when. The maximum expected temperature is important for choice of tube material etc.

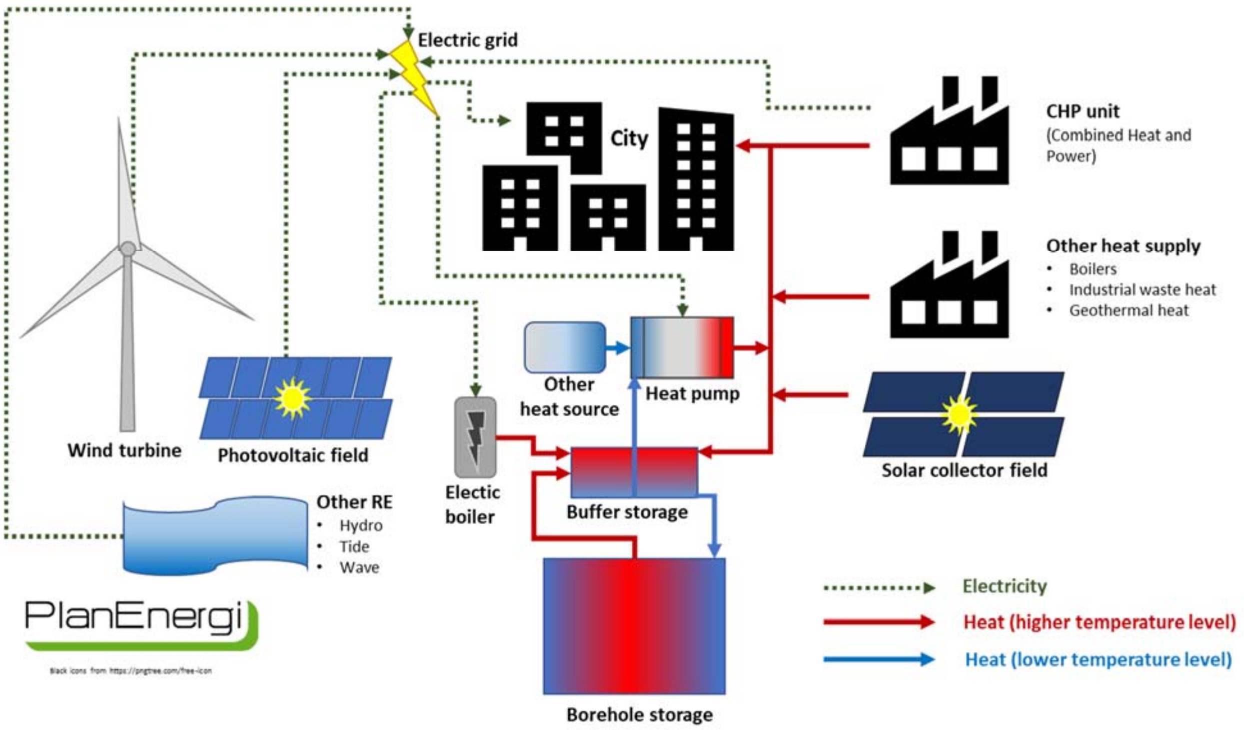

Figure 3.2 The heat storage can be connected to numerous sources and demands (PlanEnergi)

3.3.2 Borehole storage construction

Important parameters regarding borehole storage construction are:

- Physical dimensions
    - Diameter
    - Depth beneath ground level
    - Heated soil/rock volume
- Top insulation/construction
- Tubes and connection of tubes/boreholes
- Heat exchanger

3.3.2.1 Physical dimensions

The borehole storage will normally be made with an approximate circular top view, see Figure 3.3. The most effective storage will have same depth as diameter, providing the maximum volume/surface area ratio.

The nominal storage volume will then be:

$$V = \pi * R^2 * H$$

where:

R: radius of the top view cross section
H: Depth of the tubes

The effective storage volume will be bigger than that, as the soil/rock outside the outer tubes will be heated too.

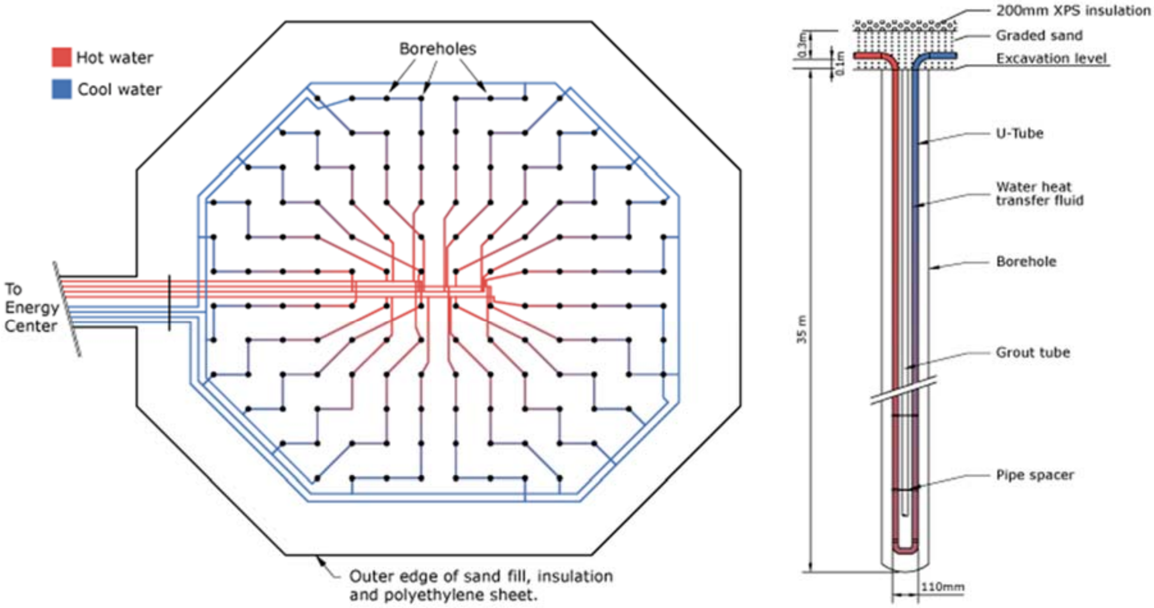

Figure 3.3 Layout of a borehole thermal energy storage and cross-section of a single borehole and u-tube, Drake Landing (from[32])

3.3.2.2 Top insulation / construction

It is only the top of the borehole storage which is insulated, as it would increase the costs significantly to insulate the sides too; and the outer part of the storage will be significant colder than the inner part most of the year.

A top insulation of the BTES is necessary to reduce the heat loss and may account for 25% of the total construction costs. The insulation should be hard insulation which will not be compressed by any weight put above (e.g. 1 meter of soil) and not vulnerable to moisture.

Good experience so far has been obtained with hard Extruded PolyStyrene (XPS), foam glass gravel and mussel shells. Especially mussel shells has proven to be a cost-effective solution.

[32] 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.

The top part should be made so the surface can be used for other purposes, such as open park, playground, parking area and maybe light buildings. Examples of such top constructions are shown in Figure 3.4 and Figure 3.5. The material above the sand layers seen in the figures, should be designed for resisting any special load.

Access to the tube connections should be made easy, e.g. by placing them in a collection well/sump.

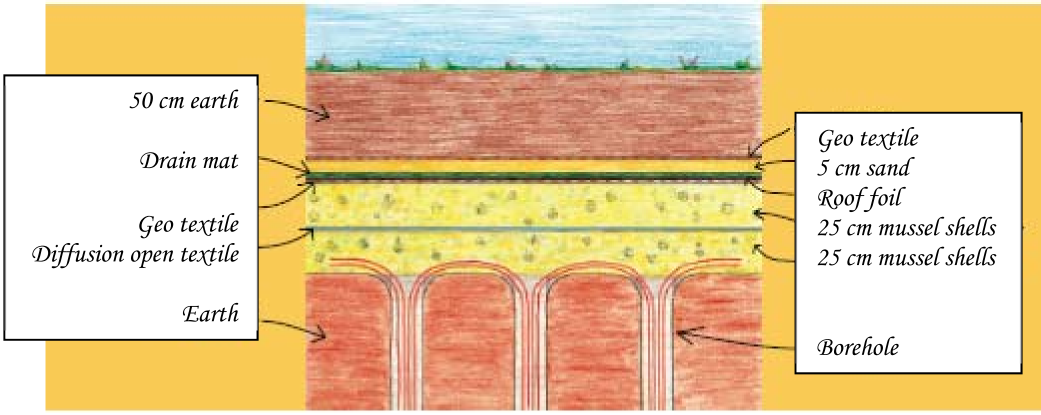

Figure 3.4 Details of upper part of the HT-BTES Braedstrup project (source: Braedstrup Fjernvarme)

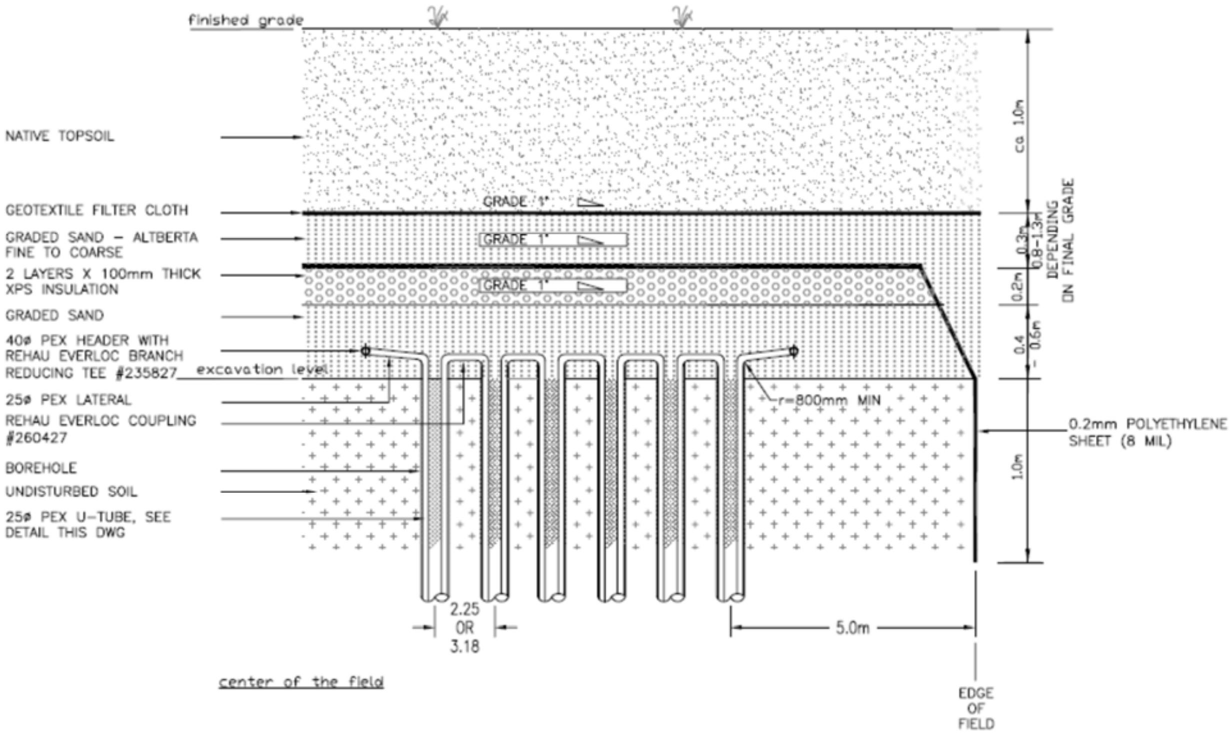

Figure 3.5 Cross-section of the top portion of one BTES circuit. Drake Landing (from[33])

[33] 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.

3.3.2.3 Tubes and connection of tubes

Once buried and in use it is very difficult to access the tubing and repair any leakage. Some basic recommendations are given to take this into account:

- Estimate the operation conditions (computer simulation) for the tubing (mainly temperature) and use tubing material with long lifetime under these specific conditions (proved by testing/certification)
- Consider use of factory-made U-tube heat exchangers produced as a single piece of tubing (without connections) to avoid the risk of a connection failure at the bottom of a borehole
- Use corrosion resistant metal fittings
- Make several parallel loops, so a loop can be cut off (in an accessible collection well) if leakage occur
- Perform a pressure test (at high temperature) before burying the tubes

An operating high temperature borehole storage (HT-BTES) may reach temperatures up to 90°C or even more. Here, e.g. a high quality cross-linked high-density polyethylene (PEX) tubing could be used since it is strong, chemical resistant and can be able to withstand the pressures and temperatures encountered with a long-expected service life.

3.3.2.4 Number of boreholes

The necessary number of boreholes depend on the available heat for storage, the thermal conductivity and heat capacity of the soil as well as the possible drilling depth with respect to geological and groundwater conditions.

As the outer shape of the BTES is also important for the storage efficiency, this should also be taken into consideration. For example, a cylindrical shape with a diameter/depth ratio close to one will favour the recovery efficiency compared to more pencil- or pancake shaped cylinders[34]. There may, however, be a practical limit for how close individual boreholes can be carried out.

Thus, 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[35,36].

[34] 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.
[35] 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.
[36] 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.

In Mangold & Deschaintre[37] 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. An advantage of BTES is, though, that it can be planned in a modular design making it possible to easily connect additional boreholes.

3.3.2.5 Grout - heat conduction from tube to soil/rock

To improve the heat transfer from the tubes through the borehole to the surrounding soil/rock and protect any groundwater resources below the BTES, the boreholes are filled with special material (grouting) which can transfer the heat (and to some extend also protect the tubing). It is recommended to consult experts for this grouting – normally the borehole drillers will have the knowledge.

The thermal conductivity of the grout is important and use of thermally improved grout is recommended. The thermal conductivity for thermally enhanced grouts is typically claimed to be around 1.8-2.2 W/(m K), but can be less in practice.

3.3.3 Specifications related to geological settings

It is recommended to perform an initial screening of the geological conditions using available existing information on geology, groundwater flow and thermal properties, but a test drilling to verify the ground conditions and the estimated drilling costs is also of paramount importance.

For example, soft sediments can be more challenging and time consuming than hard rock. For soft sediments direct rotary mud drilling is normally considered to be the most efficient method and it is recommended always to use a casing during drilling in soft sediments to avoid cavities and excessive use of expensive grout as well as collapsing boreholes.

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 as mentioned above.

Significant groundwater flow will cause advective heat loss and should be avoided. Sometimes more than one investigation borehole is necessary for assessing the local groundwater conditions.

The thermal conductivity of the soil may have an impact on the efficiency of a BTES. A high thermal conductivity will increase the charge/discharge rate, but also the heat loss in terms of heat flow away from the storage, while a low thermal conductivity will reduce the heat loss on the cost of a lower charge/discharge rate.

A number of look-up tables exists for e.g. thermal conductivity of different soil/rock types, but a thermal response test in e.g. a test borehole is also recommended to verify the thermal properties of the site. An overview of thermal conductivities for different sediment and rock types is given in Table 3.1 based on different sources from Germany, the UK and Denmark.

[37] 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.

Table 3.1 Thermal conductivity of different sediment and rock types (from[38])

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).

3.3.4 Specifications related to thermal energy demand and heat sources

To simulate the borehole storage and size it for the actual configuration, detailed information on all connected heat input sources and all connected heat demands shall be known – together with soil properties.

Based on these simulations the storage volume – and the max temperatures - will be defined. So, for each heat source the following specifications are needed:

- Annual heat input for storage
- Heat input energy profiles (monthly, weekly, daily, hourly)
- Heat input temperature profiles (monthly, weekly, daily, hourly)

Note: Heat source (store input) might depend on the weather – e.g. input from a solar collector field

Similar for the heat demands:

- Annual heat demand
- Heat load profiles (monthly, weekly, daily, hourly)
- Heat load temperature profiles (monthly, weekly, daily, hourly)

Note: Heat demand (store output) might depend on the weather – e.g. heating demand of buildings.

The annual heat flows, the profile of the heat flows and the temperature profiles will determine the size of the storage – and the need for insulation.

The heat flows and temperature profiles can be found using a detailed simulation program (e.g. TRNSYS, http://www.trnsys.com/). Several system configurations should be simulated and compared with respect to estimated performance and economy. If considered relevant, several scenarios of heat sources and heat load could be tested.

The maximum temperature and the temperature profile will determine which materials can be used for tubing (and maybe insulation).

Note: In general priority should be given to direct supply of load when possible (by-pass of storage).

[38] 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.

4 PTES (Pit Thermal Energy Storage)

4.1 Introduction to PTES systems

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. On the top is typically a floating lid with insulation between polymer liners. Temperatures up to c. 90°C can be stored.

Figure 4.1 Picture of Dronninglund Pit Storage under construction. Dronninglund District heating; 37,573 m^2 of solar collectors and a 60,000 m^3 water in pit heat storage (PlanEnergi)

The PTES concept has the possibility for quick charging or discharging, short heat storage periods. Water is ideal as storage medium due to high thermal capacity and possibility for vertical stratification (different temperature in different depths).

If the ground conditions are optimal, the construction costs are low. High groundwater levels and poor soil conditions directly affects the construction costs.

A large storage requires a large area without infrastructure, which makes it less feasible in urban areas. The top area cannot be used for other purposes.

Focus should be on temperature resistance and lifetime of liners and on construction of the lid.

4.2 General specifications for PTES

4.2.1 Regulatory and environmental framework conditions

The regulatory and environmental framework conditions will depend on national and local law/regulation - and on the design and operation conditions of the storage (materials, fluids, temperatures etc.).

So, it is necessary to have a rough idea of the storage design and operation conditions before investigating the legal framework. And before applying for permissions, it is necessary to have a close to final version of the design and the operation conditions.

Below is given a basic check list (not to be regarded complete in all cases):

- ❒ Special regulation for the area
  - ➔ Check if it is a wildlife and botanical protected area
  - ➔ Check if it is a historically protected area
  - ➔ Check if there are special restrictions due to drinking water supply area
- ❒ Change of status of land use
  - ➔ Check if changes are needed for regional plans and municipality plans
- ❒ Environmental Impact Assessment (EIA)
  - ➔ Check if full EIA or only EIA “screening” is required
- ❒ Groundwater should not be heated
  - ➔ Give evidence that groundwater will not be heated above limits in regulation
- ❒ Environmental permission issues for the energy production plant
  - ➔ Check if new/revised environmental permission for the energy production plant is needed
- ❒ Use of anti-freeze fluid
  - ➔ If a glycol or any other anti-freeze fluid is to be use, check if any restrictions e.g. requirement for leakage control
- ❒ Seepage permissions may be necessary
  - ➔ For groundwater drainage
  - ➔ For drainage of water from pit top
  - ➔ For (saline) return water from softening unit when filling storage
- ❒ Permission for new water supply drillings for water to fill storage if relevant

Note: Local and national specific regulations related to UTES will be screened in Task 6.2 of the HEATSTORE project.

4.2.2 Physical framework conditions

Some physical framework conditions shall be investigated and considered before (and when) designing a PTES:

- Space requirements
- Groundwater conditions
- Ground/soil conditions
- Maximum temperature
- Water quality

Space requirements
For pit storages with floating lid, a space corresponding to the area of the pit plus the framing must be considered "not useful" for other purposes. One may consider the possibility to put floating solar thermal collector or photo-voltaic modules on top of the storage, but this is not a well proven solution. If the top of the storage is a stiff construction some use could be considered, but until now stiff top constructions are considered much more expensive than floating constructions.

Old gravel pits could be considered as locations for pit storages.

Ground water conditions
Any moving groundwater should be at least some meters below the bottom of an un-insulated PTES. If the PTES has bottom/side insulation it is less critical – but a potential influence should be considered.

If the (not moving) groundwater level is higher than the depth of the PTES beneath ground level, pumping/draining will be required under construction. Any secondary groundwater level should also be taken into consideration.

Ground/soil conditions
The excavated soil which is put on top of the sides must be of a quality, with respect to geotechnical parameters, so it can be utilized as banks. Compression of this soil is typically needed and the angle of the banks will depend to some extend on the soil quality.

Sharp stones in the surface soil on the banks and in the bottom of the pit could be a problem for the liner.

The soil thermal conductivity and soil heat capacity should be estimated/measured.

Maximum temperature
The maximum storage temperature influences the choice of material for liners (or the material chosen sets limits to max temperature).

Water quality
Water quality influence the choice of materials (or the material chosen sets requirements to water quality). Water treatment is to be considered.

4.3 Design of PTES

The design of the PTES depends on the application, which is defining the storage volume and the temperatures in the storage.

It will also depend on the geographical and geological conditions, which will e.g. define the specific excavation (depth and bank angles).

In some cases, the local weather may influence the design; e.g. in areas with heavy rainfall and or heavy snowfall special precautions may be necessary.

4.3.1 Pit storage application

The pit storage application is given by the specific configuration of heat sources and heat demands working on the storage.

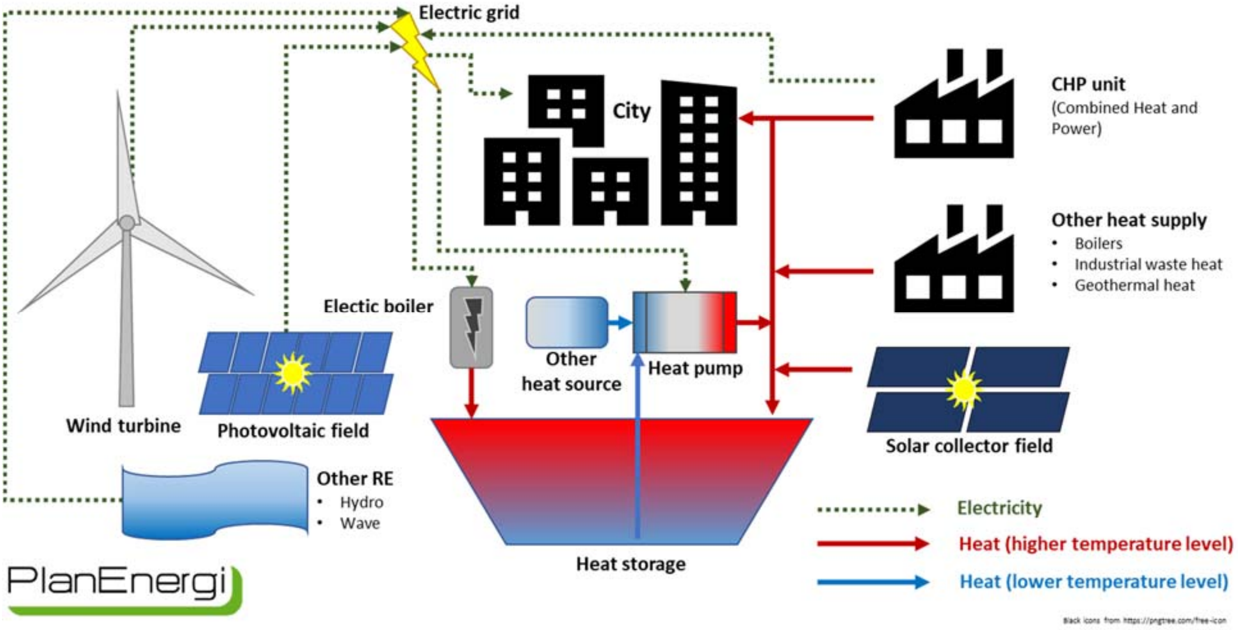

Figure 4.2 The heat storage can be connected to numerous sources and demands (PlanEnergi)

The specific application(s) and configuration sets the operation conditions for the storage. How much heat will be stored and extracted – and when.

What are the expected storage temperatures – especially the maximum expected temperature is important for choice of materials.

4.3.2 Pit storage construction

4.3.2.1 Physical dimensions

The pit storage will normally be made as truncated pyramid. The relation between volume and sides, height etc. for truncated pyramid is seen in Figure 4.3.

$$V = \frac{h}{3}(a^2 + ab + b^2)$$

V = Volume
h = Height
a = Side length at the top
b = Side length at the bottom

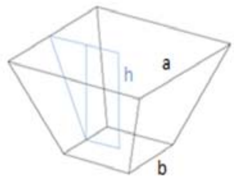

Figure 4.3 Volume of a truncated pyramid

4.3.2.2 Construction of pit sides and bottom

Under normal/typical soil conditions the angle of the bank will be approx.1:2 or around 27°. If possible, the excavated soil is put on the top sides.

The volume in the excavated part is approx. the same as in the top part (above terrain). To make this possible, 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 has to confirm that the excavated soil can be utilized as banks.

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.

The top of the banks must 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.

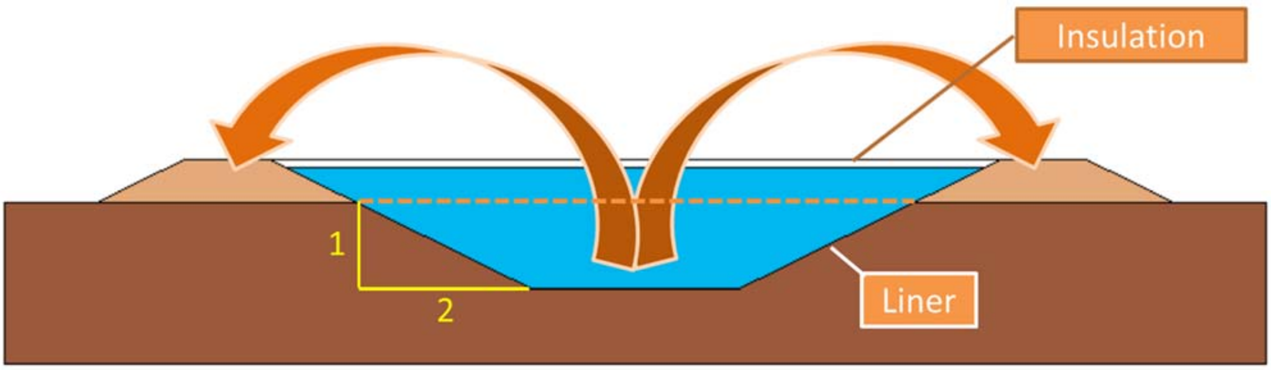

Figure 4.4 Principle sketch of a pit heat storage cross section (PlanEnergi)

Rainwater will flow from the banks to the bottom areas. Especially if clay is present 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 – see Figure 4.5 below.

Figure 4.5 Damage in excavation in Marstal, Denmark due to cloud burst (PlanEnergi)

Stones must be removed from the banks and a geotextile with high penetration resistance must be placed to protect the watertight (and vapor resistant) liner.

So far, the best liner solution found for high temperatures (up to 90°C) is HDPE[39] liners design for high temperatures. It is important to have a lifetime estimation[40] from manufacturer for the specific estimated storage temperature time profile.

Liners should be welded together in a double welding – the welding can then be tested by applying pressurized air to the air channel between the welding seams – see Figure 4.6 below.

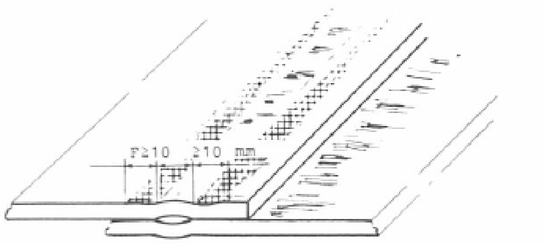

Figure 4.6 Double welding of a HDPE liner. The welding can be tested by applying pressurized air to the air channel between the welding seams (PlanEnergi)

Vapor tightness can be improved by adding a metal (preferable stainless steel) liner, but this will add considerable costs. Walls and bottom are normally uninsulated.

[39] HDPE: High Density PolyEthylen
[40] Newly developed" high temperature liners" are claimed to have a lifetime of 20 years at 90°C constant temperature

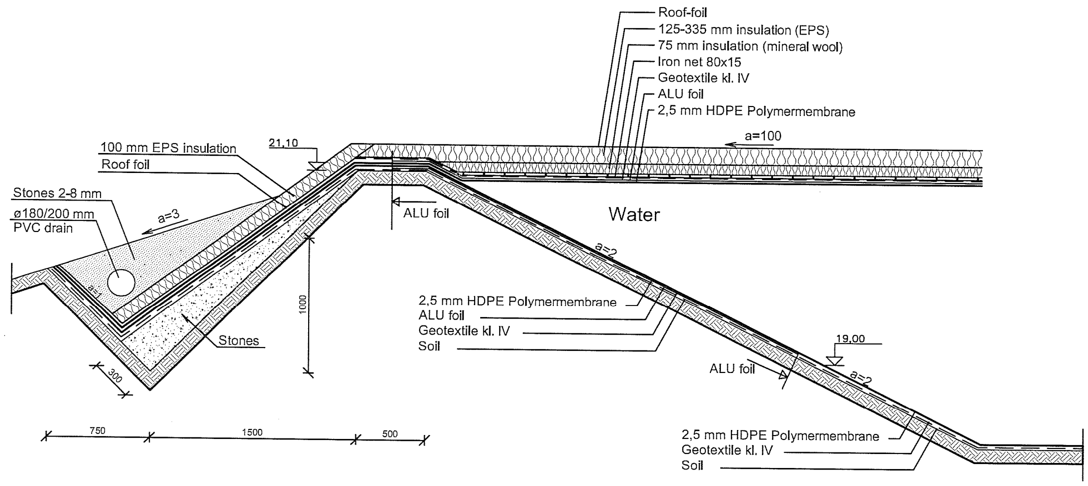

Figure 4.7 Example of PTES construction in Marstal, Denmark (PlanEnergi)

4.3.2.3 Lid construction

The lid is normally a floating insulated construction.

The overall requirements for the lid construction- within the lifetime (e.g. 20 years) - are:

a) The liner(s) under the insulation shall be able to withstand the occurring temperatures[41].
b) A liner under the insulation shall be (almost) vapor tight even at the highest temperatures occurring
c) Insulation material shall not absorb humidity (as this will increase heat loss) and humidity shall quickly be vented out of the insulation section
d) Insulation material shall be able to withstand humidity at 90°C
e) The upper liner (above the insulation) shall be raintight
f) Any water inside the lid construction shall drain out
g) Rain water shall drain from the liner[42]

Conc. a) & b) Temperature resistance and vapour tightness of liner

So far, the best liner solution found for high temperatures (up to 90°C) is HDPE[43] liners design for high temperatures. It is important to have a credible lifetime estimate[44] from manufacturer for the specific estimated storage temperature time profile.

Conc. c) Humidity in insulation layer

Some insulation foams are resistant to humidity absorption, e.g. some types of cross-linked polyethylene foam. An example of airventing is shown in Figure 4.8.

[41] Same requirement for the insulation material, but that is normally not a problem
[42] Could be active pump assisted drainage
[43] HDPE: High Density PolyEthylen
[44] Newly developed” high temperature liners” are claimed to have a lifetime of 20 years at 90°C constant temperature

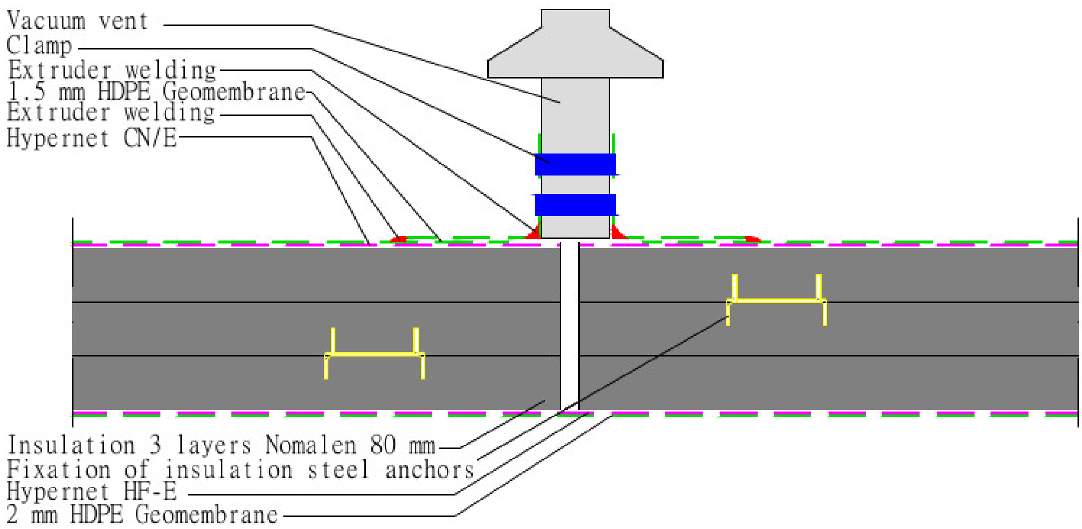

Figure 4.8 Section view of the cover with air-vent (PlanEnergi)

<u>Conc. d) Rain tightness</u>

Upper liner shall be weather proof including UV resistant, and shall and tight joints/welds.

<u>Conc. e) & f) Water drainage</u>

Channels in the lid can be made for attracting the water and leading it to central points for pumping to outside the lid. See Figure 4.9 and Figure 4.10 below.

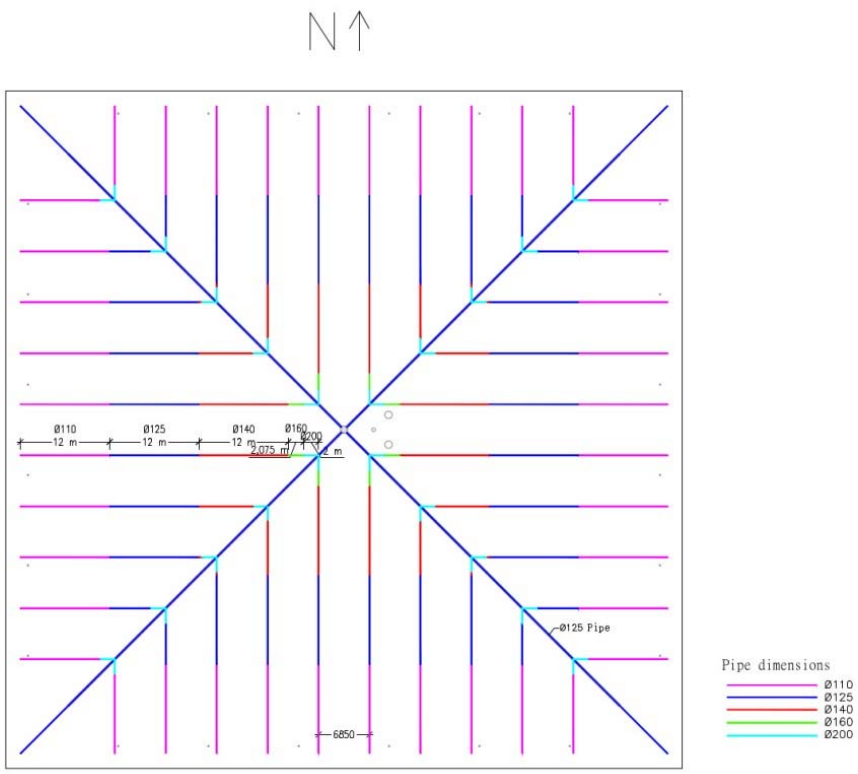

Figure 4.9 Example of a layout of the weight pipes on the floating liner (PlanEnergi)

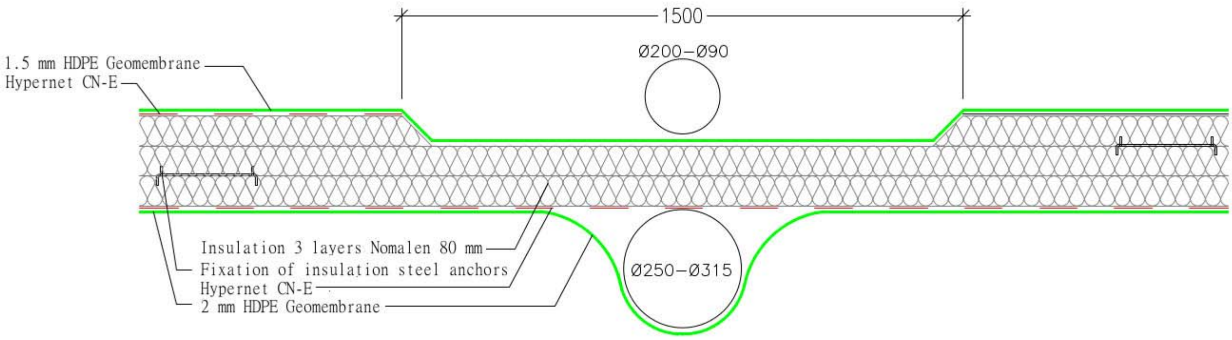

Figure 4.10 Section drawing of the weight pipe on the floating liner (PlanEnergi)

4.3.2.4 In and outlet pipes in pit storage (charge and discharge)

The in-/outlet arrangement consists of at least two pipe connections: One pipe connection led to the bottom of the storage and one pipe connection led to the top of the storage. Dependent on the system connected to the storage and the flexibility wanted, it can be advisable with three or more pipe connections in different levels to be able to utilize temperature stratification in the storage.

The pipe connections can be led through the side or the bottom of the storage – examples shown in Figure 4.11 and Figure 4.12 below.

Figure 4.11 In-/outlet arrangement led through the bottom of the storage. Three pipes ending in a diffusor in the top, the bottom and the volume middle of the storage (source: Dronninglund Fjernvarme)

Figure 4.12 In-/outlet arrangement led through the side of the storage (source: Marstal Fjernvarme)

The pipe connection through the side or bottom liner has to be sealed very carefully to avoid leakage. Outside the storage the pipes should be fixed by e.g. a concrete construction.

Diffusors for in- and outlet has to be dimensioned for a max velocity of the water of 0.2 m/s at the edge of the diffusor to avoid destroying the temperature stratification.

It is important to secure a water chemistry in the storage that will not cause corrosion of the used steel parts. Corrosion can happen very fast because of the high temperature of the water. When using stainless steel, the water chemistry is naturally not as critical as when using mild steel, but in both cases a corrosion specialist should be consulted to secure a long-lasting combination of materials and water chemistry.

4.3.3 Specifications related to geological settings

The geological/geotechnical conditions at the site is important for the construction work and may e.g. have an influence on the possible inclination of the walls of the pit and banks as mentioned above. In a first feasibility study, the geotechnical/geological conditions should therefore be investigated and a test drilling with a geotechnical perspective is recommended.

A high silt content in the soil can be a problem for the stability of the slopes of the pit and banks and soil samples from the test drilling should confirm that the excavated soil has a quality to be utilized as banks of the storage.

As also mentioned above, groundwater flow should be avoided and 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.

If secondary groundwater levels are localized, it is important to get an estimate of the costs for drainage measures from the excavating entrepreneur.

4.3.4 Specifications related to thermal energy demand and heat sources

To simulate the pit storage and size it for the actual configuration, detailed information on all connected heat input sources and all connected heat demands shall be known.

Based on these simulations, the storage volume - and the max temperatures - will be defined. So, for each heat source the following specifications are needed:

- Annual heat input for storage
- Heat input profiles (monthly, weekly, daily, hourly)
- Heat input temperature profiles (monthly, weekly, daily, hourly)

Note: Heat source (store input) might depend on the weather – e.g. input from a solar collector field

Similar for the heat demands:

- Annual heat demand
- Heat load profiles (monthly, weekly, daily, hourly)
- Heat load temperature profiles (monthly, weekly, daily, hourly)

Note: Heat demand (store output) might depend on the weather – e.g. heating demand of buildings.

The annual heat flows, the profile of the heat flows and the temperature profiles will determine the size of the storage – and the need for insulation.

The heat flows and temperature profiles can be found using a detailed simulation program (e.g. TRNSYS, http://www.trnsys.com/). Several system configurations should be simulated and compared with respect to estimated performance and economy. If considered relevant, several scenarios of heat sources and heat load could be simulated.

The maximum temperature and the temperature profile will determine which materials can be used for liners and insulation.

Note: In general priority should be given to direct supply of load when possible (by-pass of storage).

5 MTES (Mine Thermal Energy Storage)

5.1 Introduction to MTES systems

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, 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, 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[45], is 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 General specifications for HT-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 relative source needs to be taken into consideration.

[45] RAG Aktiengesellschaft 2015

5.2.1 Regulatory and environmental framework condition

The regulatory and environmental framework condition for MTES are not clearly defined yet, as a pilot plant has not been put into permission. Heat storage within abandoned collieries depend on the depth of the wells, tapping into the public grid, spatial or operational context to supplied estates and the proposed amount of stored heat. Based on the above mentioned criteria the storage of thermal energy in abandoned collieries will either be evaluated by the water or mining authority. Up to this point the general distinction of the responsible authority can be made as the following:

- Water authority:
    - No tapping into the public grid
    - No spatial or operational context to supplied estates
    - Wells below 100 m depth
    - Positive heat balance (more thermal energy is stored underground than produced)
- Mining authority:
    - Tapping into the public grid
    - Spatial or operational context to supplied estates
    - Wells deeper than 100 m
    - Negative heat balance (more thermal energy is produced from underground than stored)

5.2.2 Physical framework conditions

During the feasibility study of a possible MTES the following physical framework conditions should be investigated:

- Layout of the mine
- Depth and condition of the mine
- Mine water analysis and temperature at foreseen depths
- Influence of possible mine water dewatering systems
- Possible connection to heat consumers

5.3 Design of MTES

The design of the MTES will depend on the availability and condition of the existing mine layout. Therefore the existing mine layout needs to be digitized for numerical evaluation of the heat storage volumes. Based on the mine layout, suitable injection and extraction points need to be localized for well planning purposes.

5.3.1 MTES application

All underground mining sites are possible locations for MTES applications, which are in close connection to a heat source and consumer.

5.3.2 Construction

Based on the well design, the abandoned colliery has to be utilized by (directional) drilling of two wells (injector and producer).

5.3.3 Specifications related to geological settings

Drilling through gobs, faults and fractures has to be avoided. Influence of main faults and gobs have to be included in the numerical simulation.

5.3.4 Specifications related to thermal energy demands and heat sources

Maximum storage temperatures will be based on hydro geochemical modelling of the mine water during injection and production of thermal energy. Suitable heat sources have to be utilized in close vicinity of the mine layout. Possible connection to a district heating grid is preferable. Based on high storage volumes, a MTES should be operated ideally under biyearly conditions.