Task 45 Large Systems

Seasonal thermal energy storage

Report on state of the art and necessary further R+D

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Content

Preface

The IEA-SHC Task 45 "Large solar heating/ cooling systems, seasonal storage, heat pumps" comprises three subtasks, where subtask B focuses on large storages (more than 1,000 m³ water equivalent) in combination with solar heating systems using sensible storage materials.

The general objective of this report is to present an overview of the state of the art of seasonal thermal energy storage and to summarize the further necessary research and demonstration work (R+D).

Subtask B of IEA SHC Task 45 only could gather quite few partners with quite low budgets. This strongly restricted the scope of this report. We especially thank Bruce Sibbitt from Natural Resources Canada, Per-Alex Sørensen from Planenergi, Dr. Dan Bauer from the University of Stuttgart and Dr. Thorsten Urbaneck from the Technical University of Chemnitz for their input to this report.

1 Introduction

1.1 Background

The technology of large scale seasonal thermal energy storage (STES) has been investigated in Europe since the middle of the 70's. First demonstration plants were realized in Sweden in 1978/79 based on results of a national research program. Thanks to an international collaboration via the International Energy Agency (IEA) (IEA SHC Task 7) seasonal thermal energy storages found their way through a part of Europe: Denmark, the Netherlands, Switzerland, Italy, Greece and Germany. While most of these countries stopped their research programs for seasonal thermal energy storages, in 1993 Germany raised the R&D program Solarthermie-2000 and the successor Solarthermie2000plus that was implemented by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Several technologies for STES have been further developed and tested within these projects, and eleven research and demonstration plants for solar assisted district heating with STES have been built in Germany since 1996.

The European market follows these developments, although slower in most of the countries. Since 2010, different European projects have begun, for example PIMES, in which the feasibility of three STES is studied in countries where the technology is not yet developed: Hungary, Spain and Norway. More European projects like EINSTEIN for retrofitting applications, PITAGORAS and SUNSTORE 4 include further developments of the long term thermal storage technology. Out of Europe, the interest about this technology awakened with the construction in 2006 of the pilot plant "Drake Landing" in Okotoks, Canada.

In the last years there is a growing market for STES in Denmark focusing on using very large storage volumes not only for storing solar thermal energy seasonally but for optimizing the economics of combined heat and power plant driven district heating systems within the Danish electricity market. While the storage in Marstal that was the first very large one with a volume of 75.000 m³ was realized within the European R+D project SUNSTORE 4, the follow-ups in Braedstrup, Dronninglund and Vojens were realized without comprehensive scientific accompaniment.

The IEA in its Heating and Cooling Roadmap (IEA Technology Roadmap energy-efficient buildings: heating and cooling equipment) and the District Heating and Cooling Technology Platform in its strategic research agenda (DHC+ Technology Platform, strategic research agenda) include thermal energy storages as central components in energy efficient systems of the future.

1.2 Definition and applications of the system

In Central Europe, the sun delivers around two thirds of its yearly irradiation between May and September. On the other hand, clearly over two thirds of the oil and gas consumption occurs during the heating period, from October to April (Figure 1). For this reason, seasonal heat storages are built to store the heat produced by big collector fields in the summer months and deliver it through district heating nets to heat the connected buildings in winter.

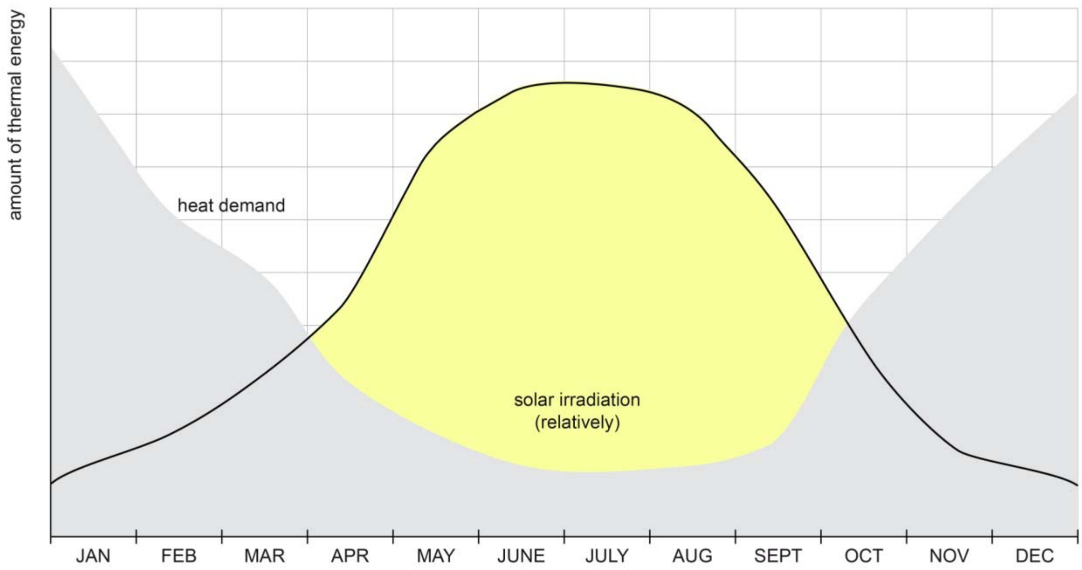


Figure 1: Solar radiation and heat demand repartition over a year (source: Solites)

Seasonal thermal energy storage offers a great potential for substituting fossil fuels using solar energy for domestic hot water preparation and space heating. However, there are further applications for this technology. Nowadays, other technologies are developed and spread, which need or could use seasonal storages of big volumes. For example:

- Increased use of biomass for electricity production
- Increased use of geothermal energy and similar
- Increased use of waste heat from the industry
- Increased use of heat energy from electricity production through combined heat and power plants. Heat storages can here regulate load variations and dissociate the electricity production from the heat production through storage.

Moreover, in a growing number of countries more and more electricity is produced from wind and solar. This means more and more variation - both short and long term - in the electricity production and more difficult conditions for the traditional CHP units. The “smart district heating” concept (Figure 2) is developing to assist in solving the problems connected to these two issues. Smart district heating combines renewable energy technologies and thermal storages in such way that the district heating system is linked in a very flexible and economic way with the liberal electricity market. Main features of a smart district heating system are long term storage, solar collectors, heat pumps and combined heat and power units.

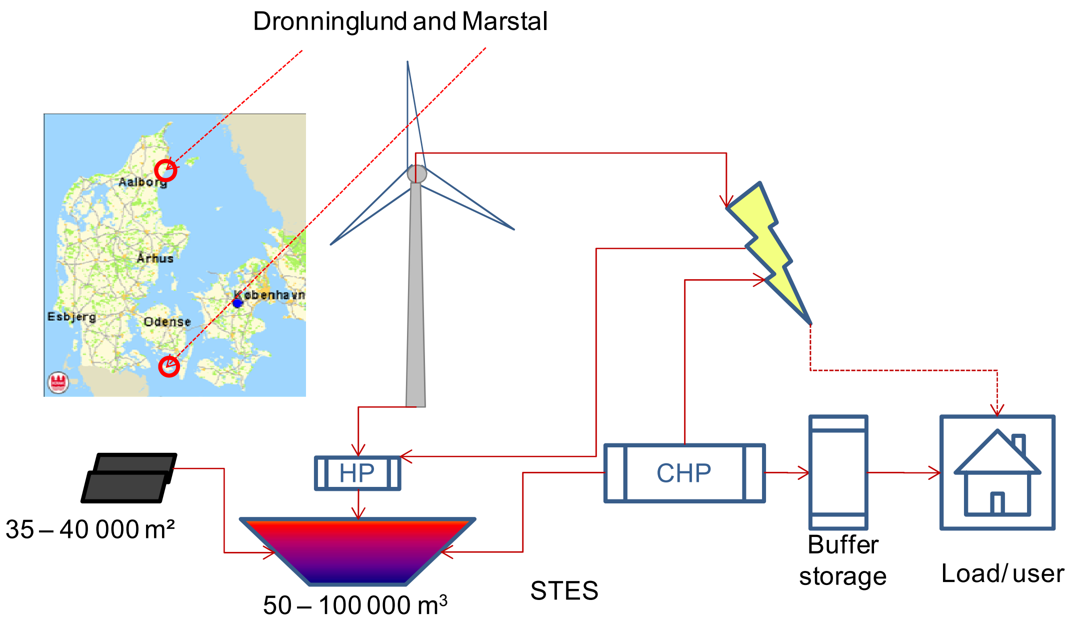


Figure 2: Example of Smart district heating system in Dronninglund, Denmark (source: PlanEnergi)

1.3 Limits of the report

This report concentrates on sensible heat storages, even if latent (using phase changing materials) and thermo-chemical storage are being researched at the moment. As the IEA Roadmap “Energy-efficient Buildings: Heating and Cooling Equipment” states (Table 1, source IEA Technology roadmap energy-efficient buildings: heating and cooling equipment), those technologies, however promising, are economically not suitable to store heat over really long periods like seasons, as sensible storages do.

Table 1: Energy capacities, power, efficiency and storage time of thermal energy storage technologies (source: IEA technology roadmap energy-efficient buildings: heating and cooling equipment, 2011)

TES technology	Capacity kWh/t	Power kW	Efficiency (%)	Storage time	Cost (USD/kWh)
Hot water tank	20-80	1-10 000	50-90	day-year	0.1-0.13
Chilled water tank	10-20	1-2 000	70-90	hour-week	0.1-0.13
ATES low temp.	5-10	500-10 000	50-90	day-year	Varies
BTES low temp.	5-30	100-5 000	50-90	day-year	Varies
PCM-general	50-150	1-1 000	75-90	hour-week	13-65
Ice storage tank	100	100-1 000	80-90	hour-week	6-20
Thermal-chemical	120-150	10-1 000	75-100	hour-day	10-52

Source: ECES and Roth, K. Zogg, R. and Brodrick, J. (2006).
Note: ATES stands for aquifer thermal energy storage and BTES stands for borehole thermal energy storage.

The first demonstration plants are already documented and studied within the IEA SHC program, Task 7 “Central Solar Heating Plants with Seasonal Storage (CSHPSS)” in 1990. The present report concentrate on the newer projects, which developments are however obviously based on the experiences exchanged within Task 7.

2 General aspects

Thanks to the construction of many model and pilot plants and their monitoring and evaluation, basic rules have been developed to design a seasonal thermal energy storage (STES).

2.1 Minimum size

To allow seasonal storage to technically and financially make sense, it needs a minimal size. A characteristic figure for the ratio of the heat losses to the amount of stored energy is the surface/volume ratio: the amount of the energy that is stored in the storage’s volume looses heat through the surface. Thus a small storage with a volume of e.g. 20 m³ has a surface to volume ratio that is eight times the ratio of a storage with 10,000 m³. Hence the heat losses referred to the stored energy are eight times higher for the small storage compared to the large one (Figure 3, source: Solites). That is the reason why storing solar thermal energy seasonally with sensible heat starts to be energy efficient with a storage volume of 1,000 m³ of water or more.

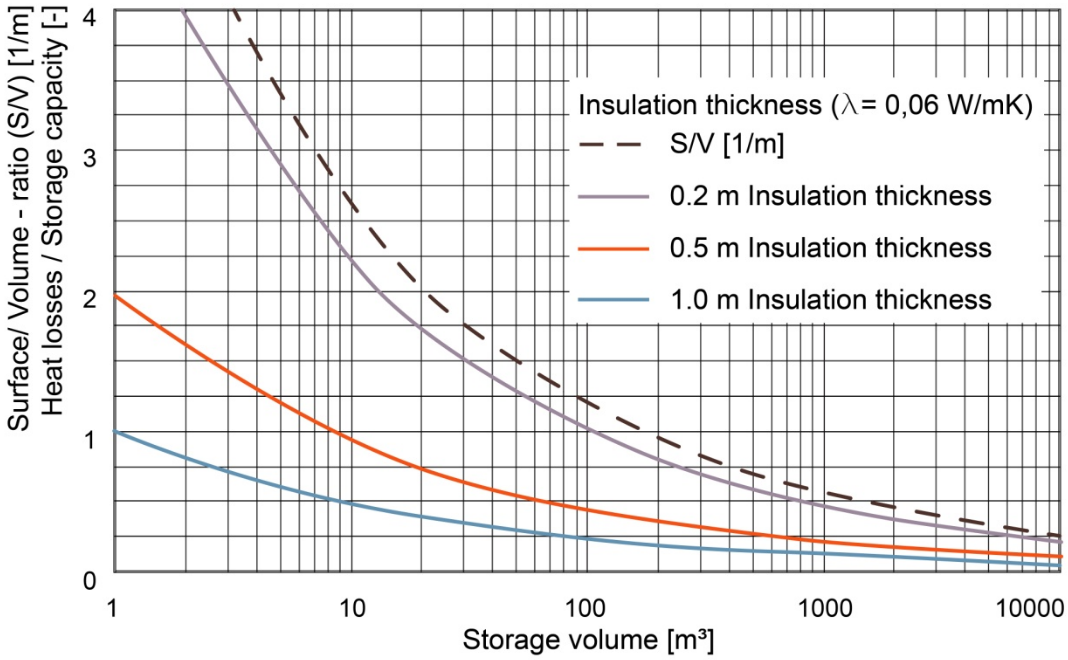


Figure 3: Heat losses/storage capacity ratio based on storage volume in m³ (source: Solites)

However, new technology developments might allow smaller storages to become energy efficient. For example, there are vacuum heat storages with volumes between 11 m³ to 30 m³ under development for single-family houses or small multi-family buildings. They consist of standing cylindrical tanks made of steel plates, isolated thanks to an air-vacuumed double wall filled with microporous insulating material (thermal conductivity 0.009 W/m*K at 20°C, 0.012 W/m*K at 120°C).

2.2 Underground

Seasonal thermal energy storages are mostly built underground:

- those big storages are often directly integrated in residential areas
- the earth adds to the insulation
- in some cases the underground itself is the storage medium
- ground pressure on the outside of the storage helps compensate the water pressure in the inside of the storage, allowing the storage's walls to be thinner than if it is built on ground level and therefore only surrounded by air.

For each storage, a hydro-geological study is needed. It must notably make clear the stratigraphy, location and drift of the groundwater tables, hydraulic conductivity of the ground, flow rate and direction of the ground water flows. Moreover, a legal authorization procedure must be started early in the project about water in the area. The conditions enabling the construction of a storage are different for each type of storage.

2.3 Integration into the system

Decisive for the optimum function of the storage system is its correct integration into the conventional heating system and the careful design of the storage system as well as of all other components for heat supply: district heating network, heat transfer substations and building services.

The operation conditions are different for each system: the operation temperatures, the quality of stratification and the return flow temperature of the heating net influence the thermal losses of a seasonal thermal energy storage. However those parameters do not depend on the storage but on the thermal energy system.

Therefore an exact prediction of the whole system characteristics is needed. A close enough estimate of the load characteristics is one of the most important design prerequisites. The temperature levels (average, minimum and maximum operation temperatures) must be predicted, along with the district heating net return temperature, as they have a great influence on the performances of the storage. The charging and discharging systems must be designed. Charging and discharging can be direct (through water flow) or indirect (through heat exchangers).

3 The different storage types

During the past twenty years of research on seasonal storage technologies four different types of storages (Figure 4) turned out as main focus for the ongoing engineering research. For every storage, the materials and structures used should ensure that the functioning is guaranteed over a period of 30 to 50 years.

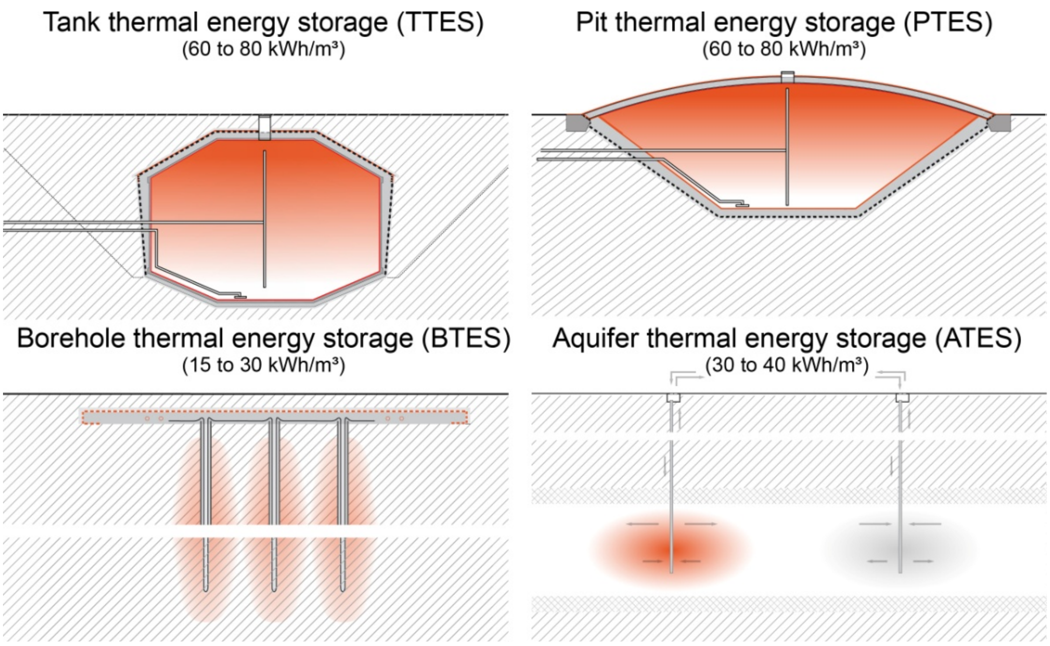


Figure 4: The four sensible seasonal storage technologies (source: Solites)

3.1 Tank thermal energy storage (TTES)

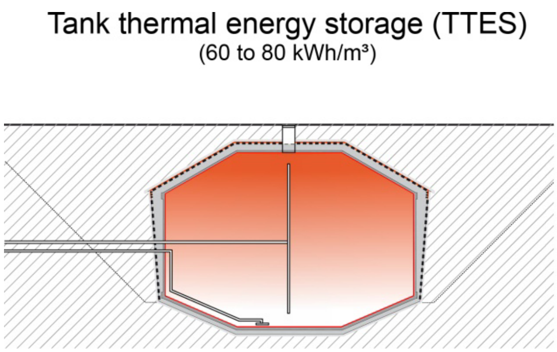


Figure 5: Tank thermal energy storage concept (source: Solites)

Tank thermal energy storages mostly consist of underground reinforced concrete tanks filled with water (Figure 5), connected to charging and discharging loops. If heat is available for charging, it is fed into the storage; the heat can then be discharged during the heating period.

Suitable geological formation for this kind of heat storage is well stagnant ground, soil class II-III, as much as possible avoiding groundwater. It can be 5 to 15 m deep. If it is designed for ground-level, there is no request about ground water deepness.

Tank thermal energy storages have a structure made of concrete, of (stainless) steel or of fibre reinforced plastic. Concrete tanks are built utilizing insitu concrete or prefabricated concrete elements. In the newest research projects pre-stressed pre-fabricated concrete elements are used that can support high loads. For storage volumes up to 1.000 m³ they can even already be under internal pressure. Building those storages underground helps balance the static forces on the walls of the system and therefore allows building thinner walls than would be needed on ground level. An additional liner (polymer, stainless steel) may be mounted on the inside surface of the tank. The insulation is fitted outside the tank: walls, bottom (recently) and top are insulated, to avoid heat losses. The insulation materials used are foam glass gravel for the bottom and expanded glass granules in membrane sheeting for walls and top.

To replace the stainless steel liner and concrete construction glass fiber reinforced plastic comes into question.

The outside of such a thermal energy storage is an assembly of several layers (Figure 6). The complexity of the design of such a composite wall arises due to the fact that on the one hand the envelope has to guarantee protection of the thermal insulation from moisture penetration from the inside and the outside but on the other hand desiccation in case the thermal insulation is already wet has to be enabled.

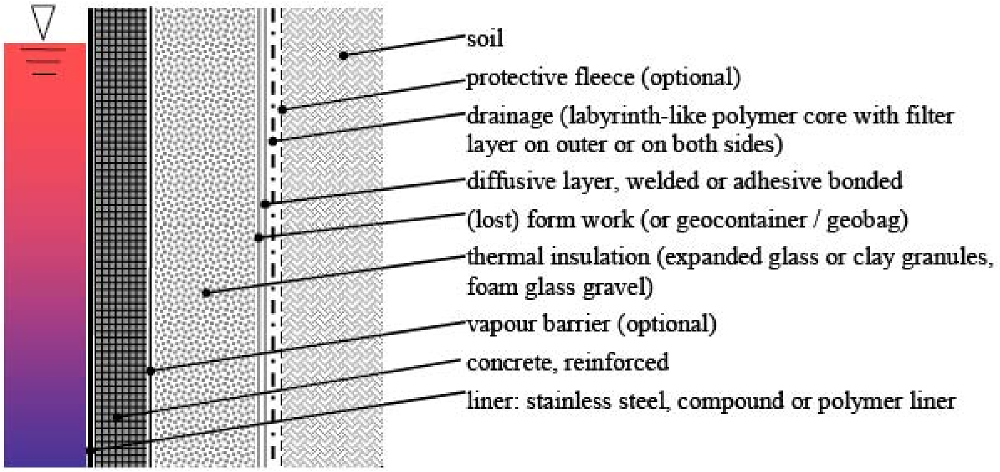


Figure 6: Multilayered (composite) side wall of a seasonal thermal energy storage, exterior insulation with respect to the concrete/steel structure (source: Solites)

The water inside the tank can be heated up to 98°C in storages without pressure. When the tank is or can be under internal pressure, and is also steam-tight, it is possible to feed-in much higher temperatures.

These seasonal thermal energy storages have heat storage capacities between 60 and 80 kWh/m³. They are the ones with the easiest technical optimization possibilities of the surface/volume ratio and thereby the heat losses.

Tank thermal energy storages made for temperatures even higher than 120°C are filled with water, because water has an excellent heat storage capacity. It is a really good heat transport medium, easy to be integrated in the hydraulic system because it is chemically inoffensive and easy manageable.

3.2 Pit thermal energy storage (PTES)

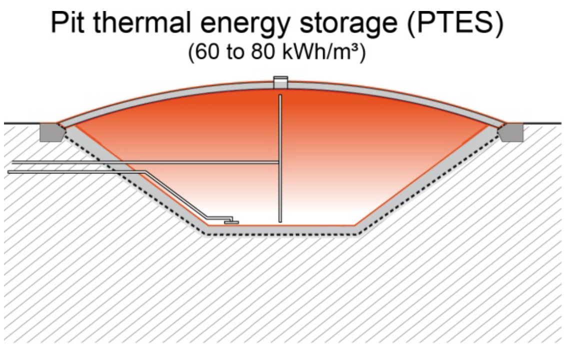


Figure 7: Pit thermal energy storage concept (source: Solites)

Pit thermal energy storages are made of an artificial pool filled with storage material and closed by a lid (Figure 7). The usually naturally tilted walls of a pit can be heat insulated and then lined with watertight plastic foil. The storage is filled with water and a heat insulated roof closes the pit. The roof can be floating on the water like in the storages in Denmark or is built like a self-supporting structure as a rugged roof. Another possibility is to fill up the storage volume with gravel, saturate it with water and store heat in this mixture. In this case, the roof of the storage easily can be carried by the gravel filling.

Suitable geological formation for this kind of heat storage is well stagnant ground, soil class II-III, as much as possible avoiding groundwater. It can be 5 to 15 m deep.

Pit thermal energy storages can be filled with water, or gravel-water mixture (gravel fraction: 60-70%) due to the fact that the construction of the roof over the storing “lake” is difficult. With this kind of filling, pit storages have heat storage capacities between 30 and 50 kWh/m³, equivalent to 1,3 – 2 m³ of water. This means that a pit storage filled with a gravel-water mixture must be 1,3 times to twice the size of a pit- or tank storage filled with water to reach the same storage capacity. An advantage might be that the filling being more solid, the space over the storage can more easily be used, for example a parking lot. The maximal stored temperature of all realized PIT storages is about 80°C.

3.3 Borehole thermal energy storage (BTES)

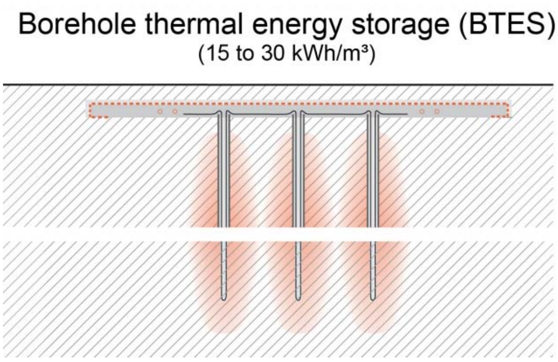


Figure 8: Borehole thermal energy storage concept (source: Solites)

In this kind of storage, the heat is directly stored in the underground. U-pipes, also called ducts, are inserted into vertical boreholes to build a huge heat exchanger (Figure 8). While water is running in the U-pipes heat can be fed in or out of the ground. During charging, the flow direction is from the centre to the boundaries of the storage to obtain high temperatures in the centre and lower ones at the boundaries of the storage. During discharging the flow is reversed. The heated ground volume constitutes the storage. The upper surface of the storage is heat insulated.

Suitable geological formations for this kind of heat storage are e.g. rock or water saturated soils with no or only very low natural groundwater flow. BTES should be implanted in grounds with high thermal capacity and impermeability. Authorities normally require calculations regarding the area influenced by the temperature change.

Depending on the heat storage capacity, the ground can be heated up to 80°C. The size of the storage has, however, to be between 3 to 5 times higher than that of a tank storage to obtain the same heat capacity, because ground can store between 15 and 30 kWh/m³.

Those storages should have a minimal volume of 20 000 m³ of ground to be energetically and financially interesting. Also, because of the lower charging and discharging power often a buffer storage has to be integrated into the system.

Moreover, BTES have a modular design: additional boreholes can be easily connected and the storage can increase, for example as the size of a housing district grows and the load increases.

Another use of BTES is under development since some years: The BTES is integrated in a system that uses energy from the soil both for heating and cooling. During the whole year, a mixture of water and antifreeze is pumped through the borehole heat exchangers in a closed loop. In winter, heat is discharged from the ground and used as a heat source for a heat pump. In summer, cold water from the ground circulates through a heat exchanger, which supplies the cold to the building. Often the distribution system for the cold is a concrete core activation system with low temperatures for heat distribution and high temperatures for cold distribution.

3.4 Aquifer thermal energy storage (ATES)

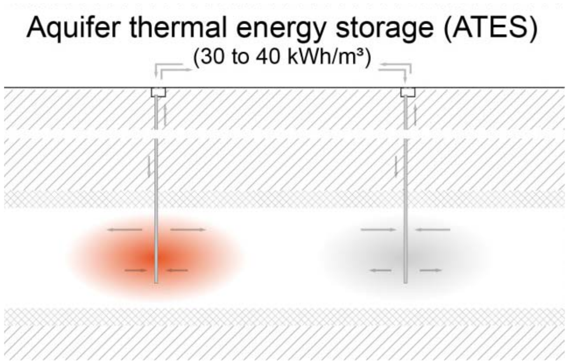


Figure 9: Aquifer thermal energy storage concept (source: Solites)

Naturally occurring self-contained layers of ground water – so called aquifers – are used for heat storage (Figure 9). Heat is fed into the storage via wells and fed out by reversing the flow direction. During charging periods cold groundwater is extracted from the cold well, heated up by the heat source and injected into the warm well. In discharging periods the flow direction is reversed: warm water is extracted from the warm well, cooled down by the heat sink and injected into the cold well. Because of the different flow directions, both wells are equipped with pumps, production- and injection pipes.

Suitable geological formation for this kind of heat storage is aquifer with high porosity, high hydraulic conductivity ($k_f > 10^{-4}$ m/s), ground water with a small flow rate, up and down enclosed with leak-proof layers. Aquifers cannot be found everywhere. Thus an extensive exploration program has to be passed for the building site before one can be sure that an aquifer thermal energy storage can be suitable.

ATES systems are not as easy to realize as BTES systems, and need more maintenance and pre-investigations, but if the conditions are favorable, payback times are typically short.

4 Cost

Construction cost of the four storage concepts vary significantly. However, there is not one optimum storage concept for all applications and not every storage concept can be built everywhere.

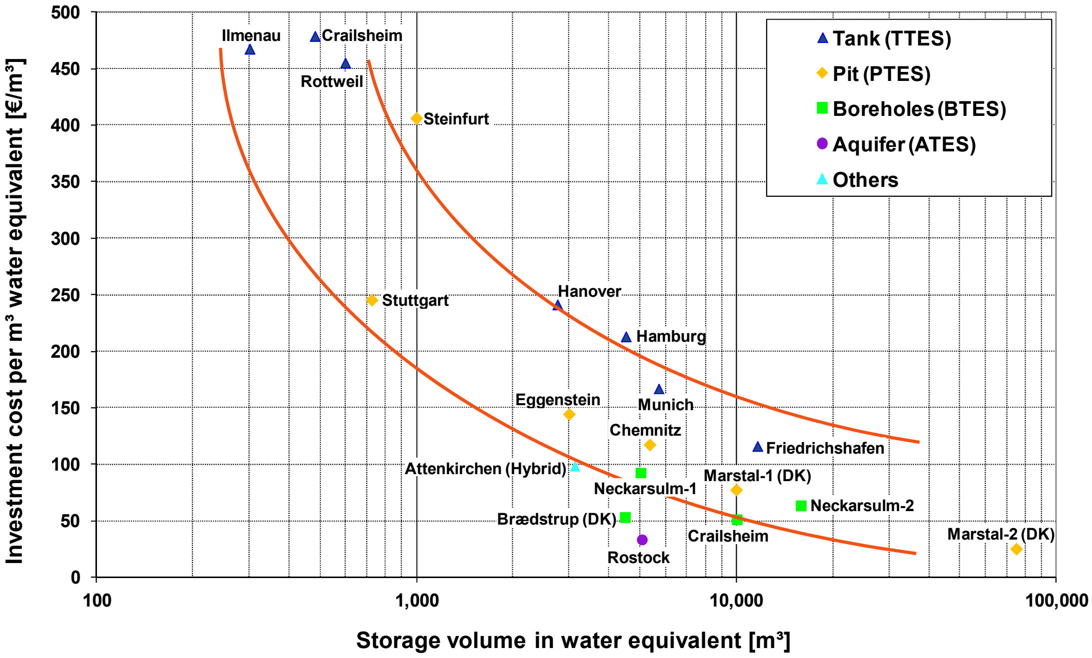


Figure 10: Specific storage costs of demonstration plants (cost figures without VAT) (source: Solites)

Figure 10 presents the cost data of built pilot and demonstration plants. To be able to compare different storage concepts and storage materials the specific storage costs are related to the water equivalent storage volume.

The graphic shows the strong cost decrease with an increasing storage volume. Appropriate sizes for seasonal heat storages are over 1000 m³ water equivalent. Within this range the investment costs vary between 40 and 250 €/m³. Generally, hot-water heat storages are the most expensive ones. On the other hand, they have some advantages concerning the thermodynamical behavior and they can be built almost everywhere. The lowest costs can be reached with ATES and BTES. However, they often need additional equipment for operation like e.g. buffer storages or water treatment and they have the highest requirements on the local ground conditions.

The economy of a storage system depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Therefore each system has to be examined separately.

5 Experience out of practice

At the moment each plant is more or less unique, as each is a new try to optimize the technology. The experience shows that large scale seasonal storages in (solar assisted) district heating systems have lower specific investment costs and reduced relative thermal losses in comparison to decentralized storage systems. Solar assisted district heating systems with seasonal thermal energy storage aim at a solar fraction of 50% or higher of the total heat demand for space heating and domestic hot water, and the objectives are mostly reached among the pilot projects.

However, monitoring and evaluation is still crucial to find the flaws in system design, construction and operation. Thanks to the monitoring of many pilot plants until today, the following needs for technical improvements could be observed.

5.1 Thermal losses

For the storages built until 2005 thermal losses are 30% to more than 100% higher than the design/simulation values. There are several reasons that cause the high thermal losses compared to the design/simulation values. Poor stratification causes higher internal (exergetic) losses. Higher thermal losses to the ground resulting from increased temperatures at the bottom region of the storage as a consequence of high return temperatures of the heating net contribute to an underestimation of the thermal losses. However the main reason was that the thermal conductivity of the insulation material was assumed too low.

For example, the thermal conductivity of the insulation was taken from DIN 4108 (DIN4108, 2004), which gives thermal conductivities for ambient temperatures of 10°C. However, as can be observed on the graphic (Figure 11), the thermal conductivity of porous materials increases with increasing moisture content and with increasing temperature. The assumption of constant material properties such as effective thermal conductivity of the insulation material and of the surrounding ground, but also the water vapour resistance index of the liner leads to wrong results. Hence, a major part of the increased thermal losses of pilot and research storages may result from moistened insulation. The quality of the envelope with respect to protection against moisture penetration is therefore often deficient. This phenomenon was taken into account in newest projects for better simulation and design.

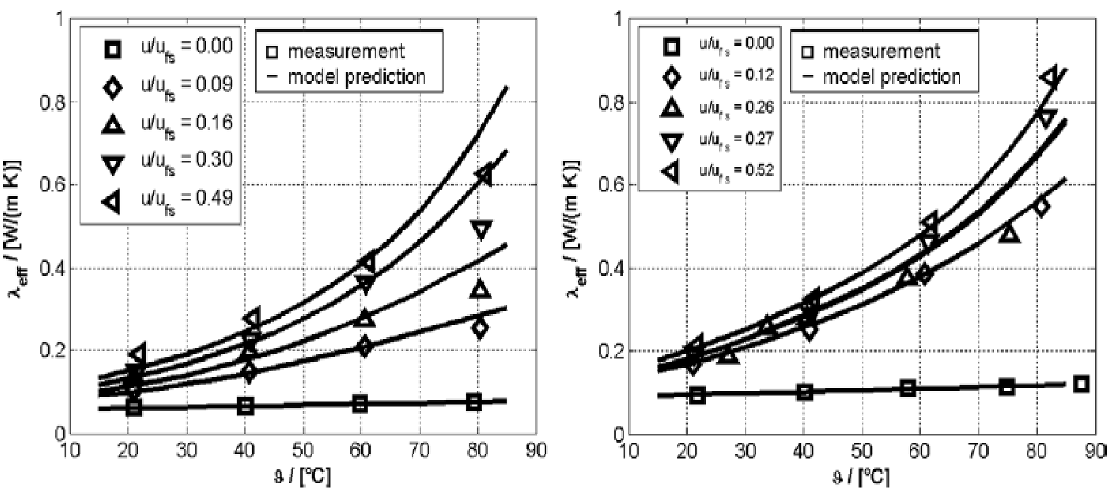


Figure 11: Model predictions and measured data for the thermal conductivity (λ_{eff}) of expanded glass granules 4-8 mm type II (EGG:left) and expanded clay 4-8 type I (EC: right) as function of the temperature (ϑ) with normalised water content (u/u_{fs}) as parameter. (source: F. Ochs, University of Innsbruck, Austria)

5.2 Leakages

With every type of liners in both TTES and PTES, leakage problems occurred. In the case of hot water thermal energy storages, leakages may be repaired, but in case of gravel/water thermal energy storages, a leakage is a worst case scenario. Problems with clay and bentonite liners were reported most frequently. However leakages also occurred in thermal energy storages with polymer and stainless steel liners. Nevertheless, with the exception of the storage in Ottrupgaard, DK initial leakage problems could be solved in the majority of cases.

5.3 Temperature stratification

Many attempts, with different systems and techniques, were made to be able to maintain a good temperature stratification in the storages, thus reducing the heat losses, by feeding-in the heat charging the storage, at the right level in this one. It would mean, that if the charging temperature is 65°C, the water would be fed in at the level at which the storage temperature already is 65°C. Floating inlets and outlets, as well as techniques already working in smaller storages have been tested, but no suniversal solution was found yet:

- Charge-switching devices:
  For this purpose, at least three levels (bottom, middle, top) have proven themselves. The storage can thus, on the one hand, simultaneously be charged and discharged and, on the other hand, stratification in the storage is improved. E.g. discharging of the storage at a high temperature level at

the top of the storage while simultaneously charging the centre of the storage at medium temperature level, or storing at medium temperature level in the middle, with high temperatures at the top of the storage.

- Stratification devices:
  In order to ensure proper functionality, one must ensure compliance of the device with the maximum flow rates to enable stratified charging of the storage.

When using mixtures of gravel and water or soil and water as a storage medium in pit heat storages, charging and discharging can take place either by direct water exchange or indirectly through coils that are installed at different heights throughout the storage medium. If this system is used, thermal stratification is less pronounced than with storages only filled with water.

5.4 Comprehensive energy concept

Before applying a STES to an existing building, settlement area, district heating network etc., it should be cleared if spending the money for a STES is the most energy and cost effective way for energy saving measures. Basically an energy efficient or renewable energy technology like STES should be adapted on systems that already checked and performed energy saving measures, if applicable. Of course there are aspects like historical heritage or equal, that preclude a lot of energy saving measures but as a rule of thumb a STES only should be applied to thermal energy systems that are already optimized to energy efficiency – at least to a certain level.

The energy efficiency of the STES especially depends on the temperature range it has to map. As lower the temperatures are for which the connected buildings, district heating area or equal, ask for, as better the storage can meet the necessary system temperatures and as lower the storage heat losses can get. In consequence, improving the heating system of the connected buildings to lower the demanded supply and return temperatures is evident for reaching a high energy efficient STES system that shows good economics. Besides that, a hydraulic adjustment of the heating system for adjusting the best mass flow through each heater, radiator or equal to reach lowest return temperatures and best comfort in the rooms is always advisable.

5.5 System integration

A STES is a passive system component not producing any energy by itself. A storage mainly depends on its usage that defines its energetic and economic efficiency. The STES depends on the amount of heat and value of temperature with which it is loaded. His input to the heating system depends on the temperature it has to deliver, the load profile (when it has to deliver which heat power) etc.

Thus the storage has to be adapted carefully to the system in which it is integrated with regard to the effect that the storage itself has on the system. Often the integration of a STES in a heating system results in an iterative technical development where the storage has to be adapted to the system it is integrated in and – in the same way – the system to the storage. It might be assumed that first the system has to be defined giving the conditions the storage has to fulfill. Typically this is the ordinary way of dimensioning the necessary heating system like e.g. boilers, burners or equal. But a storage strongly interacts with the heating system because it not only delivers heat to the building like a boiler but has to be loaded with heat, creates heat losses and temperature losses etc. The fine adjustment of STES and storage system to each other can improve the STES efficiency and in consequence the economics of the STES to a high extend.

5.6 Dimensioning by system simulation

Based on the necessity of optimizing the STES to the system it is integrated in and vice versa as described above, it might be obvious that only transient system simulation taking into account the variation of heat flux, temperatures, thermal system behavior, control strategy etc. can lead to a sophisticated system layout.

There is no technical standard or equal available that enables the technical consultant to dimension a STES "over the thumb". For first pre-dimensioning first calculation programs are available (e.g. check www.solar-district-heating.eu). But for detailed technical dimensioning only transient system simulation enables to regard the important parameters of the comprehensive system that interact with the STES. For the STES already realized it was proven that even regarding only the most influencing parameters the task is to optimize a multi-dimension parameters field of several tens of parameters that depend on each other. Since some years, pilot plants with STES went through a detailed system simulation with easily over one thousand parameter variations that were regarded in the simulation program. Thus simulating a STES system takes months and not only weeks. One of the most evaluated simulation programs for that purpose is TRNSYS.

5.7 Accuracy of the available data

When doing simulations for some months and optimizing a lot of depended parameters one might lose track of the input data on which all simulations base on. But these input data can mainly influence the simulation outcomes and the deviation of parameters. Especially in retrofitting applications it is an advantage that the heating system, the STES has to be optimized to, is already known. Best benefit can be obtained if the existing system is monitored in detail concerning load profiles (heat power and amounts), temperature levels of supply and return, ambient temperature, solar irradiation etc. in transient data that allow simulation in short time steps. Experiences show that an appropriate time step for monitoring data is data for every 10 min to every hour over one typical year of operation.

5.8 Integral planning

Optimizations should basically take place at the system level, i.e. the planning of the thermal energy storage must not ignore the rest of supply system. This integrated planning approach includes the early involvement of all stakeholders in the planning process relating to the entire heat supply system in order to define and harmonize interfaces and boundary conditions.

6 Necessary Further R+D

Within the STES experts that could be addressed within the IEA SHC Task 45 a survey for necessary further research and demonstration work for STES was derived. Because only two returns could be obtained additional knowledge was regarded and summarized in the following list:

- Development of materials for storage construction and lining that can withstand 100 °C for 30 years
- Development of cheap construction technologies for STES
- Pressurized buffer storages
- Safety of storage construction against technical hazards
- Further development of charging and discharging devices for STES
- Development of heat pumps with high COP for high supply temperatures
- Further development of TRNSYS models for STES
- Further development of system integration of STES in solar assisted district heating and in smart district heating

7 Project examples

The following chapters describe the state of the art in construction technologies of STES by means of the newest pilot plants.

7.1 The TTES in Munich

The development of the storage concept considered the four main concepts that are in use in Germany so far: hot-water, gravel/water, borehole (BTES) and aquifer (ATES) thermal energy storage. ATES and BTES require special underground conditions that are not available at the site. In the progress of the project development it was found, that the requirements regarding temperature stratification and capacity rate for charging and discharging cannot be satisfied by a gravel/water thermal energy storage. For this reason a hot-water thermal energy storage was considered to be the best concept for Munich.

Figure 12 shows a vertical section of the storage construction. The frustum at the bottom was built on-site while the side walls and the roof were built of prefabricated concrete elements that have a stainless steel liner at the inner surface. The steel liners were used as formwork during production of the concrete elements. After the installation of the wall elements they were prestressed by steel cables and the stainless steel plates were welded together to ensure water- and vapor-tightness.

The storage is insulated at the side walls and on top by expanded glass granules with a maximum thickness of 70 cm on top of the storage. A vertical drainage protects the insulation from moisture. The bottom of the storage is insulated by a 20 cm layer of foam glass gravel because of its higher stability against static pressure.

The storage is equipped with a stratification device to enhance temperature stratification and thereby the usability of the accumulated heat. Additionally during springtime the solar collectors charge only the upper part of the storage to reach usable temperatures as fast as possible. When an adequate buffer volume is available on high temperatures, the return flow to the solar collectors is switched from the upper part of the storage to the bottom.

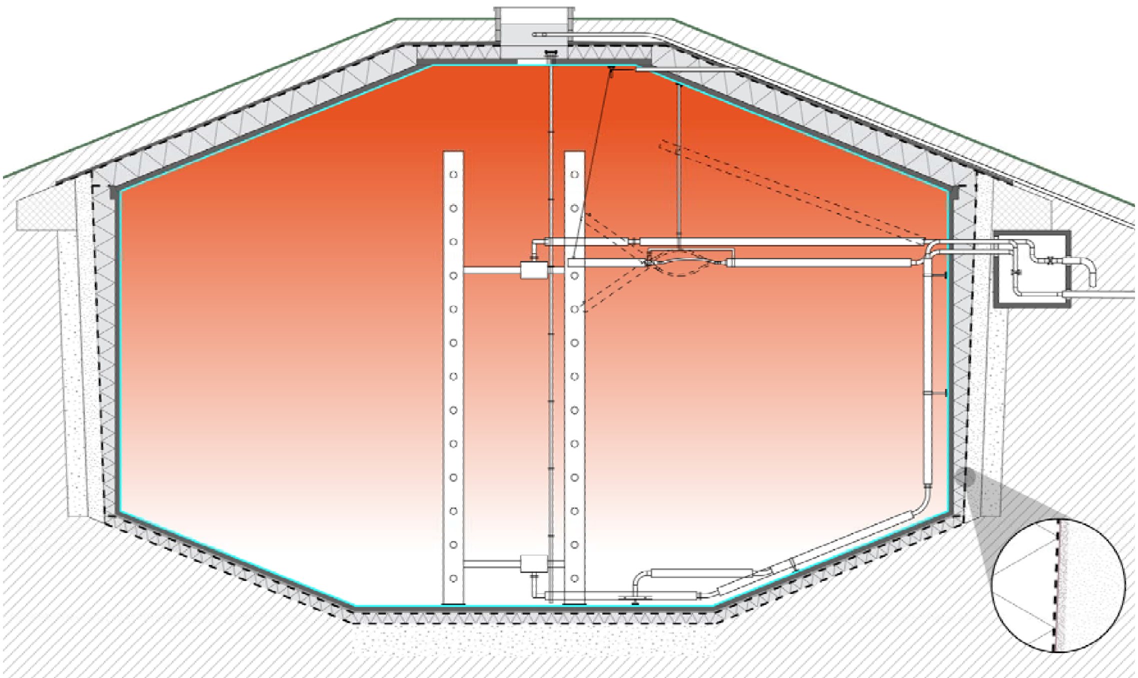


Figure 12: Vertical section of the Munich STES (source: Solites)

The construction sequence of the pilot STES in Munich is shown in the following pictures (source of all pictures: Solites):

Emplacement of 20 cm foam glass gravel as lowest heat insulation with geotextile as protection layer

Concreted bottom plate, watertight liner on geotextile on foam glass gravel

Reinforcement work on blinding concrete, that was emplaced on watertight liner

layer construction on the edge between storage bottom and wall: on the right the wall socket, in the middle blinding concrete, left: foam glass gravel as heat insulation

Concreted lower frustum, in the middle auxiliary construction during mounting of the STES

Delivery of prefabricated concrete wall elements with inner stainless steel liner, welded of 1,2 mm stainless steel plates.


Mounting of first wall elements. Thickness of 16 cm with ductwork for prestressing cables.


Stabilizing of prefabricated wall elements. Elements are mounted close together.


Mounting joint for balancing mounting tolerances (2 times). Inner side with stainless steel liner, 23 ductworks for prestressing over a height of 10 m


Closing of the cylinder with altogether 26 prefabricated elements, upper part realized as pressure ring.


Counterpart located slots for prestressing to integrate prestress cables in ductwork


Prestressing of 4 cables in each ductwork by means of a hydraulic press

Placing of prestressing cables in ductwork

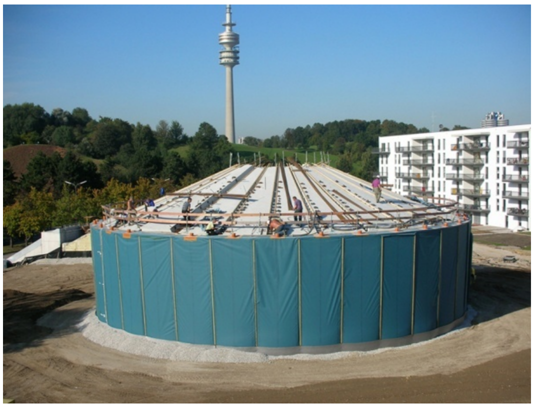
Mounting of prefabricated roof elements on pressure ring. Inner premounted stainless steel liners for closing of joints

Closing of the storage lid with two special elements that are located counterpart and integrate the slots for prestressing the lid. Mounting of the outer membrane casing on the wall.

First time application of high-temperature resisting prestressing cables on outer side of pressure ring.

Protection of membrane casing by geotextile, on the outside drainage gravel

Cost effective fixing of membrane casing by traditional woodwork, tightning with elastomer layer (red)



Filling of membrane casing with expanded glass granules for heat insulation, ,step by step in combination with outer drainage gravel and earth filling.

Closing of the joints on the roof construction by reinforcement and on site concrete.

Finished storage lid before mounting of heat insulation

Mounting of expanded glass granules as heat insulation in geotextile bags in sections on the roof. Each section is finished in one day and closed by a watertight liner that is open against water vapour diffusion. The liner is glued watertight against the concrete lid.

Emplacement of blinding concrete on watertight liner on the storage lid. Closing of the storage with manhole on top.

Earthwork on storage lid to green it after finishing.

7.2 The Danish type PIT in Marstal

The district heating utility in Marstal had a yearly heat production of app. 28,000 MWh in 2008. Solar covered app. 7,500 MWh (27%) and the rest was covered with bio oil boilers. The utilitites decided to replace the bio oil with more solar collectors, a PIT storage, a heat pump and heat from a wood chip boiler with an Organic Rankine Cycle (ORC).

TRNSYS calculations had as result, that an additional energy system with 15,000 m² solar collectors, a 1.5 MW heat pump, a wood chip boiler producing 3.25 MW heat and with the connection of a CHP based on an ORC-cycle with 0.75 MW_{el}, combined with a 75,000 m³ pit storage could cover nearly 100% of the heat consumption and more than 50% would be covered by solar and heat pump.

Figure 13 shows a cross section of the PIT design:

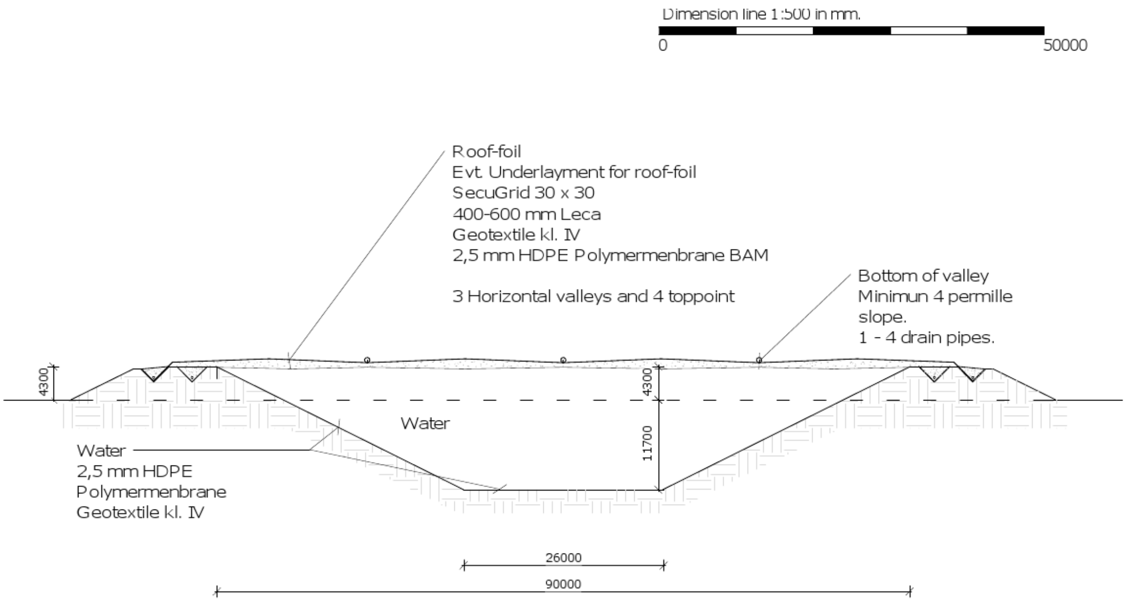


Figure 13: Cross section of the PIT storage construction in Marstal, Dk (75,000 m³) (source: Planenergi)

The realization of this PIT storage was done in the following main steps:

- Beginning from a flat top ground surface, first building step was to excavate a pit with natural tilted slope. The ground that was digged out was placed on site of the pit to highten the side walls.
- As next step a watertight plastic liner was built in the storage. Therefore most liners are delivered on roles of 5 m width. The plastic liner is rolled down the tilted surfaces on a protection fleece. The single liner strips are welded together by state-of-the-art welding equipment. After welding the water tightness of the welding itself can be controlled by different possibilities: most common is to weld the liners together in close double liners and to put pressure in the small channel between the two weldings. If the pressure lasts, the weldings are tight.
- To prevent the liners from slipping into the pit the liners are fixed in trenches that are on top of the side walls: the liners are laid on bottom of the trenches. The weight from the filling of the trenches prevents the liner from slipping into the pit. In addition, a horizontal liner surface is created to tighten the wall liner with the roof liner.
- Before filling in the water, all necessary equipment inside the storage has to be placed like water-in- and outlet pipes etc.
- Filling the basin with water is a more sensible task than it seems: the amount of water is huge, in Marstal e.g. 75.000 m³, and the water will be used in a heat transfer system. Thus the tasks have to be solved to prevent the pit from dirt during filling, to handle the oxygen that is contained in the water etc.

- When the basin is filled, the top liner is rolled out line by line on one storage side, welded together and pulled on the water level. When the entire roof liner is mounted, the basin is closed and protected from outer influences.
- For heat insulation different materials and constructions were used in the last storages, leaving this part of a PIT storage still as state-of-science. The essential task when designing the roof is to protect the heat insulation from soaking that might be caused by water vapour diffusion from the hot water inside the pit through the roof liner. In the PIT in Marstal the utilities decided to use an insulation material made of a kind of PE foam for the first time.
- The final step is the closure of the heat insulated roof with another watertight liner to protect the heat insulation from rain water. To get rid of the rain water that is gathered on the top liner different methods were applied in the last storages with good results. But long term durability is yet not proven.

7.3 The German type pilot PIT in Eggenstein-Leopoldshafen

In the frame of the energetic retrofitting of the school and sports center in Eggenstein-Leopoldshafen, a solar block heating net was renewed for these buildings in 2007. The building envelope and equipment were retrofitted, but also the leaky flat-roof was replaced by a solar roof. The storage of 4500 m³ and the collectors (1600 m²) deliver 37% of the yearly heat demand.

The design of the entire system was developed through TRNSYS simulations. For the STES two possibilities were applicable: a tank thermal energy storage and a pit thermal energy storage. In the process of project development it was stated from the city of Eggenstein-Leopoldshafen that the roof of the storage has to be able to carry high loads: in summer there are some big sport events that lead to a lot of people that will stay on the storage roof. After further static calculations for both storage types it could be found that filling a pit with gravel was the cheapest way to realize the storage due to the fact that a gravel pit is nearby the pit storage.

After an adjustment of the system that loads the storage and uses the heat that is unloaded from the storage to the gravel-water-pit design, the entire system still offered best economics. Thus the pit storage was realized. The adjustment was done virtually by TNRSYS simulations before start of planning.

The design of the pit storage in Eggenstein-Leopoldshafen bases on the results of a German research project. The intention of the storage was to apply and test the new knowledge that was obtained by the research project in a first storage. Thus the pit storage itself is a pilot storage. The risks that were connected to that, led to a funding of the realization by the federal government of Germany.

Figure 14 shows a cross section through the pilot pit storage in Eggenstein-Leopoldshafen:

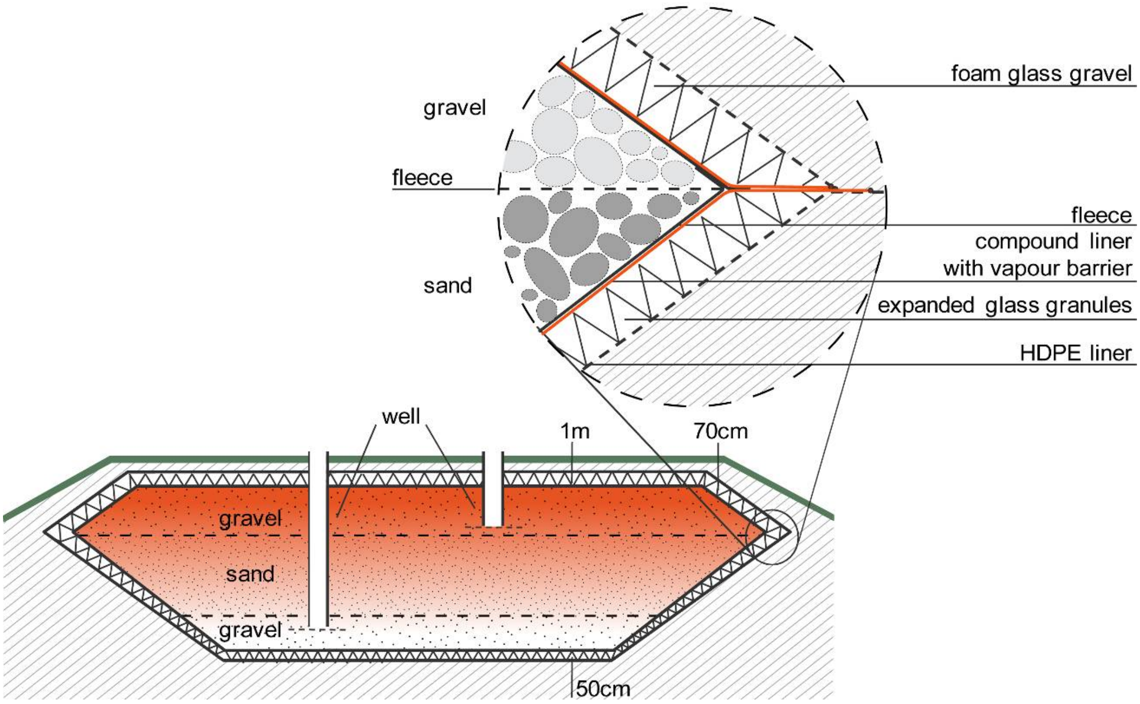


Figure 14: Cross section of the PIT storage construction in Eggenstein-Leopoldshafen, Germany (4,500 m³) (source: Solites)

The storage has the shape of two successive truncated cones. The wall construction of the storage bottom, walls and lid consists of an inner HDPE liner with integrated laminated aluminum foil, thermal insulation and an outer watertight HDPE liner. The inner HDPE -aluminum composite foil consists of two layers of HDPE which enclose an aluminum foil inside. The aluminum foil acts as a vapour barrier and prevents vapour diffusion from the storage inside into the insulation.

Between the inner and outer liner segment by segment connecting bars were welded using the HDPE outside liner, whereby large chambers are formed. In these chambers insulation was blown as expanded glass granules. By evacuating the chambers permanent tightness of the chambers could be detected during the entire construction phase. In addition, the expanded glass granules were precompressed by the vacuum and the heat insulation chambers were statically stabilized.

Initially, the subsurface gravel should be used as storage material. After excavation of the storage pit, it was found that in the underground almost only sand was available. In order to reduce the storage cost, gravel was built in only in the lower and upper region of the storage volume. In these gravel layers the storage circuit was integrated through wells. The central area of the storage was filled with the excavated sand after previous measurements showed that it is sufficiently permeable to the low flow rates of a seasonal heat storage.

The storage is heat insulated in the bottom with 50 cm of expanded glass granules. On the side walls from the bottom to the top the thickness of heat insulation rises from 50 to 70 cm of expanded glass granules. The storage lid is insulated with 100 cm foam glass gravel. The insulation thickness raises proportional to the expected temperature stratification inside the storage. This enables to optimize the cost for heat insulation to an economic optimum.

The tank with a volume of 4,500 cubic meters was built within three months, the planned construction costs of € 550,000 could be obtained.

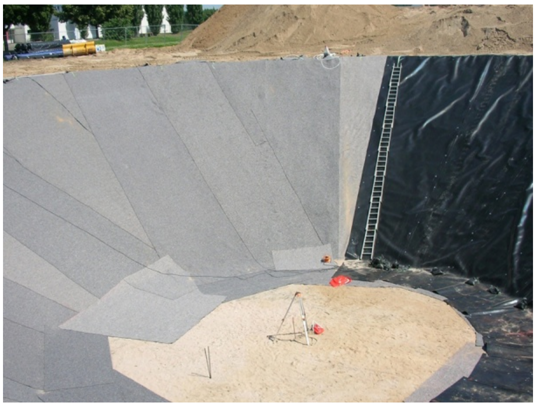
The pilot storage was monitored. There were found higher heat losses than calculated especially through the roof, that is insulated by foam glass gravel. In Denmark, the proceeding STES in Braedstrup was equipped with additional foils in between the bulk heat insulation to prevent convection through the entire heat insulation.

The following pictures show the realization of the pit storage in Eggenstein-Leopoldshafen (source for all pictures: Solites):

Excavation of the pit

Leveling of the inner surface of the pit, covering with protection layer (geotextile)

Protective geotextile is rolled down the pit in lanes



Laying of the outer liner on inner surface on the protective geotextile. The single lanes of the liner are welded together.

The inner liner is rolled out and welded with some additional liner stripes to large containments.

One of the welding methods for plastic liners: manual welding of edges

The heat insulation expanded glass granules is blown in the containments via compressed air.

Detailed view of the expanded glass granules. Due to the blowing in process a small part of the granules are pulverized to dust.

After the inner liner on the walls is welded tight (the tightness has to be checked) the heat insulation of the bottom is blown in. The heat insulation is covered with the inner liner.

After the inner liner of the bottom is completed, another protection layer is rolled down (geotextile) for gravel-water-pits. For water pits the water can be filled in directly.

Filling up of the bottom with gravel to form the lower charging and discharging layer inside the storage.

Separation of the lower gravel layer from the middle sand layer by geotextile that enables water movement and protect the gravel from sand intrusion.

After the middle sand layer is completed, again a geotextile is rolled out for filling up with the upper gravel layer

The upper gravel layer is protected by a geotextile and the inner liner. After the welding from the outside is finished, another geotextile is rolled out for protective measures and heat insulation material (foam glas gravel) is filled up. To prevent the heat insulation from possible rain the process can be parted in daily containment sizes that allow to cover the heat insulation with the outer liner in one day.

Purposeful dumping of foam glass gravel with a dumping bag on a crane

The roof and slope is coated by the outer liner in lanes and welded together.

According to the landscape architecture the outer surface is built up. If the surface of the storage is used by public, a layer of simple concrete to protect the watertight liner from damage is hardly recommended.

Here the surface is covered by grass. The shafts in the middle of the roof that enable maintaining of the charging and discharging devices can be seen.

7.4 The BTES in Crailsheim, Germany

The BTES in Crailsheim consists of 80 boreholes with a depth of 55 m. The storage volume of 37,500 m³ forms a cylinder with the boreholes situated in a 3 x 3 m square pattern, see Figure 15. The ground heat exchangers are double-U-pipes made from cross-linked polyethylene (PEX). The storage volume can be doubled when the second part of the connected residential area is going to be built in some years.

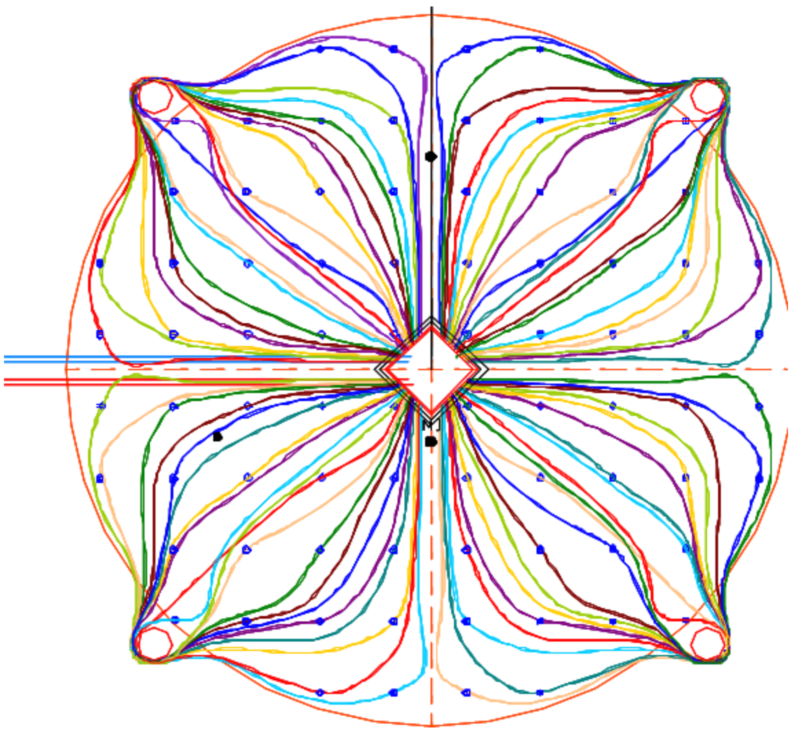


Figure 15: Top view with horizontal piping of BTES in Crailsheim, 2008 (source: Utilities of Crailsheim)

The blue dots in figure 15 show the location of the boreholes. They are orientated in straight lines for an easy and thus economic drilling: the drilling machine can move straight on from one borehole to the next. The boreholes are building a cylinder with the top view circle showed as red circle in figure 15. The diameter of this circle is adapted with the depth of the boreholes by TRNSYS simulations of the BTES itself and its system integration.

The colored lines in figure 15 show the hydraulic connections of two single borehole heat exchangers to one hydraulic circle: there is one hydraulic circle per color per quarter to connect two borehole heat exchangers to the central shaft from where the BTES is connected to the heating central. By hydraulic calculation the length of every hydraulic circle is set so that in every hydraulic circle and thus in every borehole heat exchanger the same mass flow is used. This is important for a good cooling or heating of the mass flow through the BTES and a consistent loading and unloading of the BTES.

In every quarter the single hydraulic circles meet on the outside at one shaft. There is the connection of the horizontal piping located. This enables easy maintaining, if necessary and a simple increase of the BTES by additional boreholes. These can be drilled in a circle around the existing BTES. The new horizontal piping can easily be connected to the existing BTES at these shafts.

The hydro-geological investigation was derived before the planning of the BTES. It showed an intermittent water movement in the upper part (5 m) of the storage volume. For this reason the boreholes were drilled with a bigger diameter in this part. After installation of the borehole heat exchangers the lower part was filled with a thermally enhanced grouting material (thermal conductivity 2.0 W/mK), whereas the upper part was filled with a thermally reduced grouting material to reduce the heat transfer into this layer. Figure 16 gives a cross section through the BTES.

The horizontal piping on top of the storage is embedded into a 0.5 m insulation layer of foam glass gravel. On top of the insulation layer a diffusive foil and a drainage layer (gravel) are installed below a 2 m layer of soil.

According to the simulations in regular operation the BTES will be heated up to 65 °C at the end of September, the lowest temperatures at the end of the heating period will be 20 °C. Maximum temperatures during charging will be above 90 °C. The main part of the heat will be discharged by way of a heat pump that is able to operate at very favorable conditions and is expected to have seasonal performance factors (SPF) of 4.9.

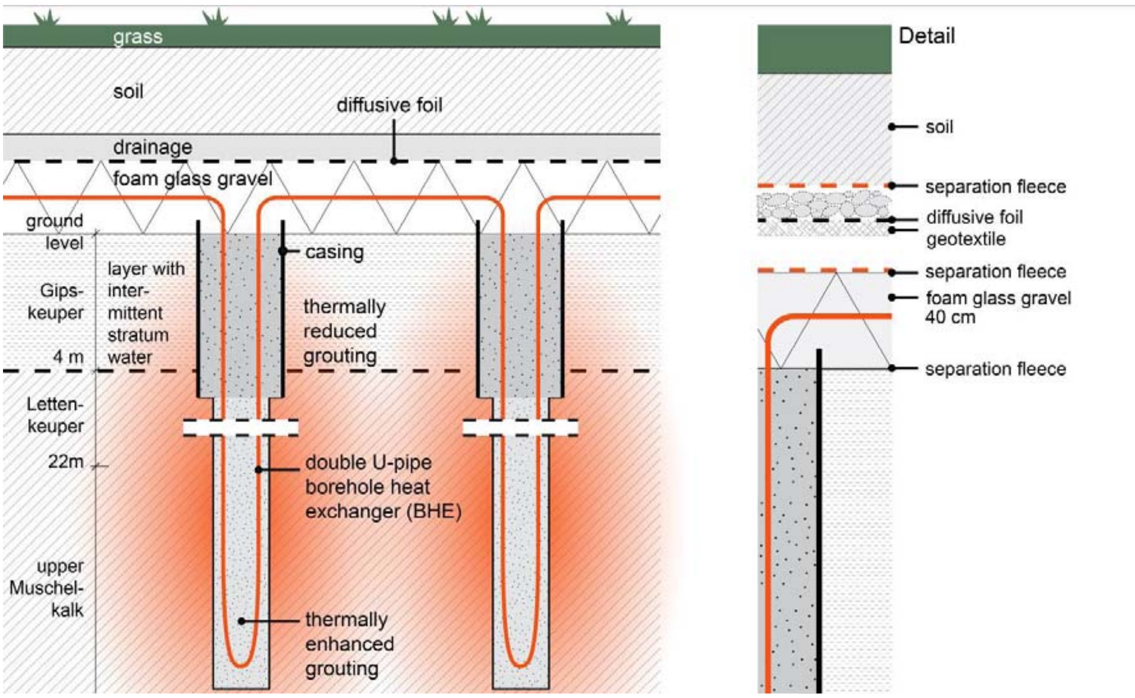


Figure 16: Cross section through the BTES in Crailsheim (source: Solites)

In the following the realization of the BTES in Crailsheim, Germany is shown (source of all pictures: Solites):

Gravel bed for drilling machine. The positions of the boreholes are determined by measurements and fixed by wooden pegs

The central shaft for connection of the horizontal piping is put on a layer of heat insulation (foam glass gravel)

Start of drilling with an auger drill for the first 5 m depths.

Casting of protection pipe into the borehole. This pipe stays in the borehole and protects the first 5 m depth from weak ground material that could fall in the open borehole.

Second drilling machine works down to 55 m by hammer drilling in the borehole

The drilled out ground is purged to the surface by water pumping. This causes the need for water drainage on the drilling area (photo shows the gravel bed and the drainage ditch round the drilling area)

The drilling rods

The drilling head

Drilling works with pumping out of the drilled material through the hose

The drilling head inside the borehole


Roling in of the borehole heat exchanger from a reel


Filling the borehole with grouting material by pumping it through a hose, the borehole heat exchanger has to be fixed in height until the grouting is solid

The grouting material is mixed with water on side. It is highly recommended to use special grouting material that is delivered ready-made on side.


Filling-up of the upper meters with grouting material. During solification it can occur that the level of the grouting material in the borehole drops some few meters.

The boreholes are filled up with heat exchangers and grouting, the horizontal piping is prepared.

Drilling work on second storage half and dumping of heat insulation (foam glass gravel) on first storage half.

It has to be secured that the plastic pipes of the heat exchangers are not bended closer than 50 cm. Therefore some of the first protection pipes has to be adapted.

First layer of foam glass gravel dumped and levelized. The light grey pipes are the borehole heat exchangers, the black one is used for filling in the grouting

Roll-out of horizontal piping. Connection of two pipes via hydraulic pressfitting. Due to the crosslinked character of the piping no welding is possible.

Pressfittings in detail: the correct connections are labeled by letters and numbers.

Heat insulation of horizontal piping by second layer of foam glass gravel. On the left side the central shaft is visible.

Always: Protection of heat insulation against rain by covering with foil during non-working time.

Protection of heat insulation from rain by watertight liner that is open for water vapour diffusion from down up (blue liner). This liner itself has to be protected from damage by protective geotextiles on both sides of the liner.

Preparation of the heat insulation by compacting for covering by liners

The covering liners are rolled out. Gravel is dumped on top to build up a drainage layer.

Quality control by the utilities

Leveling of gravel layer for drainage purposes

Covering of gravel layer with geotextile to prevent earth penetrating the gravel layer. On the geotextile earth is filled up.

Finished BTES. The only part of the BTES that is visible is the closure head of the central shaft.

7.5 The BTES in Braedstrup, Denmark

After the hydrogeologic examination of the possible BTES location it was found that the ground is suitable for BTES and that ground water level is expected to be at least 50 m below the surface. Thus the boreholes were set on a depth of 45 m.

The detailed storage design was done by TRNSYS simulations of the BTES itself and its system integration – as for the BTES in Crailsheim. A drilling can be deflected from the vertical line by e.g. stones. Therefore, the drilling company stated that the minimum (safe) distance between the boreholes is 3.0 m in order to avoid damage on a finished borehole when the neighbor boreholes are drilled. This is the main reason for choosing that the boreholes were placed in a triangular pattern as shown in figure 17.

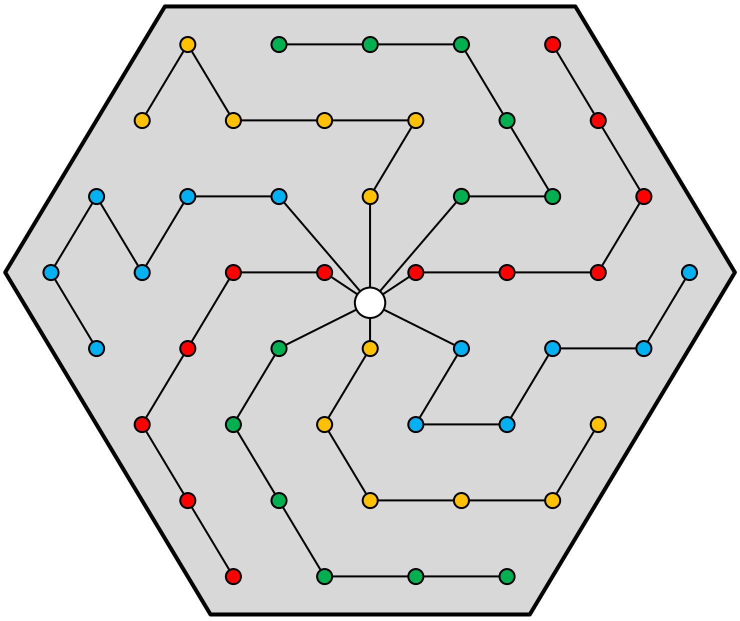


Figure 17: Pipe layout for the BTES in Braedstrup. Only connections to one of the U-pipes in each borehole are shown. The pipe layout for the second U-pipes will be mirrored through a vertical line to minimize the number of boreholes shared by two flow strings. All "dead ends" will be connected to the shaft in the center (source: Planenergi)

The top of the BTES follows the concept that was realized in Crailsheim before. The main difference is that in Breadstrup a very cheap new insulation material could be tested successfully: mussels shells. This heat insulation was adapted first time to a BTES in Braedstrup. The final design of the top horizontal layer of the BTES is shown in figure 18.

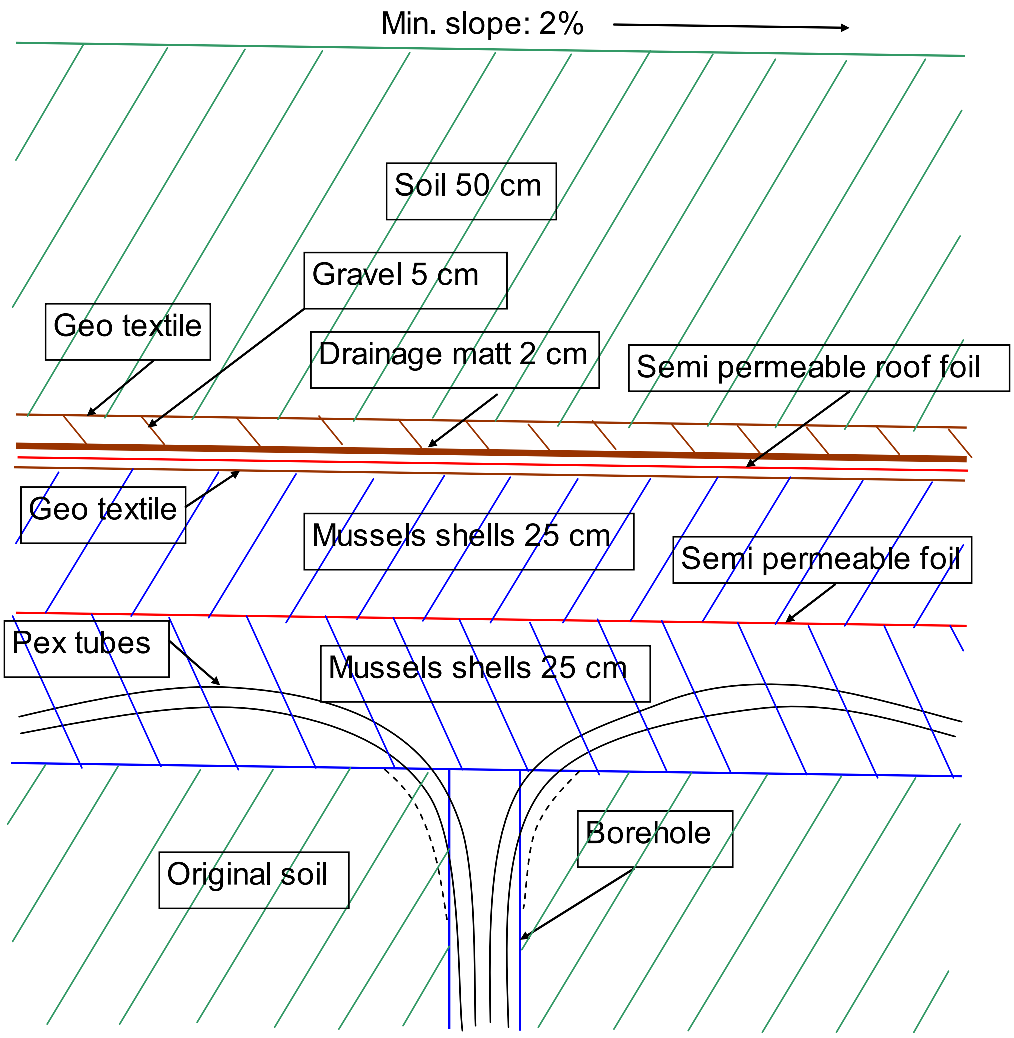


Figure 18: Cross section through the top horizontal layer of the BTES in Bradstrup (source: Planenergi)

7.6 The BTES in Drake Landing Solar Community, Canada

The Drake Landing Common in Okotoks, Alberta, Canada decided in 2003 to develop a “Solar Community” for 52 new single-family homes that were realized as a part of a larger new residential community in 2005. The yearly heat demand amounts to 800 MWh/a with 30% more energy efficient homes than conventional ones. The solar system could be finished in 2007. The R+D aim of the pilot project was to demonstrate the technical feasibility of achieving over 90% energy savings using seasonal storage of solar energy in a cold Canadian climate. More information can be found at www.dlsc.ca.

The first choice for the STES was an ATES but hydrogeological investigation showed unsuitable conditions for an ATES. The backup was a BTES and good soil conditions were confirmed for this above a depth of 45 m. The realized BTES has a volume of 34,000 m^3 with a water equivalent of 15,800 m^3. The overall system is shown in figure 19 and integrates a buffer volume of 240 m³.

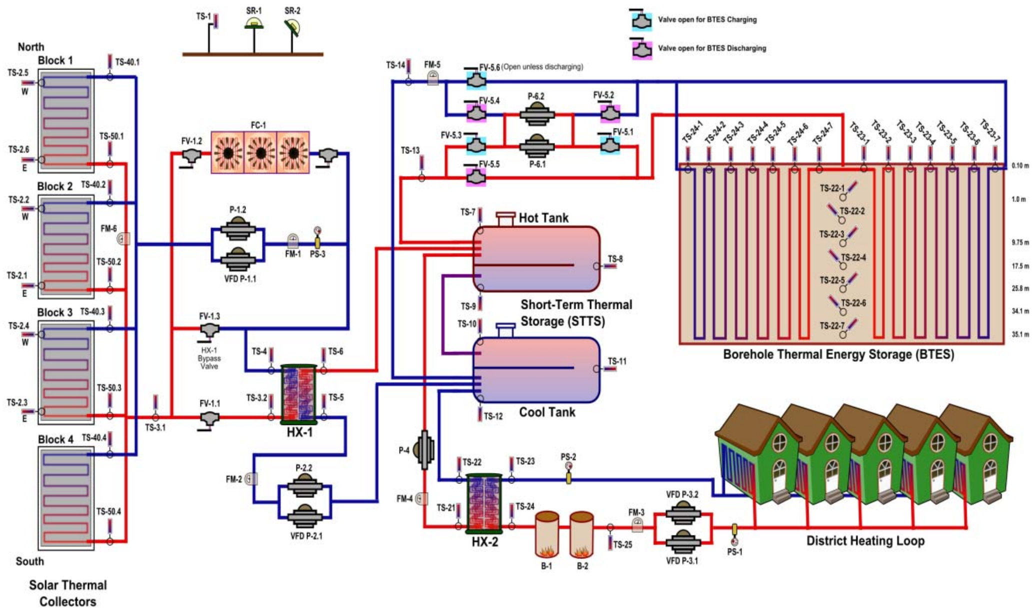


Figure 19: Overall system with the integrated BTES in Drake Landing Solar Community (source: Natural Resources Canada)

Figure 20 gives schematics to the realized BTES. The ducts are from the same material as in Crailsheim and Braedstrup. The heat insulation on top of the BTES is realized of polystyrene foam insulation.

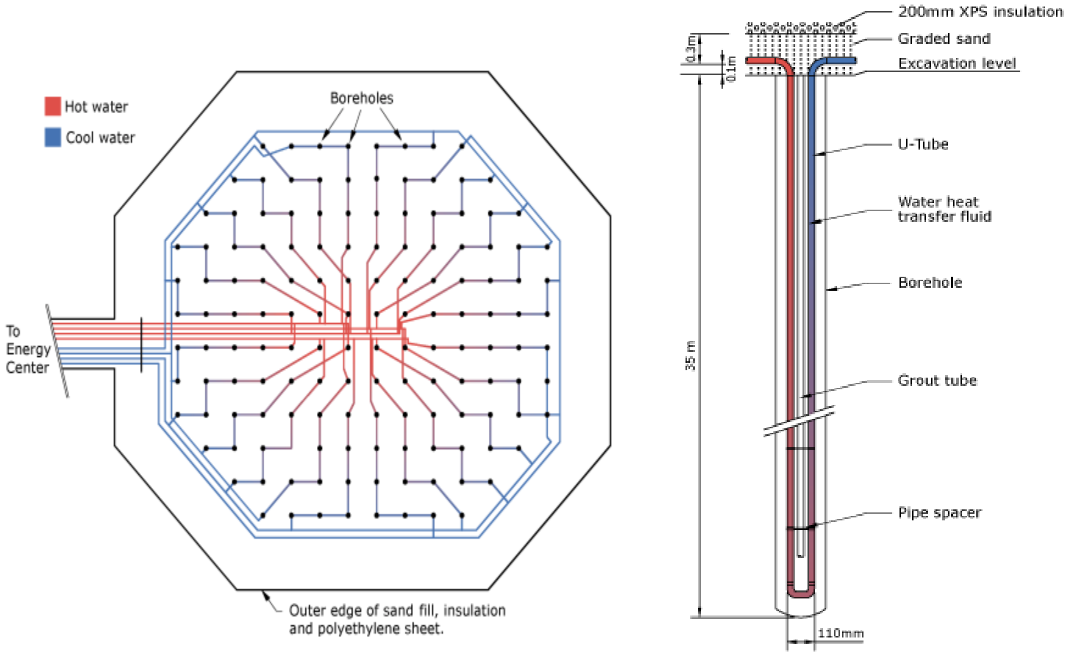


Figure 20: Storage schematic of the BTES in Drake Landing Solar Community (source: Natural Resources Canada)

The following figures gives some impressions from the pilot plant:

Figure 21: The construction cycle of the BTES in Drake Landing Solar Community (source: Natural Resources Canada)

Figure 22: Construction of the heating central with buffer storage at Drake Landing Solar Community (source: Natural Resources Canada)

Figure 23: Overview of Drake Landing Solar Community (source: Natural Resources Canada)

7.7 Aquifer Thermal Energy Storage (ATES)

Within the last years there were no ATES realized with systems that are regarded in this IEA SHC Task 45. The first ATES were realized already between 1960 and 1980. The most important lessons have been learned from the plants built between 1980 and 1990, even if due to some basic problems most of these plants were operated only for short periods of time. Table 2 gives an overview of the most important plants.

Table 2: Milestones of the development and realization of ATES (source: B. Sanner, Germany and own additions)

Year	Name	Comments
Since middle of 1960's different ATES in China (Shaghai, Changzhou)		
1976	Auburn Univ., Mobile Al., USA	ATES experiment
1982	"SPEOS", Lausanne-Dorigny, CH	ATES experiment
1982	Yamagata Univ., Yonezawa, J	ATES experiment
1982	Müllverbrennung, Hørsholm, DK Hochtemp.	ATES experiment
1982	Univ. Minnesota, St. Paul, USA Hochtemp.	ATES experiment
1982	Hokkaido Rehabily, Sapporo, J	ATES, heat storage
1982	Univ. Alabama, Tuscaloosa, USA	ATES, cold storage
1983	224 Wohng., Aulnay-sous-bois, F	ATES, with heat pump
1985	Scarborough Ctr., Toronto, CAN	ATES, heating and cooling
1987	Plaisir-Thiverval-Grignon, F Hochtemp.	ATES-experiment
1987	Hauptverw. SAS, Frösundavik, S	ATES, heating and cooling
1987	Perscombinatie, Amsterdam, NL	ATES, cold storage
1988	Winpak, Winnipeg, CAN	ATES, flow trough cold storage
1991	Utrecht Univ., Utrecht, NL	ATES, high-temperature
1998	Psych. Anstalt „Hooge Burch", Gouda, NL	ATES, high-temperature

Year	Name	Comments
1998/99	Reichstag Building, German Bundestag, Berlin, D	Two ATES, high temperature and cold
1999	Residential building „Brinckmanshöhe“, Rostock, D	ATES, high-temperature (50 °C)
2002	Eindhoven University, NL	ATES, 20 MW_{th}
2005	District heating net in Neubrandenburg, D	ATES, high-temperature
2008	Stockton College, New Jersey, USA	ATES, cold
2009	Arlanda Airport, Stockholm, SE	ATES, heating and cooling

8 Acknowledgement

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