HEATSTORE

Synthesis of demonstrators and case studies - Best practice guidelines for UTES development

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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
2021.08.31	First version
2021.10.15	Report ready for last check by demo site leaders
2021.10.25	Report ready for review
2021.10.28	Report reviewed, ready for editing
2021.11.10	Final, edited version

Table of Content

1 Introduction

Six demo sites were initially planned within the HEATSTORE project (see Table 1). They covered a wide range of technologies: Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES) and Mine Thermal Energy Storage (MTES), final users and amount of heat to be stored. As reported in Table 2, some demo sites experienced changes during the project.

This report aims at giving a status overview of the HEATSTORE demo sites as they stand at the very end of the project (October 2021). Besides, case studies (started before the HEATSTORE project and/or not funded by the HEATSTORE project) are also presented. Based on the technical feedback and an analysis of the challenges faced by the demo sites and cases studies, general recommendations for UTES implementation are given.

Table 1: Pilot demonstration projects within the HEATSTORE project, as initially proposed.

Country	Concept of pilot demonstration	Storage capacity & volume	TRL[*] advance
Netherlands	Geothermal heat doublets combined with Aquifer Thermal Energy Storage (max 90°C) integrated into a heat network used by the horticultural industry	5-10 MW 20 GWh	7 to 8
France	Solar thermal combined with a Borehole Thermal Energy Storage (55˚C) with lateral heat recovery boreholes	kW range 100 MWh	5 to 8
Switzerland Geneva	The development of a deep Aquifer Thermal Energy Storage system (>50˚C) in Cretaceous porous limestone connected to a waste-to-energy plant	~4 MW	to 5 - 6
Switzerland Bern	Surplus heat storage underground (200 - 500m, max 120 ˚C) in existing district heating system fed with combined-cycle, waste-to-energy and wood fired plants.	~1.7 MW	to 5 - 6
Germany	Mine Thermal Energy Storage pilot plant for the energetic reuse of summer surplus heat from Concentrated Solar Thermal (max. 80°C; ∆t: 50-60 K) for heating buildings in winter.	45 kW 165 MWh	to 8
Belgium	Demand side management (DSM) of a geothermal heating network, including assessment of adding thermal storage	9,5 MW[**] 3 GWh/y[***]	DSM:7 to 9

Table 2: Pilot demonstration projects within the HEATSTORE project, as implemented. Status of October 2021.

Country	Concept of pilot demonstration	Storage capacity & volume	TRL* advance
Netherlands	Geothermal heat doublets combined with Aquifer Thermal Energy Storage (max 85°C) integrated into a heat network used by the horticultural industry	10-12 MW 20 GWh	7 to 8
France	Solar-assisted Borehole Thermal Energy Storage to avoid thermal depredation of the ground	100 MWh	5 to 8
Switzerland Geneva	The development of a deep Aquifer Thermal Energy Storage system (>50˚C) in Cretaceous porous limestone connected to a waste-to-energy plant	~4 MW	to 5 - 6
Switzerland Bern	Surplus heat storage underground (200 - 500m, max 120 ˚C) in existing district heating system fed with combined-cycle, waste-to-energy and wood fired plants.	~1.7 MW	to 5 - 6
Germany	Mine Thermal Energy Storage pilot plant for the energetic reuse of summer surplus heat from Concentrated Solar Thermal power plant (max. 60°C; Δt: 50-60 K) for heating buildings in winter.	20-30 kW 50-90 MWh	to 7
Belgium	Demand side management (DSM) of a geothermal heating network, including assessment of adding thermal storage	9,5 MW** 3 GWh/y***	DSM:7 to 9

2 Demonstrator and case study synthesis

2.1 Technology-independent aspects

2.1.1 Integration of the UTES into DHN: general considerations

An important aspect of UTES, independent of their technology, is its integration into local District Heating Networks (DHN). UTES can provide a buffer storage for short-term heat storage and peak shifting or long-term seasonal heat storage. The heat source could be surplus heat from industry, waste incineration plants, combined heat and power (CHP) or from solar thermal collectors. UTES avoid the consumption of expensive and high carbon-emissions energies during the winter period while consuming relatively cheap surplus low-carbon energy during the summer storage. The energy demands, specification of the network (inlet and return temperatures) and characteristics of heat sources must be assessed in order to design a profitable heating and storage system. The efficient integration of UTES 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). The charging period of the storage to the designed temperature levels needs to be included in the system integration. In addition, to be the most efficient, the return temperature at the hot well should be as low as possible (cut-off temperature).

Figure 1 illustrates how geothermal energy stored (here case of an ATES) can feed a DHN depending on the hot well temperature and DHN inlet temperature and maximum geothermal flowrate. When the hot well temperature cannot warm the heating network water to the inlet temperature, non-geothermal available energies are used (left column). In addition, the geothermal well flow rate cannot exceed a maximum allowed flowrate, which can also limit the possible geothermal power delivered to the network (top row). Non-geothermal available energy sources are used both directly on the network as an additional energy source to geothermal power, and to warm the geothermal brine to its storage temperature during the summer (Figure 2).

Whatever the technology, UTES should consider the subsurface storage and the heating network as a single system in order to make proper energy analyses. Numerical simulations allow estimating the network's energy mix and the geothermal energy use over time. Demand Side Management System (DSM) within the HEATSTORE project was implemented in the Balmatt demo site (Belgium) to demonstrate the capabilities of smart control both on building and on network level, in order to reduce peak heat loads and consequently increase the share of geothermal heat delivered to the consumers.

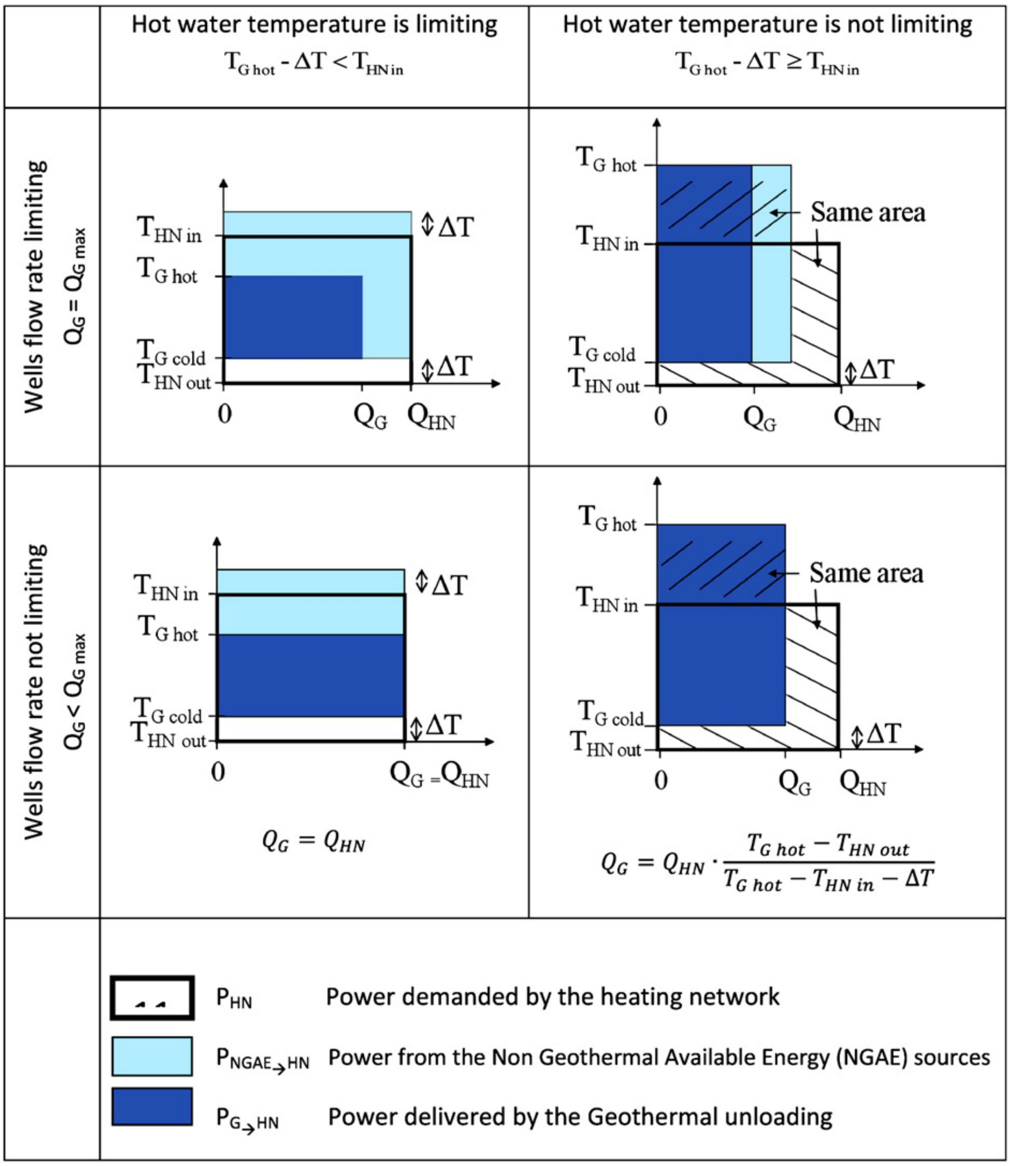

Figure 1: Use of geothermal and non-geothermal available energy sources to feed a heating network during the winter depending on temperature and flow rate limitations (source: Reveillere et al, 2013).

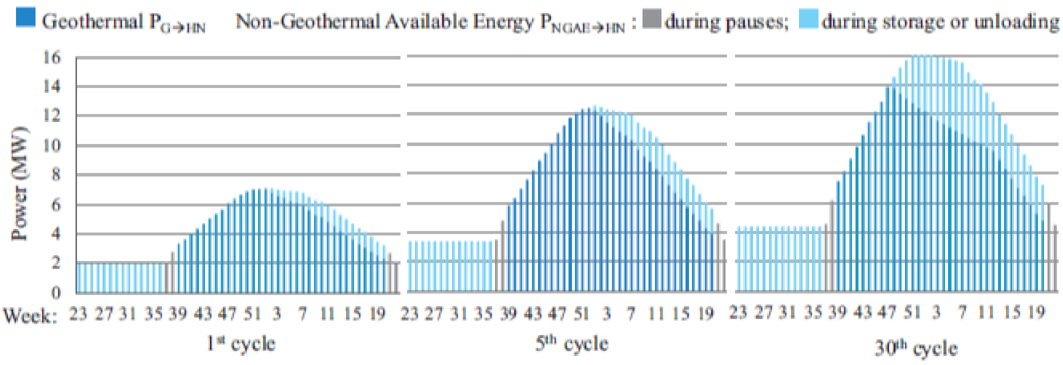

Figure 2: Example of the energy mix of a district heating network during the different cycles of heat storage and unloading (source: Reveillere et al, 2013).

2.1.2 Optimization of DHN operation: The example of the Mol demo site (Belgium)

2.1.2.1 Demo site description

The district heating network in Mol is a high temperature network that provides heat to approximately 45 buildings (offices, laboratories and warehouses). In 2021, the network expanded further to the North in order to heat a newly renovated residential area nearby. Currently, the heat is provided by 3 gas-fired boilers with a total installed capacity of 22.5 MW_{th}. Heat from a geothermal doublet will be used as primary heat source on the DHN.

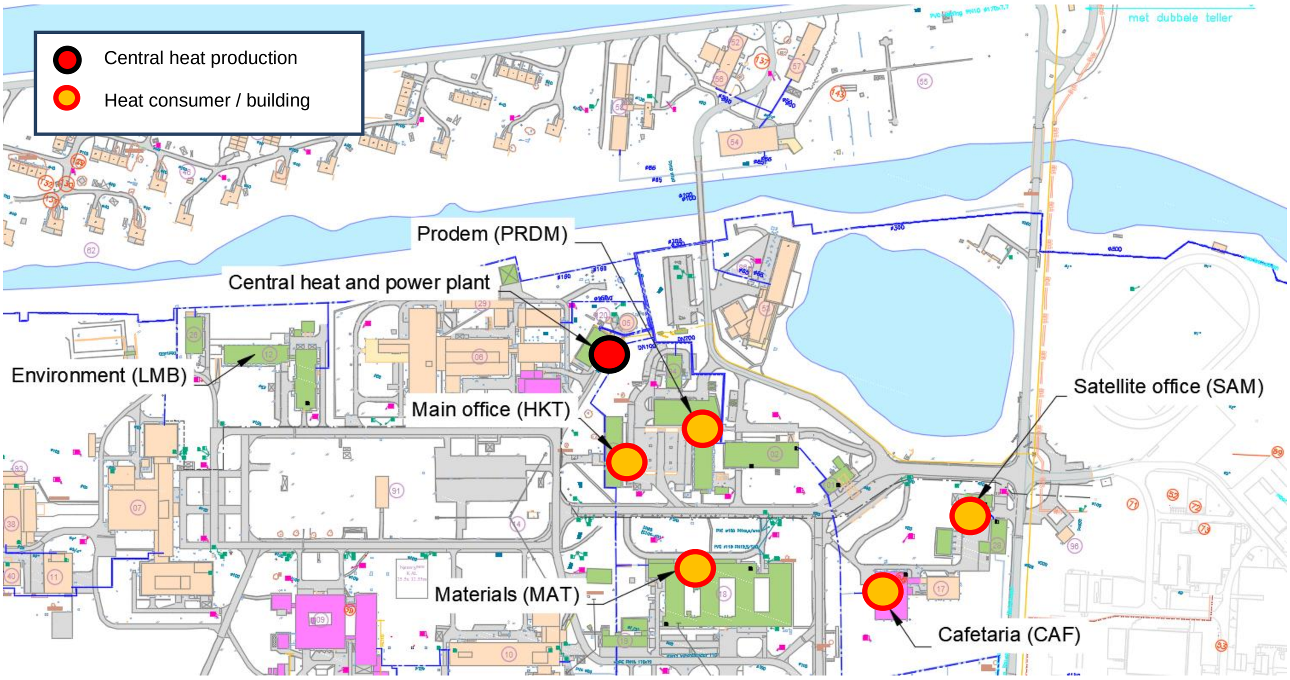

Figure 3: Map of the demosite with location of heat production units and heat consumers where the Storm controller is applied.

A Demand Side Management System (DSM) was installed to demonstrate the capabilities of smart control both on building and on network level. An overview of the heating network with an indication of the 5 pilot buildings is given in Figure 3. Within the HEATSTORE project the primary target of the system is to reduce peak heat loads and consequently increase the share of geothermal heat delivered to the consumers. The experiences and lessons learned from the implementation of this DSM platform are described further in this deliverable.

When implementing a demand side management system on a heating network, many aspects have to be considered. As soon as the control objective of DSM is clear, an implementation trajectory can be set up. This trajectory can be split up in different phases:

1. Drafting the baseline situation & technical audits
2. Defining an implementation strategy
3. Implementation and configuration
4. Monitoring and response tests
5. System online and operational

This process is mapped on a timeline for the Belgian HEATSTORE demonstrator in Figure 4.

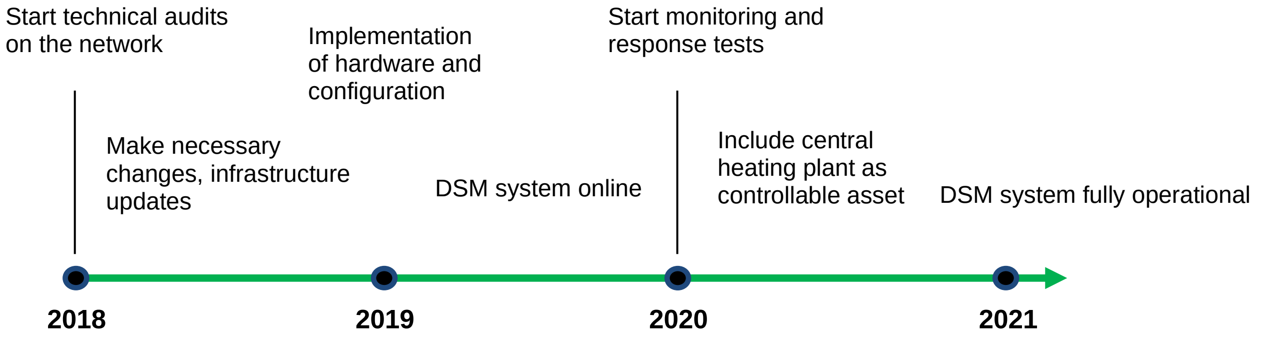

Figure 4: Implementation timeline for the Belgian demonstrator.

Before the platform was installed, an extensive technical audit on the heating network was performed. In this audit the connectivity of a building is assessed (e.g. internet connectivity, sensor data, sensor types, BMS specifications). Based on the results of this audit and the available information, the necessary hardware is selected. Next, the devices are installed, tested and connected to the data platform. From this point all data is collected in a central location and the buildings can be monitored. The following step is to perform response tests. During these tests the response of a building's HVAC system on control signals coming from the controller are evaluated. After a certain period, when enough data is available (typically a few weeks, preferably longer to increase accuracy), the forecaster algorithms can be trained and validated and the system is ready to operate.

The main challenge of implementing the Storm Controller on the district heating network in Mol proved to be dealing with the legacy equipment installed. First of all the network and the buildings already have a certain age and many HVAC controllers inside the buildings were not updated yet. The documentation is not always available (control strategy and parameters) and the older HVAC controllers are more difficult to reprogram since specific hardware and software is needed. Also, older types of heat meters are often battery powered or do not offer the possibility to exchange data. Therefore, a number of heat meters had to be replaced first. On the contrary, some building management systems were renewed recently and can be considered state of the art.

Another barrier was that certain measurement data was simply not available. As a result, additional hardware had to be installed. For example, the total heat output of the heating plant was not recorded (sub meters on the heat generation units were inaccessible), therefore an ultrasonic clamp on flowmeter with heat meter and IOT gateway was installed (Figure 5).

Figure 5: Left: Installation of an ultrasonic flowmeter, heat meter with IOT gateway on a DN250 DHN pipe. Right: New substation for the residential area.

The indoor temperature in one of the office buildings is monitored in detail (**Figure 6**). The building is equipped with one (or multiple depending on the size of the room) temperature sensor in each office (16 in total) to have a better overview on heat distribution in the building and on user comfort. This data is very useful to better understand how the building responds to changes in the operational settings of the heating system (e.g. when decreasing supply temperature).

Two different implementation methods for connecting the buildings with the IOT infrastructure were evaluated; a sensor override solution and a full BMS integration. The sensor override solution proved to be a fast and simple method to connect the buildings to the data platform. This approach was used in 5 buildings and it typically takes half a day per installation. The BMS integration is more complex since some reprogramming is necessary but the main advantage is that the control functionality becomes virtually unlimited.

2.1.2.2 Recommendation for further test operation

While the Storm controller was initially designed to unlock and activate thermal flexibility on building level, tests have indicated that also on the supply side important improvements can be made in relation to the general supply temperature of the network. During next heating season the Storm Controller will operate autonomously on the heating network to demonstrate its capabilities for peak shaving and supply temperature optimization, this will work on two levels:

- Building level (activate thermal flexibility inside the buildings),
- Central heating plant (optimize the supply temperature and activate the thermal flexibility within the heating network)

VITO will build further on optimizing the entire district heating network by implementing the Storm controller in other buildings connected to the heating network. During the second semester of 2021, the largest building will also be integrated in the Storm framework, which will drastically increase the available thermal flexibility.

In addition, VITO's technical services, responsible for the infrastructure on the domain, learned from the HEATSTORE demonstrator that the data platform that comes with the Storm Controller offers significant added value regarding monitoring, fault detection, administration and other operational aspects. Therefore, the data platform will also be used to connect all digital meters (heat, water and electricity), which will further increase the value of the system.

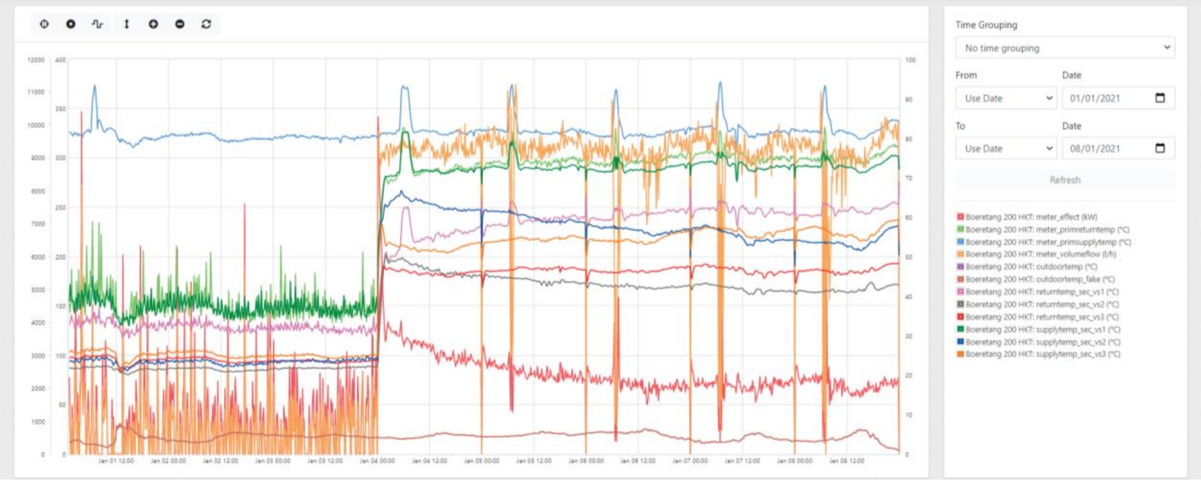
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Figure 6: Data visualization and monitoring platform (Noda Smart Heat Grid)

2.1.3 Legal framework

The legal framework is country-dependant and is often linked to the depth of the targeted formation. However, in most EU countries, not all the existing acts are specific to UTES but to conventional geothermal systems. Adapting the regulation to the UTES features would decrease the uncertainty associated with regulation. The legal framework is extensively described in HEATSTORE report D6.2 "Regulatory and policy boundary conditions". Here we give an overview of the main points.

2.1.3.1 France

Geothermal resources are classified as "mines" and their exploration and exploitation are regulated by the Mining Act (*Code Minier*). Originally, the Mining Act considered three types of geothermal resources according to their temperatures measured at the wellhead during the production tests:

(i) high temperature resources (T> 150°C),
(ii) Low temperature resources (T<150°C). Two mining titles are necessary to exploit these resources: one for the exploration phase and one for the exploitation phase.
(iii) Shallow aquifers with temperature less than 25°C, which are used for heating or cooling by using heat pumps. These geothermal resources are so-called "Geothermal resources of minimal importance" or "Shallow geothermal resources". These shallow aquifers can be exploited through close-loop geothermal systems or through open loop systems with a production well and a reinjection well. The permitting process is simplified and no mining title and operating permit are requested for exploiting these shallow aquifers. The relevant criteria are the following:
    - Boreholes less than 200 m deep,
    - Power extracted less than 500 kW_{th},
    - Water temperature below 25 °C,
    - Flow rate less than 80 m^3/h for open loop system,
    - Water must be reinjected into the same aquifer it was produced from for open loop systems.

Since 2019, the permitting procedure related to both exploration and exploitation of geothermal resources for depth over 200 m has evolved. During the exploration phase operators can choose between two procedures:

- a Research Authorisation (AR) more appropriate for areas already geologically well known. The lease is attributed by the Departmental authority for a 3-years period,
- an Exclusive Research Permit (PER) more appropriate in areas where there is less geological knowledge. The lease is granted by the Ministry of Environment for a period of 3-5 years.

During the exploitation phase, there are two types of mining permits based on the installed power (lower or greater than 20 MW). This limit in the power installed has replaced the initial temperature threshold (150 °C).

- < 20 MW: Exploitation permit (PEX) managed by the Departmental authority for a maximal initial period of 30 years that can be renewed for a period of maximum 15 years,
- > 20 MW: the operator gets a concession granted by the State Council for a maximal initial period of 50 years that can be renewed by periods of maximum 25 years.

The timeline of legal procedure is about 3 years but can be longer according to the project and includes ~5 months of prefeasibility and feasibility studies, ~18-24 months of studies including the authorization report, the instruction by the authority and the consultation of the enterprises and ~7 months of drilling and testing.

Currently there is no specific legal framework for UTES. In case of shallow geothermal, the maximum temperature change at 200 m from the well should be lower than 4°C and the maximum temperature injection should be kept below 32°C (40°C for closed loop system). For intermediate to deep geothermal energy, there is currently no legal obligations (limits) on temperature reinjection expect in the case of deep geothermal targeting drinking water resources (e.g. Albian aquifer in Paris Basin) where the temperature reinjected must not be greater than the initial temperature of the aquifer (microbiological issues).

The operator must also demonstrate in the AR or PER that the operation will not affect other neighbouring operations during the exploitation phase (a maximal impact of 1 bar in pressure is admitted, the temperature of the injected fluid must not affect the other operations).

2.1.3.2 Switzerland

The legal framework is Canton-specific and also depends on federal law according to the depth of the UTES. For example in Bern Canton, above 500 m depth, the Canton level applies while below 500 m the Federal level applies.

For the Geneva Canton, the mining titles are very similar to those applying for France for deep geothermal with 3 permits needed:

- a prospecting permit (surface exploration like geophysical acquisition): 1 to 2 years of instruction,
- an exploration permit (drilling of exploration wells): 1 year of instruction, and the testing of the horizons of relevance.

- an exploitation permit: 1 year of instruction.

The Switzerland Federal law on groundwater states that the difference of temperature must be limited to 3°C at 100 m from the injection well.

2.1.3.3 Netherlands

In Netherlands, two laws apply: the Water Act for UTES to maximum 500 m depth and the Mining Act for activities in the subsurface at 500 m depth or deeper. In the first case, the maximum injection temperature is 25°C and the permit is much easier to acquire, when compared to the Mining Act. Like in France, there are no specific rules applying for HT-UTES (>25°C).
Currently a new guideline is in development to make it easier to apply for injection temperatures above 25 °C. Actual HT-ATES projects are permitted by addressing them as pilot-projects, while they are in fact full scale projects. In order to get a permit, a discussion is needed with the authorities about the conditions and still the general permitting rule is applied that the HT-ATES system should not negatively influence other groundwater users or interest. In order to monitor the impact of an HT-ATES on the subsurface and surrounding, an extended monitoring program is applied to monitor the chemical and biological changes in the groundwater.

2.1.3.4 Germany

For the legal approval of a MTES, it is necessary to determine which field of law needs to be applied, as this is the basis for determining the competent authority for the application process. Regardless of the competent authority, the approval procedure is characterized by a comprehensive concentration effect. This means that if a project affects several different fields of law, these are considered by the authority dealing with the main proposal, so that the applicant only interacts with one legal entity. With regard to the utilization of geothermal energy and the subsequent possible thermal energy storage, the mining and water authorities are the two main legal departments responsible for such application [Weiß 2016].

In all procedures, the aspect of environmental compatibility also needs to be considered, which is enforced by the Environmental Impact Assessment (EIA) and defined in the Environmental Impact Assessment Act. An EIA is not performed as an independent procedure, but is part of the administrative approval process, if the regulative necessity is given. A preliminary evaluation for a storage system might be necessary, if the circulation volumes exceed 100.000 m^3/a and adverse effects on the groundwater-dependent ecosystems are to be expected.

In accordance with § 3 para. 3 of the Federal Mining LAW (BBergG) geothermal energy is considered a natural resource without concession status. Therefore, a mining permit is required for the exploration of geothermal energy and a mining approval is needed for the extraction of geothermal energy in Germany.

In 2006, North Rhine-Westphalia issued a decree which regulates the statewide utilization of geothermal energy and also distinguishes between different storage applications. Within the MWME decree, it is clearly stated that the injection and extraction of thermal energy into the ground for storage purposes does not resemble the extraction of geothermal energy with regard to the above-mentioned reference to the German Mining Act. This also includes the transfer of thermal energy into the subsoil, as well as the withdrawal of artificially introduced thermal energy into the ground. Also, the injection of thermal energy into the earth's body does not fulfil the relevant mining law definition of “containerless deep storage” [MWME 2006]. In summary, it can be stated that the mining law is only applicable when a negative heat balance is anticipated, which is governed by the fact that more heat is produced than stored into the underground, which is the case for the exploitation of a geothermal resource. However, this is not the case for a MTES, in which continuously more thermal energy is injected than extracted from the subsoil and therefore constitutes to a positive heat balance over a long duration.
Accordingly, the mining law does not have primary responsibility for the approval of a MTES in an abandoned colliery and would only be integrated within the approval process, if boreholes with a depth of over 100 m bgl (§ 127 BBergG) are necessary for the implementation of the storage concept. This circumstance should be highlighted as the reversal of evidence is enacted under the mining law, which means that for mining related damages, the burden of proof is within the responsibility of the operator and not the aggrieved party.
Consequently, the water authority is the active legal department for handling the approval (either permit or authorization) of a MTES application, due to the fact that the extraction, production, injection and discharge of groundwater is listed in the Water Resources Law (WHG) under § 9 para. 1 No. 5 WHG.

For the implementation of a MTES system, the issue of the legal liability has to be settled with the current mine owner. Despite the fact that the mine is closed, the mine owner remains within the legal responsibility of the previous mining operation. For instance, if subsidence appears, the mine owner will be liable to mitigate those damages.

2.1.3.5 Denmark

The regulation of geothermal energy is based on different acts according to the purpose of the installation. Deep geothermal energy is regulated pursuant to the Danish Subsoil Act (LBK nr 1533 af 16/12/2019) under the administration of the Danish Energy Agency, while shallow geothermal energy is regulated pursuant to the Danish Environmental Protection Act (LBK nr 1218 af 25/11/2019) and permissions are issued by the Municipalities. An agreement between the Municipalities and the Danish Energy Agency has been made, that if planned boreholes for geothermal energy are deeper than 250 m, the Energy Agency must be consulted to clarify whether the installation is subject to the Subsoil Act or not. There is no specific regulation for UTES.

ATES systems down to a depth of 250 m for heating and cooling are regulated by a Ministerial Order on “Heat extraction plants and groundwater cooling systems” (BEK no. 1716 of 15/12/2015) supplemented by the Danish Water Supply Act (LBK nr 1450 af 05/10/2020), according to which extraction permits are granted by the Municipalities. If heat is supplied to a heating network, a permit according to the Danish Heat Supply Act (LBK nr 1215 af 14/08/2020) is needed as well. Finally, drilling and mandatory reporting of borehole data to GEUS is regulated by a Ministerial Order on “Onshore drilling” (BEK no. 1260 of 28/10/2013).

BTES systems for heating and cooling (Borehole Heat Exchangers, BHE) down to a depth of 250 m are regulated by a Ministerial Order on “Ground Source Heating Systems” (BEK nr 1260 af 28/10/2013). If heat is supplied to a heating network, a permit according to the Danish Heat Supply Act (LBK nr 1215 af 14/08/2020) is needed and drilling and mandatory reporting of borehole data to GEUS is regulated by a Ministerial Order on “Onshore drilling” (BEK no. 1260 of 28/10/2013).

PTES is regulated pursuant to the Danish Environmental Protection Act (LBK nr 1218 af 25/11/2019) and if heat is supplied to a heating network, a permit according to the Danish Heat Supply Act (LBK nr 1215 af 14/08/2020) is needed.

For ATES, water passing the injection valve must not exceed 25°C and in monthly average it must not exceed 20°C. Furthermore, injected cooled water must have a monthly average temperature of at least 2°C. No distance requirements to other wells are given, but it must initially be assessed by numerical modelling that temperatures in neighbouring water supply wells will not rise more than 0.5°C.

For BTES systems, they must keep a distance of up to 300 m to existing drinking water wells and 50 m to other similar systems.

For both ATES, BTES and PTES, the developer or a consultant must produce the required material and submit it to the municipality. From this material the municipality will produce a scope for an EIA screening, hear neighbours and organisations affected by the project and involve other authorities responsible for elements of the project. If needed, a full EIA will be conducted. An EIA permission with specific requirements and permission related to other legislation will be granted.

2.1.4 Social acceptance and local stakeholder commitment

The social acceptance should be taken into account in the early phase of the project implementation as it may have future positive or negative impact for the project development. Social acceptance is not specific to UTES but also to conventional geothermal operation. This is particularly true in dense urban areas, for deep drilling, and in particular context like fractured reservoirs or mines. The main apprehensions concern the potential surface impacts of drilling, well testing and heat storage operation (e.g. ground movement and their potential impacts on the existing infrastructures, gas emissions and/or groundwater heating/pollution and their impacts on the environment and human health).

Therefore, efforts should be made towards awareness of the local population. For example, in Switzerland, the Geneva demo site team has organised “open days” during the drilling phase.

Bern demo site team has organized different communication levels to publicize the project:

1. a strong internet presence on the ewb website,
2. open stakeholder events to which the broader public was invited, including presentations of the project by the team and the management of ewb, followed by Q&A sessions,
3. a visitor platform was installed and the drilling site is being included in the guided tours of the power plant.

To document the possible impact of the project, the following monitoring has been started and is being continued:

1. a baseline measurement to record ground elevation and repeated measurement throughout the execution phase. The baseline measurement included a documentation of existing damage on adjacent buildings,
2. a continuous seismic monitoring in the preparation phase and throughout the execution phase,
3. a continuous video surveillance of the site with pictures taken and filed in fixed intervals,
4. a baseline measurement of a nearby water well, for the quality of the water and continuous measurement thereafter,
5. installation of fibre optic cables on both casing strings for temperature, acoustic and strain measurements.

In Denmark DHN are mostly consumer-owned and they are sensitive to “green” and costs arguments. It is normal practice with a hearing period of 8 weeks, where people can take notice of the project and submit objections. The projects are then presented to the town council, where it can be approved. Municipalities then do the environmental impact assessment. Early contact with people close to the installation is therefore very important. For Brædstrup BTES, the concern of the municipality was the risk of heating up the groundwater, as experienced in previous BTES projects. Taking into account this concern led to install extra boreholes to monitor the temperature of the groundwater below and next to the BTES, and TRNSYS calculations also were carried out to show that the groundwater temperatures around the storage would not exceed 20°C [ForskEL 2013].

The project should also be thought in close cooperation with local stakeholders that are potential future end-users. For example, in Bochum where the MTES is planned to feed into the local DHN of the University in the future, a close collaboration with the public services of Bochum (DHN owner) is already established or in the Netherlands where greenhouses owners will benefit from the geothermal energy. Therefore, in order to successfully facilitate these projects an overall acceptance with the support of the different local stakeholders and population should be considered right from the beginning of the planned implementation.

2.1.5 Importance of proper planning

Typical duration for the different phases of a UTES project is at least 3 years for ATES and MTES. Enough time should be allocated for the different phase. The process to get all authorizations may take at least 12 months, and even more if an environment impact assessment is needed.

2.2 ATES

2.2.1 Middenmeer HT-ATES Heatstore Demo site

2.2.1.1 Short site description

The HT-ATES system at ECW stores surplus geothermal heat delivered by a district heating grid during the summer at ~85 °C and delivers the stored heat to greenhouses after recovery in winter. The heat is stored in an unconsolidated aquifer at 360 – 380 m depth.

2.2.1.2 Pre-investigation and feasibility studies

To investigate the subsurface, a first exploration well was drilled in 2019. It was later used as a monitoring well. During drilling of the exploration well two target storage aquifers where encountered, the deepest of which exhibited a high content of gas and unsatisfactory flow properties. Therefore, a design was made for HT-ATES in the shallowest aquifer, using the information of the test drilling. After the realisation of the HT-ATES system, a pumping and build-up pressure test was performed. Water was produced at a constant flow rate for 4 hours after which the pump was shut down. Dataloggers in piezometers registered hydraulic heads in and around the wells with high frequency during the test. From the results a hydraulic conductivity of about 12-13 m/d (17 Darcy) was found. The risk of sand production was found to be low, even at high flow rates. The grain size of the aquifer was determined by sieve analysis on cuttings during the drilling process of the wells. A core sampling was initially programmed but failed.

Chemical fluid composition was monitored during well testing and thermo-chemical simulations were conducted using Toughreact and PHREEQC. Simulations suggested that calcite precipitation would not occur at the aimed storage temperature of 85°C. In order to prevent calcite precipitation, CO_2 will be dosed. At the abstracted groundwater, CO_2 will be dosed with a fixed amount per m^3 groundwater. The injected groundwater is enriched with CO_2. Actual measurements will monitor the CO_2 concentration (HCO_3^-) in the groundwater and also gas-analyses are performed on the groundwater to monitor the CO_2 content. The measurements will be used to improve the model and to predict the risk of calcite precipitation, which contribute to the optimization of the dosing method.

Thermo-hydraulic modelling was conducted using HST3D software from IF Technology to optimize the distance between the future hot and cold wells for the energy recovery from the HT-ATES. The simulations results show that a distance of 220 m is optimal for both the thermal recovery efficiency and the thermal interference between the hot and cold wells. This well distance corresponds to approximately 2.2 times the thermal radius of the hot storage.

2.2.1.3 Design and construction

The HT-ATES is composed of three boreholes, a doublet (one ‘cold’ and one hot well) and a monitoring well (initial exploration well). The three wells target a sandy formation at approximately 360-380 m depth (shallow geothermal ATES). The wells are aligned with a distance of 220 m between the cold and hot wells and the monitoring well is located at 30 m from the hot well. The hot and cold wells are designed identical with submersible pumps as they will work as reversible wells. An overview of the site and the position of the wells is shown in the figure below. The wells are drilled between the greenhouse (left side) and the canal (right side).

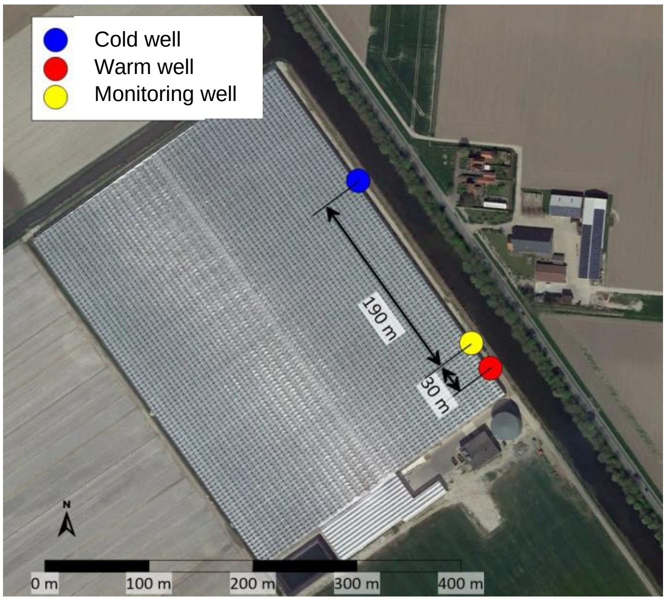


Figure 7: Picture of the site and well location.

The vertical wells are drilled with the reversed rotary drilling technique with air lift. After the drilling, the filter screen and piping has been installed, together with a optic-fibre attached to the pipes for future temperature measurements. The borehole was filled with sand and clay, restoring the original lithology around the well pipes. Piezometers were installed at various depths to facilitate groundwater sampling for chemical and microbial analysis in the storage aquifer and shallower layers. An image of the configuration of well and piezometer of the wells and the monitoring well is given in Figure 8. At the same level as the clay layers, the borehole is cemented with swelling clays in order to prevent hydraulic short cuts from one aquifer to another aquifer. This is a requirement from the drilling protocol.

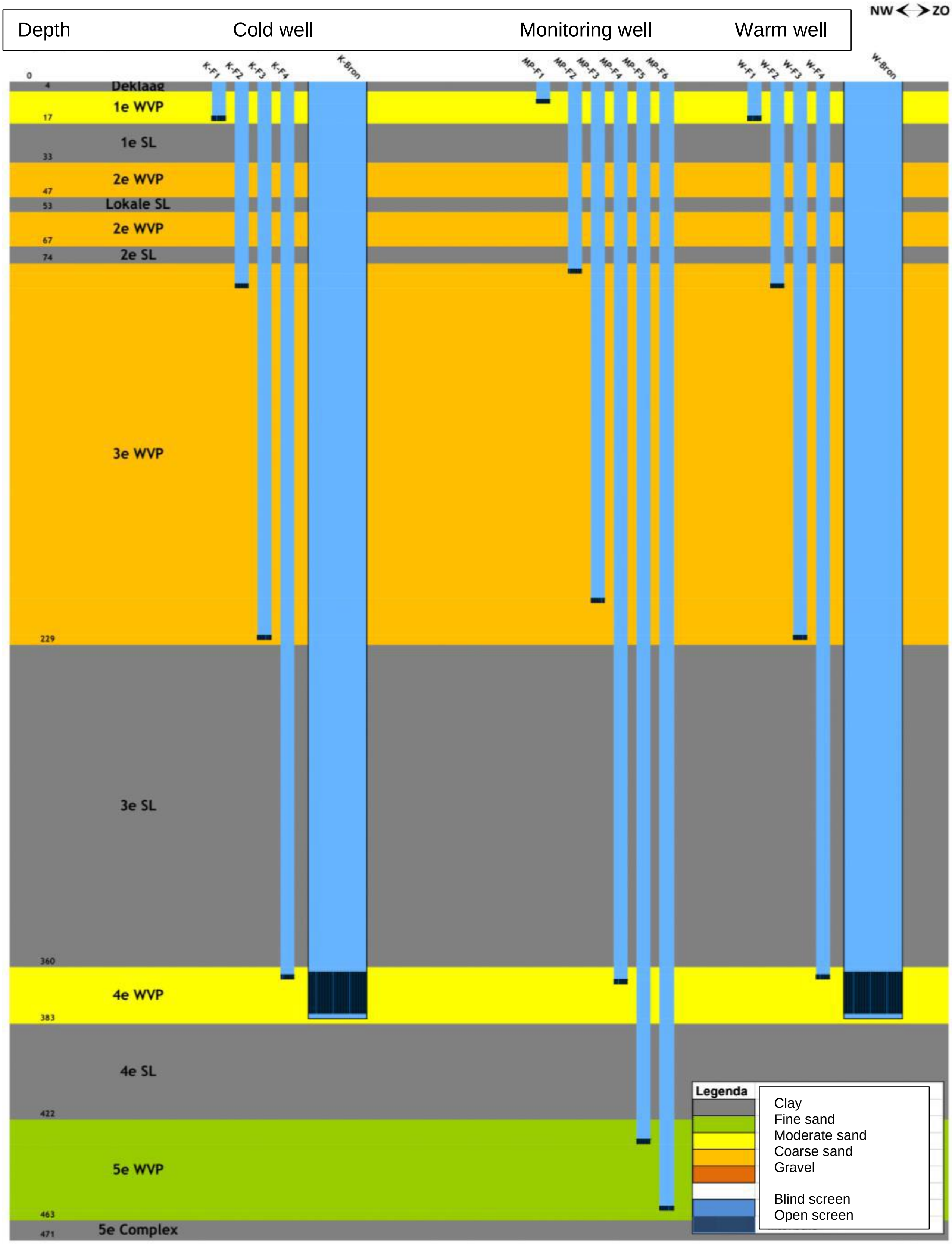


Figure 8: Vertical schematic scheme of the well design.

The casings of the wells are in Epoxy to avoid corrosion and the well screen are stainless steel. There is a specific wellhead design to allow high wellhead pressure due to change of temperature in the hot well. A picture of the well head is presented in Figure 9. On the right side a nitrogen buffer is installed to condition the pressure in the well head. On the left the well head is presented, where the bigger tube is the well and the smaller tube (middle) is the transport pipe to the technical room. The red cable is the glass fibre cable for temperature measurements.

Figure 9: Well head design.

2.2.1.4 System operation, monitoring and maintenance

The flowrate for heat loading is 150 m^3/h with a temperature of 85°C and the discharge flowrate will vary from a minimum of 30 m^3/h to 150 m^3/h with a cut-off temperature of 55°C. The injection temperature at the cold well is 30°C. Electric submersible pumps (EPS) will be used for both wells. There will be continuous measurements of flowrate, temperature, pressure, energy and water amounts, pH, oxygen and conductivity.
In year one, the water quality of the abstracted groundwater is sampled each two months. At the same moment, the water quality of the monitoring well in the target aquifer is sampled. The water will be analysed on macro and micro elements, gas content and qualitative DNA analyses of bacteria (Next Generation Sequencing Analyses).
A part of the analyses is demanded by the permit requirements but at a lower frequency. Also, more measurements are planned in order to get a better understanding of the working of the system and how to tune the operations. Within the HEATSTORE project, but also in the Warming-Up program more research will be done. The first loading cycle has started in June 2021 at full capacity. The government has approved the installation.

2.2.2 Koppert Kress case study

2.2.2.1 Short site description

Koppert Cress is a horticulture company situated in the western part of the Netherlands. To provide sustainable heating and cooling, an ATES system was installed with 4 warm and 4 cold wells (see Figure 10 left). As part of a Dutch pilot and research project the LT-ATES was converted to a HT-ATES pilot [Bloemendal et al. 2020]. To obtain insights in the heat spreading and water quality changes associated to the HT-ATES, the site is intensively monitored.

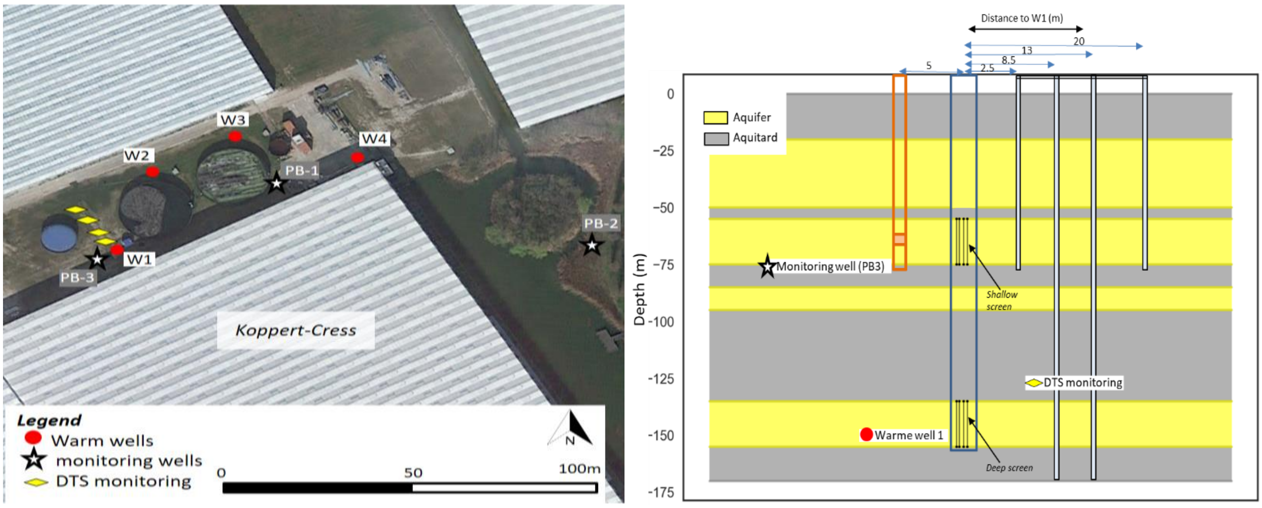


Figure 10: Left: Overview of warm well locations Koppert Cress. Right: subsurface layering and monitoring infrastructure around warm well 1 from the Koppert Cress ATES system.

Local subsurface composition is provided (see Figure 10 right), together with the locations of the ATES well screens and the subsurface monitoring infrastructure in place. The ATES system utilizes 2 aquifers with screens up to ±170m depth. The ambient groundwater flow is close to 0, there is virtually no hydraulic gradient in the area. The heating loads to/from and temperature of the warm wells is depicted in Figure 11. This illustrates the strong imbalance in heating and cooling demand of the system. The distance of the temperature front is referred to as the thermal radius (R_{th}), and is due to the imbalanced operation not larger than 15 m.

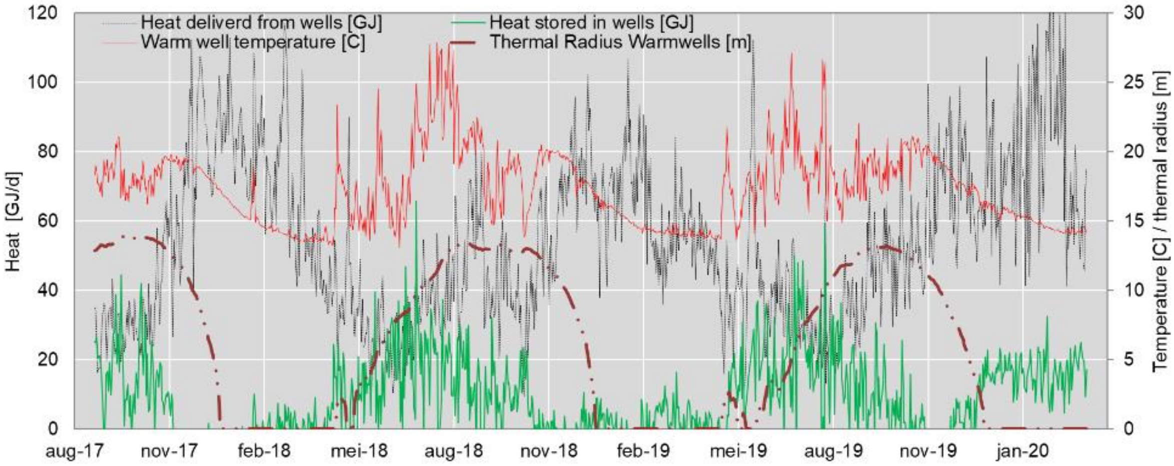


Figure 11: Example of the available data for the Koppert Cress pilot site. Daily heat to and from the warm ATES wells, well temperature and size of the thermal radius in the 2.5 year period from august 2017 to March 2020 is shown.

2.2.2.2 Challenges and Highlights during implementation

Highlights

- Higher storage temperatures resulted in larger amounts of heat to be stored and hence considerable lower GHG emissions.
- The limited increase in groundwater temperature did not lead to growth of the investigated opportunistic pathogens.
- Water quality effects are dominated by mixing effects, important changes in salinity, arsenic and sulphate are all contributed to the mixing of groundwater from the 2 different aquifers. No change in water composition is caused by changes in temperature, due to the fact that temperature changes are limited and only locally around the wells.

Challenges

The greenhouse of Koppert Kress exhibits a strong imbalance in heating and cooling demand. As a result the warm groundwater in the warm well is completely depleted each winter. Figure 12 shows the temperature increase in the shallow aquifer at two different distances from the warm well during 2020. This confirms the observation that the temperature inside the aquifer as well as in the confining layers returns towards ambient conditions during winter, due to the imbalanced use of the ATES system. The temperature change contour of 5°C illustrates how the confining layers slowly heat-up during summer and cool-down during winter.

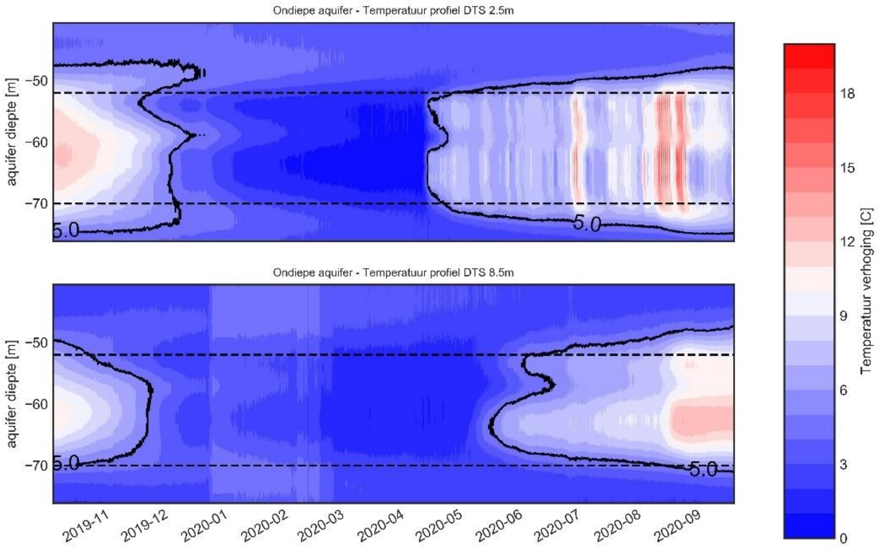


Figure 12: Temperature increase in the shallow aquifer over time, at 2.5 and 8.5 m distance.

The anticipated magnitude and extend of the temperature change contour were much larger than was realised in practice. This resulted in various challenges:

- The location of the monitoring well for taking groundwater samples assessing groundwater quality was beyond the extent of the thermal radius. Therefore, it was impossible to measure water quality effects due to temperature change from this monitoring well (PB-1 in see Figure 10 left). It was decided to drill a new monitoring well (PB-3) at 5 (m distance from the warm well to ensure thermal impact on the groundwater, when taking samples. Despite the small distance to the well, still required to take sample at the right moment to sample affected groundwater and measure changes in water quality due to temperature change.
- The harvesting of heat appeared to be more challenging. Due to large temperature difference between sources of heat also pollution of the higher temperatures could not be avoided. Still, the lower temperature heat contributed to the increased performance, but it would have been better to have had better management and control on exergy levels of the heat stored in the wells.
- Despite the quite extensive data collection on subsurface characteristics, well flows and temperature and subsurface temperature, it is always difficult to fit field data in model. Also, different monitoring data provided contradicting information on the distribution of the flow across the different well screens. The model was calibrating using the DTS (Distributed Temperature Sensing) data.

2.2.2.3 Lessons learned from problems within the implementation phase

Transition from LT-ATES to HT-ATES for Koppert Cress case study

When the Koppert Cress pilot was initiated, it was expected that over the years enough additional heat sources would be available to seasonally store large amounts of heat, resulting in storage of heat at temperatures between 30-40 °C. However, analysis of the system showed that the yearly heat demand of the greenhouses of Koppert Cress still exceeds the amount of heat stored in the wells. Also, the temperature of the available heat is limited because it is harvested from environmental sources. This results in an imbalanced ATES system that only stores heat at temperatures >25 °C during the hottest days of the years. A considerable part (25-20%) of the stored heat is retrieved within a day or week.

In spite of these conditions, with respect to energetic performance and greenhouses gas emissions savings the Koppert Cress (HT-)ATES system is highly successful, according to Bloemendal et al. (2020). By allowing storage temperatures >25°C, Koppert Cress was able to use their heating and cooling system more efficiently. More sources of heat were included over the years, which resulted in more heat storage in the warm wells. The increase in ΔT between the cold and warm wells led to a strong increase in yearly produced heat. Overall, the transition from LT-ATES to HT-ATES resulted in a decrease of 30-70% of GHG emission (depending on the electricity source). While the GHG emission decreased significantly, the costs of operating the ATES system decreased with 10%.

Expected performance of the Koppert Cress HT-ATES system at increased storage temperature and volume balance

The analysis of operational data of Koppert Cress in this research showed that the HT-ATES is not only used for seasonal heat storage, but is also frequently used as a night/day buffer. This results in highly efficient short cycle storage of heat. The generic modelling approach does not take this short cycle behaviour into account. This shows us that pumped volumes and recovery efficiencies are reasonably expected to be higher than is computed/expected based on the generic seasonal modelling approach. Also, the effect of the volume imbalance is shown to have a positive effect on the modelled recovery efficiency of the warm well.

2.2.2.4 Recommendation for further test operation

Future improvements on the HT-ATES of Koppert Cress could focus on:

- optimal HT-ATES pumping strategy (short cycle? Imbalanced?)
- further improve heat harvesting and injection temperature.

Improve control and distribution of different temperatures of heat into different well, to have warm wells at different temperature levels.

2.2.3 NIOO Case study

2.2.3.1 Short demo site description

The building complex of the Netherlands Institute of Ecology of the Royal Netherlands Academy of Arts and Sciences (NIOO-KNAW) in Wageningen, the Netherlands was built in 2010 inspired by the ‘cradle to cradle’ philosophy that mimics the regenerative cycles in nature. It was built with the highest sustainability level feasible at that time and has served as a demonstration site for sustainable buildings in the Netherlands. The building complex was inspired by nature using three principles: 1. Use energy from the sun, 2. Close all cycles where possible (water, materials) and 3. Stimulate biodiversity. Goal was to build a research complex of 9 buildings including greenhouses and climate control rooms that could operate without fossil gas. To enable a sustainable climate control system, two ATES systems have been installed that are coupled to store and supply both heath and cold to the entire building complex. The first (shallow) groundwater system is a regular (low temperature) 25 ºC ATES system in a coarse sand aquifer at 80 m depth and is the main source of cooling in summer. The second (deep) ATES system is a high-temperature heat storage system in a low permeability aquifer at 300 m depth. The HT-ATES system of NIOO has been realized in 2010 and is used to store heat with temperatures up to 45 ºC from solar collectors.

It consists of a cold and a warm well with infiltration temperatures of respectively 26 ºC and 45 ºC. Temperatures and groundwater composition have been monitored from the start. Together with the monitoring programme of the HEATSTORE programme, this now offer a unique 10-year field data series. In the framework of the HEATSTORE project the initial dataset was augmented and used to investigate the effects of HT-ATES on the subsurface; both initially after construction as well as over time. The NIOO case study was focused on temperature effects as well as chemical and microbial effects relevant for water quality. This is of particular interest in areas in which fresh groundwater is used as source of drinking water, as is the case in large parts of the Netherlands. For a detailed description of the project and the findings, we refer to the NIOO case study report, which is delivered within task 5.2 of the HEATSTORE project.

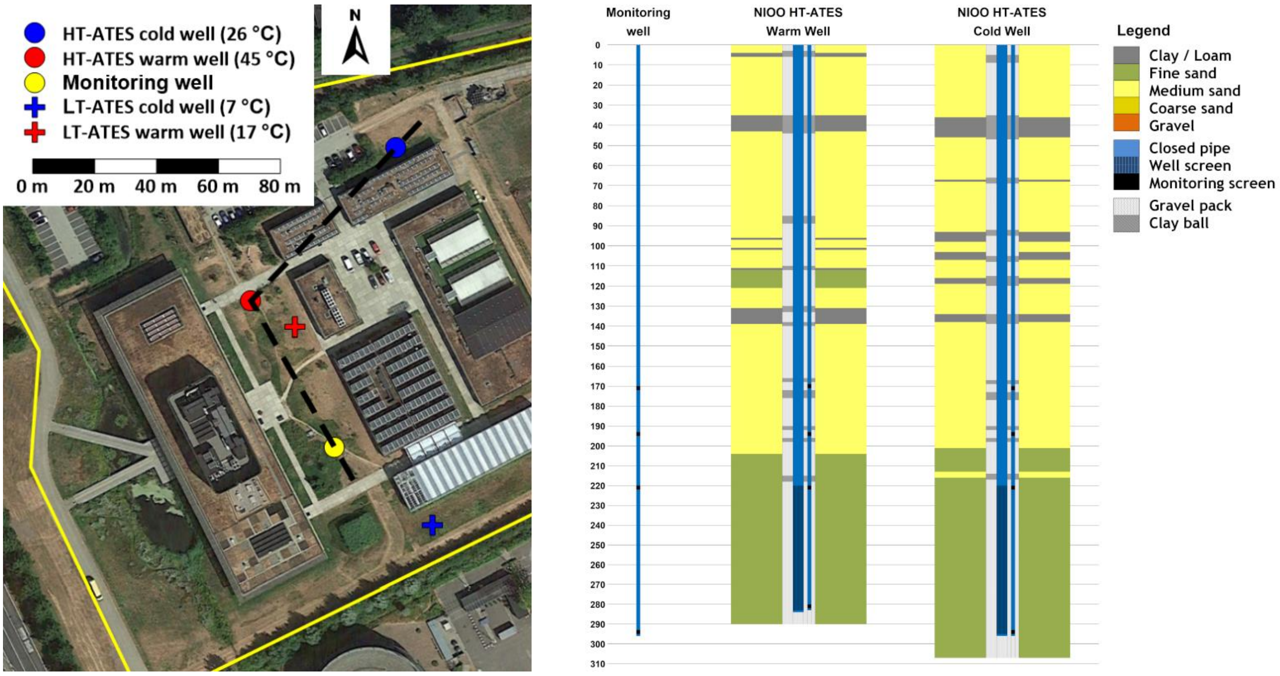


Figure 13: Left: Top view of the HT-ATES, monitoring and LT-ATES wells and location of the cross section. Right: Cross section over the HT-ATES and monitoring wells.

2.2.3.2 Challenges and Highlights during implementation

The experience with designing and operating HT-ATES systems in 2010 was very limited. Expectations were mainly based on the experience of existing LT-ATES systems and coarse model calculations. Because of the limited experience with HT-ATES and the related (bio)chemical effects, getting permission to use fresh water aquifers was (and is) not straightforward. The interests of the Netherlands water boards concerned with water quality and drinking water supplies are high and the regional authorities were reluctant to give permission to construct HT-ATES systems. Based on its research and demonstration function, NIOO received a special 'pilot status' permit coupled to a specific monitoring programme. At the location of NIOO in Wageningen, the shallow groundwater is fresh and potentially suitable for drinking water production. Furthermore, the hydraulic conductivity and the groundwater flow velocity in the more shallow aquifers are relatively high, which adversely affects the recovery efficiency and makes these aquifers less suitable for use as a storage aquifer for HT-ATES. Therefore, the NIOO HT-ATES was planned in a deeper, more fine grained aquifer that was expected to contain brackish to saline groundwater. These deeper aquifers are typically not used for drinking water production or industrial cooling due to the high salt content and LT-ATES is generally applied in more shallow aquifers. As a consequence, the amount of information that is available on these deeper aquifers is limited in many cases. At NIOO, this was also the case.

When the wells for the NIOO HT-ATES system were drilled the subsurface conditions proved to differ from what was expected. One of the main challenges was that the observed drawdown (13 m at 30 m³/h) was much larger than expected (3.6 m at 48 m³/h). The main question in such a case is whether this drawdown is due to the properties of the subsurface, or caused by clogging of the well during the construction phase (e.g. by drilling mud remnants) or a combination of both. In case (a significant part of) the extra drawdown is caused by drilling mud remnants, additional well development is advised. However, if the extra drawdown is caused by a lower hydraulic conductivity of the formation, additional well development will not help. To be able to discriminate between both possible causes, additional pumping tests have been performed combined with flowmeter testing in the wells. Analysis of these tests showed that the average hydraulic conductivity of the storage aquifer (at the depth of the well screens) was much lower than expected (1.4 m/d instead of 3.4 m/d, about 1.7 Darcy instead of 4.0 Darcy) explaining a large portion of the increased drawdown. As a consequence, it was recommended to lower the maximum flow rate of the system from 48 m³/h to 20 m³/h, which reduced the capacity to store heat significantly. Based on the analysis of the pumping tests results it was also recommended to perform additional well development actions.

On the one hand, the maximum capacity of the wells had been reduced, resulting in a smaller capacity to store heat. On the other hand, the availability of heat for storage was also reduced because (1) the heat production capacity of the solar collectors was smaller than in the design and (2) NIOO succeeded in increasing the direct use of the solar heat. All together this led to much smaller amounts of stored heat (on average 235 MWh_t in the period 2011-2016 versus 1238 MWh_t in the design), which in turn resulted in much lower recovery efficiencies than designed for (on average 8% in the period 2011-2016 versus 45% in the design). The low recovery efficiency is not only caused by the small amounts of stored heat, but also by a lower subsurface temperature at storage depth (14 °C in practice instead of 18 °C in the design) and by a small difference between the stored water temperature (45 °C) and the cut-off temperature (40 °C). After lowering the cut-off temperature to 30 °C in 2016, the average recovery efficiency has improved to 13% in the period 2017-2020.

Also, the much smaller amounts of stored heat led to a much smaller thermal impact in the surrounding area. As a consequence, no thermal impact has been observed yet in the monitoring well. Given the yearly amount of heat stored, the monitoring well is located too far from the HT-ATES wells to experience any influence from the heat storage.

Another important finding was that the fresh - saline water transition was located deeper than expected. In the top part of the well screen trajectory the native groundwater appeared to be fresh (instead of brackish) while the groundwater in the bottom part of the well screens was brackish to saline. As a consequence, fresh water and brackish water are directly mixed by the HT-ATES system, which causes salinization of the aquifer around the upper part of the well screen trajectory of the HT-ATES wells.

As a highlight, NIOO has operated the HT-ATES continuously, providing a decade of data on subsurface temperatures and chemical and microbial groundwater composition. These data have contributed to a better understanding of the subsurface processes around HT-ATES systems, while the experience during the design, realization and permit phase was highly valuable for later HT-ATES systems in the Netherlands including the design and construction of the Netherlands demonstration site ECW.

The knowledge gained from the extensive and costly monitoring programme of NIOO has been the basis for the regional authorities to significantly downsize the obligatory monitoring programme in the permit for the NIOO site in 2021: The number of chemical parameters was hugely reduced to chloride and arsenic and microbial monitoring was suspended. Moreover, the results have been used to provide better knowledge and insight at the level of the regional and national authorities that has now already been used to facilitate permitting procedures for new HT-ATES systems on the basis of a smaller and more cost-efficient monitoring programme.

2.2.3.3 Lessons learned from problems within the implementation phase

The reliability of the design is as good as the reliability of the input data. At NIOO the most important deviations were a lower hydraulic conductivity of the storage aquifer, a different depth of the fresh water – saline water transition and differences in the surface installations affecting the amount of heat available for storage. These differences led to serious deviations from the design and a strong impact on the business case of the HT-ATES system. Despite the negative impact on the business case, NIOO has kept the HT-ATES system in operation and now has a valuable data set that contributes to the knowledge around HT-ATES systems and their impact.

In order to decrease uncertainties on the subsurface conditions, 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 recovery efficiency at NIOO was (and still is) quite low. This is explained by much smaller amounts of stored heat compared to the design and a relatively high cut-off temperature. Increasing the difference between the storage temperature and the cut-off temperature by lowering the latter, helps to improve the recovery efficiency. Reducing the temperature of the cooled water that is returned through the “cold” well can also boost heat recovery significantly. Low recovery efficiencies in relation to small storage volumes are a common problem and have resulted in the recommendation for HT-ATES projects to store large volumes of heated water [Bakema & Drijver 2018].

2.2.4 Geneva Demo Site

2.2.4.1 Short demo site description

The Geneva case study is based on the results of two exploration wells (GEo-01 and GEo-02) drilled by the Services Industriels de Geneve (local energy provider) in the framework of the GEothermies program (https://www.geothermies.ch). The geothermal target of the two wells is the Upper Mesozoic carbonates which petrophysical and hydraulic properties are predominantly controlled by fractures conditions along fault corridors, and by karstification at the transition between the low permeability Cenozoic sediments and the Lower Cretaceous carbonates. The heterogenous distribution of both fault corridors and karst structures has been a clear challenge to properly identify and characterize suitable targets for thermal energy storage in the Mesozoic units. Noticing that the hydraulic properties of potential reservoir play a major role in defining the technical and economic viability of HT-ATES in such complex carbonate reservoirs.

2.2.4.2 Pre-investigation and feasibility studies

To complement the deep seated boreholes in the Geneva basin and to be able to perform heat storage experiments, a field lab was developed by the University of Neuchâtel at Concise (VD - Switzerland) in analog limestone formation. Three 50 m deep boreholes target Lower Cretaceous and Upper Jurassic fractured and karstified limestones, which are analogues to the target units in Geneva. The objectives of the tests performed at the Concise test site were to characterize the thermo-hydraulic response of the fracture and karstified limestone rock mass to heat storage. A series of hydraulic and thermal tests have been carried out in the boreholes: (i) standard open-hole hydraulic tests and tests between packers (shallower part artesian can hide more productive layer above) and (ii) tracer and heat transfer tests by using "push-pull" tests (using one well) with different duration of injection period and complemented by image and flow logs. Tracer dilution tests were performed for assessing natural flow conditions and were monitored in-situ with pressure and temperature gauge as well as with fiber optic based distributed temperature sensing.
The results show that the hydraulic of the system is highly heterogeneous and that the flow is dominated by a few structures. Intersection between bedding planes and steeply dipping fractures seems to control the position of the dominant flow paths. Fairly direct pressure connections are linking the wells but the flow paths are complex as revealed by the difficulty for transmitting heat and tracer between adjacent wells. This is also revealed by the presence of distinct piezometric levels over few meters along the wells. In these conditions, heat storage and recovery are largely dominated by the dominant flow path geometry. In the case of the Concise test site channelized planar flow path are driving the heat transport and exchange behavior. This suggests that hydraulic testing only is not sufficient for characterizing a target reservoir for heat storage and thus test with tracers (heat of otherwise) are required to assess transport and exchange characteristic. This suggests also that simulators, which are able to include local geometrical heterogeneities are required for assessing the design and sustainability of subsurface heat storage in fractured and karstified limestone aquifers.

Note that these wells are much shallower than the “main” demo sites wells GEO-1 and GEO-2 described in the section below. The volume investigated remains very low and results are difficult to replicate to real ATES.

Different modelling studies were also carried out like thermo-hydraulic (TH), hydro-mechanical (HM) and thermo-hydro-chemical (THC) modelling.

TH models have been performed to optimise the design of a preliminary HT-ATES system based on different configurations of subsurface conditions. The goal was to understand the performance of the considered aquifers for heat storage and to assess the extent of the thermal plume after 15 years of operation. The modelling considers a simple layer-cake model with different reservoir thicknesses, permeabilities, flowrates and impervious top and bottom layers of 50 m (see D6.6 §2.3.1.2 for the detail description). The results of these preliminary modelling show that the extent of the thermal plume is limited (<3°C at 100 m distance from the well).

HM model was also performed (poroelastic model) during pumping at GEO-01 and for predictive modelling (TH models) in order to assess the ground deformation. Simulations were compared to GPS monitoring near the well and at 1300 m distance from the well. GPS monitoring show no significant deformation during pumping test. Predictive simulations show larger deformation for a small Young's modulus. It appears that shallow depth, small thickness and high flowrates will induce higher deformation.

THC simulations were conducted with Phreeqc using geochemical data analysis from fluid site at GEO-1 and GEO-2. Simulations show that the calcite scaling potential depends on the initial reservoir temperature and in case of GEO-1 is higher compared to GEO-2 because of the higher difference of temperature when storing at 90°C.

Production of pyrite due to high water sulphide content in GEO-1 is also likely to occur with a risk of corrosion of the well equipment, if the well is used later for exploitation. This was confirmed during GEO-1 production where the water was dark coloured after a shutdown of 3 months and that black colour is inherited from the precipitation of pyrite likely triggered by the corrosion of the steel casing.
Mineral reactions that may occur in the reservoir where investigated using also batch experiments with fragments of dolomite from the "Calcaire de Tabalcon" and an artificial water composition from GEO-2 well. The temperature experimented were 20 °C and 90 °C. The results show dolomite dissolution with an increase of magnesium (more important at 20 °C than 90 °C) coming along with a release of calcium but which reprecipitates in calcite during the experiment. The replacement of dolomite by calcite slightly increases the porosity of the formation as calcite has a lower molar volume. However, the volumes of minerals dissolving/precipitating are so low that the effect of these mineral reactions on the porosity and permeability of the overall reservoir are assumed negligible. Nevertheless, THC simulations should be performed if a site and reservoir formation have been selected in order to identify, if mineral reactions in certain areas (e.g. near the wellbore) could adversely affect the properties of the reservoir over years of HT-ATES operation.
Mineralogical analyses were also conducted on plugs from shallow wells (analogs) and from cuttings from GEO-1 and GEO-2 and show a transition from a carbonate facies to a saline facies with depth.

2.2.4.3 Design and construction

In the Geneva demo site two deep explorations wells (GEO-1 and GEO-2) have been drilled at 744 MD for GEO-1 and 1456 MD for GEO-2 into the fractured Mesozoic limestones. The characteristics of the wells are:
- GEO-1: artesian flow of 55 l/s, temperature of 34°C, 8 bar wellhead pressure;
- GEO-2: no productive well (0,6 l/s), temperature of 55°C and 12 bar wellhead pressure.

The reservoir produces from a set of fractures mostly from the Lower Cretaceous (~70%) and partially from the Upper Jurassic (~30%). The permeability has been estimated to be up to 300 mD (GEO-1), most probably too high for an effective thermal storage implementation. The GEO-02 well characterized by an extremely low natural artesian flow suggests low reservoir transmissivity for thermal storage implementation.
GEO-1 and GEO-2 wells will not be used at the end of the project for an ATES (possibly in a later stage for GEO-1 or will be kept as a monitoring well). Future operations are planned for further subsurface characterization like the acquisition of a 3D seismic survey (2021) and the drilling of two additional exploration wells between 1500 and 2000 m (GEO-03 and GEO-04, in 2022-2023) for testing different geological contexts and characterizing the geothermal potential at the basin's scale.

For the design of a future HT-ATES, numerical thermo-hydraulic simulations based on different scenarios and their integration in the energy system were made (see D3.3, and Mindel and Driesner, 2021). Based on existing DH temperature regimes in Bern, the ATES system is charged during summertime with 90°C (DH supply temperature) and that direct discharge is possible down to 50°C (discharge cut-off, corresponding to the DH return temperature). For extracting more energy from the storage and reduction of the re-injection temperature down to 20°C, the use of heat pumps were also analysed. Based on the detailed geological study carried out by the University of Geneva (UniGe) and Services Industriels de Genève (SIG), a cube-shaped 1km^3 block was constructed by UniGe using the analysis of a collection of subsurface datasets. The modelling scenarios analysed concern variations in aquifer permeability, thickness, inclination, presence of fractured upstream and downstream the hot well, wells' configuration (single, doublet, 5 spot) and the presence of groundwater flow. Those preliminary simulations confirm observations already pinpointed in §2.1.1.4 like the effect of buoyancy driven force on recovery efficiency and the necessity of auxiliary cold wells (at least one well) to reduce well injection pressure and also mitigate the drift of the" hot bubble" due to the groundwater flow.

2.2.4.4 Challenges and Highlights during Implementation

The Geneva project allowed to implement for the first time a HT-ATES performance prediction modelling framework based on fully coupled techno-economic assessment combining subsurface, energy system, operational CO_2 emissions, and economic modelling based on a scaled DHN demand. The results show that, subject to subsurface constraints, the nominal capacity ranges from 0.4 MW to 81 MW, with aquifer permeability and thickness being the major control variables. A minimum transmissivity of 2.5×10^{-12} m^3 is required to keep the Levelised Cost Of Heat (LCOH) below 200 CHF/MWh and a capacity of 25 MW or higher is needed for the HT-ATES system to become competitive with other large-scale DHN heat sources. The capacity increase from the addition of Heat Pumps (HP) incurs non-recoverable costs and in turn increases the LCOH. Nonetheless, the addition of HP increases the nominal capacity of the system and results in higher cumulative avoided CO_2 emissions.

To complement deep seated borehole in the Geneva basin and to be able to perform heat storage experiments, a field lab was developed by the University of Neuchâtel at Concise (VD - Switzerland) in analog limestone formation (see § 2.2.4.2).

Appropriate geological conditions to build an ATES system in Geneva were not encountered (either too high permeability in Geo-01 or too low at GEo-02). Eventually, the field laboratory resulted in a partial recovery of the hot water and tracer injected demonstrating that the Mesozoic carbonates could be suited for ATES system.

2.2.4.5 Lessons learned from problems within the implementation phase

The results of the project clearly reveal the main subsurface challenges related to such fractured reservoirs, which are the hydraulic heterogeneity and reservoir compartmentalization, requiring more detailed exploration surveys (i.e. 3D seismic) to properly identify those targets potentially suitable for storage. Additionally, potential storage targets in Geneva should not be limited to the Mesozoic carbonates but could be in the Cenozoic sediments as well.

For the moment the Geneva project did not enter into the implementation phase but the field laboratory from University of Neuchatel could be useful to further test different storage set-ups in terms of charging/discharging temperature, duration, pressure and get a better understanding about the recovery efficiency and petrophysical-hydrochemical effects that could activate consequentially.

HT-ATES are a concrete opportunity to decarbonize the Geneva energy system but, in addition to subsurface challenge, the energy system needs to be suitable for an optimal integration in terms of operating temperatures and flexibility of the energy supply.

2.2.4.6 Recommendation for further test operation

- Further explore the Mesozoic fault structures and the Karstified Upper Cretaceous with high resolution geophysical methods and field lab tests,
- Consider the Cenozoic sedimentary cover as a potential target for both ATES and BTES solutions,
- In situ tests of different smart control set-ups to define the charge/discharge/rest periods and the impact on energy efficiency,
- Site analysis during drilling of the well to define well deviation in order to reach favourable geological conditions,
- Compare geochemical site samples with previous laboratory analysis to establish at first order mineral precipitation and their impacts on borehole and surface installations,
- Test different well configurations and see the impact on energy efficiency and analyse the impacts on the financial sustainability of the different solutions.

2.2.5 Bern Demo Site

2.2.5.1 Short Case Study Description

The pilot project in Bern aims to store waste heat from the nearby power generation site Bern-Forsthaus. The power generation site is operated by the local utility company Energie Wasser Bern (EWB) and contains a combined-cycle plant, waste-to-energy plant and wood-fired power station for electricity and heat production. The heat user is an existing district network, which presents an increasing heat demand and a planned expansion in the city of Bern. The project consists in storing waste heat during the low-demand season, and in delivering it during heating seasons, thus replacing the standard gas heat production.

2.2.5.2 Pre-investigation and feasibility studies

Different pre-investigation studies were carried out:

- Survey on ground level to anticipate/measure any ground movement due to production and reinjection (however there is an equilibrium of produced and injected volumes).
- Modelling of the thermal development in an anticipated sand layer over several storage cycles.
- Evaluation of a recovered core from an offset well to determine permeability, porosity, mineralogy and the sanding behaviour.
- Modelling of the thermal influence on the ground water layer and the heat transfer.
- TH and THC modelling to assess the efficiency of the storage and possible geochemical reactions (precipitations and solution) in the reservoir, in the wells or in the heat exchangers at the surface.
- With the input of the geological and hydraulic data a detailed well engineering was conducted, including Casing Design, Wellpath Design with Anti Collision Criteria, Mud Design with laboratory testing, Cement Design with laboratory testing, BHA design, tool and packer design for the hydraulic testing with a trial run on site.

Thorough THC modelling and experimental laboratory tests using drill core and formation waters from shallow wells 2 km from the site were carried out in order to assess the chemical processes and impacts of heat storage and unloading cycles at the reservoir scale. The results of the experimental tests and modelling study showed no critical issues that would imply a different storage strategy from a geo-chemical point of view.
Nevertheless, the following risks and possible complications were identified, they are viewed as non-critical but they require consideration:

- Preferential flow paths may develop between the main and supporting wells due to heterogeneous permeability of the sandstones. This could reduce the volume of rock swept by the injected hot water, lowering the efficiency of heat storage below previous expectations.
- Calcite is predicted to precipitate in some regions of the reservoir and to dissolve in others during the water injection/extraction cycles. Regions clogged by calcite may become barriers to the injection/extraction flow regimes. Regions of moderate calcite depletion may focus flow and thereby leave other regions of the reservoir unswept by the injected hot water. Thus, both calcite clogging and dissolution may contribute to lowering the heat-storage efficiency of the reservoir.
- Extreme dissolution of calcite cement may induce local mechanical disintegration and compaction of the sandstones, and mobilise fines that clog pore throats, reducing permeability and hence further lowering the efficiency of the water injection/extraction cycles.
- Microbes may form biofilms and clog the casings of the supporting wells, where temperatures are < 50 °C. Microbial activity is expected to diminish as the reservoir heats up to 90 °C.
- The evolving thermal plume and the water–rock reaction zone around the main well are predicted to remain within a 50 m radius from the well. However, the influence of the entire heat storage reservoir, if defined by the distance to which non-reactive solutes injected or released from the rock can travel in the USM (Lower Freshwater Molasse) groundwater system, is much larger. There is therefore a possibility that unwanted chemical compounds are transported over large distances.
- Significant carbonate scaling is expected in the surface installations during the heat-loading cycle. This could impede flow and exchange of heat in the surface installations.

A long term injection/production test is planned at the pilot site, including ground level measurements (which is a sensible subject because of surrounding infrastructures). This ground level surveillance has been proposed by GeoEnergie at the beginning of the project, the authority and site owner understood the necessity of this and the base measurement has been conducted.

The Bern main railway station is being extended and the geological formations encountered in wells drilled in this project are similar to the formations targeted by the UTES, though at a much shallower depth. Samples and cores of molasses have therefore been taken. Mineralogy and grain size characterization has been carried out and in-lab tests to verify borehole stability (shallow unconsolidated formations), sanding tendency (to identify whether sand movement should be expected and for the design of sand mitigation if needed) and intrinsic properties (permeability, porosity, etc.).

All wells will be cored from 200 to 550 m. Comprehensive test is planned using those samples. The risk that sand intake badly damages equipment is not foreseen as an issue in the pilot site – in case the data concluded from the cores shows very unconsolidated sands, sand mitigation measures will be taken. These can vary from sized perforation entry hole diameters to prepacked screens or even gravel packs. Though the comprehensive strength of the sand is not high, it should be enough to ensure well stability while drilling the wells.

The microbiotic activity in cold well might however be an issue and needs to be simulated based on the encountered reservoir water and the temperature profiles in these wells. (cf. GTN operation Geothermie Neu Branderburg for instance where filters have been placed to prevent the development of microbiotic films) (https://www.gtn-online.de/en/projects/aquifer-heat-storage-for-a-gas-and-steam-turbine-power-plant-in-neubrandenburg).

2.2.5.3 Design and construction

The ideal design of Bern ATES would be one central hot well for heat injection and recovery and up to 5 support cold wells to balance the water volumes (see Figure 14). All the wells would be reversible (Injector/Producer). The maximum number of six wells in total will be drilled in two campaigns. Campaign A and campaign B are planned to have three wells each. The two campaigns are interrupted for a long term production and injection test, to verify the flow behaviour of the Sand layers.

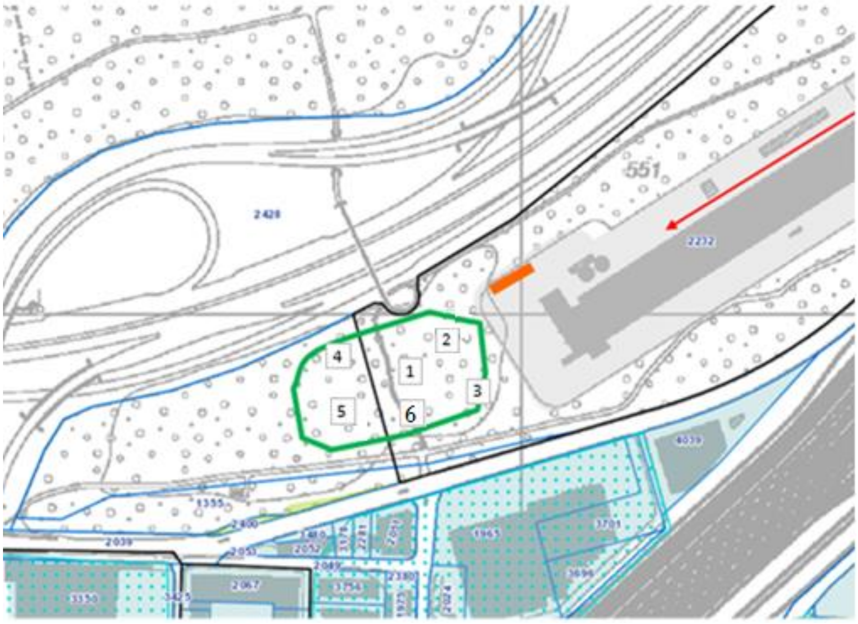


Figure 14: Area for geothermal storage with preliminary targets.

All wells will be drilled from one pad, the wellheads and Christmas Trees will be housed completely in one cellar (see Figure 15). The cellar will be covered with concrete slabs for protection.

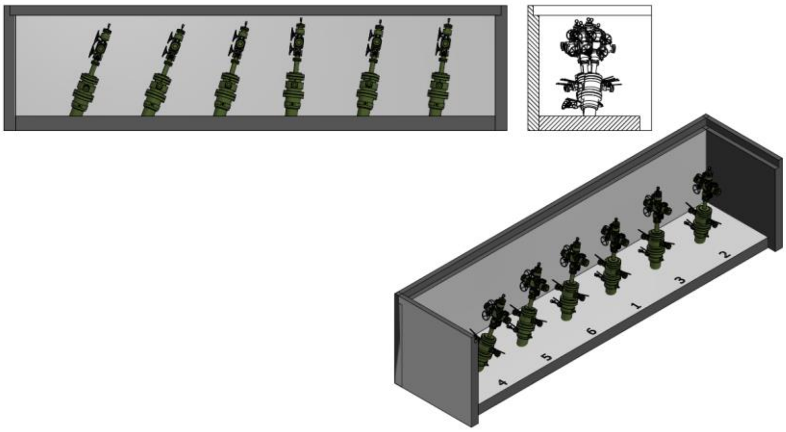
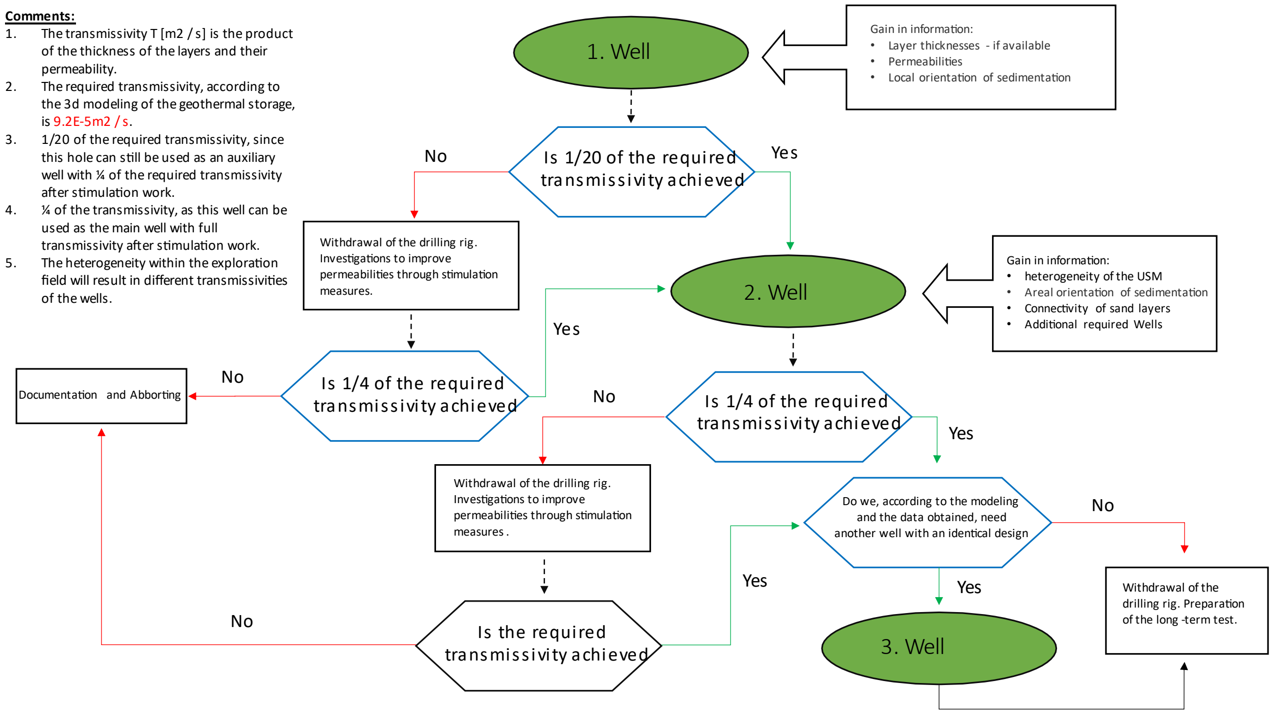


Figure 15: Cellar with inclined wellheads due to inclination of wells from surface.

Due to the high degree of uncertainty in the aquifer hydraulic properties, a decision tree for a step-by-step drilling was conceived, allowing to go to the next step only if the transmissivity was satisfying, and providing fallback solutions (see Figure 16).


Comments:

1. The transmissivity T [m2 / s] is the product of the thickness of the layers and their permeability.
2. The required transmissivity, according to the 3d modeling of the geothermal storage, is 9.2E-5m2 / s.
3. 1/20 of the required transmissivity, since this hole can still be used as an auxiliary well with ¼ of the required transmissivity after stimulation work.
4. ¼ of the transmissivity, as this well can be used as the main well with full transmissivity after stimulation work.
5. The heterogeneity within the exploration field will result in different transmissivities of the wells.

Figure 16: Decision Tree.

The reservoir transmissivity will be determined through hydraulic testing of each sand layer encountered. This will be done immediately after penetrating the layer with the coring BHA (bottom hole assembly). The coring will be interrupted, the core retrieved by wire and the hydraulic testing assembly run in hole on wire (see Figure 17 upper left).

The coring string holds a landing ring for the hydraulic testing assembly sealing it against the string.

Then the packer, which is positioned below the core head, is inflated and the mud level in the coring string is lowered with swap cups (see Figure 17 upper right).

Upon opening the hydraulic testing assembly, the production test is conducted and recorded with gauges in the hydraulic testing assembly and with gauges lowered on cable into the string (see Figure 17 lower left). After conducting the production test, the string is filled with mud again, the packer is deflated and the hydraulic testing assembly is recovered on wire (see Figure 17 lower right).

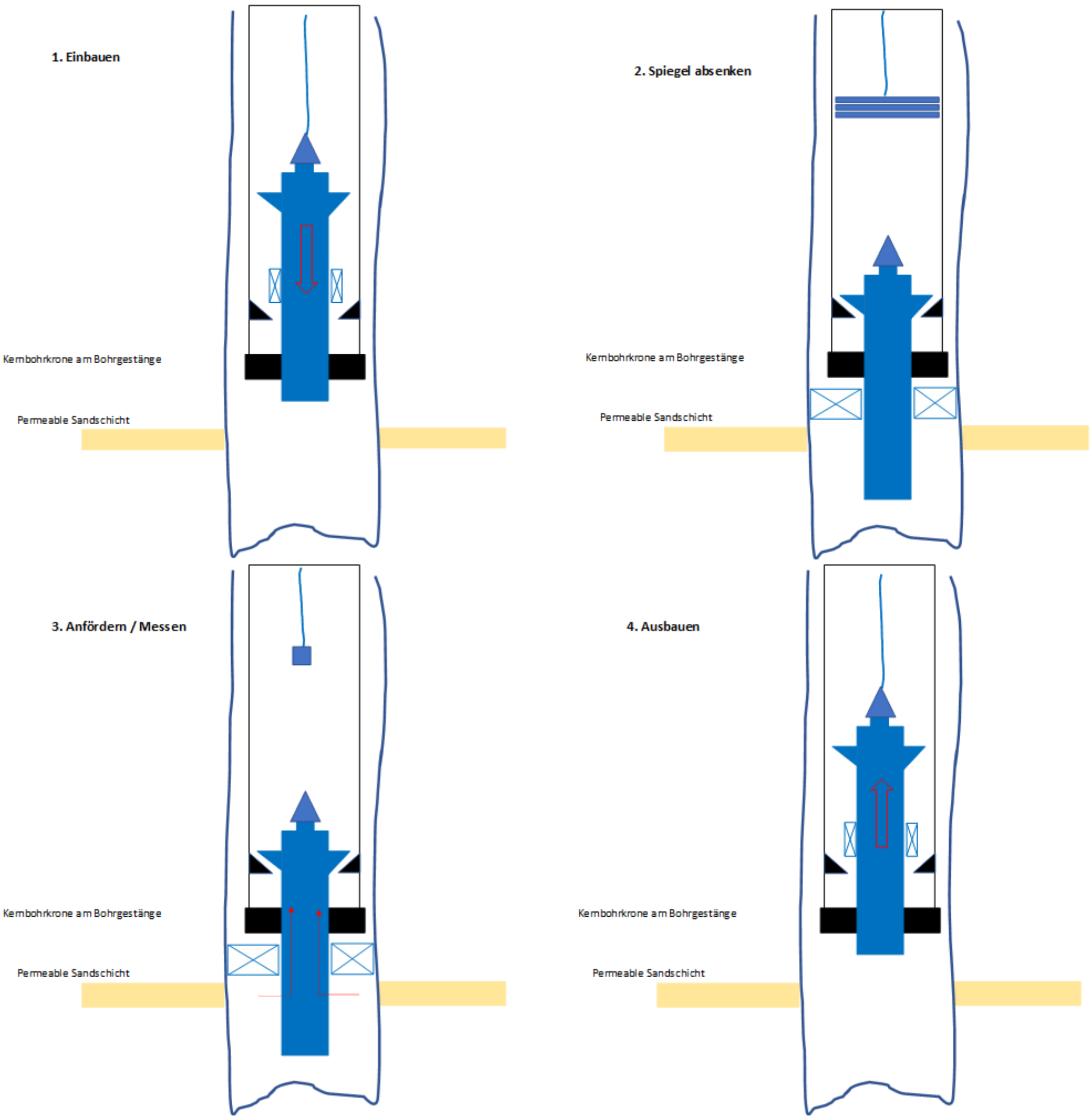


Figure 17: Operating the hydraulic testing tool.

The wells target the Upper section of the Lower Freshwater Molasse formation (USM) which is composed of sandstones and clay levels (see Figure 18). The wells are inclined between 7 and 21 degrees from surface to final depth with the first sand layer possibly being encountered at +/-200m TVD at the top of the lower sweat water molasse. The total depth of the wells is designed to be 500m TVD.

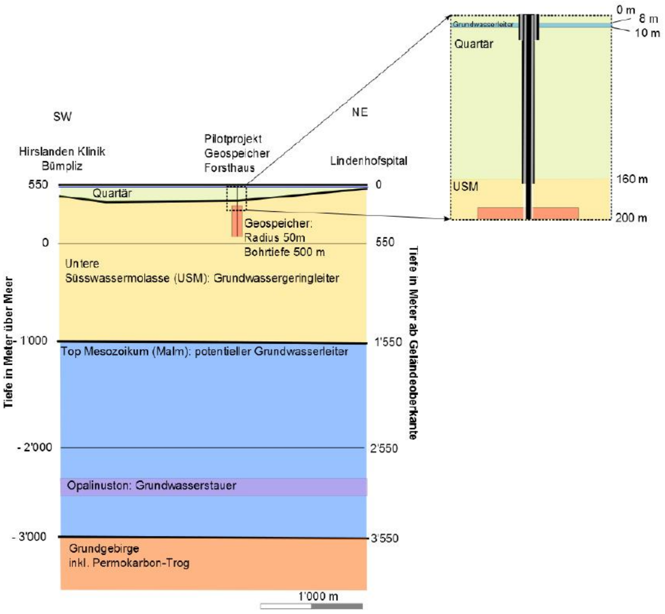


Figure 18: Expected geology of the Bern demonstration site.

The wells will be equipped with fibre optic cables attached to the outside of the steel casing for continuous acoustic, strain and temperature measurements.

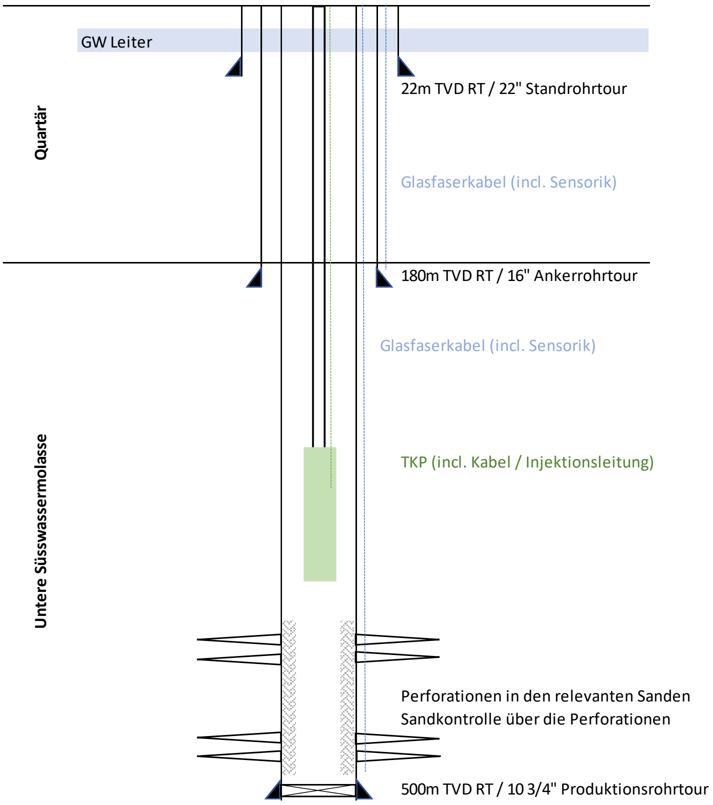


Figure 19: Final well design.

Production of the water will be through a 5 inch tubing and an electrical submersible pump (ESP), the injection is planned through the same tubing and a surface pump (see Figure 19).

The heat storage in the lower sweet water molasse will not have any effect on the surface temperature. Simulations showed, that after 20 loading cycles (20 years) the temperature will have a vertical effect of +/-80m and a lateral effect of +/-150m. Having the wells positioned on an equidistance of 50-60m the temperature effect will be less than 100m beyond the support cold well (see Figure 20).

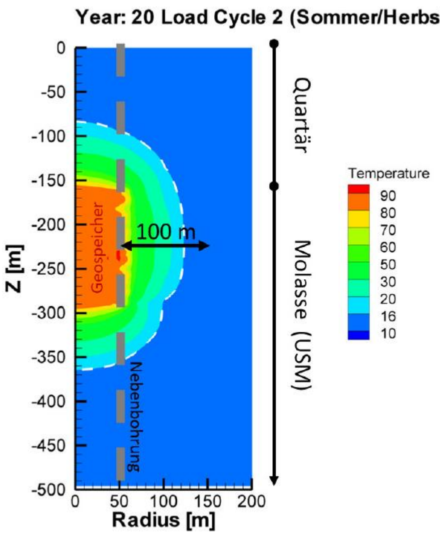


Abbildung 21: Vertikalschnitt der Ausdehnung der Wärmefront im Geospeicher mit 12 Sandsteinschichten in der Unteren Süsswassermolasse im letzten Ladezyklus des 20. Betriebsjahres. Die ΔT = 3°C Isolinie ist weiss gestrichelt dargestellt.

Figure 20: Modelled temperature distribution of storage.

Concerning the temperature impact on the shallow water horizon due to the injection of hot water through the wellbore, the simulation showed a minor temperature effect in the near vicinity of the wellbore (see Figure 21). The change of the temperature of 3K was 6m in the direction of the underground water flow and 2m vertical to it. The simulation did not take into account the isolating effect of the three cement layers surrounding the three casing strings and therefore can be seen as a conservative approach.

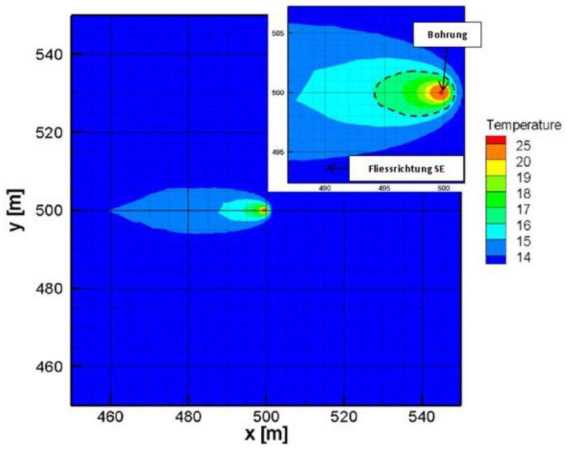


Abbildung 20: Aufsicht auf die Ausdehnung der Wärmefahne im quartären Grundwasserleiter unter der Annahme eines permanenten 20-jährigen Betriebes des Geospeichers mit Förderung von Wasser bei 120°C aus einer nicht-isolierten Bohrung. Die Grenze, bei der die Temperaturveränderung 3°C beträgt (ΔT = 3°C Isolinie) ist schwarz gestichelt dargestellt.

Figure 21: Modelled temperature distribution in shallow aquifer.

The installed fibre optic cables will verify the simulated temperature profiles. In case it is required, the production tubing can be an insulated tubing to further reduce the impact of heat transfer to the shallow aquifer.

2.2.5.4 Status of operation on the demo site in Bern

Concerning the design and planning phase the overarching well delivery process has been followed rigorously (see Figure 22 and Figure 24 to Figure 26).

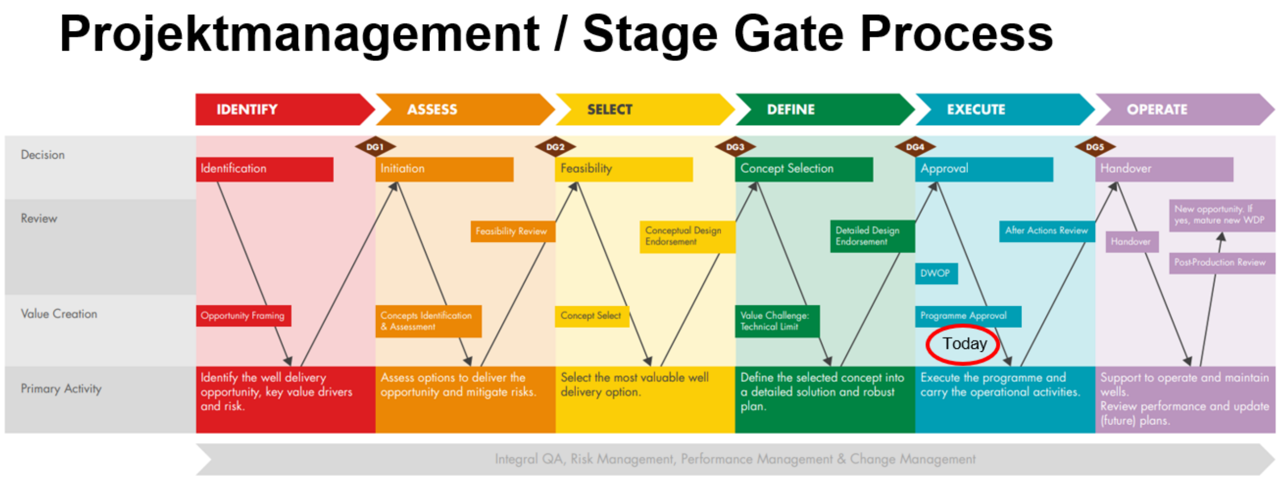


Figure 22: Bern demo site: Stage Gate Process.

The Assess and Select Phases delivered a conceptual design for the wells, which was used for the tendering process for the technical work. Stump BTE was identified as the main contractor, supplying the rig, the site construction and the majority of the drilling related services – through subcontracts.

The site construction was started in Q3 2020 and the drilling pad and the cellar were accepted in Q4 2020 (see Figure 23).

In April 2021 the project management was informed of a delay in the delivery of the rig. This was due to a delay in the manufacturing of the new drilling unit, which was mainly due to Covid related shortage of required components. This delayed the expected spud of the first well from the 15th of April 2020.

Nevertheless, the planning and the preparation on the well engineering side continued, closing out the Design Phase, presenting the detailed well design. Streamlining the process with the new expected spud date on the 31st on May 2021, the milestone of drilling the well on paper (DWOP) was held in May 2021.

Prior accepting the drilling unit, Management Process required a 3rd party inspection of the unit. This was conducted by the company RED on the first week of June. The Audit showed severe deficits in the fields of environmental safety, work safety and a lack of explosion proof equipment.

These deficits resulted in a delay of the spud until the corrections were made. Currently Stump BTE is working on closing out the findings of this first audit.

The next audit for accepting the rig is scheduled on the 15th on November 2021, with the spud expected shortly after on the 1st of December 2021.

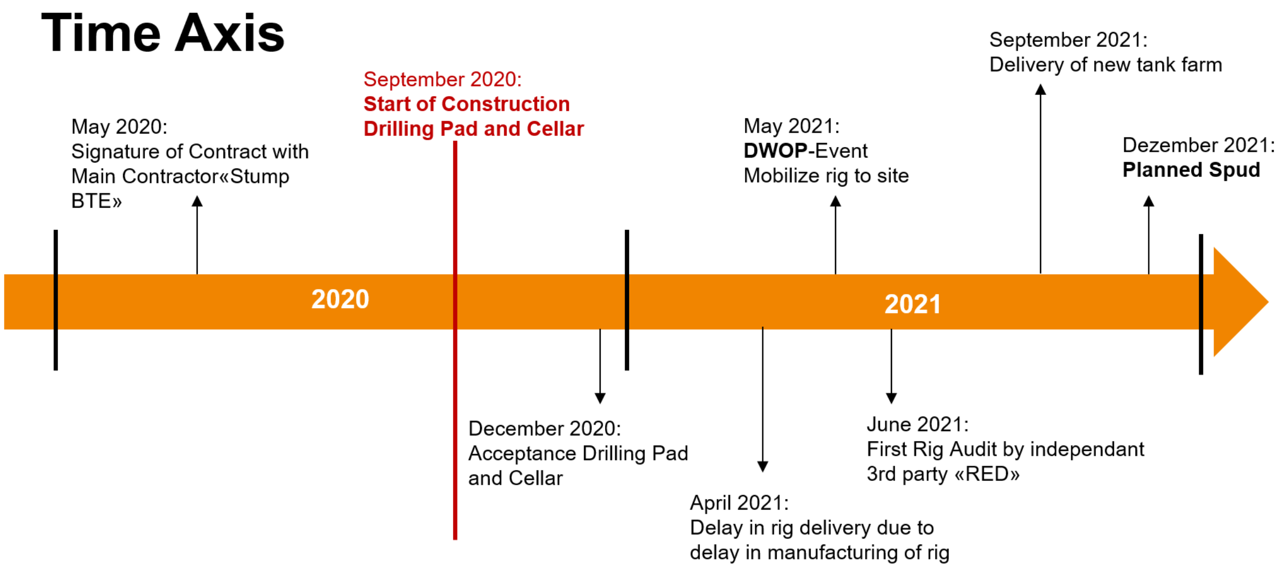


Figure 23: Time Axis of Activity.

Figure 24: Site prior start of Construction and after the construction of the drilling pad and the cellar.

Figure 25: Delivery of rig on site.

Figure 26: Status today with the drilling rig and the supporting infrastructure being placed, in final preparations for acceptance of the unit.

2.2.5.5 System operation, monitoring and maintenance

The expected flowrate from the central main hot well is 90 m³/h with an injection temperature during summer of 90°C. In winter period the multiple lateral wells (2 to 3) will see lower flow-rates for reinjection and a temperature of 50°C. The pressure and flowrate will be constantly monitored.

2.3 MTES Demo Site in Bochum

2.3.1 Short site description

The aim of the German HEATSTORE sub-project has been the development of a **mine thermal energy storage** (**MTES**) pilot plant for the energetic reuse of an abandoned small colliery below the premises of the Fraunhofer IEG in Bochum. During the German HEATSTORE project, in summer 2020 three boreholes have been drilled into existing open mine voids from the IEG drilling site. First hydraulic tests of the constructed wells MP1 and MO1 showed that mine water can be extracted from the 4th drift of the former mine and reinjected into the 1st drift (well MI1) without a measurable hydraulic connection between the drifts 1 and 4 (Figure 27).

In Winter 2020/2021, a first MTES test operation has been carried out. The underground temperature has been recorded before, throughout and after a test operation by **Distributed Temperature Sensing (DTS)** as well as groundwater temperature and pressure logger, which had been installed into the MTES boreholes. Parallel, groundwater temperature, pressure and chemical data from adjacent observation wells (O2, O3 and O4) have been also collected (Figure 27). In spring 2021, a local district heat network (DHN) has been built up at the case study site (Figure 27). In summer 2021, a **concentrated solar power plant (CSP)** as the future renewable heat source has been successfully erected at the demo site and connected to the MTES via a common heat exchanger (Figure 27).

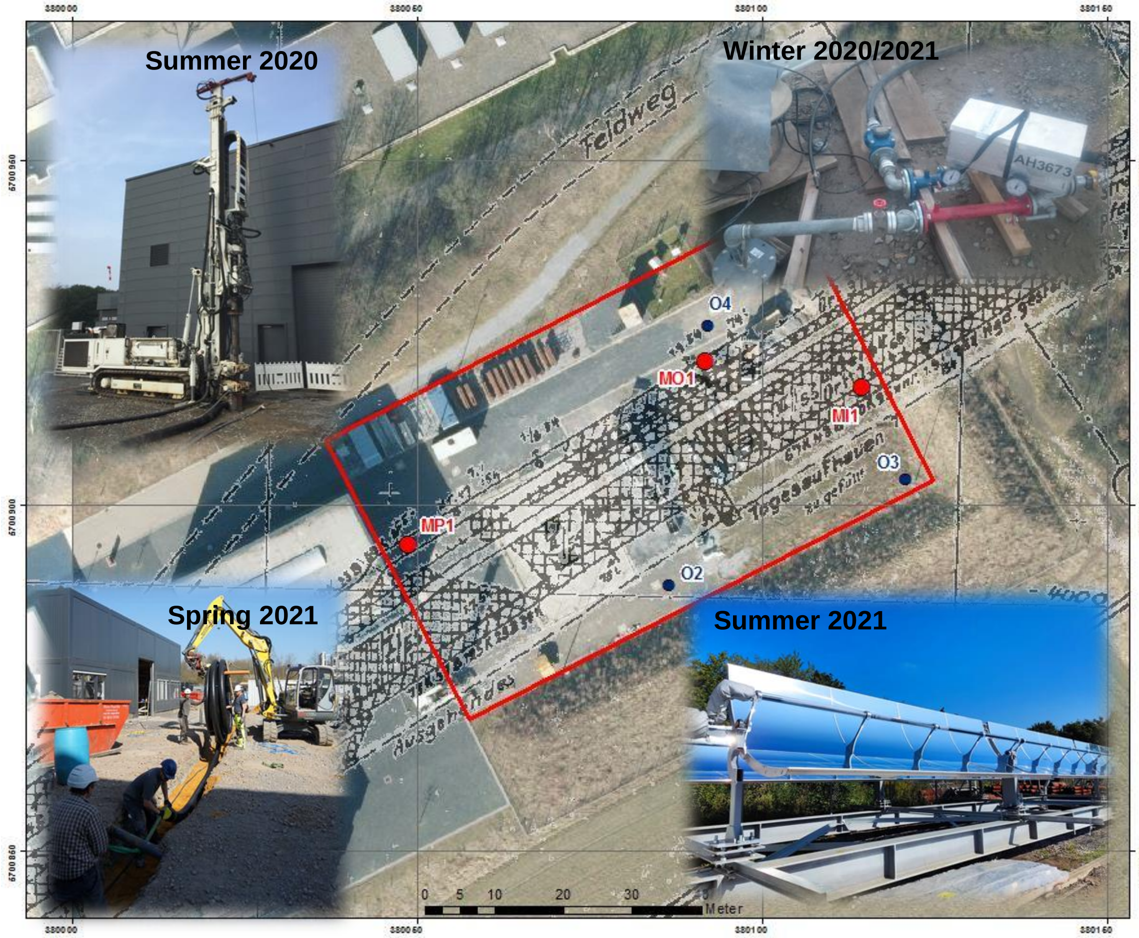


Figure 27: MTES demo site development in Bochum (Germany).

2.3.2 Pre-investigation and feasibility studies

The pre-investigation of the site includes different hydraulic and thermo-hydraulic modelling studies at different scales (Figure 28):

- At the regional scale (>10000 km²), a large 3D model was built including the mine layout and the aquifer systems to simulate the dewatering and flooding processes during mine exploitation and post-closure. This regional model provides the boundary conditions for the local model.
- At the site scale (~ 10 km²), the model includes the local aquifer system and the digitalized mine workings represented as 1D fracture elements. It gives the detailed geologic layer distribution with the local syncline structure and coal seams at the site. This model enables planning, dimensioning and optimization of the thermal energy storage pilot plant in terms of heating and cooling cycles.
- At a smaller scale (<1 km²), different parts of the pilot plant are modelled with a high detail. It is used to estimate local effects like the influence of fractures (fractured rock aquifer with low permeability), different (residual) mine void volumes and operation modes.

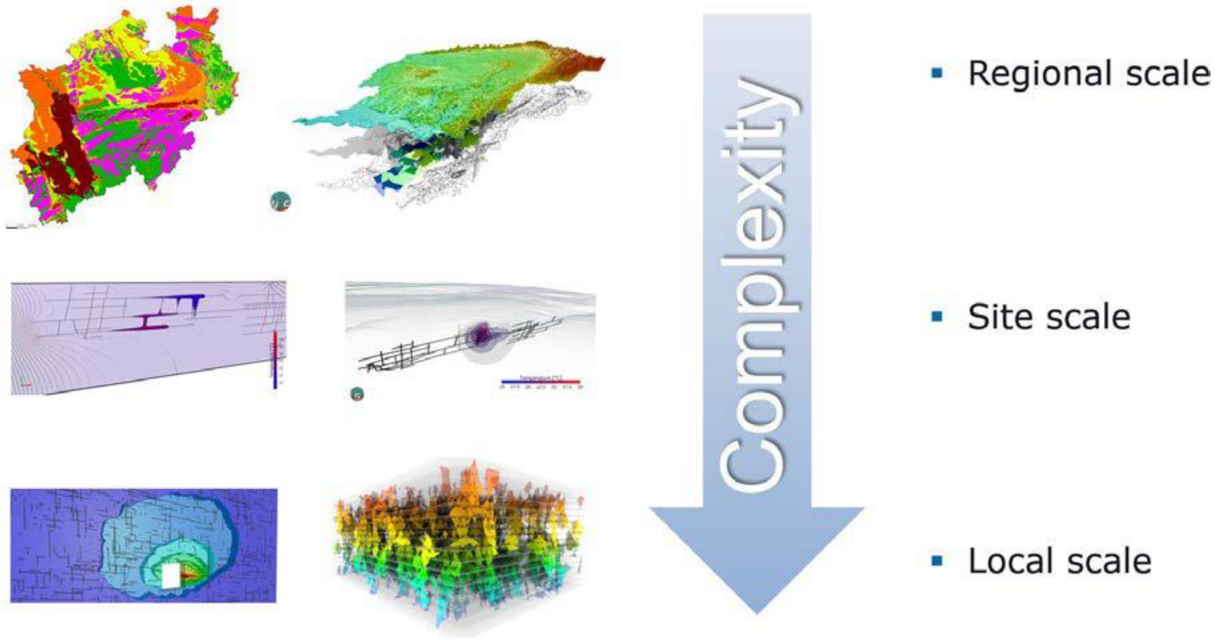


Figure 28: MTES stepwise modelling approach.

For the mine layout data, the first step was to ask the land owner or the mining operator to obtain the relevant data from the mining authority. Two versions of the mine layout were available, one from the mine owner and one from the authority but with minor discrepancies. Galleries layout seems correct, which was confirmed by the positive drilling results.

2.3.3 Design and Construction

After clarification of the permit conditions, the drilling work for the MP1, MO1 and MI1 well was carried out in the period from 15.06.2020 to 11.09.2020. All three boreholes were successfully drilled into the old mine workings of the small colliery below the IEG drilling site in Bochum. This was verified by geophysical borehole and camera surveys.

The two boreholes (MP1 and MO1) were drilled into the 4th at a depth of approx. 64 m bgl and showed the expected production rates during an initial pumping test. In contrast, the MI1 well drilled into the 1st drift (approx. 20 m gbl) failed to achieve high production rates during the initial pumping test. Therefore, MI1 well can most likely only be used as an injection borehole for future operations. The boreholes were all equipped with a PVC casing with an inner diameter of 175 mm. In order to establish a hydraulic connection with the mine water, the PVC casings are equipped with a 3 mm filter mesh within the open part of the respective drift. A packer has been installed above the filter screen, in order to perform a full cementation of the annulus up to the surface. Figure 29 shows the well-design of the production well MP1.

All wells were equipped with PVC casing, due to the cost advantage over standard steel casing. Additionally, there is no problem with corrosion and smaller risk of clogging, but on the downside they are only able to endure temperatures up to 60 °C (PVC casings that withstand higher temperatures are available, but result in higher investment costs and longer delivery time). Glass fibre casings are much more expensive, but have a life expectancy around 50 years, also no corrosion issues and smaller risk of clogging. The wells were drilled vertical with stabilizers and heavy weight drill pipes, in order to minimize the vertical deviation from the point of origin (< 25 cm). After the target was proven with geophysical measurements and camera runs, the PVC casing were installed and the annulus cemented to the top of the surface (Figure 29). The provisional protective steel-casing has been removed before cementation. Table 3 summarizes the well design and construction properties.

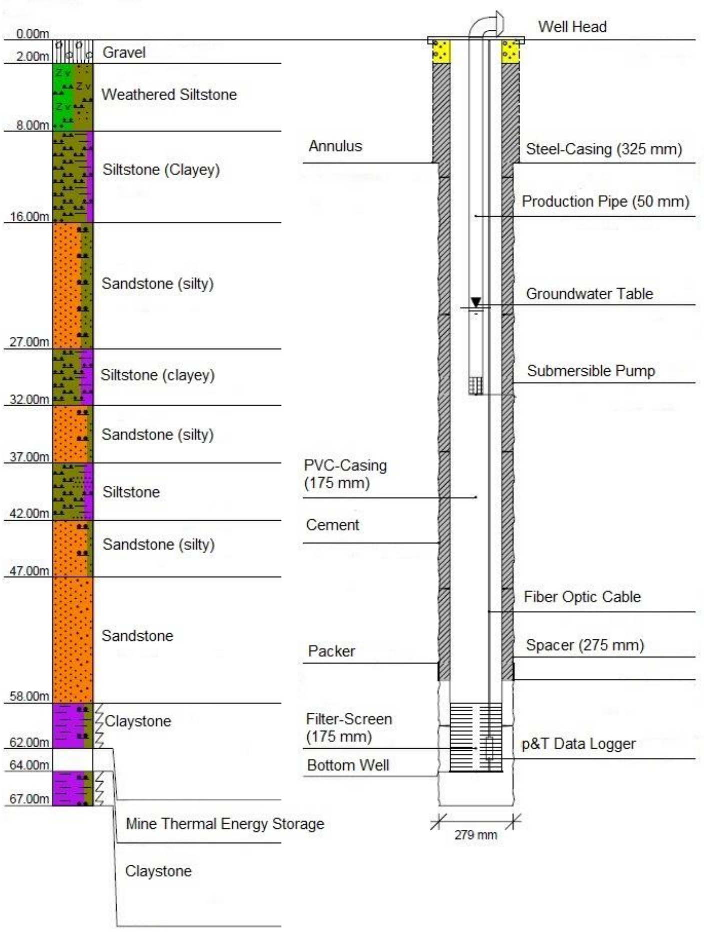


Figure 29: Design and construction of the MTES well MP1 at Fraunhofer IEG.

Table 3: Design and construction of MTES wells at Fraunhofer IEG.

Well	Depth [m]:	PVC-Casing [m bgl]:	Filter-Screen [m bgl]	Packer [m bgl]:	Fiber Optic Cable [m bgl]:	Cement Injection Pipes [m bgl]:
MP1	64,0	58,0	58,0-64,0	54,5-56,0	63,95	30,0; 54,5; 56,0
MO1	62,0	49,0	49,0-62,0	47,5-49,0	61,95	30,0; 47,5; 49,0
MI1	29,0	23,0	23,0-26,0	14,0-15,5	28,95	14,0; 15,5

2.3.4 Challenges and Highlights during Implementation

Highlights:

As a novelty in Germany, 1,234 m³ of mine water extracted out of the former 4th drift have been heated up from 10.6 °C to 45-50 °C (see Table 4) and reinjected again in an open loop system in a depth of 64 m below the Fraunhofer IEG premises (Figure 27). As an implementation result of a first MTES test loop, a slight recovery efficiency of 3.5 % during a three-month monitoring phase could have been achieved after charging the underground mine storage in December 2020 for several days continuously. In order to quantify the MTES recover efficiency, a 48-hour steady-state discharge test has been carried out in February 2021 by testing the reinjection capacity of well MI1.

Table 4 : MTES steady-state test operation data.

Time Stamp:	Operation:	Extraction Well:	Injection Well:	Mine Water flow rate [m³/s]:	Amount of Mine Water flow [m³]:	Average Mine Water Temperature [°C]:
02.12.20 (14:00) - 04.12.2020 (12:00)	Heat Injection I:	MP1	MO1	5.8	235	45
07.12.20 (11:00) - 14.12.20 (07:30)	Heat Injection II:	MP1	MO1	5.8	1.000	50
02.02.21 (10:00)- 04.02.21 (12:00)	Heat Re-production:	MO1	MI1	1.5	78	12.1

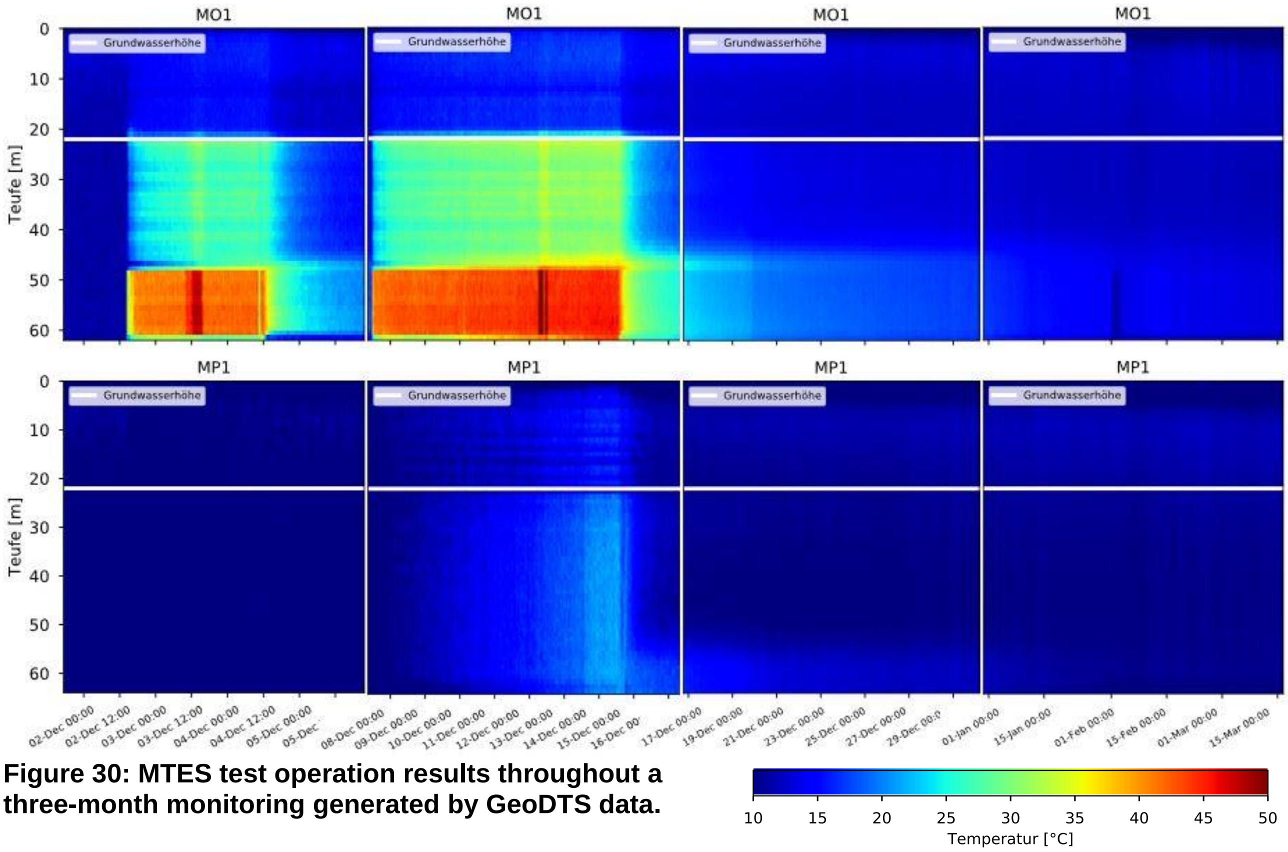


Figure 30: MTES test operation results throughout a three-month monitoring generated by GeoDTS data.

Figure 30 shows the results of a first test operation (see Table 4 as well). The total amount of 50 MW_{th} is indicated by the temperature plume injected into well MO1 in a depth of 48 m below the demo site with maximum temperatures of up to 50 °C. The water table is indicated by a white horizontal line highlighting a sharp drop in vertical temperature distribution inside the injection well MO1 above the groundwater table. MP1 shows a thermal breakthrough of 23 °C at the end of the first injection test.

The characteristics of the MTES have been empirically derived by groundwater temperature logger. A first test loop showed that it needs 20 days to fully charge the demo site MTES with a flow rate of 5.8 m³/h. Also, the storage temperature characteristics have been determined by a hyperbolic curve showing that 1 day after the injection, the storage temperature has dropped to 40 % of the initial thermal charge. Although, the “out of operation” curve starts to flatten quickly, it reveals that is was possible to output at least **3.5 %** of the injected heat amount within the scope of a first test operation within the first month and a half (Figure 31).

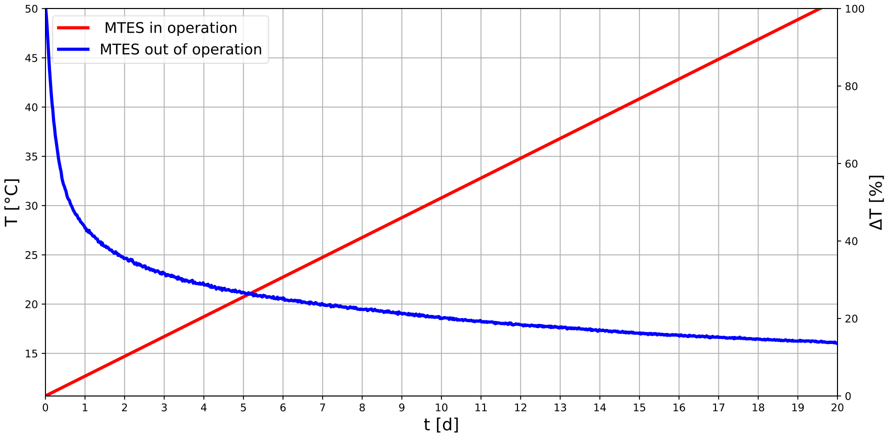


Figure 31: MTES test operation derived result functions.

Challenges:

i) Before Implementation

The surrounding naturally jointed rock has been heavily fractured and disturbed by the former mining activities several meters above the former 4th mine drift so that the installation of a packer has been necessary above the former drift. Open joints as well as several breakouts of the borehole wall have been leading to much more grout than calculated before to seal the annulus completely. The right amount of injected cement along the borehole wall has been determined in-situ by fibre optic cable which had been adhered to the PVC-casing before.

ii) Throughout Implementation

An increase of oxygen concentration has been observed in the MTES wells leading to ferrihydrite-precipitation during the MTES operation test. Basically, the injection pipes inside the heat injection well MO1 have been affected.

iii) After Implementation

Rapid cooling has been monitored by Geo-DTS as well as groundwater logger data due to:

- First time charge of the subsurface environment (i.e. adjacent fractured rock and water temperature which had an initial temperature of approx. 11 °C).
- The existing whole void volume of the former colliery is distinct higher than the amount of injected warm water during the test operation (Table 5). The input quantity of 50 MW_{th} could not heat up the whole MTES between the borehole MP1 and MO1 significantly (Figure 30).
- Turbulent conditions occurred when stopping the heat injection abruptly from 5.8 to 0 m^3/h, since the injection pipes have been open-ended without pressure-holding valves leading to an advective loss of heat.

Table 5: MTES properties of the Bochum demo site.

Total Volume of open mine voids	1,000 m^3
Drawdown MTES wells MP1 and MO1	2 cm/h x m^3
Volume Backfilled part	37,000 m^3
Hydraulic conductivity of backfilled parts	5.7×10^{-3} m/s
Depth MTES	64 m
Average height MTES	2-3 m
Water table	23 m
Initial Temperature MTES before heat injection:	10,8 °C
Temperature MTES during heat re-production:	12,1 °C
Nat. hydraulic gradient across the mine layout:	<0.0017
Thermal conductivity top layer (i.e. Sandstone)	2,20 W/ m*K
Thermal conductivity adjacent rock (i.e. claystone)	2,82 W/ m*K
Amount of first total heat injection:	50 MW_{th}
Recovery Efficiency	3,5 %

Backfilling of the colliery was only proven within the MI1 well, which is indicated as the crossed off areas within Figure 27. The MP1 and MO1 well, which were drilled into the 4th drift, did not reveal any backfilling material. This was also verified by separate downhole camera runs. Ultrasonic measurements, in order to estimate the mining void of drift 4, were executed in January 2021, but unfortunately revealed no reliable data.

First thermo-hydraulic modelling was done with a steady state model for flow and heat calculation with injection of hot water of up to 35°C (second step with injection temperatures up 60°C) and production with a steady flowrate of 1600 m^3/y at two different levels of the mine as a first assessment of the system performance (see Figure 32). After the evaluation of the heat injection test, all pressure and temperature data were forwarded to delta h for calibration of the existing numerical underground model with temperatures up 60°C and maximum flow rates of 15.000 m^3/y.

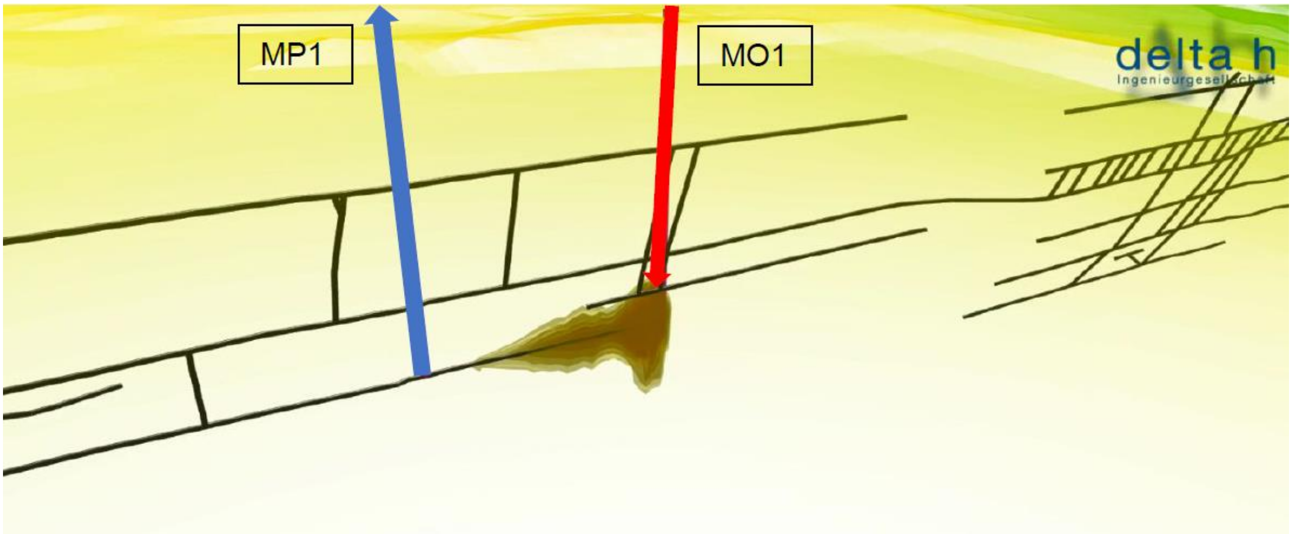


Figure 32: Numerical simulation of the first heat injection test.

Geochemical analysis during pumping tests and geochemical modelling were also carried out using PhreeqC 3 code. In general, the mineral solubilities increase with rising temperature (e.g. $Fe(OH)_3$), which is beneficial for the operation of the plant. However, the slight decrease in the solubility of carbonates, especially calcite and dolomite, is noteworthy. Siderite is not expected to form crystals even at a slight supersaturation, as the supersaturation is not considered to be high. The mineral phase $Fe(OH)_3$ known as amorphous ferrihydrite typically forms rapidly in the presence of oxygen and then precipitates as iron ochre (“iron clogging”).
Since the iron content of 6.4 mg/l is relatively high for mine waters based on experience, the dissolved iron content is estimated to be a potential hazard for the designed plant.

Therefore, a particular attention should be given to the heat exchanger (type: plates, pipes, etc.) and material given the cleaning easiness and the clogging risks. A tool is currently being developed to pre-select and optimize the heat exchanger material, in order to minimize the operating risk. This will be carried out in a collaboration with the Technical University of Freiberg in the near future.

Preliminary geomechanical modelling was also performed, in order to assess the potential ground deformation during the different cycles of (heat) loading and unloading. The preliminary model did not reveal any hazardous ground deformation within the foreseen temperature range of the pilot operation of the MTES. This is currently monitored utilizing photogrammetry and an onsite “Mineberry” system.

2.3.5 Lessons learned from problems within the implementation phase

- The production well(s) need(s) to be drilled into open (non-backfilled) fully-flooded parts of the mine either per vertical or directional drilling techniques. If the borehole for the production well can be directly vertically drilled (Figure 27), heavy drill-collars and stabilizers are required to guarantee a penetrating of the open mine void target.
- Temperature of the surface heat source has to be approx. 10-15 °C higher than the desired downhole heat injection temperatures.

- Elimination of oxygen access into the mine water system is one of the biggest struggles. Otherwise, a rapid precipitation of iron minerals (i.e. ferrihydrite) may occur.
- In a nutshell: A first heat injection test of 50 MW_{th} was just a drop in the ocean to generate a long-term significant recovery efficiency (i.e. >50 %). However, a general MTES feasibility was demonstrated within the scope of a first successful heat injection test.

2.3.6 Recommendation for further test operation

- Geological Boundaries:
  - Full saturation and a non-backfilled former drift to be reutilized as MTES.
  - Former mine should not be actively (via submersible pumps) or passively (via drainage galleries) dewatered leading to steady-state hydraulic gradients (this could be proved by a monitoring before MTES test operation).
  - A low rate of water table drawdown is preferred. This is achieved by drilling into open mine voids without surrounding backfilled parts of excavated areas. At least a depth which is minimum 2x higher than the water table could be recommended for shallow MTES.
  - No hydraulic connection between underground mine heat storage and re-infiltration well after thermal usage to avoid a thermal shortcut. Therefore, lateral to vertical distance ratio of 1:3 is recommended.
  - Iron and oxygen concentrations are most challenging regarding to severe scaling. The amount of precipitation should be calculated before to plan counter-measures.
- Technically:
  - Installation of a packer as a cement plug above the underground mine storage. It's recommended to observe the grout column by fibre optic cable along the PVC-casing.
  - Casing diameter of min. 7 inches and filter screen of min. 3 mm due to chemical precipitation of metals (i.e. ferrihydrite) preventing well-clogging.
  - Utilization of a frequency-driven submersible pump controlled by temperature-regime (which is able to operate automatically starting for a desired T_{min} of heat source (e.g. solar power plant) and stopping when a T_{max} is reached in the MTES boreholes.
  - MTES needs to be as continuously charged as possible. One or more buffer tanks are required to increase the amount of warm water, especially during the night-time of solar driven systems.
- Monitoring of:
  - mine and land subsidence,
  - groundwater analytics from adjacent carboniferous rock layers,
  - heat plume inside and outside MTES with help of temperature and pressure logger as well as fibre optic cable to further validate existing numerical model.

2.3.7 System operation, monitoring and maintenance

Based on the first experiences gained by the heat injection test, the underground storage of heat within the small colliery will be further tested within the 4th drift between the MP1 and MO1 well. Storage temperatures will have a maximum of 60 °C based on the installed PVC casing. The annual maximum flowrate will be increased to 15.000 m^3 (planned), in order to utilize the maximum thermal output of the CSP plant. However, the increased flowrate still needs to be approved by the mine owner and the water authority after the test phase has been concluded within the HEATSTORE project.

The site monitoring includes monitoring of the hydraulic heads, temperatures, fluid chemistry and seismic monitoring. Seven monitoring wells (six observation wells between 29 to 185 m depth and one research well at 500 m depth) are located on the Fraunhofer IEG Campus in Bochum, where the MTES site is located.

They are targeting upper and lower jointed sandstone formations, where groundwater flow takes place. The well monitoring includes continuous logging of temperature and pressure (30 minutes intervals since 12/2019) and also sampling in two wells since the beginning of April 2020 with different in situ measurements (temperature, pH, Oxygen content, electrical conductivity, redox potential) and laboratory analyses (major anions and cations and trace elements).

In addition, three seismic monitoring stations were installed at the site, in order to complement to the regional seismic network, which records potential activity due to the well operation and pre-investigation activities (e.g. injection test in December 2020).

Geo-mechanical monitoring is also done using inclinometers measurement at the surface of a former backfilled shaft and photogrammetry measurements within a first campaign in spring, summer, autumn and winter 2021 to monitor any possible natural ground subsidence.
The overall operational system is demonstrated in Figure 33.

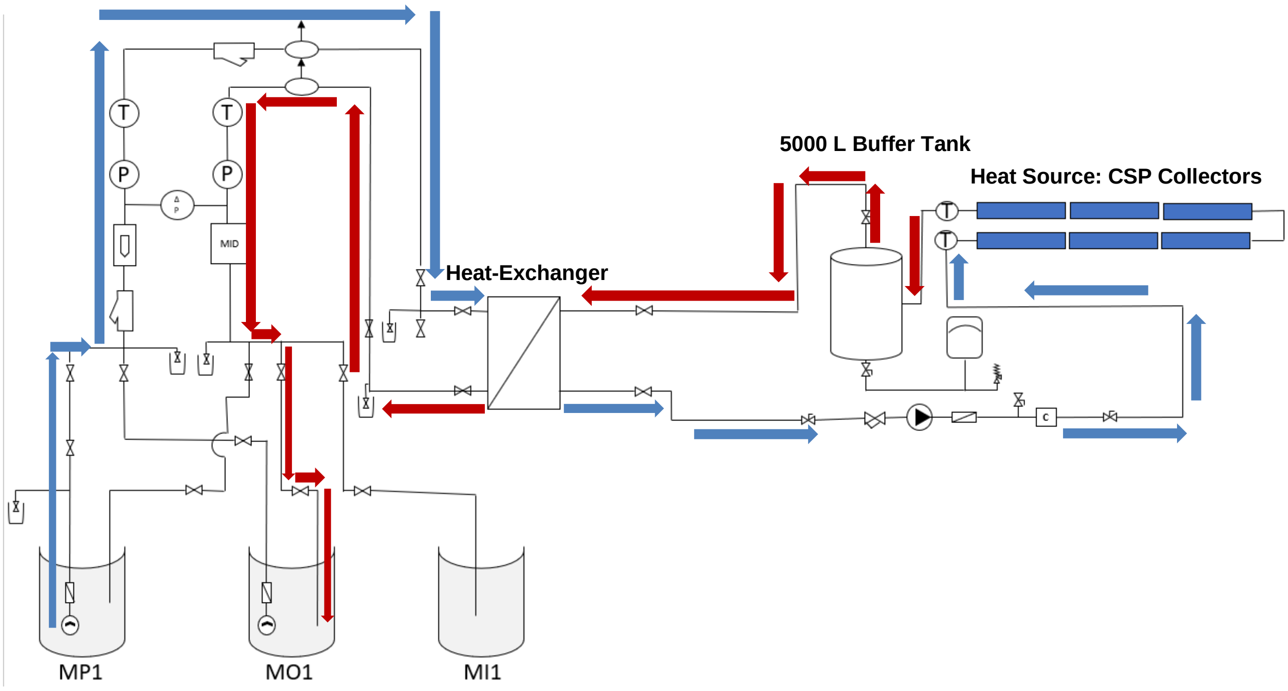


Figure 33: System overview of MTES (left) in combination with a CSP plant (right).

2.4 BTES

2.4.1 Brædstrup BTES pilot-plant

2.4.1.1 Short site description

The thermal energy storage implemented in Brædstrup is a pilot-plant BTES of 19.000 m^3 soil coupled to 18.600 m^2 of thermal solar collectors and to an electrical heat pump with 1.8 MW heating capacity. 7.500 m^3 steel tank thermal energy storages are also connected to the solar heating system as a buffer storage (Figure 34). The BTES was implemented in 2012 in the middle of Jutland in Denmark.

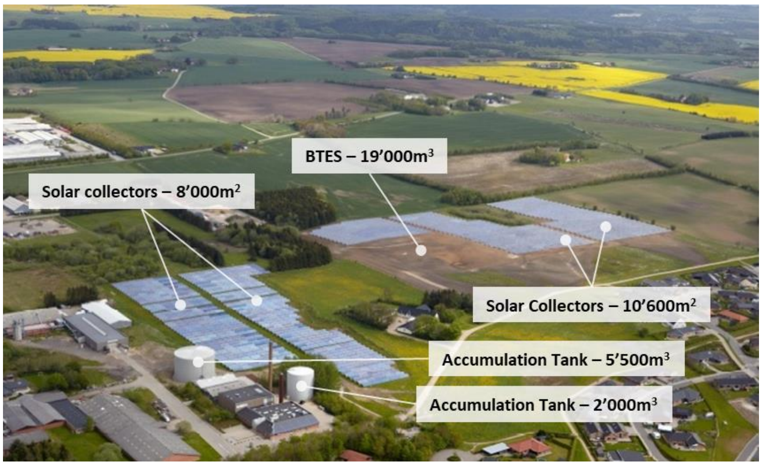


Figure 34: Aerial view of the BTES in Brædstrup.

2.4.1.2 Pre-investigation and feasibility studies

A test drilling was performed to determine the water table depth, in order to ensure that the BTES boreholes would be located above the water table and not affect the groundwater temperature. A 56 m thick layer of sand was identified, with groundwater deeper than 50 m below the surface (while the BTES boreholes are 45 m deep). Five extra observations wells were drilled to monitor the subsurface temperatures: four of them were placed inside the boreholes area, with a depth of 59 m, such that temperatures below the BTES base can be measured. The last one of them was placed outside of the borehole area, to the side, 20 m from the centre of the BTES, downstream compared to potential groundwater flow. “Classical” Thermal Response Tests (TRT) based on inlet/outlet temperatures were performed to evaluate the thermal conductivity of the geological layers of the BTES volume. “Distributed” TRT (i.e. with temperature measurements along the borehole) were not performed, since it did not seem to be relevant for a homogeneous geological formation as in Brædstrup. Hydrogeological investigations can help characterizing heat transfer by groundwater flow (convection), but were not conducted in Brædstrup as the BTES is above the groundwater zone.

In Denmark, DHN companies are mostly consumer-owned. Consumers are sensitive to “green” and costs arguments. It is normal practice with a hearing period of 8 weeks, where people can take notice of the project and submit objections. The projects are then presented to the town council, where it can be approved. Municipalities then perform the environmental impact assessment. Early contacts with people close to the installation is very important. For the Brædstrup BTES, the only concern of the municipality was the risk of heating up the groundwater, as experienced in some previous PTES projects, which explain the mitigation measures described above. The whole process takes at least 12 months, but could have been more if an environment impact assessment had been needed.

2.4.1.3 Design and construction

The design of the Brædstrup BTES is such that the individual Borehole Heat Exchangers (BHE) are arranged in 8 streams of 6-BHE, which results from the search of a trade-off between pressure drop and thermal transfer. TRNSYS-DST component was used for design modelling (using parameters from the TRT and geological investigation). Later, in Heatstore Deliverable TR2.3, the same TRNSYS component was tested against measurements, and the simulation results were at first in decent agreement with the monitoring: energy input and output were underestimated, but thermal losses were in good agreement. After calibration of the component, very good agreement was found, validating the relevance of the model for system design calculations.
During construction phase of the BTES, some costs had not been planned, which resulted in a higher expense for the district heating company.

2.4.1.4 Challenges and Highlights during implementation

Being the first BTES implemented in Denmark, Brædstrup had no reference project to make use of lessons learned. The main challenges faced during the implementation phase were the following:

- During drilling of the boreholes, the drilling equipment broke on an unexpected stone layer, which led to a long replacement procedure.

- The amount of grouting material was underestimated, because the chosen drilling technique (wash drilling) resulted in larger drilling diameters for soft soil layers, and the total bored volume was therefore larger than expected/calculated.
- For the BTES lid (insulation at the top of the BTES), the amount of man hours was underestimated for the connection of the pipes to the boreholes' well.

2.4.1.5 Lessons learned from problems within the implementation phase

The drilling method chosen in Brædstrup (wash drilling) caused the two main issues encountered during implementation (Figure 35). It is therefore highly recommended to adapt plans to the chosen drilling method. In this case, the amount of grouting material should have been expected to be higher than the theoretical values. The stone layer that broke the drilling equipment was however unexpected and it is hard to recommend anything to prevent this from happening.

Figure 35: Picture of the wash drilling equipment used in Brædstrup.

2.4.1.6 Recommendation for further test operation

Generally speaking, the amounts of man-hours required for the work was underestimated by a lot in this project, and the final costs were significantly higher as a result. For these kinds of highly technical ground works, it is therefore highly recommended to get it done by an entrepreneur that has dealt with the same kind of work before, and that they detail as much as possible the different task to evaluate properly the projected costs

2.4.1.7 System Operation, monitoring and maintenance

The Brædstrup BTES is no longer in regular operation. Originally it was sized with a short-term buffer (water tank) and this water tank was oversized as the associated solar panel fields was expected to be significantly expanded, which, however, did not happen. Therefore, the water tank is sufficient for the needed seasonal heat storage. Today, the BTES is used in case of heat surplus from the solar collector field, which last happened in the year 2018, as well as a geothermal well. Heat is extracted from the BTES with the use of a heat pump.

2.4.2 French demo site

2.4.2.1 Pre-investigation and feasibility studies

The French demo site was initially planned on the same location as an underground gas storage facility. The cost of this French demo site soared up because of the BTES was in a gas storage facility which felt under the COMAH (Seveso) regulations. It induces significant additional costs and operational constraints to the project compared to similar BTES projects. Consequently, it is highly recommended to check all the applicable regulations at a very early stage, especially for the UTES located within existing industrial areas with their own specific regulations. Besides, the injection temperature was limited to 40 °C at the beginning of the exploitation to benefit from the “declarative” regime. Challenging and cutting the costs indeed demanded more time than the permitting phase.

The project was cancelled after the drilling of a test borehole. Cuttings were taken every meter. They were dried and the grains were separated with mortar and pestle, delicately, before being observed with the binocular magnifying glass. A particle size analysis was carried out for five of these samples, chosen to detail the particle size of the different facies identified. This helped to detail the first geological section, drawn during the drilling. A “classical” TRT was also carried out.

The new demo site is located in Annecy. The school Vallin-Fier is already heated by a BHEs field of 18 BHEs, 100 m each. A first geological section was drawn during the drilling in 2012 and a “classical” TRT was also carried out. For monitoring the conversion of this geothermal field on a BTES, with heat re-injection, 2 additional wells were drilled during summer 2021. The permitting procedure was discussed with the local authorities early enough. The prefecture of Haute-Savoie asked to fill in one declaration for both the environmental and mining codes. It consists in three parts: main declaration form (2 months before the beginning of work), complementary elements (1 month before the beginning of work), completion report (2 months after the end of work).

2.4.2.2 Design and construction

The BHEs field is made of 18 BHEs, with 3 lines of 6 BHE’s. On each line, there are 14 m between 2 BHEs. Between each line, there are 8 m. All BHEs are connected in parallel to the collector. It may not be the best set-up for BTES, like the one in Braedstrup, but this was a unique opportunity to measure the real performances improvement of the conversion of an existing geothermal field into a heat storage.

The heat to store will come from solar thermal panels. The whole system will further be modelled using TRNSYS, while more investigation of the underground behaviour will be carried out using FEFLOW.

2.4.2.3 System operation, monitoring and maintenance

The demo site in Annecy will be fully operational in autumn 2021. More temperature sensors and energy meters will be added to a better follow-up of the system.

The 2 additional wells were drilled to 130 m to be able to catch the underground temperature change under the heat storage and so, estimate the heat losses from the basement of the BHEs field. 32 temperature sensors were installed on each well. The sensors line was inserted in a PVC tube, filled with water, so that sensors can be repaired. The data logger, which uses a battery, is in the manhole at the top of the well and can send data through GPRS. This solution was chosen as it did not required to dig a trench to power the data logger and retrieve data.

2.5 PTES

2.5.1 Marstal Case Study

2.5.1.1 Short Description

The thermal energy storage implemented in Marstal is a PTES of 75.000 m^3, coupled to 33.300 m^2 of thermal solar collectors and to an electrical heat pump with 1.5 MW heating capacity (Figure 36). It was implemented in 2012 on an island called Ærø, in the Southern part of Denmark.

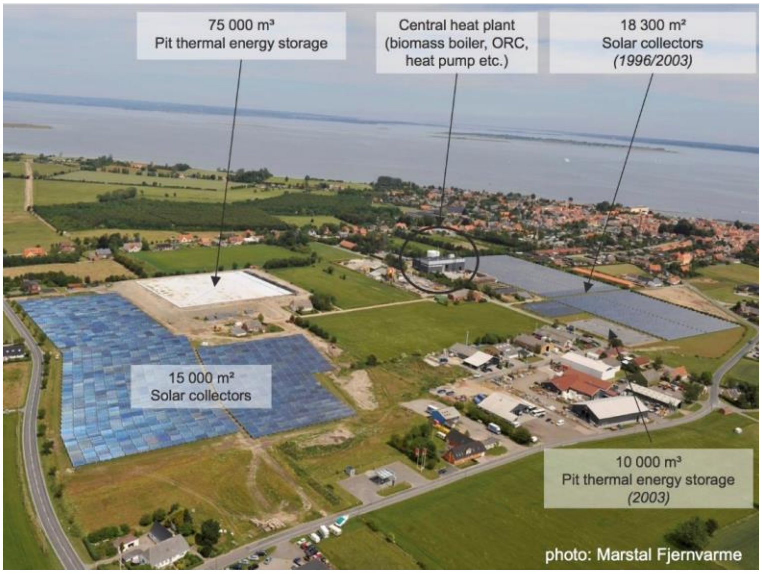


Figure 36: Aerial view of the PTES in Marstal.

2.5.1.2 Challenges and Highlights during implementation

Being the first large-scale PTES of Denmark, this Marstal PTES has encountered many challenges during implementation.

- Weather conditions (rain, wind, ice) caused some issues with excavation, water filling and lid implementation.
- Not precise enough excavation made it impossible for the liner entrepreneur to start their work right away.
- Some errors committed during liner welding resulted in leakages.
- The initial absence of a water treatment system and of a floating cover during water filling caused corrosion of the inlet/outlet pipes as well as the solar heat exchanger.
- The insulation was infiltrated with water during lid implementation.
- No authorization had been given to discharge water linked to the lowering of the groundwater level, and therefore the release of this water created an issue with local authorities

2.5.1.3 Lessons learned from problems within the implementation phase

The following measures from Marstal can be recommended to prevent issues during implementation:

- Obtain the proper permissions for discharging water (from rain, or groundwater lowering procedure).
- An independent land surveyor is needed to control the excavation work and make sure the construction is done with precision.
- Liner work should be tested for leakages continuously and after welding by electricity conduction for instance.
- Temporary liners are highly recommended to prevent (rain)water from damaging the excavation work and prevent contamination of the filling water with bacteria or dust.
- Water quality during filling should be controlled and kept to a high pH value (9.8) to avoid corrosion. Reverse osmosis is needed to remove salts such as calcium from precipitating and clogging the heat exchangers.
- Some equipment should be available to dry the insulation during implementation.

2.5.1.4 Recommendation for further test operation

- For future implementations, it is highly recommended to follow lessons learned from previous projects, and implement solutions that account for known and encountered issues (water puddles, air caught under the lid, leakages and humidity, etc.).

Concerning the Marstal site, it was recommended to:

- Often check the lid for leakages.
- Frequently test the water quality and properties (salts, pH, bacteria).
- Check the inlet/outlet pipes for corrosion, every year

2.5.2 Dronninglund Case Study

2.5.2.1 Short Description

The thermal energy storage implemented in Dronninglund is a PTES of 60.000 m^3, coupled to 37.500 m^2 of thermal solar collectors and initially to an absorption heat pump with 2.1 MW cooling capacity (Figure 37). It was implemented in the Northern part of Jutland in Denmark in 2013.

Figure 37: Aerial view of the PTES in Dronninglund.

2.5.2.2 Challenges and Highlights during implementation

Dronninglund benefitted from the lessons learned in Marstal. The main challenges faced were linked to:

- The inlet-outlet pipes that, in Dronninglund, come into the storage through the bottom.
- Prevention of corrosion.
- Lid leakage prevention.

2.5.2.3 Lessons learned from problems within the implementation phase

The main challenges in Dronninglund were answered with the following solutions:

- The inlet/outlet pipes arriving at the bottom of the PTES were stabilized with cables, in order to prevent them from falling under windy conditions (before the PTES filling is complete, Figure 38).
- A corrosion expert was consulted, and the following measures have been taken during water filling:
  - Pipes between solar central, storage and district heating network were cleaned before water was filled in.
  - Filters were implemented to protect the solar heat exchangers.
  - Water was treated with reverse osmosis to remove all salts (especially chlorides).
  - The pH was raised to 9.6-9.8.
- After implementation of the HDPE-liner, the liner was tested for leakages. A wet geotextile was rolled over the weldings, electrical potential put on and if electric conduction could be traced outside the storage wall, a leakage was found. During the test no leakages were found.

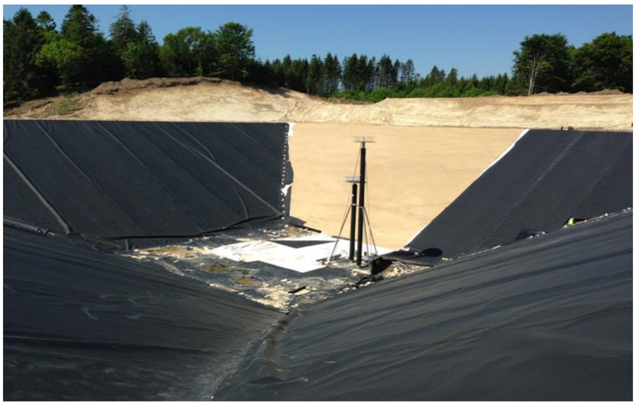


Figure 38: Picture of the inlet/outlet pipes coming from the bottom of the PTES in Dronninglund, stabilized by cables.

2.5.2.4 Recommendation for further test operation

Generally speaking for the Dronninglund site, the amounts of man-hours required for the work was underestimated by a lot in this project, and the final costs were significantly higher as a result. For these kinds of highly technical ground works, it is therefore highly recommended to get it done by an entrepreneur that has dealt with the same kind of work before, and that they detail as much as possible the different task to evaluate properly the projected costs.

2.5.3 Gram Case Study Site

2.5.3.1 Short Description

The thermal energy storage implemented in Gram is a PTES of 122.000 m^3, coupled to 44.800 m^2 of thermal solar collectors (Figure 39). An extra steel tank thermal storage of 2.300 m^3 is also coupled to the heating system. It was implemented in the southern part of Jutland in Denmark between 2014 and 2015.

Figure 39: Two aerial views of the PTES in Gram.

2.5.3.2 Challenges and Highlights during implementation

Gram had the advantage of being built after the large-scale PTES in Dronninglund and Marstal, and thus benefit from many of the lessons learned during their implementation. The main issue encountered in Gram was related to the establishment of the lid insulation material. The lid is made of LECA balls, which are very complicated to evenly distribute over a large area. In Gram, it has been impossible to fill the lid with LECA in a uniform pattern, which means that the lids had a lot of spots where the insulation was thinner, creating thermal bridges as well as room for water puddles.

2.5.3.3 Lessons learned from problems within the implementation phase

When filling the lid with two times 2 m^3 of LECA, the resulting volume of LECA could be less than 4 m^3 due to the way the LECA balls distribute themselves. The solutions that have been identified to make up for this uneven insulation layer thickness during implementation is to carefully check the thickness of newly deposited LECA layer for each new portion covered, with a broomstick or equivalent. Then the implemented lid should be inspected for holes (areas missing LECA fill) and fill up those areas, where the insulation thickness is insufficient. Once this is done, an extra layer can be implemented on top of the LECA layer to add rigidity and even the surface of the lid, while also adding insulation.

2.5.3.4 Recommendation for further test operation

For future implementations, it is highly recommended to follow lessons learned from previous projects, and implement solutions that account for known and encountered issues (water puddles, air caught under the lid, leakages and humidity, etc.).

After encountering these issues in Gram, the lid has been further studied with thermal imaging (Figure 40 and Figure 41). The identified thermal bridges were corrected by filling of the uneven areas and installing of an extra layer of XPS (as suggested by PlanEnergi), on top of the LECA. This was implemented in October 2020. Figure 42 presents the design of the extra layer that has been installed in Gram after having filled the areas where the existing LECA insulation was thinner.

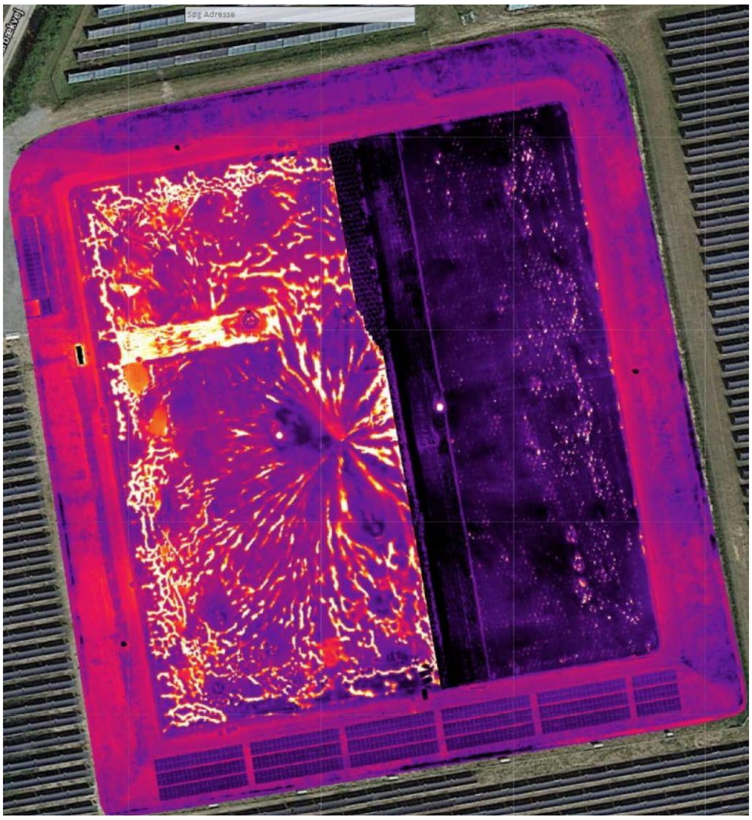


Figure 40: Thermal imaging of the lid in Gram during extra insulation implementation [Gram District Heating 2020].

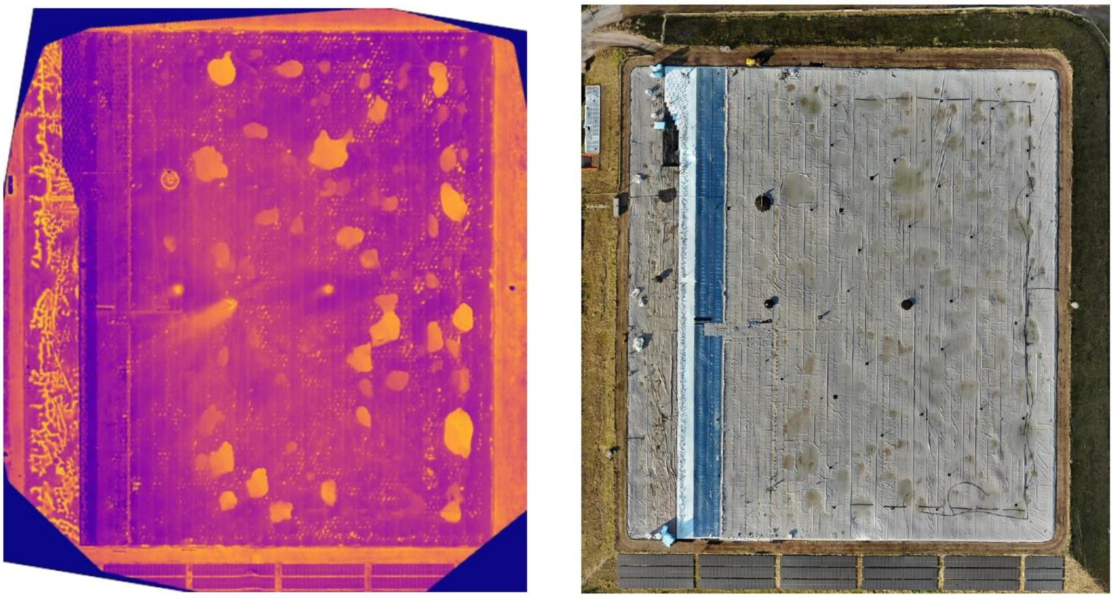


Figure 41: Thermal imaging of the lid in Gram towards the end of extra insulation implementation [DTU 2020].

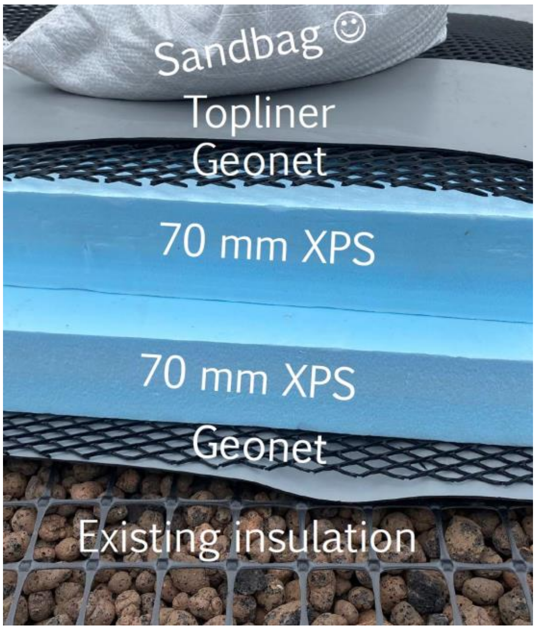


Figure 42: Picture of the extra insulation while it is being installed in Gram.

2.6 Portuguese and Icelandic Case studies

The Portuguese and Icelandic national sub projects were focussing on applying field survey data to calibrate models with data of geothermal mature fields (see WP2).

2.6.1 Portuguese case study – Caldeiras da Ribeira Grande site

2.6.1.1 Short description of case study

Caldeiras da Ribeira Grande area, located in the north flank of Fogo Volcano (São Miguel Island, Azores), was used as test site to apply the models developed in WP2 to high enthalpy geothermal areas.

One of the purposes was to identify geochemical tools that can be used to infer subsurface conditions before any drilling and compare with data obtained from geothermal wells. The other main goal was to select the geochemical parameters that showed to better fit as input in the models developed.

2.6.1.2 Challenges and Highlights during implementation

No constructions were done and the studies were carried out using data obtained in field surveys, which were compared with information from already drilled geothermal wells. The study site was used essentially to calibrate and to check the adequacy of the models developed in WP2 in high enthalpy geothermal sites, such as the Azores islands.

The results obtained during the current project showed that gas equilibrium data from the fumarolic emissions, as well as diffuse degassing (CO_2, ^{222}Rn) mapping, were adequate to use both in pre-drilling phase as well as during production stages in high enthalpy sites. Geochemical tools allowed inferring equilibrium temperatures in the feeding reservoir (231 to 258 ºC).
Soil diffuse degassing surveys showed to be useful to map permeable structures, which represent possible sites for fluid circulation, crucial for any geothermal exploitation. Thermal energy was also estimated by integrating data from fumaroles and diffuse degassing areas, and was calculated as 7.7 MW, for an area with 0.218 km^2.
The hydrothermal mineral assemblages recognized in the rock samples from a well drilled in the site up to 1343 m confirmed both the above-mentioned inferred temperature, as well as the permeability structures at depth.

2.6.1.3 Lessons learned from problems within the implementation phase

One of the difficulties was to use data from the mineral waters (thermal and cold CO_2-rich springs) as geothermometers, since they were in disequilibrium conditions and oversaturated regarding silica solid phases. Study of the springs showed to be useful to distinguish the origin of the volatiles as well as the hydrogeochemistry processes dominating in the area.

2.6.1.4 Recommendation for further test operation

Testing the usefulness of these geochemical data on other study sites and, consequently, feed and constrain any holistic geothermal reservoirs models.

2.6.2 Icelandic case studies: Hengill and Reykir

The two case studies in the Icelandic national sub projects within HEATSTORE are simulation studies for heat storage schemes that have not yet been implemented. However, because both fields are mature fields that have been in operation for decades, we include the case studies in this deliverable focusing on the descriptions of the fields and the challenges we would expect upon implementation based on the challenges during normal operation of the fields and simulation results from the project.

2.6.2.1 Hengill case study

The Hengill volcanic and tectonic area is located in SW-Iceland, about 30 km east of Reykjavík. Two co-generative geothermal power plants are operated in the area: The Nesjavellir Power Plant, commissioned in 1990, in the northern part of the volcanic complex and The Hellisheiði Power Plant, commissioned in 2006, located in the southern part of the volcano. The combined installed capacity of both power plants is 423 MW_e in electrical power and 540 MW_{th} in thermal power.
The temperature of the geothermal reservoirs, from which is produced, is 230-330°C. The reservoir is water dominated and the fluid, a mixture of steam and water, is produced from 88 production wells. The spent fluid is reinjected into the reservoir via 26 injection wells. The depth of the wells (both production and injection wells) is normally around 2500 m, the deepest one being more than 3000 m.
The Hengill case study within HEATSTORE revolves around accessing and producing energy from deeper and hotter formations than have previously been utilized – i.e., deeper than 3500 m and hotter than 400°C. The aim of the case study was to intertwine academic process models of conditions around magmatic heat sources, developed at ETHZ, and the conventional field scale model of the area, run by Reykjavík Energy, and to advance the conventional model to greater depths. The results from the model simulations are presented in detail in project deliverable 2.1 [Driesner et al. 2021]. This project is a non-UTES project

included in the HEATSTORE project to transfer academic/research codes beyond HT-UTES to real world application. The aim is to have modelling tools that can simulate different utilization schemes for the greater depths and their effect on the shallower system. Deeper drilling is planned in the field in the next few years within the Iceland Deep Drilling Project (IDDP).

2.6.2.2 Reykir case study

The Reykir/Reykjahlíð geothermal field is located within Iceland´s capital area in the Mosfellsbær municipality. The system is separated into two subareas, Reykir and Reykjahlíð. Today, active production wells are 34, 22 in Reykir and 12 in Reykjahlíð. Production from deep wells in the fields started in 1971 and today the average combined production is about 1000 L/s of 86 °C warm water which is supplied to the district heating system. The district heating system receives water from two other geothermal fields within the city limits of Reykjavík, but it is also fed by heated groundwater produced at the two power plants in the Hengill area. The chemical composition of the geothermal water and the heated groundwater is different. Thus, these two water types cannot be mixed within the distribution system due to precipitation of magnesium silicates. In Iceland, the heating demand is higher during the cold winter months than the warmer summer months. The power plants operate on base load and one of them produces excess 80 °C hot water over the summer months.

The aim of the second Icelandic case study within HEATSTORE was to estimate the feasibility, using numerical simulations, of injecting and storing this excess hot water from the Hengill area within the Reykir low temperature system during the summertime for later use during the wintertime when demands rise again. The aim was also to investigate if mixing the two above mentioned water types within the reservoir would solve the precipitation problems. The overall aim with the injection would be to store heat, provide pressure support in a field that has suffered from pressure decline due to increasing demand and to reduce wasting of the excess heat produced during the summer.

Demand for hot water in the capital area has been increasing rapidly in recent years with a record increase of about 10 % between 2019 and 2020. This calls for innovative ideas for better resource utilization, because exploring new areas to meet growing demand is a costly measure that takes several years.

2.6.2.3 Challenges and Highlights during implementation

2.6.2.3.1 Hengill case study

Exploring the greater depths, and thereby higher temperature, in the Hengill area will enlarge the accessible geothermal resource downwards. It would allow for a better utilization of currently exploited areas and infrastructure instead of expanding laterally to maintain production capacity.

Modelling studies have shown that a well producing from a superhot geothermal reservoir could produce more energy than a well in conventional high-temperature geothermal reservoirs. The main challenges with operating the geothermal fields in the Hengill area have been H_2S in the steam and induced seismicity related to the reinjection of spent geothermal fluid. The H_2S pollution problem has been largely solved by injecting the H_2S back into the reservoir where it mineralizes, a method developed during the SulFix project [Gudbrandsson et al. 2014]. Normally, induced seismicity does not cause problems in geothermal production fields in Iceland. However, when a new injection field, Húsmúli, was commissioned in Hellisheiði in 2011 it caused significant induced seismicity [Gunnarsson 2013]. Thus, induced seismicity needs to be addressed when injecting into geothermal reservoirs. To minimize the risk of induced seismicity, injection rates are maintained as stable as possible.

The main foreseeable challenges with implementation of deeper utilization are related to the high temperature and pressure in the formations that are going to be drilled into. Difficult chemistry of the geothermal fluid in hot environments can also be a problem. In Figure 43, two examples of the effect of a difficult chemical environment in a superhot well are shown. Both examples come from well NJ-32 in Nesjavellir that was drilled into a formation that is known to be very hot (T>380°C has been measured at the depth of 2100 m).

The main challenge is to come up with a robust well design, i.e. casing material and methods and cementing, that can withstand high stresses due to thermal expansion, high pressure and temperature and corrosive fluid chemistry. Surface equipment that can withstand high temperatures, high pressure and corrosive chemistry is also needed. Another challenge is to understand the deeper parts of the geothermal systems and figure out how to extract the thermal energy from there in an efficient way.

Figure 43: Two examples of the effect of corrosive environment in a superhot geothermal well. Left: A well logging instrument of stainless steel that came black out of a well compared to an instrument of an original color. Right: Corroded spinner from a logging tool.

2.6.2.3.2 Reykir case study

No injection has taken place in the field, nor in any of the utilized fields in the capital area, and for that reason no specific injection wells have been drilled. Utilization of the field has been very successful. The main challenge in the operation of the field has been cooling in a few wells, particularly at the southern and southwestern margin of Reykir. Some wells are for this reason rarely used because their temperature is below the desired temperature of the district heating system. The temperature of the water that would be injected is 80°C which is similar to the temperature within the Reykir geothermal system. The injection would be into the geothermal reservoir itself and could take place in research wells, inactive production wells or new wells that could be drilled. Simulation results show that the system is very permeable. The results show that a likely challenge with the implementation would be fast dissipation of the injected water causing the pressure support to be short lived. Results from reactive chemistry simulations indicate that under these reservoir conditions and fluid composition the change in volume fraction due to mineral precipitation resulting from the injection of heated groundwater into the geothermal system is negligible and no adverse impact is seen on the reservoir porosity. These are positive results as they mean that mineral precipitates would not cause clogging of the injection well. However, the long-term simulations indicate that because of little precipitation, the magnesium in the injected fluid would be transported long distances and could thus reach production wells risking magnesium silicates forming in the distribution system. This would be a challenge that would require careful chemical monitoring of produced water [Driesner et al. 2021]. The experience of induced seismicity resulting from reinjection into the Hengill area would raise similar concerns for any planned injection closer to the capital area. Injection of more than 10 L/s or into active fracture systems in Iceland always requires an assessment of seismicity risk. If injection would be started following this project, an analysis of seismicity risk would be performed as that would be a possible challenge.

3 Best practice guidelines for UTES

3.1 Best practice guidelines for ATES

3.1.1 Best practice guidelines for pre-investigation and feasibility study

The prerequisite for investigating the potential of ATES is the knowledge of the local geological settings (e.g. nature of the geological formation, information on lithology…), the aquifer hydrogeological and hydrochemical characteristics (e.g. hydraulic conductivity or transmissivity, aquifer productive thickness, regional hydraulic gradient, chemical composition of groundwater...) and the soil/rock thermal properties.

When the target aquifer is not well known, a pre-investigation phase should be carried out; performing hydraulic tests on a first (exploration) well before the design phase of the ATES is a key element in order to mitigate unknown parameters and to evaluate the initial reservoir performance (maximum flowrate, initial productivity and injectivity indices, natural temperature of the resource) and consequently the storage capacity. During drilling and pumping tests other key parameters such as groundwater geochemical composition, lithology and grain size (important for the design of well screen and gravel pack in unconsolidated formation) and productive thickness of the targeted aquifer are also measured.

Different hydraulic tests can be conducted according to the parameters to be evaluated (productivity/injectivity of the wells, skin factor, transmissivity, vertical and lateral connectivity of layers…) and the type of formation (e.g. porous limestones or sandstones, fractured limestones…). If there is already a first well, or when drilling the second well, well interference tests provide also important information on the hydraulic connectivity of the reservoir, which is primordial for an ATES as well as conventional geothermal open loop systems.
Also, in the prefeasibility study, geological and thermo-hydrodynamic models should be considered to optimize wells configuration and distance and updated during operation phase. A too short distance between hot and cold wells could reduce the storage efficiency due to thermal interferences between the hot and cold wells and conversely a too high distance may hinder the storage efficiency because of heat losses in the surroundings and higher pressures at the wells during charging and unloading periods.

Lower aquifer permeability and thickness allow better energy containment but in the other hand lead to higher injection pressure for the same injection flowrate and thus may result in a smaller well capacity.
Thermo-hydraulic modelling (TH) is a prerequisite for assessing the energy recovery efficiency of an ATES. It will mainly depend on the stored volume of hot/cold water, the well screen length/productive thickness of the aquifer, the hydraulic conductivity and natural flow of the aquifer, the initial temperature of the aquifer and the temperature of the stored water. TH modelling shows that buoyancy driven flow impacts greatly the storage efficiency at storage temperature >45°C. The recovery efficiency decreases significantly with high temperature storage and for high aquifer permeability and/or productive thickness. Also, the recovery efficiency improves significantly when the storage volume is increased, especially at high storage temperatures. Also, the cut-off temperature (minimum extraction temperature from the hot well during heat unloading, typically the temperature of the fluid flowing back from the DHN plus the pinch of the primary/secondary heat exchanger) should be as low as possible to increase the recovery efficiency.

Preliminary thermo-hydro-chemical modelling (THC) can be useful for a first assessment of geochemical reactions that may occur in the well or close to the well in the reservoir when increasing or decreasing the aquifer natural temperature due to storage cycle, which could hinder the storage efficiency. It allows assessing the necessity of implementing specific water treatment in the well or at surface before or after the heat exchanger to avoid corrosion or scaling issues.

In some contexts, hydro-mechanical modelling (HM) is also recommended to investigate the possible effect of subsidence or ground movement (namely for fractured reservoirs).

3.1.2 Best practice guidelines for design and construction

The design and localization of the wells should minimize thermal interferences between the production and injection wells. It should also prevent undesirable hydraulic and thermal impacts in the surrounding environment.

Existing guidelines for intermediate to deep conventional geothermal systems (400+ m) proves to be useful for ATES. For example, in France, best practice guidelines were developed by BRGM with the support of ADEME (French Agency of Environment and Energy Management) and thanks to the experience of the exploitation of the Dogger limestones and Albian sandy and clayey formation in the Paris Basin. This guide concerns all phases of a geothermal deep well like the conception, drilling, casing, cementing, deviation, logging, development of the wells (see https://www.geothermies.fr/outils/guides/good-practice-guide-lessons-learned-deep-geothermal-drilling).

The most important characteristic that distinguishes ATES wells from geothermal wells is the alternating flow direction of ATES well. This yields to the following recommendations:

- **Insulation of the well casing**(s) in the hot well can minimize heat losses of the storage and prevent heating up shallow (fresh water) aquifers.
- Regarding **drilling aspects**, they are similar to conventional geothermal wells and dependent mainly of the depth and type of formation (unconsolidate or consolidate). Reverse rotary drilling with air-lift is generally applied as standard technology for ATES systems because of large well diameter and a clean drilling process. The drilling mud flows into the annular space between drill pipe and borehole wall downwards by gravity. The cuttings at the drill bit in the bottom of the hole are continuously brought out to the surface through the drill pipes with air lift. The cuttings from the geological formations and the drilling mud are then drained into a sedimentation tank where representative geological samples can be collected. Rotary drilling is relatively similar to reverse rotary drilling except that for rotary drilling the drilling fluid is circulated from the drill stem and then flows up the annulus between the outside of the drill stem and borehole wall.
- Regarding **casings and screens,** it is recommended to use Glass Reinforced Epoxy (GRE) or stainless steel if storage temperatures exceeds 60°C. For high temperature wells up to 95°C GRE is preferred above steel or stainless steel. Cold wells can be constructed with PVC screens and casings in situations where temperatures are below 60ºC.
- Regarding **well completion specifications**, they do not differ from conventional geothermal well:
  - the thickness of the gravel pack varies between a minimum of 100 mm to a maximum of 300 mm,
  - the grain size of the gravel and the size of the screen slots have to be adjusted to the grain size distribution of the selected reservoir layers according to the rules already applied for designing gravel pack well completion,
  - to prevent mixing of different types of groundwater and to be sure the water is extracted and injected at the depth selected, low permeability layers (e.g. clay, loam) that were perforated have to be sealed during backfilling.
- Regarding **well equipment**: Specific ESP pumps (Electric Submersible Pump) commonly used in geothermal applications are suitable for high temperatures in the hot well.
- Contractual specifications of standards (e.g. drilling standards, equipment standards, ex-zone standards) and the rigorous monitoring if these standards are followed.
- Selection of contactors, are they capable and willing to supply the services. Ensure of awareness of Contractors to the Terms and conditions of the contract.

3.1.3 Best practice guidelines for operation, monitoring and maintenance

In the operating phase, it is highly recommended to monitor the system in order to diagnose and optimize the system and prevent any failure. To monitor the heat and water chemistry in the aquifer, it is advised to install a separate monitoring well at a certain distance from the hot well (inside the hot plume radius).

Performance monitoring is essential to optimize the system and to be able to deliver the energy efficiency that the system was designed for. For monitoring temperature, it can be considered to use fibre optic techniques instead of measuring temperatures in the wells or around the wells.

Preventive maintenance is also important to avoid well deterioration and ESP failure.

When the thermal balance in the underground is significantly changed due to the different annual heating demand and availability of heat in summer, provisions might be required to restore the balance in order to avoid interference between extraction and injection wells or undesired environmental impacts.

Flushing of well(s) at maximal capacity for about one hour per well to remove collected fines is recommended namely for sandy and clayey formation. Flushing is scheduled preferably near the end of the winter season and the end of the summer season. To remove the fines from the system, the groundwater extracted during Flushing is not returned to the aquifer, but discharged to (e.g.) the sewer. During flushing the specific capacity of the wells is also assessed, to verify well quality.

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

- specific water treatment (HCl or CO_2 to reduce carbonate concentration, corrosion inhibitors),
- repeated regeneration of wells,
- maintain pressure as constant as possible in the system all the time and above bubble point (avoid degassing),
- continuous analyses of possible changes in groundwater composition/chemistry.

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 and the use of adapted filters. Good monitoring with pressure and temperature transmitters makes early detection of heat exchanger or surface filters possible fouling.

3.2 Best practice guidelines for MTES

3.2.1 Best practices guidelines for pre-investigation and feasibility study

The prerequisite for investigating the potential of MTES potential is the knowledge of the mining layout (geometry, volumes, connections between galleries, shafts...), the mine water hydrogeological and hydrogeochemical characteristics, the temperature measurement and existing mine water drainage sites.
Modelling hydraulic and thermal impacts on a regional scale for the MTES project presented many challenges, including appropriate discretization of mine drifts as well as accurate modelling of the surrounding rock mass and aquifer system.

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.
The experience from the German demo site give some insight on the data to collect for the pre-investigation study:

- The temperature and hydraulic level (inside and outside the mines). Temperature is currently measured in the mines with optical fibre and data loggers,
- The geochemistry of the fluid,
- Pumping tests to estimate mining voids volume,
- Mechanical measurements should be followed up mostly in the main shaft, which has a connection to the surface. Changes in ground elevation will be monitored by drones and installed inclinometer (assumed to be negligible),
- Rock strength, thermal conductivity measured in lab with temperature cycles (limited effect on the properties observed).

3.2.2 Best practices guidelines for design and construction

The design primarily depends on mine depth, extent and possible locations to drill boreholes, if existing shafts could not be utilized for heat storage purposes. If it is necessary to drill, an adequate distance between the production and injection wells have to be considered. Here, the most important factor is finding a balance between costs (e.g. standard PVC vs. steel casing or glass fibre casings) and lifetime guarantee as scaling and clogging problems may occur, when water is injected into the subsurface.

3.2.3 Best practices guidelines for operation, monitoring and maintenance

The monitoring of a MTES is relatively similar to ATES with the follow-up of the flowrate, injection and extraction pressures and temperatures. Regarding geochemical follow-up, oxygenation of the fluid may be a problem in the injection well if air intake (possible iron precipitation) occurs, so no air must enter the system (sealed connection in the surface system, minimize start/stop operations). Therefore, it is recommended that the system operates continuously (summer vs. winter modes) which also enhances the pump life expectancy. In the context of mines, the monitoring of surface subsidence and shaft stability is highly recommended.

3.3 Best practice guidelines for BTES

3.3.1 Best practices guidelines for pre-investigation and feasibility study

Geology, groundwater flow, thermal properties of the underground (initial temperature, thermal conductivity, heat capacity) should be estimated, first based on bibliographic investigations. Soon after, a thermal response test should be carried out. As significant groundwater flow will cause advective heat loss, it should be avoided. Significant groundwater flow may be a knock-out criterion. Performing a test drilling is essential to verify the ground conditions and the estimated drilling costs. Always perform a simulation of the BTES integrated into the energy system (e.g. with pieces of software like TRNSYS or Modellica). This is also valid for ATES and MTES applications.

3.3.2 Best practices guidelines for design and construction

The BTES design should preferably be cylindrical in order to maximize the storage volume to surface area ratio and minimize the heat loss. The distance between the boreholes should be chosen as a trade-off between the investment and the heat exchange capacity of the BTES. High quality cross-linked high-density polyethylene (PEX) pipes are normally used as they are strong, chemical resistant and can withstand high pressures and high temperatures.

The drilling cost may account for approx. 50% of the total construction costs. Soft sediments can be more challenging and time consuming than hard rock and normally direct rotary mud drilling is considered to be the most efficient method for soft sediments. The drilling contractor will normally require a “safety distance” between boreholes in order not to risk drilling through neighbour boreholes, if the borehole path is deflected from vertical. It is recommended to use a casing during drilling in soft sediments to avoid cavities and excessive use of expensive grout as well as collapsing boreholes.
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. Grouting must be carried out from the bottom of the borehole and upwards. It is recommended to use a thermally enhanced grout in order to reduce the “thermal resistance” of the borehole.

A top insulation of the BTES is necessary to reduce the heat loss and may account for 25% of the total construction costs. The top insulation must be designed taking local climate and BTES temperatures into consideration together with the actual need for reducing the heat loss. Foam glass gravel have been used as insulation material, but is expensive and mussel shells have proven to be a significantly more cost-efficient option. A BTES system should always include dedicated boreholes for temperature sensors both in- and outside the storage volume to monitor the storage temperatures and heat loss to the surroundings. The environmental impact of increased ground temperatures in connection with HT-BTES can potentially lead to microbiological and geochemical changes, but the subject is not well investigated. Antifreeze is hardly necessary in the heat carrier fluid in HT-BTES, but is also not necessarily a significant environmental problem, while different types of additives can potentially be more problematic.

Regarding the system integration, HT-BTES is relevant in combination with especially solar panels, waste incineration, industrial waste heat and power to heat applications. A BTES reacts relatively slowly during charging and discharging and normally a buffer heat storage like e.g. a water tank is necessary as part of the system. All elements and subsystems and their interaction with each other must be modelled and designed carefully using e.g. TRNSYS or other model tools. For modelling of the BTES performance, it is important to represent the borehole depth, number of boreholes and borehole spacing as correctly as possible as well as defining parameters such as the thermal conductivity, heat capacity and diffusivity of the soil/rock, the combined thermal conductivity of the tubes and grout (the borehole resistance) and the thickness and thermal conductivity of the top insulation. The thermal properties of the ground can impact both the efficiency of the BTES in terms of heat loss and the total system efficiency e.g. in terms of solar fraction used. The local climate should be taken into consideration in the design of a BTES system, but is not likely to have a major impact on the system performance.

3.3.3 Best practices guidelines for operation, monitoring and maintenance

In general, the maximum and minimum storage temperatures, respectively, during charging and discharging are ranging between 30℃ and 60℃ and sometimes up to 70-80℃. Where it can be observed/calculated, the storage efficiency is ranging between 45% and 60% and is lower than expected/modelled. In general, a start-up period of a few years should be expected to heat up the storage and the surroundings. A buffer system is necessary to take full benefit from e.g. the solar panel-BTES coupling. Lower performance than expected can be due to the modelling approach used in the planning and choice of parameters not reflecting the actual conditions.

3.4 Best practice guidelines for PTES

3.4.1 Best practices guidelines for pre-investigation and feasibility study

This section is based on the feedback collected from existing PTES systems in Denmark. Lessons learned and recommendations for PTES design and realization can be found in report D1.1 and D1.2, based on the experience collected on six Danish PTES.

Various geographical data (topographical, geotechnical, hydrogeological, etc.) can help to exclude locations not well suited for PTES early in the planning/screening process. A PTES requires a lot of surface space and is subject to availability and possible constraints (archaeological, etc.), and they must in some cases be located several km away from the DHN.

3.4.2 Best practice guidelines for design and construction

Several TRNSYS components for PTES have been tested in the framework of HEATSTORE, with or without axial symmetry (i.e. cylinder Type 342, inverted truncated pyramid Types 1300 and 1301, inverted truncated cone Type 1322). All are in good to excellent agreement with the experimental data (see report D2.3), especially after calibration. Comparison with system measurements have also shown that such components used in the design phase can provide results in good accordance with monitoring (see report D2.1). The inverted truncated cone model, Types 1300 and 1301, seems to be the appropriate tool for design calculations, as it is both faster than Type 1322 and more accurate than Type 342. Type 342 may however be used in early stage feasibility studies, where little information is available, as it is extremely fast and provides decent results. No matter the component used, using advanced system calculation programs such as for instance TRNSYS can enable the study and optimization of the entire system, including control strategy, sizing of the system's elements, etc., provided that the underground storage model behaves in a realistic way.

During construction, experience from several cases showed that a specific attention should be drawn to weather adaptation (rainfall, snow/freezing, wind) and anticipation. Measures should be ready in case any likely/standard climatic event (for the construction location) should occur. Another important measure is to check water-tightness of the liner. For this purpose, some specific electrical tests can be carried out to check the welding areas, but there are also permanent solutions that can be installed under the liner and that will detect any leakage, as well as where it occurs. The last main point of attention during the commissioning phase is the corrosion and more generally speaking the water quality. During filling of the PTES, the conditions should be such that no dirt can come in from the outside. Inlet water should be filtered, its pH controlled (to a high value of 9.6-9.8) and contained salts, removed (through a reverse osmosis process). Several measurements should be checked to ensure water quality is maintained throughout the filling process as well as during operations: pH, oxygen content, bacteria, salts. Good practice also calls for a contractually independent quality check of the work done, especially for the liner work.

3.4.3 Best practice guidelines for operation, monitoring and maintenance

Besides from the aforementioned storage water quality monitoring required during the operation phase, other parameters need to be managed during operations of a PTES. Rainwater "puddles" have been observed to form on the surface of several PTES, including Dronninglund (see "Danish HEATSTORE Theme Day" on the HEATSTORE website www.heatstore.eu). It was estimated to be the greatest threat to the long-term viability of this PTES since it compresses the insulation and leads to an increase of the heat losses. The compressed insulation in turn caused the fixation irons of the insulation blocks to penetrate and tear apart the floating plastic liner above the water volume of the PTES. As a result, the intake of hot water from these holes caused the insulation to deteriorate at an even faster rate. The mitigation measures include identification of hot “puddles”, opening the top-liner above those puddles, patching any hole, replacing the insulation layer that got too thin and removing any iron pieces.

Another problem encountered by the PTES lids is the presence of air bubbles under the lid, which increases heat losses from the top water layer to the insulation (and in turn to the air).

Infrared (IR) measurements of the PTES surface from a drone can help identifying any unexpected/irregular raise of temperature. This has been done on five PTES in Denmark in October 2020: Vojens (203.000 m^3), Dronninglund (60.000 m^3), Gram (122.000 m^3), Toftlund (85.000 m^3), Marstal (75.000 m^3). Similar puddles and hot spots were observed on Vojens, Gram, Toftlund and Dronninglund, but not Marstal, which was equipped with a new lid solution. The insulation of the Gram PTES was refurbished: the PTES was covered with an extra thin layer of Leca (expanded clay) and 15 cm of Extruded Polystyrene (XPS) placed between 2 Geonets. IR measurements proved that this was effective – at least in the months following the refurbishments. Recent monitoring data confirmed the improvement, with estimated losses of over 40% before the change and 23% after (presentation by PlanEnergi at the 3rd Danish national sharing day on October 27th, 2021).

A new lid solution has been developed for Marstal by Aalborg CSP (Figure 44). It relies on the combinations of a cover divided into sub-sections, and a multi-layer lid including a PE foam designed by the company NMC termonova to withstand temperatures of 100°C, and testing showed that it can withstand 95°C for several years. The top cover construction is open to diffusion in order to avoid water accumulation inside the insulation material. The top cover surface is built in sections, each with their own drainage system for surface water and air bubbles under the lid (see Figure 44). The latter innovations are subject to patents. IR measurements show that the new lid in Marstal only has detectable hotspots at ventilation and pump housings, as expected. Therefore, the proposed solution seems to be effective.

During operations, using monitoring data to estimate the total heat losses over the past year is a good way to follow up on the insulating properties of the PTES lid. Total heat losses can be estimated by monitoring PTES energy content, and energy charged into or discharged from the PTES. Such a procedure has been presented during the 3rd Danish national sharing day. Applied to Dronninglund, this procedure would have led to identifying degradations of the lid sooner and maybe avoid completely renovating the lid. It can also help following up on the results of a renovation (like in Gram, Marstal, and soon Dronninglund).

Figure 44: Aerial view of the new lid solution implemented in Marstal, displaying the 12 sub-sections[1].

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[1] https://www.aalborgcsp.com/projects/10000-insulating-lid-solution-for-ptes-denmark/

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