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HEATSTORE – Underground Thermal Energy Storage (UTES) – State of the Art, Example Cases and Lessons Learned

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ABSTRACT

As part of the EU GEOTHERMICA – ERA NET Cofund project HEATSTORE, important lessons learned and operational experience from existing High-Temperature Aquifer Thermal Energy Storage (HT-ATES), Borehole Thermal Energy Storage (BTES) and Pit Thermal Energy Storage (PTES) have been compiled together with Mine Thermal Energy Storage (MTES) current state of technology. Through a literature study and based on actual experience and know-how among the HEATSTORE project partners, relevant cases in, and outside, Europe have been described. Essential learnings covering the entire process from the first pre-investigation phase and feasibility studies through the construction phase, system integration and operations as well as different national legislative, political and public issues are summarized.

1. INTRODUCTION

Throughout the world, we are beginning to experience more extreme weather conditions with cloudbursts and storms, floods, drought and forest fires, believed to be associated with climate change and increasing global temperature. As a response, the majority of the global community has agreed in the Paris Agreement to pursue efforts to limit the temperature increase to 1.5°C. According to the IPCC, this will require a 45% reduction in greenhouse gas emissions by 2030 compared to 2010 and zero emissions by 2050 and in the necessary transition to fluctuating renewable energy sources, energy storage will be essential to balance the match between demand and availability. In Europe, half of the total energy consumption is for heating and cooling and around 85% of this energy is produced from fossil fuels, and Underground Thermal Energy Storage (UTES) has the potential to play an essential role in the implementation of e.g. geothermal, waste heat, wind and solar as alternative energy sources in the district heating sector. However, UTES technologies need to be further developed and to become an integral component in the future district heating infrastructure in order to meet the expected variations in both availability and demand of heat. Therefore, the EU Geothermica HEATSTORE project aim to pave the way for commercial implementation of the technology through de-risking, cost reduction and optimization. This will be achieved by conducting 6 new high temperature (~ 25°C to ~ 90°C) underground heat storage demonstration pilots and 8 case studies of existing heat storage systems with distinct configurations of heat sources, heat storage and heat utilization.

One of the first activities in the HEATSTORE project has been to compile important lessons learned from existing UTES systems. The experience from the different project phases will be presented here, starting with pre-investigation and feasibility studies followed by the construction phase, system integration and the system operation stage. These lessons learned will now feed into the demonstration sites in HEATSTORE in the Netherlands, Belgium, France, Switzerland and Germany, where pilot projects are established. The HEATSTORE project is carried out by 23 partners in 9 countries.

2. THE UTES TECHNOLOGIES IN HEATSTORE

The HEATSTORE project comprises four different UTES systems:

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

2.1 HT-ATES

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

Figure 1 illustrates the principles of seasonal heat storage by the use of ATES in district heating. In the summer e.g. solar collectors will add surplus heat to the aquifer. The heat is then stored for the winter period, where it is used in the district heating network. Large heat pumps can be installed to boost the temperature depending on the outlet temperature from the aquifer storage.

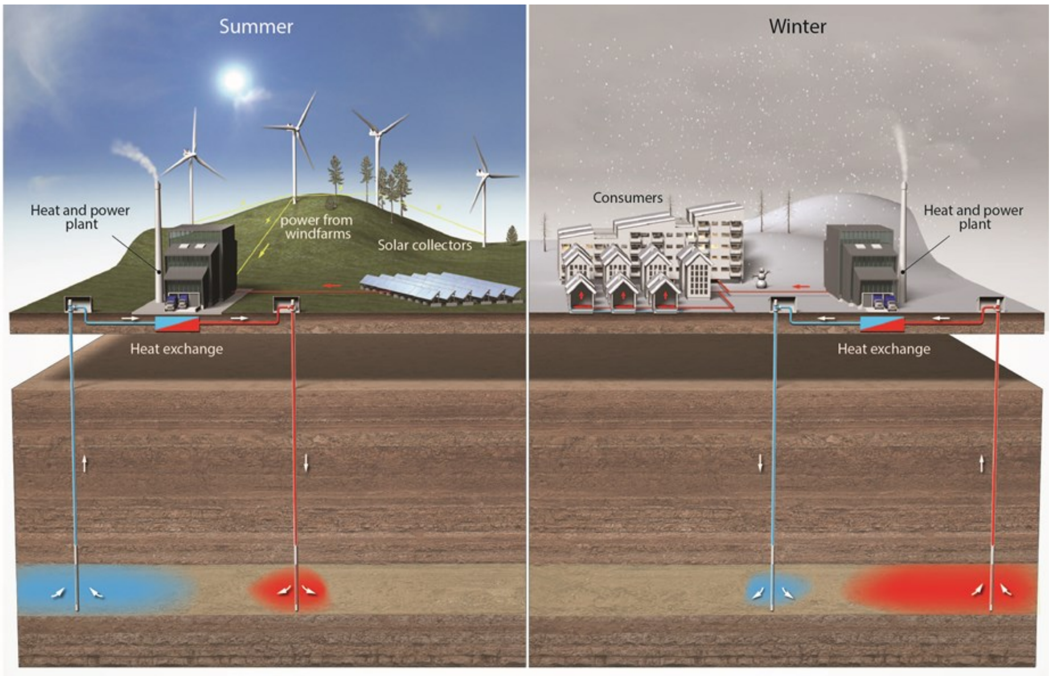

Figure 1: The principles of seasonal heat storage by the use of ATES in a district heating network (from GEUS, 2019).

2.2 BTES

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

Temperatures up to approx. 90°C can be stored (Sibbitt and McClenahan, 2015) and BTES can be used to store excess heat from industries, incineration plants and heat from renewable energy sources such as solar thermal for use in district heating. BTES is ideal for integrating heat from various sources, e.g. heat pumps, solar thermal and CHP (Combined Heat and Power) plants in combined energy systems utilising power to heat (heat pumps) in periods with excess electricity production and store heat from periods with need for electricity production from CHP. Due to a relatively low heat transfer coefficient, BTES storage does not react very fast. In cases where fast reaction is required a fast reacting buffer storage (e.g. a water tank) can be used (Sibbitt and McClenanhan, 2015).

2.3 PTES

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

The main advantages of the PTES concept are the possibility for quick charging or discharging, short heat storage periods and the fact that water is ideal as storage medium due to high thermal capacity. If the ground conditions are favorable, the construction costs are low. One of the disadvantages to keep in mind is that the system is space demanding. The storage requires large areas without infrastructure, which makes it less feasible in urban areas. The lifetime of liners and the lid construction is still partly unknown. High groundwater levels and poor soil conditions directly affects the construction costs.

2.4 MTES

Mine water of abandoned and flooded coalmines can be used as a low-temperature energy source for heating buildings and a few plants exist in Germany and the Netherlands. However, so far, no attempts have been made to store thermal energy in mine water and thus, the planned HEATSTORE MTES pilot project in Germany will be the first of its kind.

3. LESSONS LEARNED COMPILED IN HEATSTORE

Screening for geographical parameters such as geological conditions, surface activities and district heating networks etc., in an early stage, is a prerequisite for pointing out potential locations and assess which type of heat storage application is most likely suitable. In the design phase, careful modelling of the entire existing and future energy system including the subsurface dynamics is very important to predict the behavior and performance of a UTES. In order to define the optimal design, it is necessary to account for the performance of all of the subsystems and their interactions with each other as well as for the heat load and the local climate and weather conditions. Mathematical models representing each of the components can be connected together to simulate the whole system. Several different simulation tools for system level analysis are available, e.g. TRNSYS, EnergyPlus, and ESP-r, with TRNSYS being one of the most commonly used for simulating large scale seasonal storage systems in many countries (Sibbitt and

McClenahan, 2015). Other important factors having an impact on the development of UTES systems are different socio-economic and legal/regulatory barriers. The market barriers of HT-UTES are to some point similar in the HEATSTORE partner countries, but different stages of market matureness influence how, and to what degree, the national regulations are adapted to HT-UTES applications.

3.1 HT-ATES systems

Low temperature (< 30°C) heat and cold ATES systems are the most common systems, especially in the Netherlands with around 2,500 operating systems. When looking at systems with injection temperatures above 30-40°C, the number of implemented systems are very few, and only 5 high temperature systems (>60°C) are currently in operation worldwide (Fleuchaus, P. et al., 2018).

The advantages of ATES systems include very large storage potential, low operational costs and high long-term profitability. The known technical challenges mainly include high return temperatures on the surface site and hydro-geochemical challenges such as precipitation and scaling in wells and pipes. Weathering of the geological formation and other geochemical and rock mechanical effects resulting in formation damage are also known challenges which could be encountered at the demo sites in the HEATSTORE project.

Heat storage by the use of HT-ATES can be applied in areas where large thermal storage capacities are required. The expected important markets are found to be: Large-scale storage of residual heat from the industry, from waste incineration plants or residual heat from power plants/Combined Heat and Power (CHP).

Two of the first systems in Europe to demonstrate the High Temperature ATES approach were Plaisir Thiverval-Grignon in France (1985-1987) and Utrecht University in The Netherlands (1991-1997). The system in France was designed to store excess heat from a waste incineration plant and the intended storage temperature was 180°C. Due to problems with well clogging in especially the injection wells, the demonstration site was closed down. At Utrecht University the HT storage was stopped due to well problems and a system integration mismatch regarding the required temperatures and the temperatures the storage could provide (Bakema and Drijver, 2018).

A total of nine HT-ATES and two MT-ATES systems described in the literature have been identified, see Table 1. Supplementing these are four planned systems, with three of these being a part of the HEATSTORE project. Conventional geothermal systems (i.e. direct use of heat) are not included in the compilation.

Table 1: Table overview of previous, existing and planned HT-ATES and MT-ATES systems in and outside Europe.

Year	Location/project	Status	Heat source	Injection temp.	Aquifer depths
1976	Auburn University, Mobile/AL, USA	E/C	Hot waste water	55°C	41-61 m
1982	SPEOS, Lausanne - Dorigny, Switzerland	C	Waste water treatment	69°C	-
1982	Hørsholm, Denmark	D/C	Waste combustion	100°C	10 m
1982	University of Minnesota, St. Paul, USA	E/C	-	115°C (150°C)	180-240 m
1987	Plaisir Thiverval-Grignon, France	E/C	Waste combustion	180°C	500 m
1991	Utrecht University Netherlands	D/C	CHP	90°C	220-260 m
1998	Hooge Burch, Zwammerdam near Gouda, Netherlands	D/C	CHP	90°C	135-151 m
1999	Reichstag, Berlin, Germany	D/O	CHP	70°C	300 m
2004	Neubrandenburg, Germany	O	CHP	75-80°C	1,250 m
2009	Geostocal, France	E	Waste combustion	95°C	1460 m
2015	Duiven, Netherlands	FS	Waste combustion	>140°C	-
Planned	BMW, Dingolfing, Germany	FS	-	130°C	500-700 m
2019 -	HEATSTORE pilot (ECW), Netherlands	D	Surplus geothermal heat	90°C	300-400 m
2019 -	HEATSTORE pilot, Geneve, Switzerland	FS/D	Waste combustion	>50°C	1100 m
2019 -	HEATSTORE pilot, Bern, Switzerland	FS/D	Surplus heat	120°C	200-500 m

D = demo site , E = Explorative, C = Closed, FS = feasibility study; O = in Operation; CHP: Combined Heat and Power

3.1.1 Pre-investigation (feasibility study)

Experiences from the pre-investigation and feasibility phase emphasizes that a geological/hydrogeological screening and stakeholder involvement from the start are essential elements. Next step is to do a first test drilling that reaches the potential storage aquifer. The drilling should include pump testing and geophysical borehole logging (Pauschinger et al., 2018). Important in the design phase is also to calculate the thermal efficiency with 3D heat transport models based on thorough 3D geological and hydrological models. Regarding the local groundwater chemistry, hydro-chemical modelling as a first assessment of the necessity of water treatment is recommended by Bakema and Drijver (2018).

3.1.2 Construction

In the construction phase reverse rotary drilling with air-lift is typically chosen in unconsolidated sediments as a standard technology for HT-ATES because of well diameter and clean drilling process. In the wells the use of submersible pumps are preferable. Specifically ESP's (Electric Submersible Pump) are suitable for high temperatures (warm wells), and are commonly used in oil and gas or geothermal applications). In the cold wells standard low temperature submersible pumps can be used. All materials should generally be resistant to corrosion (Bakema et al., 2018).

3.1.3 System integration

An efficient integration of HT-ATES in e.g. district heating is dependent of a match between the requirements of the consumers (demand profiles, temperature profiles etc.), the specifications of the network (size, base load, peak load, supply and return temperatures etc.) and the characteristics of the HT-ATES storage (production temperature, flow rate, flexibility) as described in Fleuchaus et al. (2018). Also the charging period of the storage to the designed temperature levels needs to be included in the system integration. Bakema and Drijver (2018) states from the Dutch experiences of HT-ATES that systems generally should be large enough to store at least 300,000 m^3 of water per season and that a thermal power of minimum 5 MW is required to prevent high thermal losses. Early HT-ATES systems show that storage temperatures (warm well, cold well and cut-off temperatures, i.e. outlet temperature from the district heating network) in some cases have not been well fitted to the building system. Likewise, the heating system in buildings have not always been adapted to the possible extraction temperatures from the heat storage. Finally, also the well capacity (and declining well capacity) needs to be evaluated and not overestimated in the process of realizing a proper system integration with the surface installations.

3.1.4 Operations feedback – monitoring and maintenance

Detailed performance monitoring of the operation of a HT-ATES system is important in order to diagnose and optimize the system in order to be able to deliver the energy efficiency that the system was designed for. To monitor the heat and water quality in the aquifer, it is advised to install a separate monitoring well at a certain distance to the hot well of the HT-ATES system. It can be considered to use fiber optic techniques instead of measuring temperatures in the wells or monitoring lines using temperature sensors (Bakema et al., 2018).

Regarding maintenance of HT-ATES systems one of the key challenges is to prevent clogging of especially the injection wells. Clogging of the well screens can happen due to changes in water chemistry affected by mixing of waters, change of temperatures and change in pressure. Known challenges in water treatment for systems handling high storage temperatures are clays swelling due to Ca/Na ion exchanges, precipitation of $CaCO_3$ or corrosion. Water treatment such as HCl treatment is a proven technology to use in water with a high pH. The main disadvantage is the use of large quantities of HCl. In some cases the use of reaction inhibitors to decrease or prevent chemical reactions can be relevant to consider. Repeated regeneration of wells should also be implemented in the maintenance budget to prevent significant decreases in system efficiency (Bakema et al., 2018).

3.1.5 External factors

The national legislative framework is generally described as a main barrier to overcome regarding development and implementation of HT-UTES in many countries in Europe. The legislation is currently generally not adapted to e.g. HT-ATES systems, and as a consequence the permit procedures can be long, uncertain and expensive. A common challenge is that injection temperatures to the main storage aquifer often not are allowed to exceed 20-25ºC for ATES applications in the upper few hundred meters of the subsurface. Requests for a clear regulative framework are therefore high on the agenda in order overcome this barrier and help bridging the knowledge gap for important stakeholders.

The investment costs are typically mentioned as an economic barrier for implementing HT-ATES applications. Comparing HT-ATES with other more conventional energy systems, the initial investments cost are relatively high, but the payback time of the systems are potentially low - the break-even point is often within 10 years. However, test drillings and the need for additional field data in the feasibility study can deter project developers as well as the fact that there is not full certainty for a successful outcome (Bloemendal et al., 2016).

3.2 BTES systems

A total of eight HT-BTES systems described in detail in the literature have been identified as well as four less well-described HT-BTES systems and five low-temperature BTES systems. Out of the 17 identified systems, 11 are located in HEATSTORE partner countries and 6 in other countries and in HEATSTORE a pilot BTES is planned in France.

The size of the systems varies significantly and appears to have an impact on the BTES efficiency although other parameters like the shape of the storage volume and the maximum storage temperature can also play a major role. In the following, the lessons learned from the review of existing information on the 17 identified BTES systems are summarized, see Table 2.

Table 2: Table overview of previous, existing and planned HT-BTES and BTES systems in and outside Europe.

Country	Location	Energy source	Application	Start of operation	Borehole depth (m)	Max. Temp. (°C)	Estimated capacity (MWh)	Storage efficiency	Soil type
Canada	Drake Landing	Solar	Domestic (52 homes)	2006	35	80	780	50%	Sand silty, clayey
Sweden	Luleå	Industrial	n/a	1983	65	65	2000	45-55%	Crystalline rock
	Emmaboda	Industrial	Office buildings	2010	149	45	3800	n/a	Crystalline rock
	Anneberg	Solar	Domestic (50 homes)	2002	65	45	1467	46%	Crystalline rock
Czech Republic	Paskov	CHP	Test site	2011	60	78	555	n/a	Clay/miocene rocks
Germany	Neckarsulm	Solar	Domestic (300 homes, shops)	1997	30	65	1000	n/a	Clay
	Crailsheim	Solar	School buildings	2008	55	65	1135	n/a	Mudstone/ Limestone
	Attenkirchen	Solar+ hybrid	Domestic (30 homes)	2002	30	n/a	77	n/a	n/a
Denmark	Brædstrup	Solar	District heating	2013	45	70	616	61%	Clay/till
Belgium	Mol	Wast heat	Building	2002	30	82	130	n/a	Sand saturated
Netherlands	Groningen	Solar	Domestic (96 homes)	1985	20	50	595	n/a	Sand, clayey
Finland	Kerava	Solar+ hybrid	Domestic (44 homes)	1983	25	50	n/a	n/a	Soil and bedrock
Switzerland	Wollerau	Heat pump-Gas	Office buildings	1998	120	n/a	350	n/a	n/a
	Root Lucerne	LTN-heatpumps	Office buildings	2003	160	n/a	n/a	n/a	Sandstone
	Suurstoffi	Building cooling	District heating and cooling	2012	150	n/a	n/a	n/a	n/a
	Oberfeld	PVT	Domestic (100 homes)	2012	125	n/a	n/a	n/a	n/a
	Blatten Belalp	Solar	Residential	2014	120	n/a	n/a	n/a	n/a
France	HEATSTORE pilot, Chémery	Solar	Office buildings	2020?	-	-	-	-	-

3.2.1 Pre-investigation (feasibility study)

First of all, an initial feasibility screening with an evaluation of the geological conditions based on available data and taking existing or planned/expected heat load and heating infrastructure into consideration must be carried out and followed by modelling of the entire planned system. The required preliminary geological parameters of the site are:

- Geology
- Groundwater flow
- Thermal properties

Significant groundwater flow through the storage volume will cause advective heat loss and should be avoided (Catolico et al., 2016) and the local geology have an impact on the drilling costs as well as on the thermal properties of the soil/rock. For the thermal properties, the higher the heat capacity the better, while a low thermal conductivity of the storage volume increase the recovery efficiency, but decrease the rate of charging/discharging, e.g. Sibbitt and McClenahan (2015) and Catolico et al. (2016). Since the rate of charging/discharging can be an important factor and is favoured by high thermal conductivity, medium thermal conductivities may turn out to be the most favourable (Catolico et al., 2016).

Secondly it is recommended always to perform a test drilling to verify the ground conditions and the estimated drilling costs and also to perform a thermal response test to verify the thermal properties of the site.

3.2.2 Construction

Materials and system design

Regarding the shape of the storage volume and layout of boreholes, the BTES design should preferably be cylindrical in order to maximize the storage volume to surface area ratio and thereby minimize the heat loss (Sibbitt and McClenahan, 2015). Furthermore, the layout of borehole locations are important and should be optimized according to both the most favourable cross section area per borehole and distance between drilling locations required by the drilling contractor.

Normally the tubing of the Borehole Heat Exchangers are connected in order to heat up the storage from the center and outwards, and vice versa when discharging as this will reduce the heat loss and optimize the efficiency (Sibbitt and McClenahan, 2015). Regarding tube material, high quality cross-linked high density polyethylene (PEX) tubes are normally used as they are strong, chemical resistant and can withstand high pressures and high temperatures. Double u-tubes are more efficient than single u-tubes, but coaxial tubes are, at least theoretically, the most favourable, e.g. Malmberg et al. (2018). It is recommended to use so-called spacers to separate the down- and upflow tubes and avoid a "shortcutting" heat transfer between the tubes. Open tubes with direct contact between the heat carrier fluid and the borehole wall (rock/soil) should be avoided as operation problems were previously experienced in older systems in Sweden (Luleå and Emmaboda, see Table 2).

Drilling and grouting

The drilling cost may account for approx. 50% of the total construction costs for a BTES, e.g. Schmidt and Miedaner (2012), and soft sediments can be more challenging and time consuming for the drilling work than hard rock. Normally, direct rotary mud drilling is considered to be the most efficient method for soft sediments and 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. 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.

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. The general recommendation is, that the grouting is carried out from the bottom of the borehole and upwards and it is recommended to use a thermally enhanced grout in order to reduce the "thermal resistance" of the borehole.

Top insulation, monitoring, environmental impact
A top insulation of the BTES is necessary to reduce the heat loss and may account for 25% of the total construction costs, e.g. Schmidt and Miedaner (2012). Foam glass gravel have been used as insulation material, but is expensive and mussel shells has proven to be a significantly more cost-efficient option. The top insulation must be designed taking local climate and BTES temperatures into consideration together with the actual need for reducing the heat loss.

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 in order to be able to determine and understand the system efficiency and (hopefully) verify the business model for the system.

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 and more research in this topic is probably needed in order to improve the public acceptance of the technology, e.g. Bonte et al. (2011), Gehlin et al. (2016) and Malmberg et al. (2018). Antifreeze in the heat carrier fluid is normally applied in Borehole Heat Exchangers (BHE) used only for heat extraction in combination with heat pump technology, but is hardly necessary in the heat carrier fluid in a HT-BTES system. Neither is antifreeze necessarily a significant environmental problem, but different types of additives frequently used in BHE's can potentially be more problematic for the environment.

3.2.3 System integration

HT-BTES is relevant in district heating in combination with especially solar panels, waste incineration, industrial waste heat and power to heat applications, but since a BTES system reacts relatively slowly during charging and discharging, normally a buffer storage like e.g. a water tank is necessary as part of the system (Lanahan and Tabares-Velasco, 2017).

When designing the storage, all elements and subsystems and their interaction with each other must be modelled and designed carefully. 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, e.g. Sibbitt and McClenahan (2015).

In order to include all the systems a BTES interacts with, it is usually necessary to include parameters such as the heat load imposed by a district heating system or building complex etc., the heat supply from each source (e.g. a solar collector array) and the expected seasonal storage scheme (Sibbitt and McClenahan, 2015). The local climate should also be taken into consideration in the design of a BTES system, but is not likely to have a major impact on the system performance.

The volume of a BTES has to be 3-5 times larger compared to an above-ground tank storage because of the lower heat capacity of the ground than water and the minimum volume of a BTES in order to be energetically and financially viable should be around 20,000 m^3 according to Mangold and Deschaintre (2015). With respect to size, one advantage of BTES is that it can be planned in a modular design making it possible to easily connect additional boreholes.

3.2.4 Operations feedback

In general, the maximum and minimum storage temperatures, respectively, during charging and discharging are ranging between 30˚C and 60˚C and sometimes up to 70-80˚C in the 17 identified BTES systems. It has only been possible to obtain a measure of the storage efficiency from 4 of these (Drake Landing, Luleå, Anneberg and Brædstrup, see Table 2) and here the efficiency is ranging between 45% and 60% and is often lower than expected. According to e.g. Malmberg et al. (2018) part of the reason can be that in general a start-up period of a few years should be expected to heat up the storage and the surroundings. Also a higher heat loss in the distribution system and higher indoor temperatures on the demand side than expected as well as lack of a short term buffer system can reduce the overall system efficiency compared to the expectations (Malmberg et al., 2018) and in general lower performance than expected is often due to the modelling approach used in the planning and choice of parameters not reflecting the actual conditions (Lanahan and Tabares-Velasco, 2017).

3.2.5 External factors

Among the potential barriers against HT-BTES is the lack of a clear regulative framework in many countries as well as lack of knowledge on the technology among important stakeholders. Also the risk of not getting a permit or a time consuming permit procedure can be an obstacle and furthermore, the initial investment costs are relative high as well as the business case for a HT-BTES may to a high degree depend on cheap or almost free surplus heat.

3.3 PTES systems

The PTES concept is presently realized at five locations in Denmark and one new system is currently being planned. The first system in Marstal started as a pilot plant in 2003. All five operating PTES systems are used in combination with solar heat and connected to district heating networks. Location, storage volume and capacity are shown in Table 3 below.

Table 3: Overview of existing and planned PTES systems in Denmark.

Year	Location/Project	Storage volume	Storage temp.	Capacity
2003/2011	Marstal, Denmark	75.000 m^3	Up to 90°C	6.000 MWh
2013	Dronninglund, Denmark	60.000 m^3	Up to 90°C	5.600 MWh
2014	Gram, Denmark	122.000 m^3	Up to 90°C	10.000 MWh
2015	Vojens, Denmark	203.000 m^3	Up to 90°C	12.000 MWh
2017	Toftlund, Denmark	85.000 m^3	Up to 90°C	6.900 MWh
2019 – planned	Høje Taastrup, Denmark	70.000 m^3	Up to 90°C	3.300 MWh

As described in Section 2.3, PTES provides an efficient and fast reacting storage system, but requires a lot of open space, both for the pit storage itself and e.g. for solar collectors. These space requirements can make the system less feasible in urban areas.

3.3.1 Pre-investigation (feasibility study)

The important elements in the pre-investigation and feasibility phase, looking at the possibilities for establishing a PTES, is to investigate relevant characteristics of the geology and groundwater in the specific area of interest. Careful geotechnical investigations will help localize the groundwater levels. If near-surface groundwater levels are located it is important to get an estimate of the costs for drainage measures from the excavating entrepreneur (Jensen, 2015). The excavated soil from the pit is typically used to increase the height of the banks (see Figure 2) and thereby the total storage volume and the geotechnical investigations should therefore also confirm the quality of the soil to be excavated. Too much silt in the soil can potentially be a problem to achieve sufficiently stable pit banks.

3.3.2 Construction

In the construction phase, compression of the excavated soil rebuilt into the banks is necessary and must meet certain standards to be defined in tender documents and documented by samples and laboratory tests. Furthermore, the top of the banks must be precisely in the same level to account for a horizontal water level. A maximum deviation of 2 cm in bank elevation is normally tolerated in order not to lose storage capacity, see principle sketch in Figure 2.

The pit bottom and sides are covered with special liners, but before the liner contractor begins the liner installation on the pit floor and sides, stones have to be removed from the banks, and a geotextile with high penetration resistance must be placed to protect the polymer liner. Care has to be taken with liner material with respect to lifetime (temperature resistance) and vapour permeability. So far, the best experiences are with HDPE (High Density Polyethylene) material (Jensen, 2015). Research and testing on even more temperature resistant materials is ongoing. The liners needs to be welded together, typically with so-called double weldings, and pressure testing of the weldings is recommended as well as electrical tracer detection of the total area of liner and welds after the liner work has been completed. Insulation of sides and bottom is normally not necessary.

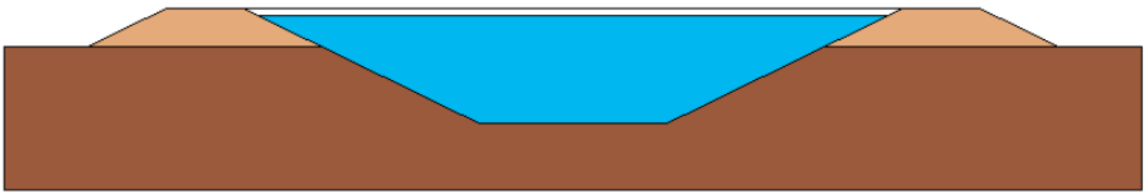

Figure 2: Danish PTES concept with soil balance shaped as a truncated pyramid placed upside down.

Construction of an insulating lid/cover to prevent heat loss is a crucial element in the construction phase. The lid is typically a floating element (as a fixed construction can be very expensive) and care therefore has to be taken with respect to tightness, draining of rainwater and preventing air pockets under the lid, which has proven to be a challenge in some cases. Examples of suitable insolation materials are: Leca (nuts of fired/expanded clay), Polyurethane, Nomalén, PE/PEX (cross-linked Polyethylene) mats (Pauschinger et al., 2018).

3.3.3 System integration

Regarding system integration PTES is well suited for seasonal storage (e.g. solar, waste heat, etc.), and short-term storage. PTES can be used with (or combinations of) solar heating, CHP, heat pumps and e.g. industrial waste heat. It enables flexible operation of CHP plants and grid balancing e.g. with excess renewable electricity using electrical boilers and heat pumps.

3.3.4 Operations feedback - monitoring and maintenance

Operating a PTES system requires effective monitoring and maintenance. Monitoring of the water temperature levels in the whole water column from bottom to top is important to ensure the best possible system yield. These measurements should be in general agreement with system calculations. As a part of the maintenance it is important repeatedly to check the storage water quality (district heating standards, e.g. pH and oxygen content). Equally important is that the filters protecting the heat exchangers should be cleaned regularly (Pauschinger et al., 2018).

The risk of leakage from lid or liner sides has to be assessed as it directly effects the system efficiency. Therefore it should be monitored continuously how much water is added to the pit as well as the water level in the PTES should be monitored. Eventual leakage in the liners can be repaired under water by divers (when the storage is not too hot). Awareness should also be on heat stratification in the PTES by temperature monitoring. If e.g. the PTES is connected to solar thermal, too high bottom temperatures might cause boiling in the solar system. It is recommended that rain water pumps for draining the lid are checked daily together with checking for water puddles on the lid and the entire construction should be checked yearly under water by a diver inspection.

3.3.5 External factors

The experience regarding legislative requirements for obtaining permission to establish a PTES system is primarily from Denmark. In Denmark the heaviest requirement is an environmental impact assessment to evaluate the impact of a future PTES system on the local environment. Also permission for seepage of groundwater drainage or seepage of rainwater from the top of the pit lid is needed. Regarding planning restrictions, change in status of land use and changes in district plans or municipality plans are necessary. None of these issues need to be regulative barriers if the process is carried out thoroughly.

3.4 MTES systems

The idea of obtaining thermal energy from an inoperative coal mine has been pursued for a long time, although to a limited extent, and until now thermal energy storage in a former coal mine has not been demonstrated in a pilot project. There are, however, examples of well-known projects that utilize mine water for heat extraction in Germany and The Netherlands. This is e.g. the Mijnwater-project in Heerlen (Netherlands), where an already completely flooded and no longer accessible mine layout was accessed through directional drilling technology to use the mine water as energy source for a heat pump. Also, mine water is being utilized at the former Robert Müser colliery in Bochum (Germany) as an energy source for the heat supply of two schools and a fire station. Within this pilot plant the 20°C warm mine water, which originates from the mine drainage of the RAG AG from a depth of -570 m NHN, is being used.

The thermal utilization of the mine water from existing mine drainage stations e.g. in Bochum show high economic efficiency, as no additional pumping costs are being generated. However, due to the lack of suitable customers, a further expansion currently only takes place to a limited extent. The “open” utilization plan of the Mijnwater-project could be realized in the Netherlands because the mine workings were already flooded after being closed down.

The aim of the German HEATSTORE sub-project is to create a technically and fully functional seasonal MTES pilot plant for the energetic reuse of the abandoned coal mine Markgraf II in Bochum, with the emphasis on an extended operating and monitoring phase during the HEATSTORE project lifetime. The conceptual idea is based on storage of seasonal unutilized surplus heat during the summer from solar thermal collectors within the mine layout and to use the stored heat during the winter for heating purposes of the institute buildings of the International Geothermal Centre (GZB).

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

5. CONCLUSIONS

5.1 Conclusions HT-ATES

The advantages of ATES systems include very large storage potential, low operational costs and high long-term profitability. Experiences from the existing HT-ATES systems have been that some are designed in a too small scale which makes them vulnerable for high thermal losses. Experiences from the Netherlands show that a thermal power of at least 5 MW is required. The storage temperatures (warm well, cold well and cut-off temperatures) have in many cases not been well fitted to the building system. Or, the heating system in the building(s) has not been properly adapted to the possible extraction temperatures from the heat storage (Bakema and Drijver, 2018).

The aquifer characteristics and thus heat storage parameters are defining the heat storage potential and performance. Experiences from unconsolidated sediments in the Netherlands show that aquifers with a horizontal hydraulic conductivity between 3-7 m/d are preferable. If the aquifer consists of too coarse sands, heat losses by density driven groundwater flow will be large. As a guideline, experience from HT-ATES systems so far indicate that the aquifer should be able to store at least 300,000 m^3 of water to make the storage profitable (Bakema and Drijver, 2018).

Important research topics that are part of the HEATSTORE demonstration projects are water treatment (e.g. use of CO_2 as treatment agent), focus on component selection to prevent corrosion and improved knowledge on scaling of wells and heat exchangers as well as focus on thermal efficiency in different geological conditions (computer modelling and field testing).

5.2 Conclusions BTES

A BTES storage is a passive system and the economical and energetic efficiency will be defined by the input and output parameters in terms of temperatures and heat load, the thermal properties of the storage and the entire system integration. The design of each project must be adapted according to the specific geological parameters of the actual site (soil/rock types, groundwater level, groundwater flow, thermal properties etc.) as well as each element of the system should be optimized in the design phase using well-validated pre-design tools.

The specific costs drops significantly with increasing storage size and BTES systems should generally be larger than 20,000 m^3 of storage volume in order to be financially viable (Mangold and Deschaintre, 2015).

5.3 Conclusions PTES

Large scale PTES are so far mainly used in Denmark and in connection with solar district heating. Cost reduction has been the main driver for developing the Danish PTES concept with soil balance shaped as a truncated pyramid placed upside down. The status is that water is used as storage medium, welded polymer liners are used for tightening, the lid is floating on the water, and insulation materials in the lid are expanded clay or PE/PEX mats. The bottom and sides of the pit are uninsulated. The maximum storage temperatures are 90ºC.

The construction costs for large PTES storage systems are relatively low. A number of large-scale PTES were built in Denmark with investment costs of 20 – 40 €/m^3. High groundwater levels and poor soil conditions directly affects the construction costs. PTES integration facilitates high shares of renewable energy, enables flexible operation of CHP plants, can be used for both heating and cooling and has a high charge and discharge capacity.

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