The use of borehole thermal energy storage (BTES) systems

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6.1 Introduction

Among underground thermal energy storage systems (UTES) the borehole thermal energy storage (BTES) is one of the most promising technologies for long-term storage from both the technical and the economical points of view.

6.1.1 Historical development

The first BTES activities date back to the 1970s when the oil crises initiated an intensive search for alternatives to fossil fuels [1, 2]. In particular, solar radiation can be considered as an inexhaustible source for thermal use in applications such as space heating with solar collectors, which meets the need for seasonal storage of large quantities of thermal energy. The first activities started in Scandinavia, especially in Sweden, and in The Netherlands with solar district heating plants with BTES for seasonal storage.

6.1.2 Specifics of borehole thermal energy storage (BTES)

Borehole thermal energy storage (BTES) uses the underground itself as the storage material. Underground in this context can range from unconsolidated material to rock with or without groundwater. The material can contain pores or fractures in the case of hard rock. Depending on the water content of the underground it is called saturated if all pores or fractures are fully filled with water. Typically for solid state material as storage medium, the heat transport mechanism is heat conduction and thus requires heat exchangers for injection and extraction.

Because of their construction principle, BTES are not thermally insulated to the bottom and the side, only a top insulation layer reduces the losses to the environment. As the thermal conductivity of underground material is rather moderate, in a range of 1–5 W/mK, heat losses can be kept low if the total volume is large enough to achieve a good surface-to-volume ratio. Size is important because heat losses are proportional to the storage surface while the storage capacity is proportional to the volume.

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Therefore BTES are typically large and thus contain a high storage capacity. Additionally, BTES construction can be relatively cheap, even to a high quality, which allows its use even from an economical point of view for seasonal storage with 1–2 storage cycles per year.

Due to geological conditions different types of borehole heat exchangers (BHEs) have been realized. In the hard rock areas of Scandinavia, open water-filled boreholes became popular because of their excellent heat exchange performance. This technique is not applicable in the unconsolidated rock typical of the geological conditions in the rest of Europe. Here, closed systems with plastic pipes in grouted boreholes are used.

6.1.3 Principles of BTES

For sensible heat storage, in principle a high heat capacity is required. However, all types of underground material show a volumetric thermal capacity which is about half that of water (4.15 MJ/m^3K). Major influences on this value are the material itself, the bulk density and the water content.

In order to achieve a proper heat transport into and from the ground, a high thermal conductivity is desirable, while from the point of view of heat losses the thermal conductivity should be as low as possible. In porous underground a high groundwater can increase the heat capacity, while a groundwater flow can reduce the performance of BTES significantly, because of increasing losses due to convective heat transport. Therefore the local geology and hydrogeology are crucial for the feasibility and thus for the selection of storage type (BTES or others).

Typical values of thermal conductivity and heat capacity are given in Table 6.1 [3].

6.1.4 Underground thermal conditions

The thermal regime and temperature distribution in the shallow underground results from the different heat transfer processes – conduction in the rock and convection of flowing fluid (water) – combined with the thermal capacity of the materials. The surface of the earth is in a thermal equilibrium between the incoming solar radiation, the geothermal heat flux from the inner part of the earth and the emission of thermal radiation to space. Solar radiation is in the order of 1000 W/m^2 with a high variability (day/night), the geothermal heat flux in Central Europe is all year round constant and in the range of 0.05–0.12 W/m^2.

Close to the surface, ambient influences result in a seasonal variation of temperature which declines with depth (Figure 6.1). At a typical depth of 10–20 m this variation is less than 0.1 K and the temperature remains constant over the year but increases with depth by about 3 K per 100 m [4].

Table 6.1 Thermal properties of underground material

Material	Thermal conductivity (W/mK)	Volumetric heat capacity (MJ/m^3)	Density (10^3 kg/m^3)
Unconsolidated			
Clay/silt, dry	0.4–1.0	1.5–1.6	1.8–2.0
Clay/silt, water-saturated	1.1–3.1	2.0–2.8	2.0–2.2
Sand, dry	0.3–0.9	1.3–1.6	1.8–2.2
Sand, water-saturated	2.0–3.0	2.2–2.8	1.9–2.3
Gravel/stones, dry	0.4–0.9	1.3–1.6	1.8–2.2
Gravel/stones, water-saturated	1.6–2.5	2.2–2.6	1.9–2.3
Till/loam	1.1–2.9	1.5–2.5	1.8–2.3
Sedimentary rock			
Clay/silt stone	1.1–3.4	2.1–2.4	2.4–2.6
Sandstone	1.9–4.6	1.8–2.6	2.2–2.7
Conglomerate/breccia	1.3–5.1	1.8–2.6	2.2–2.7
Marlstone	1.8–2.9	2.2–2.3	2.3–2.6
Limestone	2.0–3.9	2.1–2.4	2.4–2.7
Dolomitic rock	3.0–5.0	2.1–2.4	2.4–2.7
Magmatic and metamorphic rock			
Basalt	1.3–2.3	2.3–2.6	2.6–3.2
Granite	2.1–4.1	2.1–3.0	2.4–3.0
Gabbro	1.7–2.9	2.6	2.8–3.1
Clay shale	1.5–2.6	2.2–2.5	2.4–2.7
Marble	2.1–3.1	2.0	2.5–2.8
Quartzite	5.0–6.0	2.1	2.5–2.7
Gneiss	1.9–4.0	1.8–2.4	2.4–2.7
Other materials			
Bentonite	0.5–0.8	~3.9	
Water (+10°C)	0.59	4.15	0.999

From VDI 4640 Part 1; 06/2010 [3].

6.1.5 Applications of BTES

The first projects carried out in Sweden in the 1980s used BTES for storing solar or waste heat from summer to winter for space heating. In the vast majority of systems heat pumps were integrated for extraction of heat from the storage to provide the required supply temperatures for the end users. In the following decades in Europe several solar district heating systems at locations with favorable geological conditions were equipped with BTES as this technology has the potential to build large heat storage at rather low cost.

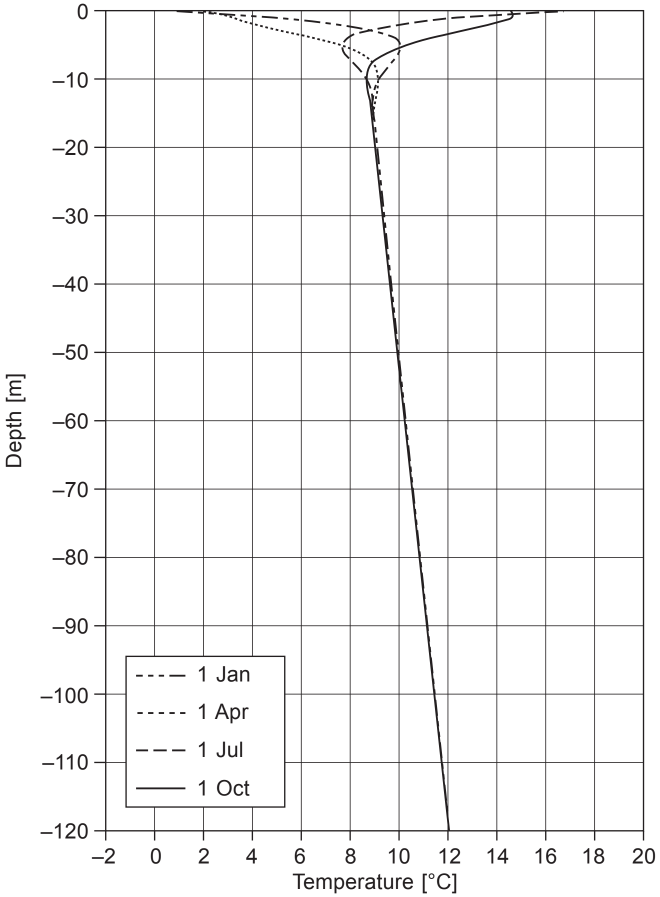

Figure 6.1 Typical vertical underground temperature distribution. Drawn according to the calculations given in Koenigsdorff [4].

While in the early days BTES development was dominated by heating applications, an improved thermal building standard and a growing number of internal heat sources increased the demand for cooling. Today BTES is also used for cooling purposes and in most cases for combined heating and cooling. Typical applications are well-insulated office buildings which require cooling in summer because of their internal heat sources. This waste heat is delivered to the BTES and stored for winter space heating. Because of this dual use, the energy conservation is rather high and the economics are favorable.

6.1.6 Environmental aspects of BTES

Environmental protection is an important issue not only from the point view of energy saving and reduction of CO_2 emissions but also from the point of view of protection of soil and underground in general, the groundwater and the neighboring buildings. Although this technology has proven to be very secure in thousands of projects, a few accidents happened in complicated geological conditions in the past resulting in serious problems.

In principle, problems which affect the environment can occur during design, construction and operation of BTES. Major aspects to be considered include:

- Are the geological and hydrogeological conditions appropriate to build a BTES?
- Are water-sensitive geological layers (anhydride) connected to an aquifer while drilling?
- Proper grouting of boreholes is crucial to avoid connection of aquifers with different pressure or different water qualities.
- Groundwater pollution by leakage of BHEs – operational fluid (water with antifreeze and corrosion inhibitors) can leak from the BHE into the groundwater.

Intensive site investigation is necessary to provide optimal knowledge on the geology and to avoid any potential hazard during construction and operation. The following general rules should be considered in advance:

- Don’t connect aquifers of different pressure and water quality.
- Avoid any connection of water-sensitive geological layers and aquifers.
- Thorough grouting is most important.

Damage resulting from such hazards can be extremely serious and remediation may be very difficult and expensive. Guidelines and standards on design construction and operation help to avoid any of these problems. In many countries (e.g., in Germany) the approval procedure of the water authorities or the geological survey have to be passed. Their focus is mainly on environmental aspects, especially groundwater protection.

6.2 System integration of borehole thermal energy storage (BTES)

6.2.1 Energy balance (ordered annual performance curve)

The need for thermal energy storage results from some surplus in heat production and a deficit at another time period. For example, if in domestic applications a HPC unit is operated according to the electricity demand, surplus heat has to be stored at part load heat demand for later use. The principle of storage can be demonstrated by an ordered annual performance curve [5]. Figure 6.2 shows an example of a typical performance curve for a residential quarter combined with varying heat demand and that of a HPC unit with constant heat delivery. It can easily be seen that in combination with storage all of the heat produced by the HPC unit can be used. Additionally the dynamics of the heat demand have to be analyzed to get information on the time periods as well as the temperature levels of charging and discharging.

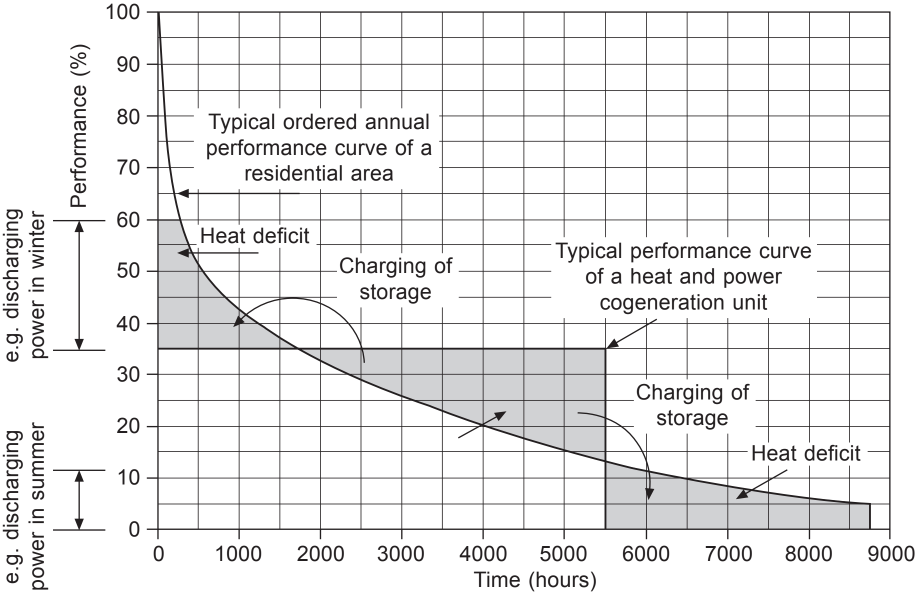

Figure 6.2 Ordered annual performance curve.

6.2.2 Temperature levels

For optimum integration of the storage into the system, temperatures of the heat source and of the demand have to be optimized. As in other sensible heat storage, the temperature level in the store decreases due to heat losses to the surrounding underground. Therefore the charging temperature of the heat source has to be significantly higher than the discharging temperature. This especially applies for the system return temperature and has to be considered in the design of the heating system. By using a heat pump for discharging, this problem can be resolved as the temperature levels are no longer interacting. Additionally, the total temperature differential and thus the total storage capacity can be increased.

6.2.3 BTES for heating, for cooling and for combined heating and cooling

In the 1980s BTES application started with storage for heating purposes especially in solar district heating systems. The first pilot projects were carried out in Sweden and The Netherlands followed by plants in Germany in the 1990s. BTES was designed to store solar heat from large solar collector fields during summer for winter heating of residential areas via a district heating network. These systems were partly designed with and partly without heat pumps. This application has recently been incentivized in Denmark by the solar district heating initiative. The solar fraction ranges from about 50% for space heating and domestic hot water in the German systems to over 90% in the Drake Landing Solar Community in Okotoks, Canada for space heating only.

Improved building insulation standards combined with increasing internal heat sources require more and more cooling, especially in commercial buildings. Highly efficient cooling techniques like ceiling panels or thermal activation of building structures allow direct cooling at relatively high temperatures. BTES can serve as long-term cold storage when the underground is cooled down during the winter by ambient cold. This technique of direct cooling has proven to be highly efficient with a minimum of energy input (electricity) required to operate the system.

But most popular has become the BTES for combined heat and cold storage. In this case the underground serves as a low temperature heat source of a heat pump for space heating in winter and is cooled down to temperatures close to 0°C. When the cooling season starts in early summer, the system is operated first in direct cooling mode. Later on, when the underground temperature has reached the limits for direct cooling, the system is switched into indirect cooling mode with the heat pump. Therefore typically reversible heat pumps are used which charge the condensation heat into the BTES. Coming back to the winter heating mode, the underground is already at a higher temperature level than the undisturbed ground temperature. Due to a combination of both operating modes via the underground storage, this is the most efficient application. Besides the ground source heat pump for space heating, this system has developed into the most popular and economic BTES application in Germany, especially for commercial buildings.

6.3 Investigation and design of BTES construction sites

In the last decade ground source heat pumps and BTES have become increasingly popular in several countries. Proper BTES design requires good knowledge of the heat demand and the heat sources. Not only is the total energy charged and discharged to the storage important, but also the dynamics of the heat flux due to the limited thermal conductivity of the underground. Often additional buffer storage is required. If supplementary heating is sourced from conventional fuels, the operational temperature range of the storage is restricted. The minimum is determined by the return temperature of the district heating net and the maximum by the solar system. Typical for sensible heat storage is that these return temperatures of the heating system are important for discharging.

Heat pumps are an additional option to a backup based on conventional fuels to adjust the temperature level to the system supply. Because of this strong interaction of storage and heating system, computer simulation is used for design. Such simulation tools require detailed information on the physical properties of the underground which are only partly available from geological databases.

Heat pumps allow a higher operational temperature range of the storage which results in smaller size and lower costs. If the space heating in the houses is designed for low temperatures like floor or wall heating, the district heating system can be designed for lower temperatures with smaller heat losses. For smaller housing areas heat pump systems are more favorable for technical and economic reasons than conventional supplementary heating.

6.3.1 Site investigation: thermal response test

As only a rough overview of the geology and hydrogeology of a location can be obtained from geological maps, geological databases have been developed which provide relevant data in more detail on the local formation. But still the resolution of these data may be not good enough to provide information on the exact location and BHE construction as required for computer simulation. Therefore site investigation by test drillings is essential, especially for larger projects, to gain good knowledge of the thermophysical properties of the underground. Preferably core drilling and sampling can provide valuable information like a detailed geological profile as shown in Figure 6.3. This allows a more reliable assessment of the most efficient drilling technology for economic construction and an estimation of the thermal properties of the underground.

A test procedure called the Thermal Response Test (TRT), developed at Oklahoma State University (USA) and Technical University Luleå (Sweden), allows such site investigation determining an effective thermal conductivity over the whole length of the BHE and the borehole resistance. The measurement is carried out at a first test drilling located in the BTES field which later on can be used as a regular borehole heat exchanger. A standard test procedure of the Thermal Response Test and further developments were carried out within a working group IEA ECES Annex 21 of the International Energy Agency (IEA) Implementing Agreement ‘Energy Conservation through Energy Storage’ (ECES) [6, 7].

This test procedure evaluates the temperature response of the borehole during injection or extraction of constant heating power. While injecting this heat pulse, the temperature response is determined as the mean value of borehole inlet and outlet temperature of the fluid. Based on the line source model a simplified approximation of the heat transport of an infinite linear heat source in the underground thermal properties of the formation can be determined. As the model assumes a homogeneous medium and conduction as the only heat transport process, the test delivers an effective thermal conductivity of the underground over the whole length of the BHE and the thermal borehole resistance between the fluid and the formation. Different thermal properties of different geological layers as well as groundwater are not considered. The vast majority of tests carried out worldwide use heat injection which is easier to provide. The major influencing factor on the quality of such a test is the accuracy of temperature and heating power measurements which are determined by the quality of sensors and monitoring equipment. Additionally the evaluation method of data and the accuracy of the mathematical model of the BHE is of significant importance.

In most cases the rather simple mathematical model of an infinite line source in

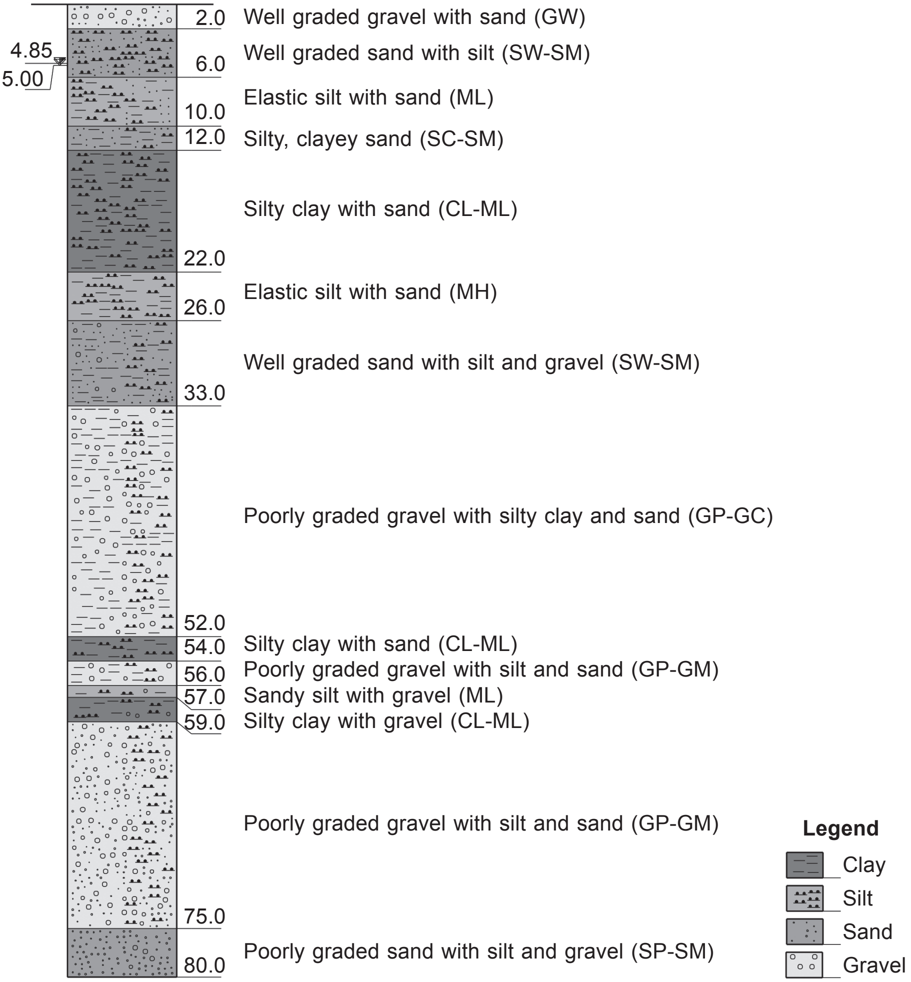

Figure 6.3 Geological profile gained from core drilling.

a homogenous underground is used, which requires highly constant heating power and highly accurate temperature measurement. This allows the determination of the effective thermal conductivity of the formation with an overall accuracy better than 5% and of the borehole thermal resistance (heat transfer coefficient from the formation to the heat transfer fluid) better than 10%.

A typical layout of the Thermal Response Test equipment is shown in Figure 6.4. The whole experimental setup has to be mobile and well protected against ambient conditions to allow highly accurate measurement at the construction site. Therefore often the equipment is mounted in a trailer (Figure 6.5) which can be brought to the test borehole easily. The hydraulic loop with the circulation pump, the heater, flow measurement and control, as well as a de-aeration unit and the relevant security

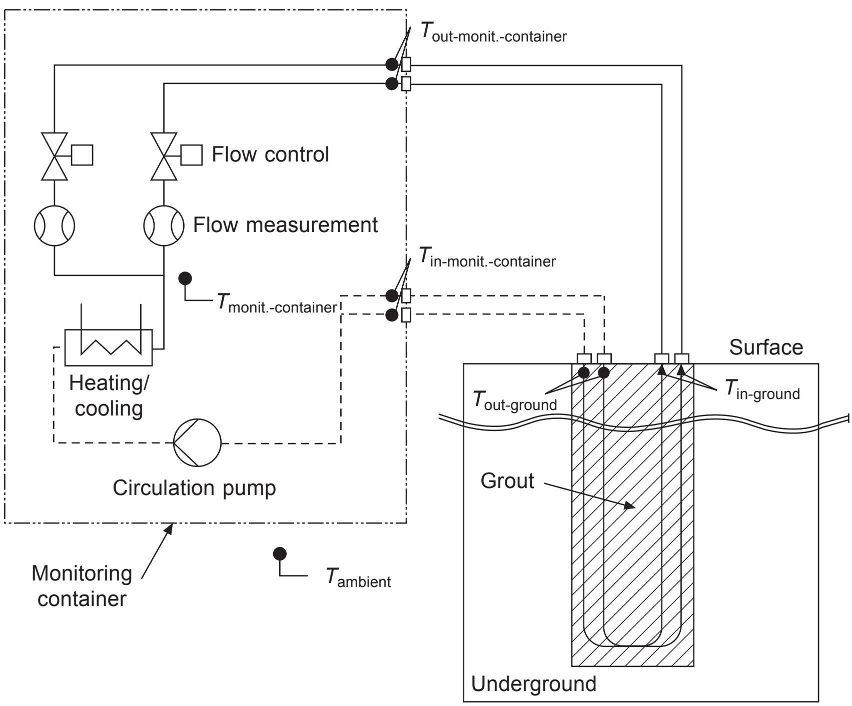

Figure 6.4 Scheme of the Thermal Response Test.

features like expansion vessel are mounted in this container together with the data acquisition system. Kelvin's line source model, which is used for evaluation in most cases, requires a constant heat flux injected into the ground. Therefore control of the heating element and flow control is strictly recommended. Piping between the trailer and the borehole has to be well insulated to avoid ambient influences. The supply and return fluid temperatures have to be measured at the borehole entrance just below the surface but already in the grouted part.

Before starting the heat pulse the undisturbed ground temperature has to be determined. This can be measured by insertion of a small temperature sensor inside the piping prior to its connection to the test rig. Another procedure is the determination of the fluid temperature which is in thermal equilibrium with the formation by circulation. The only temperature readings that are evaluated range from start of the circulation pump for the time period a single volume element needs to travel from the U-tube inlet to the outlet.

After determination of the undisturbed ground temperature, the real test can be started. Then a constant heat pulse is injected into the underground. The flow rate must not be changed during the whole test and the heating power is kept constant by a control unit.

Of the different methods to evaluate the temperature response, the most popular is the direct evaluation of the thermal conductivity from the simplified analytical solution of the line source model (Eq. 6.1).

Figure 6.5 Trailer with Thermal Response Test equipment connected to a test borehole.

$$T_f(t) = \frac{\dot{Q}}{H \cdot 4\pi \cdot \lambda} \ln(t) + \frac{\dot{Q}}{H}\left[\frac{1}{4\pi \cdot \lambda}\left(\ln\left(\frac{4a}{r_b}\right) - \gamma\right) + R_b\right] + T_g \tag{6.1}$$

The so-called direct evaluation procedure requires minimum effort and the approximation errors are negligible if all required boundary conditions are fulfilled. The time dependency can be separated as follows:

$$T_f(t) = k \cdot \ln(t) + m \tag{6.2}$$

with

$$\lambda = \frac{\dot{Q}}{H \cdot 4\pi \cdot k} \tag{6.3}$$

The thermal conductivity of the underground can be derived from the slope of the straight line which results if the temperature response is plotted versus the natural logarithm of time. Figure 6.6 shows that for a well-performed test the temperature response plotted versus ln(t) is a perfect straight line.

After determination of the thermal conductivity from Eq. (6.3) the thermal borehole resistance and the volumetric heat capacity of the underground are left as unknown parameters. But only one of these two values could be determined as with Eq. (6.4) only one equation for determination of two variables is available. The volumetric heat capacity has a much smaller influence and is easier to estimate from the knowledge of the geology.

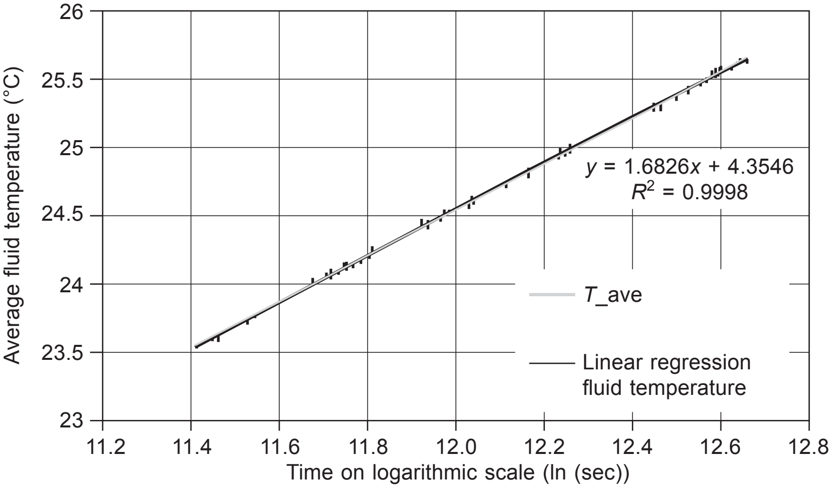

Figure 6.6 Linear regression of the temperature response as a function of ln(*t*).

$$R_b = \frac{H}{\dot{Q}}(m - T_g) - \frac{1}{4\pi \cdot \lambda}\left(\ln\left(\frac{4a}{r_b}\right) - \gamma\right) \tag{6.4}$$

The thermal borehole resistance is then the parameter to be identified.

The determination of the minimum duration of the heating pulse is based on the requirement that the result must not change significantly while increasing the heating and measuring period. The result of the thermal conductivity converges with time against a constant value.

The evaluation of TRT measurements and groundwater influence are in fact subject to verification. Appropriate evaluation models which consider convective heat transport in the groundwater may allow a valid evaluation. Nevertheless this has to be verified by the convergence method.

Additional to the basic Thermal Response Test, further measurements like temperature profile over the depth of the borehole can deliver valuable information [6–8]. This method can be used for determination of influence of geological layers and potential groundwater flow.

6.3.2 Geometry: the arrangement of compact hexagonal or quadratic borehole heat exchangers (BHEs), distance and depth of BHEs

In principle the storage consists of a maximum number of BHEs arranged in compact geometry. The volume-to-surface ratio should reach an optimum (maximum volume/ minimum surface), as the storage capacity is proportional to the volume and the heat losses are proportional to the surface. Beside the spherical geometry which is complicated to realize, cylindrical and cubical geometries are most favorable. As a high share of heat losses occur at the top surface, this area should be small. For hexagonal geometry each BHE has the same distance to the surrounding neighbors and the top area is about 25% smaller than in a rectangular arrangement of the same distance between BHEs.

To achieve optimum compactness, the depth and diameter of the BTES should be approximately equal. The distance between the BHEs will be determined by the time period between charging and discharging, the thermal properties of the formation and the density of boreholes given by the design. This distance is typically 2–5 m, which is also influenced by drilling aspects.

From hydraulic perspectives serial connection of BHEs may be convenient which is especially interesting if a horizontal thermal stratification is a design option. During charging, fluid flow passes first through the center BHEs and then through the outer ones while during discharging the flow direction is reversed. Thus the center reaches higher temperatures than the circumference.

6.3.3 Design procedure, geological and hydrogeological survey, system simulation and numerical simulation

The following detailed information on the geological and hydrogeological situation at the construction site is important:

- geological profile
- thermal conductivity
- heat capacity
- water content (unsaturated, saturated, groundwater flow).

Especially in the case of water saturation, whether there is a groundwater flow has to be investigated. Only small flow velocities compared to the storage size are acceptable to avoid large heat losses, otherwise BTES is not an option.

Based on the energy demand, the operational temperature range and the geological information, the design process is started with a first attempt. The storage efficiency depends mainly on the storage size due to the relatively high temperature level compared to the ground temperature. Typical values are 50–60% for about 30,000 m^3 storage volume; a much larger system in the order of 150,000 m^3 can achieve 80–90%. It takes typically 3 years to reach 80% of these values.

A first estimate of the storage size can be derived from the volumetric heat capacity, the feasible temperature rise in the storage and the discharged energy. The final design requires detailed numerical simulation of the storage and the system respectively. The simulation model used should be able to describe the geological and hydrogeological situation at the site.

For unsaturated ground at low temperatures (<40°C) models with pure thermal conduction can be used, while at higher temperatures moisture transport has to be considered. In saturated underground, convective heat transport has to be taken into account in the simulation model, especially for highly permeable ground.

It is recommended to use system simulation models which describe the heat delivery, the storage and the heat consumption. Such a dynamic system simulation tool can take into account varying temperature levels and the dynamic system behavior of components and their influence on the storage design. The time resolution should be at least one hour and the total simulation period should be several years to cover the transient oscillations in the first years.

6.4 Construction of borehole heat exchangers (BHEs) and BTES

6.4.1 Construction of single-U, double-U and coaxial BHEs

The construction of BHEs is similar to that for ground source heat pumps [9]. All classic construction principles – single-U-BHE, double-U-BHE and coaxial-BHE – can be used for storage as well as for ground source heat pumps. While single-U-BHEs have the lowest cost, double-U-BHEs have the advantage of higher reliability as long as each U-string becomes connected to the manifold separately. If during operation one U-string becomes clogged, still the other one can be operated. Coaxial types are not so popular because of higher costs.

Spacers between the supply and return pipes (see Figure 6.7) are also recommended as they reduce the thermal short-circuiting and improve the thermal resistance

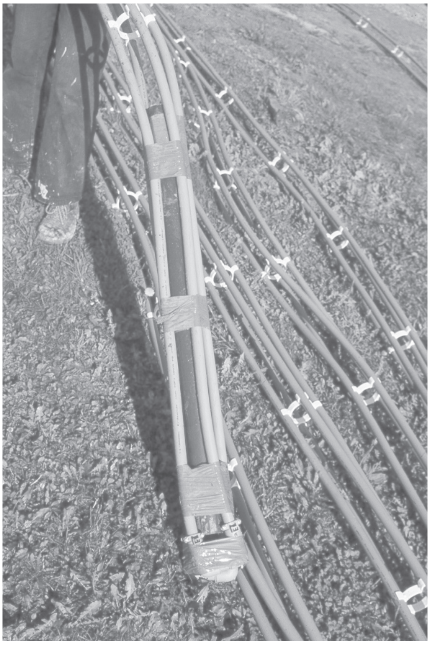

Figure 6.7 Polybutene double-U-BHE with spacers (BTES Neckarsulm, Germany).

significantly, which means that the temperature gradient as the driving force for the heat transport can be reduced and the performance is increased. Centering elements for the pipes in the borehole which are recommended by some water authorities show the contrary effect and should be avoided.

Typically for storage the boreholes are closer together and less deep to achieve a compact geometry and thermal interaction between the BHEs for heat extraction. Compact geometry means a favorable surface-to-volume ratio – minimum surface at maximum volume. Minimum heat losses result just from the compact geometry as only the top area of the storage can be insulated, not the side or the bottom. A cylindrical shape with a slightly larger diameter than depth is ideal. The distribution of boreholes should be as even as possible with a hexagonal or quadratic arrangement. The hexagonal geometry is favorable as all boreholes have the same distance to their neighbors while the quadratic arrangement is easier in construction but has a surface area which is 25% larger.

The borehole distance is determined by the time period between charging and discharging, the thermal properties of the underground such as thermal conductivity and heat capacity, and by the density of the boreholes from the design process.

6.4.2 Drilling

In general such construction work requires approval from the local water and/or mining authorities before starting, which may impose restrictions due to the local geology and hydrogeology. From detailed information on the geology available, the most appropriate drilling technology can be decided. No adequate drilling technology, e.g. drilling without casing in unconsolidated rock, can result in a collapsing borehole and the heat exchanger cannot be mounted properly to the required depth and grouting is a constraint. Figure 6.8 shows a drilling rig with a double head system for drilling with casing as shown in Figure 6.9. Therefore an experienced driller and adequate technology is crucial to achieve high quality in the construction and thus an economic system. Additionally provisions have to be taken in advance to allow fast reaction in case of any accident at the drilling site, for example if artesian groundwater or gas cannot be excluded at all.

All drilling and construction activities should be documented thoroughly and communicated to the authorities for conservation of evidence and quality management. The analysis of several accidents with borehole systems in Germany has identified mistakes in the construction process as the primary cause. It is important to realize that such accidents typically do not occur immediately but show up after weeks or even months. Often surrounding buildings were affected at high cost for reconstruction.

6.4.3 Materials for BHEs

The underground may contain numerous, often unknown minerals, which, together with groundwater or even with the humidity in pores or fractures, create a highly corrosive atmosphere, especially if the temperature is rising. Therefore plastic piping

Figure 6.8 Double head drilling rig.

Figure 6.9 Drilling with casing.

for BHEs has proven to be most appropriate for this application. Due to the high corrosion resistance, the flexibility and the rather low price plastic materials are favorable. Only for very high temperatures or in case of high pressure must metal pipes be selected.

The material of the BHE pipes has to be selected according to the maximum operating temperature and operating pressure. Some physical properties of typically used pipes are given in Table 6.2 [5, 9].

Additionally it has to be checked whether the materials used may affect the environment and if, after closing-down of the system, they have to be removed or may remain in the underground.

6.4.4 Installation and grouting

After finishing the borehole the BHE pipes have to be inserted. BHEs are manufactured industrially and have to be tested for leakage before delivery to the construction site. Test documentation is important and part of the product. All handling of the BHEs from production via transport and mounting in the borehole has to be carried out extremely thoroughly to avoid any damage such as bends, deep notching or scratches. This may result in leakages in the long term. Therefore it is recommended to use appliances like a decoiler or a crane (Figures 6.10 and 6.11) for proper mounting of the piping.

For insertion of the BHE pipes in the borehole, a weight at the bottom and filling with water is recommended to compensate for uplifting (Figure 6.12). Additionally this prevents collapsing of the pipes if the critical buckling pressure is exceeded during grouting of the borehole. Forced insertion of the pipes is not recommended due to the potential for damaging the plastic pipes.

Grouting is required to seal the borehole properly and to provide good thermal

Table 6.2 **Material properties of BHE pipes**

Material	**Continuous operating temperature for 50 years**	**Peak temperature during 1 year**[a]	**Thermal conductivity (W/mK)**	**Maximum operation pressure for 50 years at 20°C SF = 1.25 (Bar)**
PE100	40°C at 11.6 bar	70°C at 6.2 bar	0.42	16.0
PE100-RC	40°C at 11.6 bar	70°C at 6.2 bar	0.42	16.0
PE-RT	70°C at 6.5 bar	95°C at 5.2 bar	0.42	13.4
PA	40°C	70°C	0.24	28.0
PB	70°C at 12.1 bar	95°C at 8.1 bar	0.22	21.8
PE-X	70°C at 8.5 bar	95°C at 6.8 bar	0.41	15.1

[a] Exceeding the peak temperature even for a short time period can result in permanent damage of the material.
[2] SF = security factor.
Source: VDI 4640 Part 2; 2014 [9].

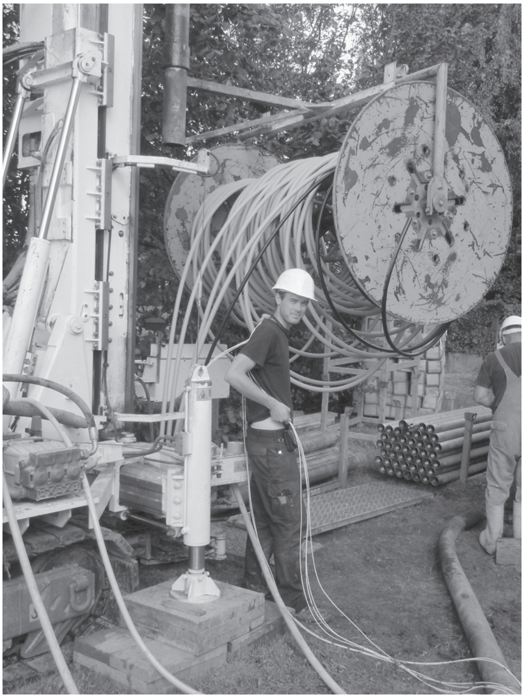

Figure 6.10 PE-X double-U-BHE on a decoiler for insertion of long BHEs.

Figure 6.11 Installation of double-U-BHE at the BTES in Neckarsulm, Germany.

Figure 6.12 PE-X double-U-BHE with bottom weight.

contact between the heat exchanger pipes and the surrounding underground. Connection of aquifers of different water quality or different pressure via a leaking borehole may result in serious damage such as clogging or pollution of aquifers or settlement due to groundwater lowering.

Together with the heat exchanger pipes an additional pipe for pumping down the grout to the bottom of the borehole has to be inserted. The borehole must be filled from the bottom to the top to avoid any cavities which ultimately could result in leaking boreholes. For borehole grouting industrially produced mixtures of cement, bentonite and sand are used which are mixed with a defined amount of water and pumped down the borehole. For underground storage, especially for higher temperature applications the suitability has to be approved by the producer. In recent years thermally enhanced grouts have been developed which show a higher thermal conductivity and thus a lower borehole resistance. Adequate mixing devices and pumps recommended by the producer of the grout have to be used to allow a proper sealing of the borehole.

Before the hardening process starts a final flow and pressure test of the BHE is recommended to determine any damage to the piping during installation. All activities in connection with grouting as well as details like the mixing parameters and the amount of grout pumped in the borehole have to be added to the documentation.

6.4.5 Heat transfer fluid (water or water/antifreeze mixture)

In all borehole storage systems that are used for heat storage only and are permanently operated at a temperature above 4°C, pure water can be used as that heat transfer fluid. But nevertheless provisions against freezing of supply lines or manifolds in outside shafts during shutdown periods have to be considered. The water quality should meet the requirements of regular heating systems to avoid precipitation of minerals like scaling. This use of pure water will facilitate the approval process of the water authorities. Only for cold storage or combined heat and cold storage, when the temperature can reach or fall below 0°C, is a water/antifreeze mixture required.

6.4.6 Layout of the hydraulic circuit

The design of the hydraulic circuit and the adjustment of components are crucial for high performance of the storage system. In contrast to BHEs of ground source heat pumps, in BTES systems more control issues have to be considered. The utilization of BTES as well as the mode of operation are directly influencing the design. Therefore it is recommended to carry out a detailed design of the piping network which takes into account the different operation modes like charging and discharging.

BTES are frequently divided into different zones which are operated individually according to a separate operational concept, and therefore the BHEs of such a zone are connected together in a group with its own manifold. A typical application of this approach is the combined heat and cold storage when in spring and autumn heating and cooling modes alternate in short time periods. The hydraulic design should start with the groups and subsequently be carried out for the whole system.

Due to the compact geometry of BTES, the length of a BHE is small compared to those of ground source heat pumps and therefore frequently several BHEs are connected in series. Such a connection should take into account also the operation mode and allow for charging from the center to the outer part and vice versa during discharging from the outer part to the center. Furthermore, the hydraulic design must provide connection points and shafts for a potential enlargement of the system.

A uniform flow distribution in the BHEs and in the different zones is of special importance and has to be considered when planning the connection. The pressure drop in the different zones and groups should be uniform and can typically be achieved by equal pipe lengths or by appropriate regulation valves. The total pressure drop has to be met by the circulation pump.

The heat transfer power of BHEs is dependent on the thermal conductivity of the underground and the borehole thermal resistance which itself depends among others on the construction of the BHE – single-U or double-U – the thermal conductivity of the grout and the shank spacing of the pipes. The storage capacity is determined by the thermal capacity of the underground material itself. If the peak power to be transferred to the underground and the dynamics require more BHEs than to access the storage capacity, buffer storage (Figure 6.13) should be included in the system. This is especially important in solar district heating systems with BTES due to the high and dynamic variation of power of solar collectors. In most cases a well-insulated water tank serves as buffer storage and is installed above ground; only in the solar district heating system in Attenkirchen is the buffer integrated in the borehole field and thermally coupled to it. A more detailed description is given in the next section.

6.5 Examples of BTES

The first BTES systems for seasonal storage were installed in Sweden and also in The Netherlands in the 1980s for solar district heating systems and use of waste heat from industrial sources. Within the R&D program 'Solarthermie 2000' several solar district heating systems were built with different types of seasonal storage and among these three systems with BTES.

Figure 6.13 Buffer storage (100 m^3 volume) in the solar district heating in Neckarsulm.

Among the different types of seasonal storage in realized solar district heating systems the construction costs of BTES have proven to be the lowest, in the range of 5,000–20,000 m^3. Figure 6.14 [10] shows the investment costs per m^3 water equivalent of projects in Germany carried out within Solarthermie 2000 and some projects in Denmark, the fastest growing market for solar district heating with seasonal storage at the moment.

For seasonal thermal energy storage with only 1–2 storage cycles per year heat losses are more important. They are influenced by the quality of the insulation but also by the storage geometry itself, especially by the surface (heat losses) to volume (storage capacity) ratio. This already demonstrates that the seasonal storage is only efficient and economically feasible with large volume for a high amount of energy. All types of large seasonal storages show a significant reduction of construction costs (Figure 6.14), whereas the variations for the different types result from the different construction techniques.

6.5.1 Solar district heating in Neckarsulm, Germany

The solar district heating in Neckarsulm Amorbach in the south-west of Germany is designed for space heating and domestic hot water for a new housing estate. After overall completion, approximately 700 apartments of different sizes and types of residential buildings (single family, multi-family houses, senior residents and school building) will be supplied by this system. To cope with the development of the residential area over several years, the solar collector field and the storage were increased in several stages.

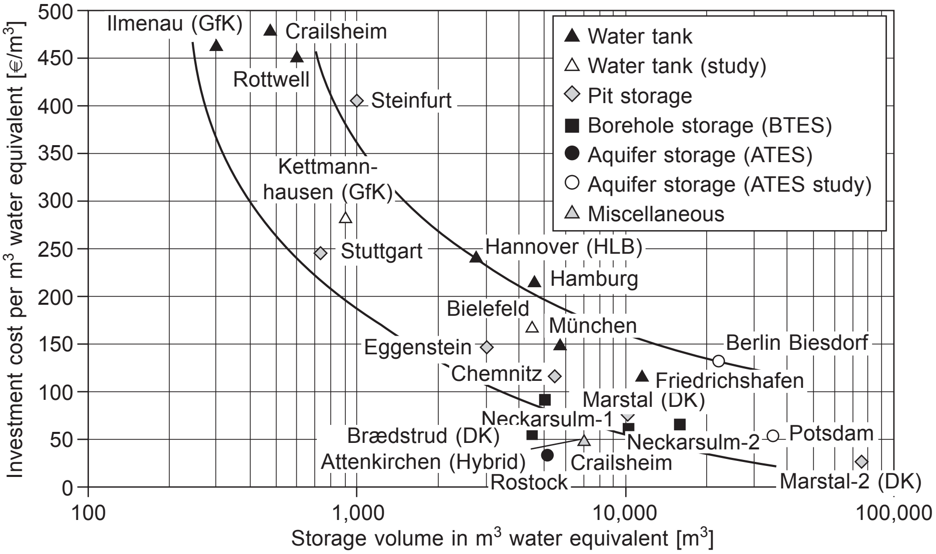

Figure 6.14 Specific investment costs of different seasonal storage types in realized solar district heating systems (without planning and VAT) [10].

The overall heat delivered to the residential area via the district heating is about 3000 MWh/a with a design value for the solar fraction of 50%. About 5000 m^2 of solar flat-plate collectors installed on several buildings in this new developing area deliver the heat to the buffer storage (two hot water tanks of 100 m^3 each) and from there to the district heating directly or to the seasonal storage. A gas boiler in the heating center provides supplementary heating if required. Due to the geological and hydrogeological conditions a BTES was selected for seasonal storage in this system. It was also the first large BTES built in Germany. Operation started with a first pilot storage (36 boreholes) in 1997 and was extended in two stages by 2001 to 528 boreholes with a total volume of about 63,000 m^3.

At the site the geological formation shows a 30–35 m thick clay layer of low hydraulic permeability ($k_f \sim 10^{-8}$ m/s) which is followed by a highly permeable dolomite layer of $k_f \sim 10^{-5}$ m/s with groundwater flow. Therefore a total depth of the BHEs of 30 m was chosen to avoid high bottom losses. From sampling at the test drilling a volumetric heat capacity of the top layer of 2.85 MJ/($m^3 \cdot K$) and thermal conductivity of 2.2 W/(m*K) was determined, which agreed well with values gained from a Thermal Response Test carried out at the second extension in 2001.

A rectangular geometry was selected for the BTES to allow an extension in several stages according to the growth of the building area. In the first extension a borehole spacing of 2 m was chosen which was optimized by simulation in the second extension to 1.5 m in the center and 2.5 m at the edges of the store to reduce the side losses (see Figure 6.15). To reduce the top losses the whole storage area is covered with a 20 cm thick insulation layer of XPS wrapped in a compound of sealing liner, drainage mat and water vapor barrier topped by a 2–3 m thick layer of soil. The storage is integrated in a recreation area between the buildings.

The BHEs are double-U pipes made of polybutene (PB) which provides a high

Figure 6.15 Construction phase of the first extension to 168 boreholes.

life expectancy at temperatures up to 85°C and a pressure up to 10 bars. It is also advantageous that PB is weldable and a full set of electro-fusion joints is available on the market. The 30 m long double-U pipes with an outer diameter of 25 mm (25 × 2.3 mm) are inserted in a 150 mm borehole with spacers every meter. For grouting a slurry of bentonite, quartz sand and cement (CEM III) was used as at this time industrially produced grouting material were not yet on the market. Due to the quartz sand the thermal conductivity could be enhanced to about 1.6 W/m*K to provide good thermal coupling to the underground.

Due to the geological conditions the boreholes could be drilled to a depth of only 30 m and therefore six BHEs were connected in series to achieve turbulent flow conditions and thus a small thermal borehole resistance. These rows of BHEs are connected to manifolds in the center and at the edge. Thus horizontal temperature stratification with high temperature in the center and low at the circumference can be achieved by charging from the center to the edge and a discharging from the edge to the center can be achieved. Besides the high useful temperature which is important for operation, this measure minimizes the side heat losses.

In such heat supply systems a low return temperature of the district heating is of significant importance. It is the lowest temperature of the installation and thus determines the lowest storage temperature. The upper temperature limit of the storage depends usually on the heat source and in the case of BTES on the materials used also. The BTES in Neckarsulm is in principle operated between the return temperature of the district heating and 90°C, which is the limit of the plastic pipes of the BHEs. The designs of the heating systems in the buildings determine the return temperature of the district heating. A heat pump for discharging can reduce this problem but requires operational energy and influences the solar fraction and the overall performance.

6.5.2 Solar district heating at Okotoks, Canada

Drake Landing Solar Community (DLSC) in Okotoks, south of Calgary (Alberta, Canada) is the first solar district heating system installed in North America. This project aimed to demonstrate heating of 52 residential buildings with a high solar fraction up to 90% by using seasonal underground thermal energy storage to store solar heat collected in summer to cover the heat demand in winter. An aerial photo of the housing estate is shown in Figure 6.16 [11]; the energy center and the seasonal storage is located in upper right corner.

Calgary (at 51.1°N) has with about 5200 heating degree days a higher heat demand for space heating than Munich (at 48.1°N) with about 3750 heating degree days, while Calgary receives a solar radiation of 1785 $kWh/m^2{*}a$ (on a surface with 51° inclination) and Munich only 1320 $kWh/m^2{*}a$ (on a surface with 48° inclination). Despite the higher heat demand, the climatic conditions are favorable for solar heating in combination with seasonal storage due to the high solar radiation.

A solar collector field of approximately 2300 m^2 in four arrays serves as heat source in the system and delivers the solar heat to the short-term storage of 240 m^3

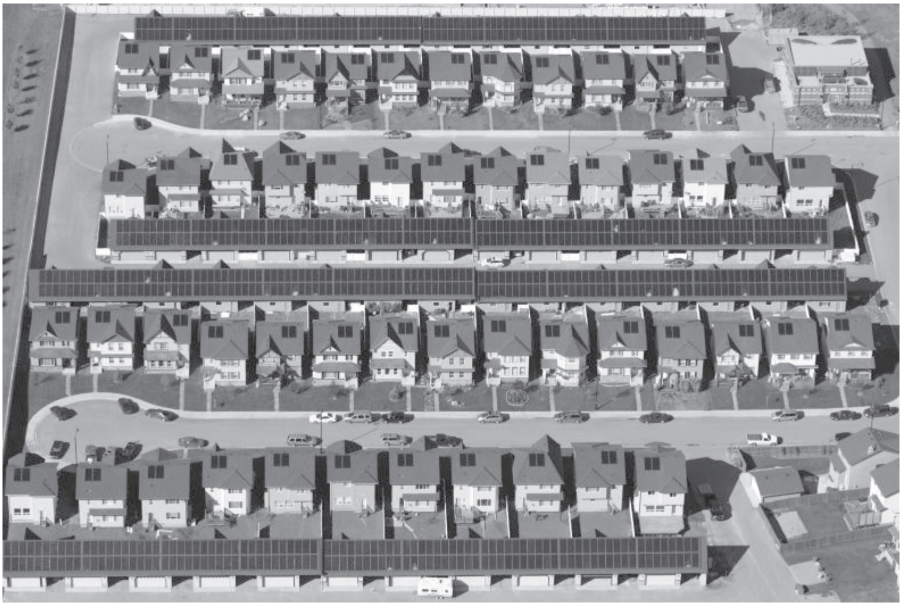

Figure 6.16 Drake Landing Solar Community, Okotoks, Alberta, Canada [11].

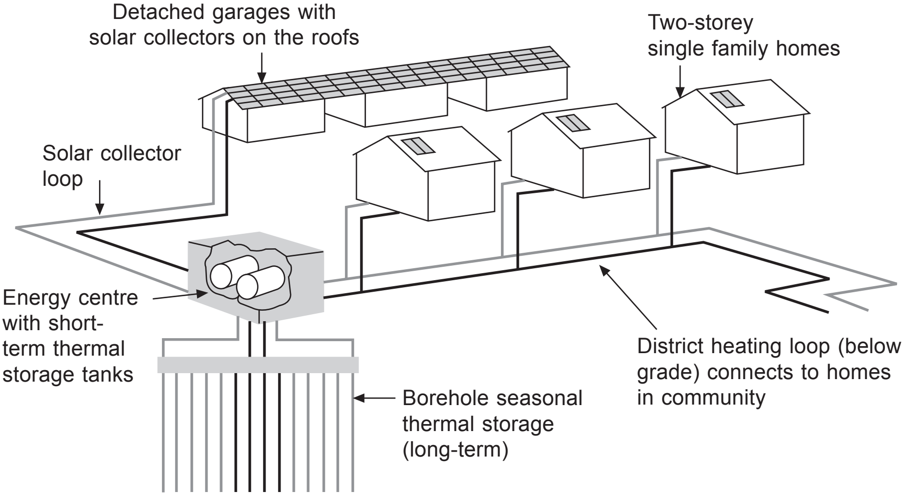

Figure 6.17 Layout of the solar district heating of Drake Landing Solar Community [12].

in two water tanks which are located in the energy center. A general layout of the system is shown in Figure 6.17. The buffer store serves as the central distribution unit which delivers heat to the houses via the district heating and charges thermal energy into the long-term storage. The low permeability of the upper geological layers at the location qualifies the site for BTES for long-term storage.

The BTES field consists of 144 boreholes of 150 mm diameter, each 35 m deep, with 2.25 m distance. This store is equipped with single-U pipes of PE-X, the first time PE-X piping was used in a high temperature BTES. For grouting a mixture of cement (CEM III), fine sand and water was used. Here also a quadratic geometry for arrangement of the boreholes was selected. With an almost circular top area of 35 m diameter, the BTES has an optimal cylindrical geometry. The 144 BHEs are joined together in 24 parallel strings; each of them consists of six BHEs connected in series (see Figure 6.18). All strings are directed from the outer edge towards the center to allow a fluid flow from the center to the edge during charging and vice versa during discharging so that the highest temperature will always be at the center. The strings are connected to collecting pipes directly instead of manifolds which reduce the construction costs but require a thorough hydraulic design. The top area of the BTES is insulated with a 20 cm thick layer of XPS foam which is covered with soil.

The DLSC project is designed for space heating only with rather low and variable supply temperatures in the district loop of 37°C at –2.5°C ambient temperature and 55°C at –40°C outside. Specially designed air handlers were installed in the buildings to manage the low supply temperatures and corresponding low return temperatures. In quasi-steady-state conditions, which are reached after some years of operation, the BTES is heated up to about 80°C at the end of the summer with sufficient energy for an entire heating season. These low temperatures in the district heating are the major reason for the rather high solar fraction which reached remarkable values above 90% in recent years. For domestic hot water supply, which requires

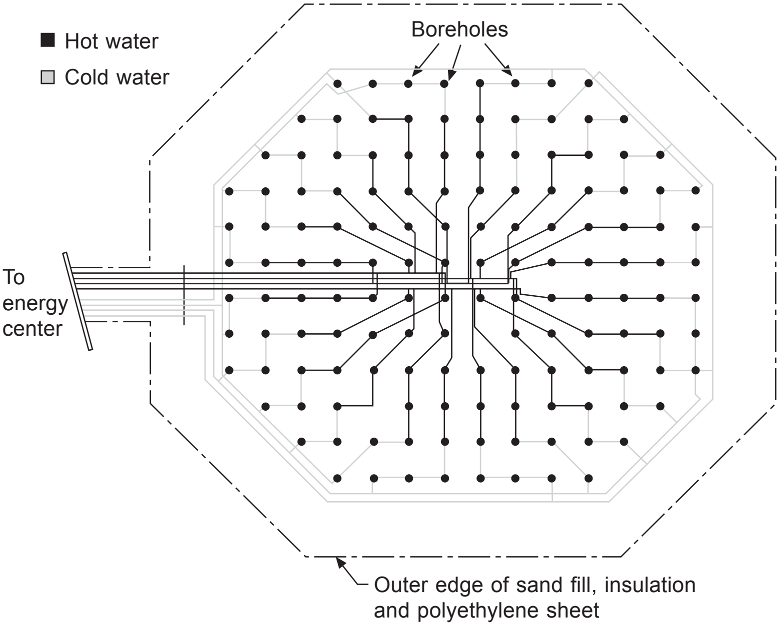

Figure 6.18 Top view of the BTES [12].

temperatures typically above 60°C, independent small solar systems were installed on each house with a gas boiler as backup which cover about 50% of the demand. These promising results and the related awards helped to make Drake Landing Solar Community well-known worldwide.

6.5.3 Solar district heating with hybrid storage in Attenkirchen, Germany

The selection of storage type depends on the geological and hydrogeological conditions of the site as well as on the size of storage capacity required. For technical and economic reasons borehole storage systems always need a buffer for power matching, otherwise the ducts have to be designed for peak power which is not cost effective. In many locations in Germany aquifer storage systems are not applicable due to the hydrogeological situation, legal restrictions or the required size of system. Borehole or pit storage as well as hybrid storage can be an option.

A rather new development is the combination of a cylindrical water tank and a field of borehole heat exchangers surrounding the tank (see Figure 6.19). It promises to combine the operational advantages of high heat transfer power of tanks and pits with the economical ones of duct systems. When it comes to larger volumes (>100 m^3), steel as material for buffer tanks can be replaced by concrete, especially if it is cast in-situ. But still insulation is required to reduce heat losses and the construction has to be sealed inside with a stainless steel liner to avoid water vapor transport through the concrete by diffusion. The reason is not only the water losses but also the latent heat transport through the concrete wall which can be significantly higher than the conductive heat transport.

The concept of hybrid storage combines the buffer tank and the BTES for seasonal storage. The concrete water store is installed in the center of the BTES field and also

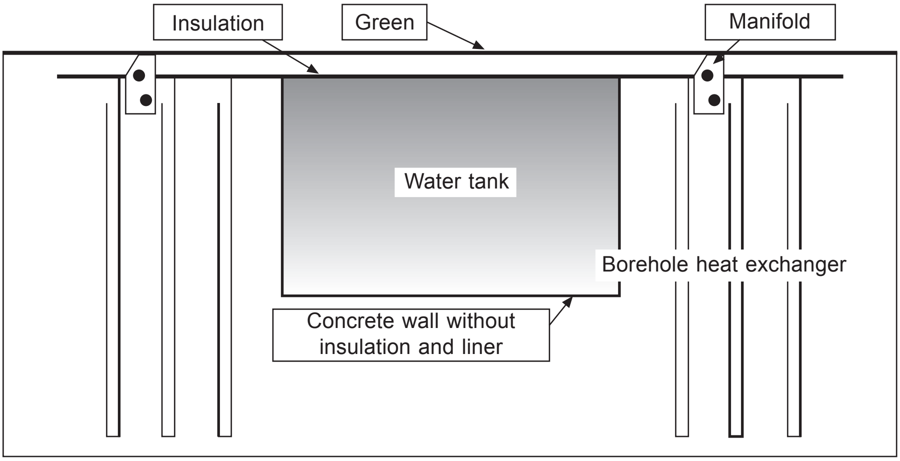

Figure 6.19 Hybrid storage.

thermally coupled to it. Heat losses through the side walls and the bottom are heat gains which can be recovered in the BTES. This applies not only for the conductive but also for the latent heat transport and thus thermal insulation and steel liner of the water store are no longer necessary. Nevertheless, it is still important to install a top insulation over the whole storage field.

This storage was the first of its kind built as the solar district heating system for 20 houses in Attenkirchen, about 40 km north of Munich. The total heat demand of the residential buildings is about 490 MWh/a. About 765 m^2 of solar collectors serve as heat source delivering the useful heat to the buffer storage. The system is, like all other solar district heating projects in Germany, designed for a solar fraction of 50%.

At the construction site in Attenkirchen the geology with a sequence of clay and silt layers with low permeability without groundwater is favorable for BTES. At this location one of the first Thermal Response Tests in Germany was carried out at the first test drilling.

The central water tank (Figure 6.19) made of pre-stressed concrete (Figure 6.20) serves as short-term or buffer store while the surrounding borehole field represents the long-term storage. The tank measures 9.0 m in diameter and 8.5 m in depth with a total volume of 500 m^3. This combination allows a simpler and cheaper construction of the water store. The top area of the whole storage is insulated by a 20 cm thick layer of polystyrene (XPS). For long-term storage a BTES field with 90 BHEs (Figure 6.21) of 30 m depth was installed in three rings surrounding the water store, which gives a volume of 10,500 m^3. The average volumetric heat capacity of

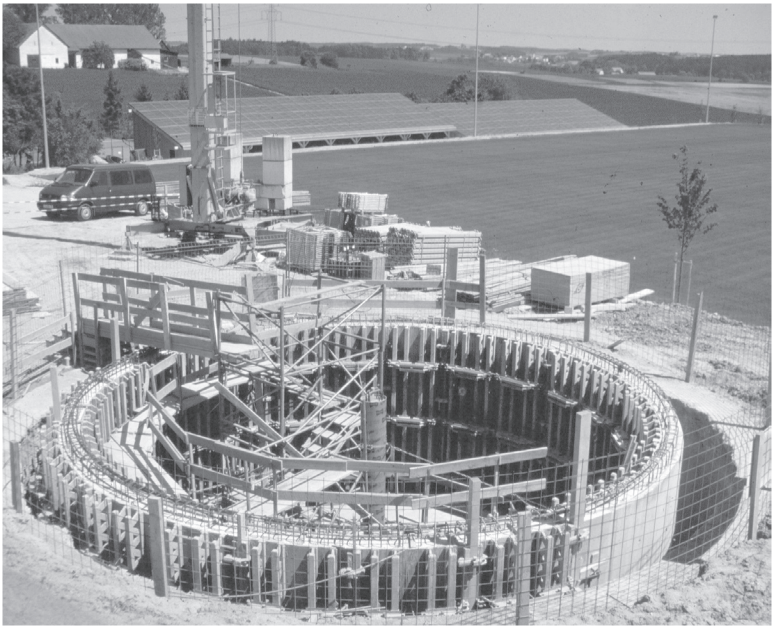

Figure 6.20 *In-situ* casted concrete tank (500 m^3).

Figure 6.21 BTES construction surrounding the concrete tank.

the underground measured at this location is 2.7 MJ/m^3/K. Thus the borehole storage volume corresponds to 6,800 m^3 water equivalent and both together 7,300 m^3.

The borehole heat exchangers are like in Neckarsulm, constructed as double-U-loops made of polybutene pipes (20 × 2.3 mm) with spacers every 2 m. They are mounted in grouted boreholes of 150 mm diameter. For investigation of the long-term performance of thermal grouts, two different materials were used. Half of the boreholes were grouted with a bentonite/cement/quartz-sand/water slurry, while for the other half the convenience blend ThermoCem was used.

In the design phase a systematic analysis of different system concepts was carried out comparing the system with gas boiler and heat pumps as backup. The options with heat pumps showed technical and operational advantages as the useful temperature heave in the store is higher and the dependency of the system and storage performance on the return temperature of the district heating is avoided.

As shown in the system scheme (Figure 6.22) discharging of the water store as well as of the borehole storage can be done directly or by heat pumps depending on the temperature levels. Additionally, direct supply to meet heat demand in the houses is possible. This option is used for domestic hot water in spring, summer and autumn. Furthermore, low-price electricity can be used for discharging the borehole store with the heat pump during the night. This heat is charged in the water storage for direct use later.

The construction of the plant has proven the technical and economic expectations (see Figure 6.14). The specific costs of the total storage amount to about €50/m^3-

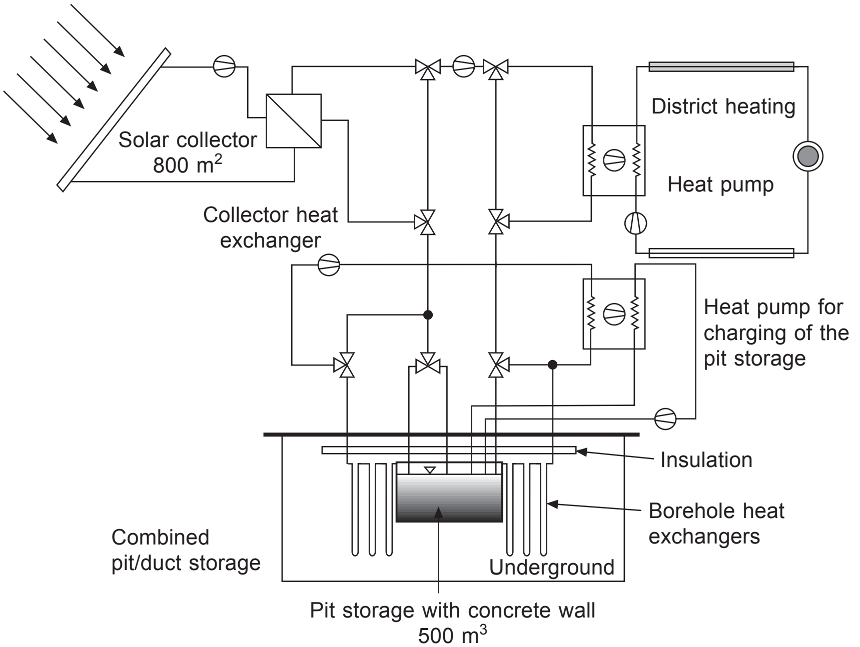

Figure 6.22 System layout of the district heating in Attenkirchen.

water equivalent. There is still potential for cost reduction of the water tank by about 20–30% in the earthwork and the tank construction.

6.6 Conclusion and future trends

In general the feasibility of BTES requires appropriate geological and hydrogeological conditions like low permeable underground or hard rock without groundwater flow. For efficient operation, BTES needs a minimum size of at least 1000 m^3. The operational temperature range is typically that of classical water storages (0–90°C): below freezing a problem may occur due to underground freezing and the temperature limits of the plastic materials for BHE construction are reached at 90°C.

Low temperature BTES will be of increasing importance for future thermal energy supply especially for large buildings with demand for heating and cooling (e.g., commercial buildings), as it allows a significant reduction of operational costs for cooling and improved heating operation. The increase of efficiency in heat supply and the energetic renovation of the building stock form together with the expansion of renewable energies in the heating market the basis to meet the German goals of CO_2 emissions reduction in the heating sector.

Among high temperature applications (<90°C) BTES is favorable for seasonal storage of solar thermal energy as well as waste heat from industrial processes and heat and power cogeneration. The use of biogas in a heat and power cogeneration can serve as an excellent example for BTES application. Gas production is a biological process running continuously and can hardly be influenced without major implication. Also the storage of gas is complex and expensive. If efficient long-term thermal energy storage for large amounts of heat is available, the cogeneration unit can be operated according to the electricity demand and not to the heat demand. BTES can improve the economy of such a system significantly.

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