Borehole thermal energy storage

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Abstract

Borehole thermal energy storage (BTES) systems utilize boreholes in rock, soil, or clay to transfer heat and cold to the surrounding ground material, so that the thermal energy may be seasonally stored. BTES systems have been used for more than 35 years in diverse applications. This chapter reviews characteristics of BTES systems and their applications.

11.1 Introduction

Borehole thermal energy storage (BTES) systems store sensible heat (or cold) in the ground surrounding individual boreholes. In a sense, all systems that use boreholes for heat or cold extraction could be considered BTES systems, even single borehole residential systems. However, this chapter will focus on systems with multiple vertical boreholes used for some sort of active and intentional storage of heat and/or cold in the ground.

11.1.1 Definition of borehole thermal energy storage

There is no uniform definition of a BTES system, and there are a number of other terms used in literature for systems that could be regarded as BTES systems. The abbreviation BTES first shows up in literature in a report by the International Energy Agency Energy Conservation through Energy Storage working group (IEA ECES, 1997). It is largely through the various IEA ECES workgroups that the term has been most widely used and spread. In proceedings from the international conferences on thermal energy storage ("Stock" conferences) arranged by IEA ECES since 1981, the abbreviation BTES did not appear until the Terrastock conference in Stuttgart in August and September 2000. In that conference, it suddenly appeared as a widely used and established term (Benner and Hahne, 2000).

Prior to that, BTES applications were included in the more general terms seasonal thermal energy storage (STES) or underground thermal energy storage (UTES). The abbreviation DTES (duct[1] thermal energy storage) was also used to distinguish storage

[1] The term "Duct Thermal Energy Storage" results from an unfortunate translation of the Swedish word *kanal*. Although the word duct in English can mean a channel through which liquid flows, it is used in the North American heating and cooling industry to mean a channel through which air flows. Nevertheless, as used in this chapter in conjunction with "thermal energy storage" it always means a channel through which liquid flows.

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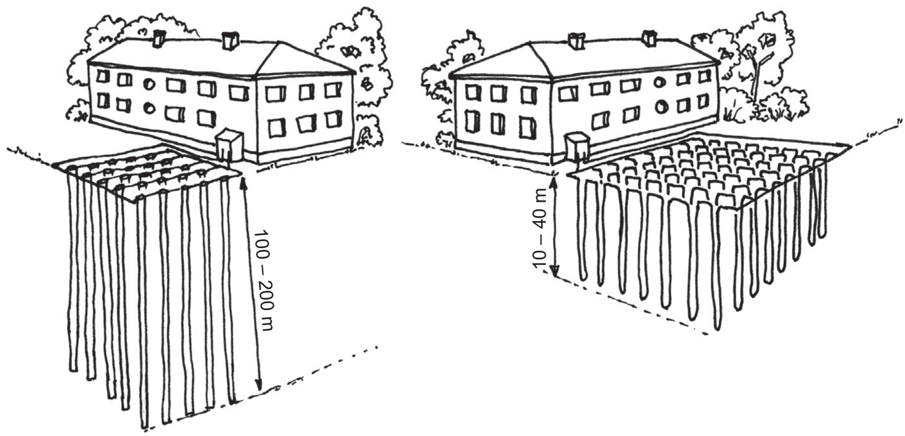

Figure 11.1 Borehole thermal energy storage drilled in rock (left) and with pipes inserted in clay (right).
Illustration by S. Gehlin (2015).

in rock or clay from aquifer thermal energy storage (ATES) systems. Even after the introduction of BTES as a term, DTES is sometimes still used to distinguish systems where vertical heat exchangers are inserted in soft formations such as clay or soil without drilling (ie, there are no boreholes, only a heat exchanger that has been driven into the soft formation). Fig. 11.1 shows BTES systems in rock and soft formations.

BTES systems are referred to by many names in the literature including "ground heat store," "borehole store," "borehole heat store," "seasonal thermal energy storage in rock ducts or ground," "energy storage with borehole heat exchangers (BHEs)," "ground-coupled thermal energy storage (GCTES)," "storage system in rock," "multiple-well storage system," "vertical heat exchanger store," and "vertical loops." BTES systems do not necessarily use heat pumps, but when they do, they are sometimes referred to as "geothermal heat pump systems," "ground-coupled heat pump (GCHP) systems," "ground-source heat pump (GSHP) systems," or "geo-exchange systems."

There are diverse definitions of BTES in the literature. The IEA ECES report from 1997 (p. 33) defined BTES as systems where rock or soil is the energy storage medium accessed by closed-loop heat exchangers placed in boreholes. The energy recovered or stored in the subsurface environment is used for heating and cooling. Nordell (2000) gave a wide but detailed definition of BTES. He divided the technology into small-scale, large-scale, and seasonal storage. His definition of BTES comprised systems that provide cooling and/or heating, with or without heat pumps and with or without recharge, at all temperature levels, and any number of boreholes or ducts in rock, soil, or clay. In Paksoy (2007), BTES is defined differently by the various chapter authors, but the given examples are all multiple-borehole systems for seasonal storage of heat and cold. Banks (2012, pp. 395–396) defined BTES as "deliberate thermal energy storage" in multiple-borehole systems with closed loops. Lee (2013, p. 98) makes a distinction between BTES and "true BTES," which in the latter case implies systems where the cold is actively stored and not passively recharged by heat transfer from the surroundings. He defined BTES as multiple-borehole systems in rock, soil, or clay. In Cabeza (2015, p. 11), BTES is said to consist of several closely spaced boreholes, but also that many countries have thousands of BTES systems with one to a few 100 boreholes, usually for heating and cooling of buildings. The distinction between vertical GSHP systems and BTES is vague. A distinction suggested by Sanner and Stiles (1997) is that if less than 25% of the annual thermal turnover from the borehole system is being exchanged with the surroundings, the BHE system would qualify as a BTES system.

This chapter on BTES will define BTES in the wide context as given by IEA ECES (1997) and Nordell (2000), but will focus on larger applications with multiple boreholes and active storage, with or without the assistance of heat pumps.

11.1.2 Some borehole thermal energy storage history

One of the first descriptions of vertical BHEs in the ground is found in Kemler (1946). In Kemler (1947), he suggested nine different heat exchanger designs for extraction of heat from the ground to serve as heat sources for a domestic heat pump. Four of these were horizontal coils, of which one is placed in a trench surrounding the building foundation; four were vertical open or closed (U-tube or coaxial) loops, and one was a vertical helical coil heat exchanger. Kemler concluded that all nine methods are potentially feasible. IEA ECES (1997) and Nordell (1994) give credit to Brun (1965) for conceptualizing borehole or duct ground heat storage. Brun, however, had a rather different approach to how the heat be transferred in the ground. He suggested injection of solar-heated high temperature (450°C) steam into boreholes drilled in rock, and recovering the stored heat by injecting water into the boreholes. His impressive proposed field of 800,000 boreholes to a depth of 200 m was never realized.

It was not until the oil crisis in the 1970s that the interest in large-scale storage of heat in the ground took off. The objective was seasonal storage of high temperature solar heat or waste heat, initially in storage tanks, rock caverns, or aquifers, and later also in boreholes or ducts in clay and rock. These systems were intended to work without heat pump assistance. By the end of the 1980s, interest increased in thermal energy storage at lower temperatures for heating and cooling. These systems typically involve heat pumps for extraction of heat, while cooling may be provided without heat pumps. This type of application has proven to be very efficient and feasible, as the demand for comfort cooling increases with improved building insulation.

The first multiple-borehole BTES system was possibly a 12-borehole system built for seasonal storage of solar energy in the Jura mountains of France in 1976 (Guimbal, 1976; Hellström, 1991). Large-scale BTES systems were built in Sweden around 1980 and reported at the first International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage in Seattle, Washington, in October 1981. A full-scale experimental BTES system was built for a single-family house in Sigtuna, Sweden, in the late 1970s (Platell et al., 1981; Platell and Wikström, 1983). The research project was called Sunstore, and the system consisted of 42 boreholes drilled in rock to a depth of 23 m, and connected to 162 m^2 of solar collectors. It was constructed in sections with drilling starting in November 1977 and was completed in 1981. During this period the ground was preheated with electrical heating. In May 1981 the solar collector circuit was connected and solar heat was stored in the ground. The first solar heat extraction started in the fall of 1982 and the store provided temperatures of 10–40°C.

About the same time, a small-scale pilot plant for high-temperature BTES was set up close to the Luleå University of Technology campus in the north of Sweden, in 1980−1981 (Andersson et al., 1983; Nordell, 1994). Nineteen boreholes with a diameter of 52 mm and 1.3 m spacing were drilled to a depth of 21 m. The soil overburden was 6 m. The boreholes were arranged in a hexagonal configuration and fitted with open loops. The plant was used to operate and evaluate the thermal behavior of the store during five cycles, and was in operation from July to November 1981. Positive results from this pilot project led to construction of the experimental full-scale high-temperature demonstration BTES system Lulevärme Heat Store in 1982−1983 (Nordell, 1994). The store was in operation between 1983 and 1989. It consisted of 120 boreholes in a 10 × 12 rectangular configuration in granitic rock to a depth of 65 m. The 152-mm diameter boreholes were spaced 4 m apart and fitted with open loops. Waste heat at a temperature of 70−82°C from a steel industry plant was transferred to the storage via the district heating network during the summers. The heat was recovered at 35−55°C in the winters for heating of one of the university buildings.

Early BTES systems in clay and soil were constructed in Sweden, Switzerland and the Netherlands in the 1980s. In 1979 a single-family building in Utby, Sweden, was connected to a heat storage consisting of 37 vertical tubes inserted in clay to 10-m depth. The heat store was charged with low temperature heat from the outdoor air with an air-to-fluid heat exchanger in the summers (Rosenblad, 1983). The Sunclay heat store in Kungsbacka, Sweden, consisted of 612 vertical plastic single U-tubes inserted in clay to a depth of 35 m and at 2-m spacing (Hultmark, 1981). The storage was heated by 1500 m^2 of unglazed roof-integrated solar collectors in the summers and operated in the temperature interval 15−30°C. It was built and tested in 1980−81. In Mont de Pitié, Cortaillod-Neuchâtel, Switzerland (Matthey and Pillonel, 1985), a system was being constructed in 1978−81 where 12 family houses were heated with solar heat from 320 m^2 solar panels, stored in a BTES system with 400 coaxial tubes in sandy loams, to a depth of only 6−8 m. The system was assisted by gas-driven heat pumps. Other similar systems with a large number of shallow vertical loops inserted in clay, sand, or soil were built in Groeningen (Wijsman, 1985), Genève (Matthey, 1988), and Cormontreuil (Baudoin, 1988).

When interest in storing low temperatures for cooling increased by the end of the 1980s, BTES systems that combined heat extraction with heat pumps and extraction of cold from boreholes without heat pump (free-cooling) developed. In the 1990s, this type of application, which could be constructed at a smaller scale, spread rapidly in Europe and North America. Hellström (1991, p. 17) lists early BTES systems, and examples of German BTES systems are found in Sanner (2005). Bakema et al. (1995, pp. 14−17) provides an extensive table of UTES systems, of which 22 are BTES systems in Sweden and Germany. Early BTES systems reported in the literature are compiled in Table 11.1.

11.2 Typical features of borehole thermal energy storage

BTES systems are said to be the most general type of UTES system and are most efficient for large energy loads with slow changes over time (Nordell, 2000). As discussed earlier in this chapter, the term BTES is subject to wide interpretation, and though the

Table 11.1 **Early full-scale borehole thermal energy storage systems reported in the literature**

First year of operation	Plant name/ location	Ground	Configuration	Collector type	Temperature	References
1979	Utby Sweden	Clay	37 boreholes of 10 m	Two-channel tube	2–12°C Ambient air	Rosenblad (1983)
1981	Sunstore Sigtuna Sweden	Rock	42 boreholes of 23 m	Coaxial	10–40°C Solar	Platell et al. (1981) and Platell and Wikström (1983)
1981	Sunclay Kungsbacka Sweden	Clay	612 ducts of 35 m	U-tube	15–30°C Solar	Hultmark (1981)
1981	Mont de Pitié Cortaillod, Neuchâtel Switzerland	Sandy loams	400 boreholes of 6–8 m	Coaxial	7–25°C Solar	Matthey and Pillonel (1985)
1982	Treviglio Italy	Sand and gravel	220 + 194 boreholes of 11 m	U-tubes	Solar	Dalenbäck (1990)
1983	Kerava Solar Village Finland	Rock	54 boreholes of × 25 m surrounding a 1500 m^3 water pit storage	n.a	Solar	Peltola et al. (1985) and Dalenbäck (1990)
1983	Lulevärme Luleå Sweden	Rock	120 boreholes of 65 m	Open	35–82°C Waste heat	Andersson et al. (1983) and Nordell (1994)

Continued

Table 11.1 Continued

First year of operation	Plant name/ location	Ground	Configuration	Collector type	Temperature	References
1983	Kullavik Kungsbacka Sweden	Clay	130 + 156 ducts of 12 m	U-tube	10–50°C Solar	Hultmark (1983) and Olsson (1984)
1984	CSHPSS Groeningen Netherlands	Sand and clay	Unreported number of boreholes within 38 m diameter, 20 m depth	U-tube	30–50°C Solar	Wijsman (1985) and Wijsman and Havinga (1988)
1984	Viberga Finspång Sweden	Rock	24 boreholes of 110 m	U-tube	Heat/cold	Edstedt and Nordell (1994) and Energiverk (1986b)
1985	Grosvad Finspång Sweden	Rock	126 boreholes of 110 m	U-tube	10–35°C Low temp heat from hockey rink	Edstedt and Nordell (1994) and Energiverk (1986a)
1986	Cormontreuil France	Rock	24 boreholes of 25 m	Coaxial	30–60°C Solar	Baudoin (1988)
1986	Höstvetet Suncourt Stockholm Sweden	Rock	25 boreholes of 80 m	U-tube	6–15°C Solar	Kellner et al. (1986) and Werner (1988)

1987	Ramunderskolan Sports Hall Söderköping Sweden	Clay	382 boreholes of 18 m	Double U-tube	10–31°C Solar	Magnusson et al. (1992)
1988	Meyrin Genève Switzerland	Soil	258 boreholes of 15 m	Double U-tube	4–32°C Solar	Matthey (1988)
1988	GLG-center Upplands Väsby Sweden	Rock	64 boreholes of 110 m	U-tube	Heat/cold	Edstedt and Nordell (1994)
1988	Capella Kristinehamn Sweden	Rock	17 boreholes of 110 m	U-tube	Heat/cold	Edstedt and Nordell (1994)
1988	Infra city Upplands Väsby Sweden	Rock	64 boreholes of 110 m	U-tube	9–20°C Heat/cold	Nordell (1994)
1990	Technorama Düsseldorf Germany	Sand and gravel	77 boreholes of 35 m	Steel tube coaxial	0–25°C Heat/cold	Sanner and Knoblich (1991)
1990	Onoff Järfälla Sweden	Rock	20 boreholes of 110 m	U-tube	Heat/cold	Edstedt and Nordell (1994)

focus in this chapter lies on larger systems for active thermal energy storage, most features listed in this section apply for large as well as small borehole systems, with or without active storage. BTES systems use hard rock and soft formations such as clay, sand, and soil as a storage medium. The boreholes perforating the ground volume are fitted with pipes[2] circulating a heat carrier fluid, and serve as heat exchangers between heat carrier and ground. Heat transport between the heat exchanger and the ground takes place primarily by conduction. Thermal energy is stored in the ground between the BHEs. The ground is an inexpensive storage medium and enables large amounts of heat and cold to be stored over short- or long-term periods at relatively low cost.

11.2.1 Ground properties and storage

The function of BTES is based on the ground material's ability to store and conduct heat. A high volumetric heat capacity is desirable for sensible heat storage, as done with BTES systems. Volumetric heat capacity of the ground is in the order of 1.3−2.8 MJ/m^{3}K for unconsolidated ground material and 1.8−3 MJ/m^{3}K for solid rock. In comparison, volumetric heat capacity of water is 4.2 MJ/m^{3}K. A rock volume with a typical volumetric heat capacity of 2.2 MJ/m^{3}K will hold about 0.6 kWh/m^3 if heated 1°C. This means that a storage volume measuring 100 m × 100 m × 100 m has the capacity to hold 600 MWh/K. Fig. 11.2 shows the storage capacity as a function of

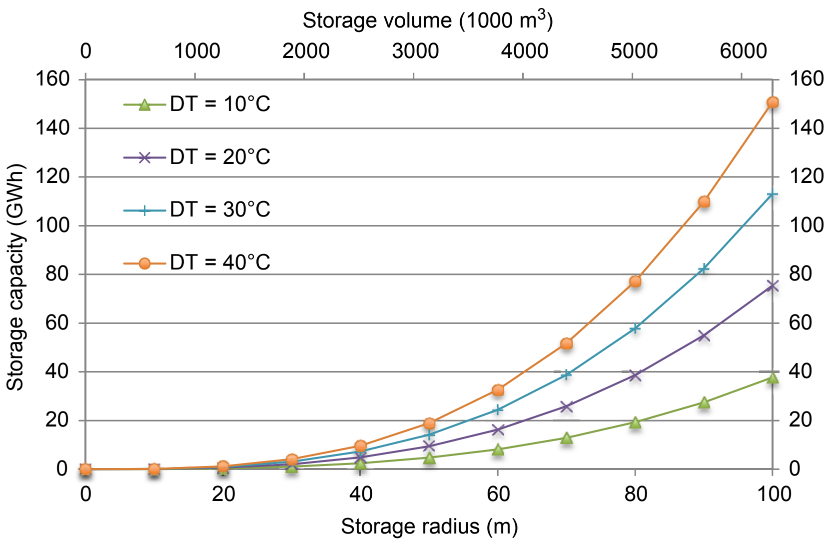

Figure 11.2 Storage capacity as a function of radius (R) and storage temperature range for a cylindrical heat storage in rock with depth $H = 2R$ and volumetric heat capacity of 2.2 MJ/m^{3}K. DT denotes the difference between highest and lowest temperature in the store.

[2] The pipes are a type of heat exchanger sometimes referred to as "collectors" but are more commonly called "ground heat exchangers" or "borehole heat exchangers."

storage radius and the difference between highest and lowest storage temperature, $\Delta T = T_{\max} - T_{\min}$, for a cylindrical heat storage in rock with depth $H = 2R$ and a volumetric heat capacity of 2.2 MJ/m^{3}K.

To achieve efficient heat transport in the ground and to/from the ground heat exchangers (GHEs), high thermal conductivity of the ground is desirable. However, high thermal conductivity will also cause higher heat losses from the store. Thermal conductivity of the ground is typically on the order of 1−5 W/m·K. Higher conductivity values are typically found in formations with high contents of quartz minerals, high bulk density and water saturation.

11.2.2 Ground heat exchangers

GHEs for BTES systems are drilled to a certain depth in hard or soft formations, and then fitted with the collector pipes. In soft formations the collector pipes may also be pressed or vibrated into the shallow formation. A typical depth for shallow installations where the collector pipes are pressed or vibrated in is 10−40 m. Common borehole depths are 100−200 m. In most countries, boreholes are backfilled or grouted. The grout serves to stabilize and seal the boreholes and also to achieve good thermal contact between the ground material and the collector pipes. In the Scandinavian countries where geology and hydrology are characterized by hard rock and high groundwater levels, boreholes are typically left ungrouted. Natural groundwater will then fill the borehole to the groundwater table level. Groundwater offers excellent thermal contact between borehole wall and collector pipe and enhances heat transfer due to natural convection (Kjellsson and Hellström, 1997; Gustafsson and Gehlin, 2008).

A wide range of GHE types are used for BTES: single and double U-tubes are most commonly used due to their reliability, simple installation, and low cost. Various types of coaxial collectors, with hard or soft outer shell are used occasionally, due to their low thermal resistance and pressure drop but are more expensive, more complicated to install, and involve higher risk for leakage. Low thermal resistance in the BHEs is particularly desirable in BTES systems with active storage of heat and cold as poor heat transfer in the collectors will affect the storage efficiency both at injection and rejection.

In high-temperature BTES and low-temperature BTES systems permanently operated at temperatures above +4°C, pure water may be used as heat carrier fluid in the borehole collectors (Reuss, 2015). Water mixed with an antifreeze solution—typically ethanol or propylene glycol, and sometimes ethylene glycol—is used for systems where the heat carrier fluid is allowed to fall below 0°C, such as some applications of combined heat and cold storage, or if there is a risk for freezing of the horizontal pipes interconnecting the BHEs and connecting the boreholes with the building. Ethanol cannot be used for high temperature applications.

11.2.3 Storage geometry

The geometry of the BTES system is important for the heat loss. While storage capacity is proportional to storage volume, heat losses are proportional to surface area. The

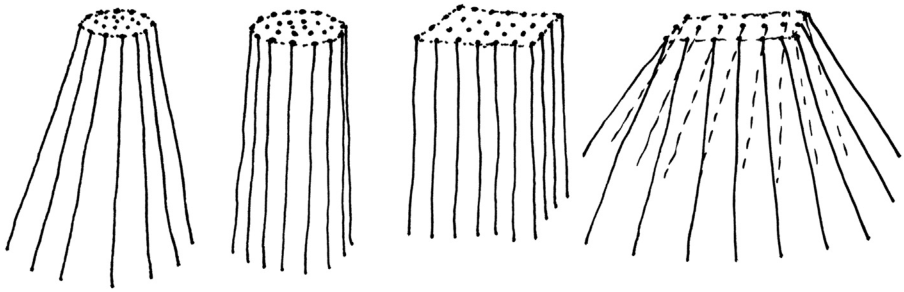

Figure 11.3 Circular configurations (left) and rectangular configurations (right) with or without diverging boreholes.
Illustration from S. Gehlin (2015).

relative heat loss decreases with increasing storage volume. Accordingly, a design with small surface-to-volume ratio is desirable. Annual heat loss for a given annual mean temperature of the store (during steady−periodic seasonal operation) is a function of the volume, shape, and ground thermal conductivity. Thermal conditions at, and distance to, the ground surface are also important factors for the operational heat loss. Hellström (1991) gives a comprehensive analysis of heat loss from BTES systems of various shapes. Storage efficiency is defined by Nordell (1994, p. 12) as given by the ratio between stored and extracted thermal energy. This efficiency is favored by large storage volume and compact geometry, ie, a small surface-to-volume ratio.

The ideal storage shape in an infinite medium would, from a heat loss perspective, be a sphere. However, this is obviously a complicated geometry from a construction perspective. Therefore the most commonly used storage geometries are the cylinder or parallelepiped (box) shapes. If available ground surface is limited, the storage can be given a larger volume by letting the boreholes diverge from the vertical line, so that the boreholes form a broom-like shape (Fig. 11.3).

Boreholes are placed in a symmetrical arrangement, usually in a circular, rectangular, or hexagonal pattern (Fig. 11.4), with borehole distance typically in the range 4−6 m. Borehole depth, distance, and configuration must be carefully optimized for each project, using advanced design software such as Earth Energy Designer (Hellström et al., 1997) and GLHEPRO (Spitler, 2000). Hellström and Sanner (2001) describe and compare a number of available design software of this type.

BTES systems are not insulated on the sides or at the bottom, but top insulation is sometimes used to limit heat loss to the atmosphere (Reuss, 2015).

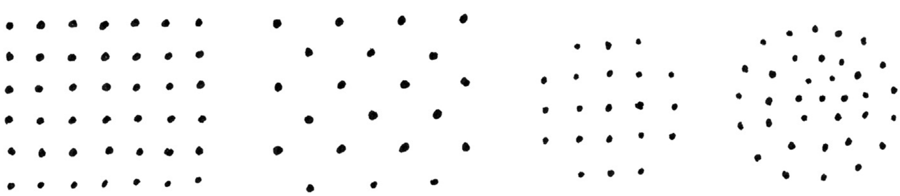

Figure 11.4 Boreholes may be arranged in rectangular, hexagonal, or circular drilling patterns.
Illustration from S. Gehlin (2015).

11.2.4 Groundwater flow

Heat loss calculations typically only take into account the conductive heat transport in the ground. Convective heat transport with groundwater flow may also affect the heat storage performance (van Meurs, 1986; Claesson and Hellström, 2000). Åberg and Johansson (1988) studied the effects of groundwater flow on BTES systems, both in porous formations and in fractured hard rock. They conclude that for natural groundwater flow in an evenly fractured ground volume, and with common hydraulic conductivity of the ground, the convective heat transport from the storage will be insignificant. For highly permeable ground and large hydraulic gradients, the stored body of heat would move on the order of a few meters downstream over one year. In the case of highly fractured rock or large fractures intersecting the rock volume, the groundwater transported in the fracture may cause significant heat loss from the store. The authors recommend cement injection to eliminate this problem in such rare cases. Chiasson et al. (2000) made numerical simulations of the ten-year performance of a cooling-dominated borehole field in groundwater flow. They found that even moderate groundwater flow affects the year-by-year ground temperature increase compared to pure conductive conditions. Effects of groundwater flow on long-term performance of a BTES system with unbalanced winter and summer loads are discussed by Zanchinia et al. (2012). They conclude from their study that groundwater flow has little effect on short-term peak loads but positively influences the long-term performance by enhanced thermal exchange with the surroundings.

For high temperature BTES systems, convective heat transport induced by the thermal gradients becomes important and must be considered (van Meurs, 1986; Hadorn, 1990).

11.2.5 Storage temperature

An important factor in the design and operation of BTES systems is the average storage temperature in relation to the average temperature of the surrounding ground. If the annual average temperature of the store is lower than that of the ground surrounding the store, heat will be gained to the store (Hadorn, 1990). The amplitude of the temperature variation over the year ($T_{max} - T_{min}$) does not affect heat loss from the store, as the net heat flow through the storage boundaries becomes zero for an annual cycle. Steady-state heat loss depends on the temperature difference between the annual average storage temperature and the undisturbed ground temperature ($T_{avg} - T_o$).

Hadorn (1990, p 57−58) classified UTES systems according to storage temperature level, and identified technical difficulties related to storage temperature. For storage temperatures below 0°C phase change problems related to freezing occur. Within the interval 0−30°C few temperature-related problems occur. Heat loss from the store is low and the store may be left uninsulated, but a heat pump must typically be used if the storage is used for space heating. Above 30°C the store may be used without a heat pump to provide heat to low and medium temperature distribution circuits. However, heat loss to the surrounding ground becomes an issue, and above 60°C problems related to materials and the environment may appear. Storage temperatures above 100°C may be desirable for existing urban district heating circuits, but there will be technical issues related to boiling groundwater, material properties, and the environment (Hadorn, 1990).

Examples of suitable heat sources for low-temperature BTES systems are excess heat from cooling machines in office buildings, commercial buildings, and other facilities. Exhaust air is an excellent heat source as it may also allow for decreased installed heat pump capacity for the winter period. Industrial waste heat and solar heat are suitable for high-temperature BTES applications.

Various schemes of operation are used for BTES. The most common scheme involves parallel-coupled boreholes, with simultaneous charging and rejection of all boreholes in the ground volume. Another strategy is to charge the storage beginning at the center and continuing outwards. This is done by either connecting the boreholes serially in the radial direction, or by dividing the store into circular sections. Heat extraction from a heat storage system would take place in the opposite direction. That means that the heat storage volume would always be warmest in the middle.

11.3 Environmental aspects

Protection of the environment is important at a global level as well as locally. Work has been carried out within IEA ECES (Bakema et al., 1995; IEA ECES, 1997) to evaluate environmental benefits as well as risks related to UTES. BTES systems help to reduce emissions of CO_2, NO_x, and SO_2 to the atmosphere by replacing fossil fuels and increasing the efficiency of energy utilization. By replacing conventional chillers with direct cooling from BTES, the risk for release of refrigerants into the atmosphere is decreased. BTES systems increase the potential for storage of solar heat and waste heat in both the short and long term. Compared to conventional systems, BTES systems are visually unobtrusive (essentially invisible), take up little space, and are quiet.

Like all types of construction work, BTES systems have potential risks for the local environment. Problems may occur during construction as well as during operation. Reuss (2015), Paksoy (2007), and Banks (2012) give advice on environmental concerns related to BTES and how to avoid them.

11.3.1 Risks related to temperature

In some countries (eg, Germany) concerns regarding disturbance to the ground temperature have been raised, and restrictions to how much the ground temperature may be disturbed have been formulated. The temperatures in the underground are, however, already disturbed by urbanization. We like to keep our buildings at a constant temperature around 20°C, and temperature logs in urban areas show clearly the contribution of heat leakage from buildings to the ground temperature profile. This thermal front may reach more than 100 m below ground surface, depending on how long the building has been in place. Similarly, paved streets, sidewalks, and parking lots also raise the underground temperature. The temperature change in the ground caused by low-temperature BTES systems would be of the same order of magnitude.

Frost heaving has caused problems in rare occasions where horizontal connection piping has been placed near the surface in saturated fine sands, silt, or clay and the BTES system has been allowed to operate at temperatures below 0°C for long periods of time. Geotechnical problems related to freezing of vertical pipes in clay have been investigated by Gabrielsson et al. (1997). Severe settling around the boreholes were observed due to structural changes in the clay. The clay collapsed during the thawing process. Freezing around permanent steel casing of boreholes penetrating overburden clay layers may also cause problems with structural changes and collapse of the clay. Proper design and construction should minimize this risk.

In closed systems such as BTES the risk of geochemical problems due to altered ground temperatures around the boreholes is limited, especially when operating at temperatures close to or below undisturbed ground temperature. BTES systems operating at temperatures higher than 40°C are more likely to experience geochemical effects, and a more detailed consideration of geochemistry is recommended (IEA ECES, 1997).

Changes in ground and groundwater temperature may result in alterations in the balance of microorganism species; however, temperature is not the only controlling factor for microorganisms. Light, oxygen, nitrogen, phosphorous, and sulfur are examples of other factors that affect microorganisms. Microbiological risks with BTES systems are unlikely to occur or cause problems, especially at low operating temperatures. Studies on possible microbiological effects may be considered for BTES operating at temperatures above 40°C (IEA ECES, 1997).

11.3.2 Risks related to geology and geohydrology

During drilling, in situ testing, construction, and operation, care must be taken to prevent surface contaminants from the surface entering the borehole and mixing with groundwater. It is essential to avoid interconnecting two aquifers with different pressure conditions and water quality. This is prevented by proper backfilling of boreholes in such cases.

BTES systems are unsuitable for areas with artesian aquifers. Consequences of large uncontrolled artesian flow are severe and costly and must be avoided. In areas with geological formations containing layers of evaporites, such as halite, sylvite, gypsum, and anhydrite, BTES systems should be avoided. Consequences of penetrating such layers and exposing them to water may cause severe settling over large areas (Reuss, 2015).

11.3.3 Risks related to construction

Although the high-density polyethylene pipe used for BTES construction is extremely robust, there is the possibility of leakage of the heat carrier fluid from the heat exchanger pipes into the natural environment. Antifreeze solutions used as a heat transfer (carrier) fluid should therefore be nontoxic and not adversely affect the physical, metallurgical, or chemical integrity of the piping system. Today ethylene glycol, propylene glycol, or ethanol are used as heat transfer fluids. Of these three, ethylene glycol is the most toxic, but biodegrades quickly. Propylene glycol and ethanol are relatively nontoxic and rapidly biodegradable. Denaturation additives degrade more slowly. If leakage would occur, the quantities of carrier fluid reaching the environment would typically be moderate, and the system pressure drop would soon trigger a shutdown of the circulation pump.

Drilling through contaminated layers of soil or groundwater should be avoided. If contaminated layers have been penetrated, boreholes must be thoroughly grouted to seal the borehole and eliminate risks for migration of pollutants.

Before drilling starts, precautions must be taken to eliminate risks of hitting other subsurface constructions and infrastructure such as gas pipes, water, and sewage pipes, electric or telecommunication cables, tunnels, natural or man-made underground cavities and constructions, and possible archaeological remains.

It is important to make appropriate arrangements for the disposal of drill cuttings so that the material does not affect the local environment.

Other risks may be evaluated (and often eliminated) by investigation of the existence of other water wells or energy wells in the neighborhood, overhead cables or constructions in reach of the drill rig, protection zones for water or nature, and adjacent buildings.

11.3.4 Regulation to protect the environment

Guidelines, standards, and codes can all help avoid environmental concerns related to BTES. Furthermore, in many locales, approval from local authorities for specific projects must be obtained. The existence and comprehensiveness of legislation concerning BTES and protection of groundwater and the underground environment varies between countries and within countries. Banks (2012, p. 433) provides a list of legislation and codes that may or may not have impact on closed-loop BTES systems. This includes water resources legislation, energy efficiency legislation, and codes of good practice by industry and environmental bodies. Den Braven (1998, 2000) reported on state-to-state regulations on antifreeze and grouting (backfilling) of boreholes in the United States.

Considering the large number of BTES systems constructed over the years, few accidents with environmental impact have occurred and been reported. When BTES systems are being considered, the very low risks of environmental hazards from a properly designed, constructed, and maintained BTES system should be weighed against the considerable environmental benefits from reduction of emissions and energy conservation.

11.4 Worldwide borehole thermal energy storage applications

BTES systems can be applied in a large variety of ways, with different storage temperature levels, sizes, and system configurations. This section gives examples of various

BTES applications around the world over the last few decades. Early BTES applications are listed in Table 11.1 and examples of BTES systems around the world are summarized in Table 11.2.

BTES systems can be categorized in terms of storage temperature:

1. High temperature storage: solar or waste heat, typically large scale and often connected to district heating network or industrial processes.
2. Low temperature storage: temperature levels close to undisturbed ground temperature for heating and/or cooling—typically for residential buildings, office buildings, commercial, or institutional buildings.

Applications can also be categorized according to what type of user the BTES system serves:

1. residential heating and/or cooling
2. heating and/or cooling of commercial and institutional buildings
3. cooling and/or heating of industrial processes
4. heating of roads and other paved surfaces

The most abundant type of BTES system is low-temperature BTES for combined heating and cooling of office buildings, commercial, or institutional buildings. Design and construction techniques are well understood and the system size may be readily scaled as needed. With growing awareness of the need for energy storage as a crucial component in sustainable energy systems based on renewable energy resources, there is now a budding renewed interest in solar energy usage and high-temperature storage in district heating networks. High-temperature BTES applications are appealing as they do not require heat pumps to make the stored heat useful. To keep relative heat losses acceptably low, high temperature BTES systems need to be large scale with many boreholes and are therefore usually appropriate for district heating systems.

11.4.1 High-temperature solar heat storage

Storage of high-temperature solar heat was the intention that first led to development of BTES systems, and many examples exist. Gao et al. (2015) discuss this type of BTES application and provide lists of full scale and pilot plant BTES systems used with solar heating. More descriptions of early solar heating BTES systems are found in Section 11.1.2, and Table 11.1.

The solar district heating BTES system in Neckarsulm-Amorbach in southwest Germany was designed to provide space heating and domestic hot water for a new-built housing area comprising some 700 residential buildings and a school (Reuss, 2015). The total annual heating load is 3 GWh. Five thousand square meter flat-plate solar collectors are connected to two short-term storage water tanks, each 100 m^3, and the seasonal storage BTES system. The Neckarsulm-Amorbach plant was the first large-scale BTES system in Germany, and has been built in two steps. In a first stage, 36 boreholes were drilled in 1997, and later extended to a total of 528 boreholes in 2001. The borehole field is laid out in a rectangular configuration to allow for future extension. Geological formations at the site

Table 11.2 **Examples of borehole thermal energy storage systems worldwide**

Country	City	System type	Year	Number of boreholes and borehole depth	Heat/cold	References
Canada	Oshawa, Ontario	University campus	2004	384 × 213 m Limestone	Heat/cold	Dincer and Rosen (2007) and Wong et al. (2006)
Canada	Okotoks Drake Landing Solar Community	Residential	2007	144 × 35 m	Solar heat High temp	Sibbitt et al. (2012) and Wong et al. (2006)
China	Tianjin	Business center	2011	3789 × 120 m	Heat/cold + ice storage	Yin et al. (2015)
China	China Academy of Building Research Beijing	Office building Net zero energy	2014	20 × 100 m + 50 × 60 m	Solar + heat/cold	Yu et al. (2015) and Li et al. (2015)
China	Zhungguancon International Center Beijing	Office building	2008	1060 × 123 m	Heat/cold	Zang and Xu (2014)
Denmark	Brædstrup	District heating	2012	48 × 45 m	Solar heat and district heating	Miedaner et al. (2015)

Finland	Sibbo	Logistics center	2012	150 × 300 m +159 in Phase 2 Rock	Heat/cold	Huusko and Valpola (2014)
Germany	Neckarsulm Solar district heating	Residential	1997 + 2001	528 × 30 m Clay	Solar district heating	Reuss (2015, pp. 138–140)
Germany	Attenkirchen	Residential	2002	90 × 30 m	Hybrid solar district heating with central tank	Reuss et al. (2006)
Germany	Crailsheim	Residential + school	2007	80 × 55 m	Solar	Bauer et al. (2007) and Mangold (2007)
Norway	Akershus	Hospital	2007	228 × 200 m Rock	Heat/cold	Midttomme et al. (2010) and Bäcklund (2009)
Poland	Atrium 1	Office building	2014	50 × 200 m	Heat/cold without heat pump	Skanska (2014a)
Romania	Bucharest	VW Bucharest Auto Showroom	2009	112 × 72 m	Heat/cold	Polizu and Hanganu-Cucu (2011)
Romania	Bucharest-Marguele	ELI-NP research center	2015	1080 × 125 m	Heat/cold	Bendea et al. (2015)
South Korea	Lotte World Tower Seoul	Skyscraper	2015	720 × 200 m	Heat/cold	Viessmann (2012)

Continued

Table 11.2 Continued

Country	City	System type	Year	Number of boreholes and borehole depth	Heat/cold	References
Sweden	Karlstad	Karlstad University campus	2015	204 × 240–250 m	Heat/cold	Olsson (2014) and Gehlin et al. (2015)
Sweden	Entré Lindhagen	Office building	2014	144 × 220 m	Heat/cold without heat pump	Skanska (2014b)
Sweden	Näsbypark	Historical building	2004	48 × 180 m	Heat/cold recharge with lake water heat	Lund et al. (2004)
Sweden	Luleå	University building	1981–1989	120 × 60 m	Industrial high temp	Nordell (1994)
Sweden	Anneberg	Residential	2002	99 × 65 m	Solar high temp	Dalenbäck et al. (2000), Lundh and Dalenbäck (2008), and Heier et al. (2011)
Sweden	Lund University	Astronomy House	2001	20 × 200 m Clayey soil and shale	Heat/cold	Andersson (2007)
Sweden	Emmaboda Xylem	Industrial waste heat	2011	140 × 150 m Rock	Industrial high temp	Nordell et al. (2015)
Switzerland	Därlingen SERSO	Road heating	1994	91 × 65 m Rock	Heat from road	Eugster (2002) Eugster (2007)

United Kingdom	Croydon	Office and warehouse	2000	30 × 100 m Chalk	Heat/cold	Witte and van Gelder (2007)
United Kingdom	DMU Leicester	Hugh Aston University building	2009	56 × 100 m	Heat/cold	Naicker and Rees (2011) and Cullin et al. (2015)
United States	Richard Stockton College Pomona, New Jersey	Campus buildings	1994	400 × 135 m Sand/clay	Heat/cold	Stiles (1998)
United States	Oakland University Rochester Michigan	Human Health building	2013	256 × 100 m	Heat/cold	Kistler and Karidis (2015)
United States	Ball State University Muncie Indiana	University Campus	2013	1800 × 140–150 m + 1800 in Phase 2	Heat/cold	BSU (2015)

consist of a 30–35-m thick low-permeable clay layer on top of a highly permeable dolomite with large groundwater flow. Therefore the boreholes were drilled to 30-m depth to prevent high heat loss at the bottom. The boreholes are fitted with double U-tube heat exchangers, and the borehole spacing is 2 m. The top of the BTES field is thermally insulated. The system is designed for 50% solar fraction, and a gas boiler provides supplementary heating.

The Kerava Solar Village in Finland is an early large-scale, high-temperature solar-heating system built as a pilot project in 1983 (Peltola et al., 1985; Dalenbäck, 1990). The village containing 44 apartments with large south-facing windows and flat-plate solar panels has a total annual heating demand of 495 MWh, and taking into account heat loss, the solar heating system (including heat pumps and back-up heating) was designed to deliver 550 MWh annually. The BTES system is a hybrid utilizing 54 tilted boreholes of 25-m depth surrounding a 1500 m^3 cavity in the rock, filled with water. The water-filled cavity reached 20-m depth and provided stratified heat storage, with 55–65°C water at the top and as low as 8°C in the winter at the bottom. The water at the top is used for short-term storage and domestic hot water. The boreholes are arranged in two circles around the central water cavity, with 18 boreholes in the inner circle and 36 in the outer circle (Fig. 11.5). A 240 kW heat pump supports the system in the winter, and two electrical boilers of 200 kW each provide back-up heat. A solar fraction of 40–50% was obtained by the system.

The Attenkirchen hybrid solar district heating system was constructed in 2002 to serve 20 residential buildings with a total annual heating demand of 490 MWh (Reuss et al., 2006). It was designed for a solar fraction of 50% and collects solar heat from 765 m^2 of flat-plate solar collectors. The hybrid storage consists of a cylindrical

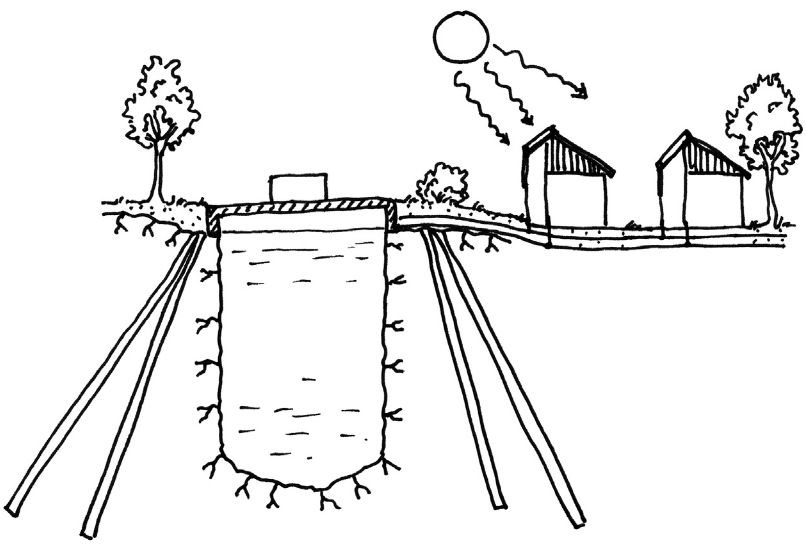

Figure 11.5 The Kerava Solar Village BTES and water-filled rock cavity.
Illustration from S. Gehlin (2015).

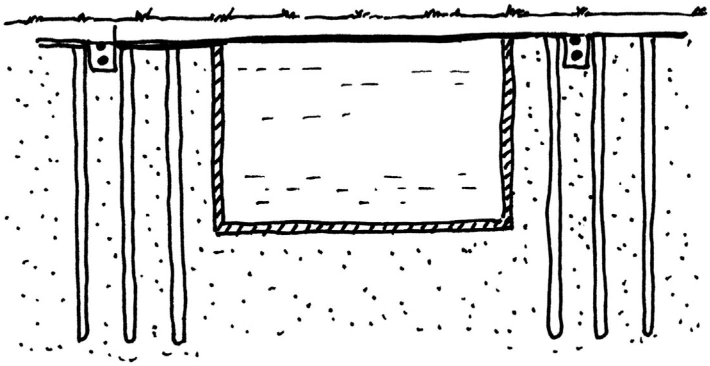

Figure 11.6 Three circles of boreholes surround the top-insulated concrete water tank in Attenkirchen.
Illustration from S. Gehlin (2015).

concrete water-storage tank measuring 9 m in diameter and 8.5 m depth (volume 500 m^3), surrounded by three circles of 30-m deep boreholes (Fig. 11.6). In total, there are 90 boreholes fitted with double U-tube heat exchangers. The top of the storage area is thermally insulated with 20-cm polystyrene.

The Anneberg high-temperature solar-heating BTES (Fig. 11.7) without heat pumps in Stockholm, Sweden (Dalenbäck et al., 2000; Lundh and Dalenbäck, 2008; Heier et al., 2011), was completed in late 2002 and serves a residential area with 50 houses. The buildings have an annual heating demand of 565 MWh, including domestic hot water. The BTES system consists of 99 boreholes drilled to 65 m into hard rock, and fitted with double U-tube heat exchangers. The low-temperature space heating system has three ways in which heating can be supplied: directly from the 2400 m^2 of flat-plate solar collectors, stored heat from the BTES, or from individual electrical backup-heating units when the first two options are

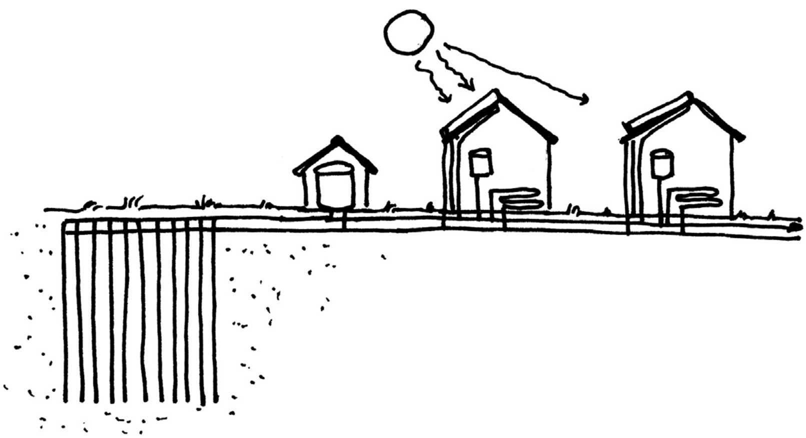

Figure 11.7 The Anneberg high-temperature BTES.
Illustration from S. Gehlin (2015).

insufficient. The system was the first system in Europe with seasonal solar storage in rock and not utilizing a heat pump during discharge. The borehole field is rather small; hence heat loss is significant (40%).

Drake Landing Solar Community in Okotoks, Alberta, Canada (Fig. 11.8), has been in operation since 2007 and supplies space heating to 52 detached houses through a local district heating network, without heat pumps (Sibbitt et al., 2012; Wong et al., 2006). Solar heat from 2293 m^2 of roof-mounted flat-plate solar collectors on the detached garages is stored in the 144-borehole BTES system in soil. The boreholes are 35-m deep and fitted with single U-tube heat exchangers. The top of the BTES system is thermally insulated. The cylinder-shaped borehole field is configured to maintain the center of the field at the highest temperature to maximize heating capacity and the outer edges at the lowest temperature to minimize heat loss. A 240 m^3 short-term thermal storage water tank is used to interconnect the solar collectors, distribution network, and BTES subsystems. The Drake Landing Solar Community BTES system has undergone detailed monitoring since it was brought into service in July 2007. The system met a solar fraction of 97% in its fifth year of operation and should inspire more projects of its kind, in Canada and beyond.

In Crailsheim, Germany, a high-temperature solar-heated BTES system serves 260 apartments, a school, and a gymnasium (Bauer et al., 2007; Mangold, 2007; Miedaner et al., 2015). Solar collectors are mounted on the roofs and along a noise protection wall. The solar collectors are connected to a diurnal storage tank of 100 m^3 and the BTES for seasonal heat storage consisting of 80 boreholes of 55 m depth. The borehole field is connected to a 480 m^3 buffer tank, which serves to even out the solar heat gain peaks in the summer. Heat is distributed to the buildings either directly from the BTES, or via heat pumps if needed. Total heating demand for the area is 4100 MWh annually, and 485 kW of electricity is used for heat pump operation. The measured solar fraction during 2012−2013 was 51%.

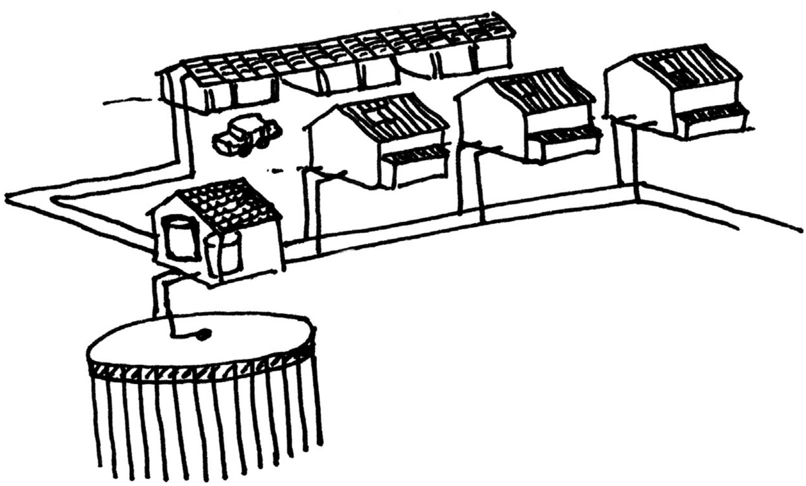

Figure 11.8 The Drake Landing Solar Community local district heating with BTES. Illustration from S. Gehlin (2015).

The Brædstrup high-temperature solar BTES district heating plant in Denmark (Miedaner et al., 2015) began operation in May 2012, and is part of Brædstrup Total Energy Plant, which is the production plant for the Brædstrup district heating system. The production plant, of capacity 40,000 MWh, was originally a natural gas−fired CHP unit with a 2000 m^3 steel buffer tank, but is now converting to 100% renewable heat production in several steps. In addition to the waste heat from the gas-fired CHP, heat is collected from 18,600 m^2 of solar collectors, connected to two steel tanks of 5500 m^3 and 2000 m^3 volume. Solar heat is stored in the BTES consisting of 48 boreholes drilled to 45 m depth spaced 3 m apart in a triangular configuration. Double U-tube heat exchangers are used. The top of the storage is insulated to reduce heat loss. The system also includes a 1.2 MW heat pump and a 10-MW electrical boiler. Heat loss from the BTES is estimated at 24%.

11.4.2 High-temperature industrial heat storage

There are few BTES applications that store industrial heat at high temperatures, even though the potential for such systems is significant.

The Emmaboda Xylem high-temperature BTES system began operation in 2010 (Nordell et al., 2015). As of March 2015 approximately10 GWh has been stored and a storage temperature of 40−45°C has been reached. Only a fraction of the stored heat has been extracted so far, and the storage is expected to reach full capacity in 2015. The purpose of the system is to make use of the waste heat from the industrial processes in the molding factory for space heating of the factory and office buildings. When the demand for space heating is lower than the waste heat production, surplus heat is stored in the BTES. The system works without a heat pump, but heat pumps may be added later to improve the system and reduce heat loss. The system consists of 140 boreholes in a rectangular configuration drilled to a depth of 150 m, and with a borehole spacing of 4 m. The storage is divided into seven sections with 20 boreholes in each section. The sections are individually operated for injection or extraction of heat depending on storage temperature. Coaxial BHEs are used, where the circulated water is in direct contact with the borehole wall. The BTES has reduced the amount of bought district heating for space heating by approximately 4 GWh/year.

The Lulevärme Heat Store in Luleå, northern Sweden (Nordell, 1994), was in operation from 1982 to 1989. The 120 boreholes drilled in granitic rock to a depth of 65 m in a 10 × 12 rectangular configuration were used to store high-temperature (70−82°C) waste heat from a steel plant. The heat was transferred to the storage via the district heating network during the summers. The heat was recovered at 35−55°C in the winters for heating a university building.

11.4.3 Low-temperature solar heat storage

Low-temperature solar heat storage is attractive for small-scale solar heating systems, as heat loss is low and potential problems related to high temperatures are eliminated. In most cases, however, heat pumps are needed. There are several interesting examples of applications of this type, including deicing of road surfaces.

The Höstvetet Suncourt project in Stockholm, Sweden, in 1986 was an early low-temperature BTES solar heating project (Kellner et al., 1986; Werner, 1988). The 71-apartment residential building contains a large glazed courtyard that works like a solar collector in the summers. When the air temperature inside the courtyard exceeds 20°C, the air is used as a heat source for heat pumps providing domestic hot water. In this process the courtyard is cooled down. When heat produced from the courtyard air exceeds the hot water demand, excess heat is stored in a BTES system beneath the building, consisting of 25 boreholes of 80-m depth in hard rock. Storage temperature varies between 6 and 15°C.

The Grosvad Finspång BTES system built in 1985 in Sweden (Energiverk, 1986a) offers an interesting system combination with a 7000 m^2 bandy[3] field used as a heat source in combination with BTES to provide heat for 550 apartments and a school. The 126 boreholes, placed below a parking lot, are drilled to 110 m depth. In the summers, 3 GWh solar heat from the bandy pitch is stored in the borehole field, and in the winters the heat is recovered and supplies the building with the aid of three heat pumps with total heating capacity of 2.5 MW. Storage temperature varies between 10 and 35°C. In wintertime when the bandy field is artificially frozen, phase change heat from the freezing process is used for space heating of the residential buildings, through the same heat pump unit.

The SERSO Därlingen Solar heat for road deicing (Eugster, 2002; Eugster, 2007) is a well-known and well-documented BTES installation in central Switzerland (Fig. 11.9). It began operation in 1994 and uses horizontal piping beneath the road surface to collect solar heat from the road in the summer. The heat is stored in the 91 boreholes drilled in hard rock to a depth of 65 m. In the winter, the stored heat is used to stabilize the road temperature just above 0°C, preventing ice formation and freezing of compacted snow. The annual runtime is less than 1000 h in the winter and another 1000 h in the summer. The supply temperature is regulated based on ambient air temperature, and is generally below 10°C. Typical average heat output of the system is around 100 W/m^2 of road surface.

11.4.4 Low-temperature storage for heating and cooling

BTES systems used for combined heating and cooling are the most widely spread applications and exist in a range of sizes. Many buildings such as offices and public buildings have an energy load profile with fairly balanced heating and cooling loads, making these systems very energy efficient. Almost every GSHP system with both significant heating and cooling demands can be considered BTES systems of this kind. Here, just a few examples are presented.

The Croydon building in Sussex is one of the larger BTES systems in the United Kingdom (Witte and van Gelder, 2007). The building is a three-story office building also hosting warehouse facilities. Annual cooling and heating loads are

[3] Bandy is a team winter sport played on ice in which skaters use sticks to direct a ball into the opposing team's goal. It is played on a bandy field, the size of a football pitch.

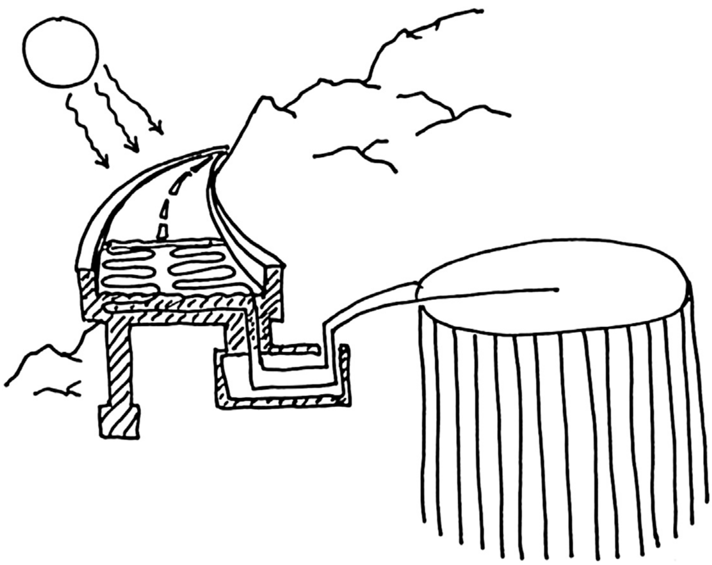

Figure 11.9 The SERSO Därlingen borehole thermal energy storage system for road deicing. Illustration from S. Gehlin (2015).

100−125 MWh and 90−100 MWh, respectively, with summer peak cooling loads reaching up to 130 kW. A BTES system comprising 30 boreholes of 100 m depth, drilled in chalk and fitted with U-tubes, is combined with a dry cooler that stores cold in the ground in early spring. An under-floor heating system and the 85 distributed GSHPs in the building allow for simultaneous heating and cooling in different parts of the building if needed.

In 2004, University of Ontario Institute of Technology in Oshawa, Canada, installed a BTES system for heating and cooling of the entire campus (Dincer and Rosen, 2007; Wong et al., 2006). Three hundred eighty-four boreholes were drilled to 213 m in limestone and hard rock and are water-filled, as in the Scandinavian practice, instead of the typical North American practice of grouted BHEs. The BTES system is charged in the summer by chillers and heat pumps of total nominal capacity of approximately 7 MW cooling. In the winter, the heat pumps provide warm water for campus use at a temperature of 52.5°C. Supplemental heating is provided by condensing boilers.

Ball State University in Muncie, Indiana, is going through a large-scale BTES conversion project in two phases (BSU, 2015), which will result in its four aging coal-fired boilers being shut down. In the first phase, completed in 2013, 1800 boreholes were drilled to 140−150-m depth in the North District Energy Station. The second phase will add another 1800 boreholes to the South District Energy Station. Two 8.8 MW heat pumps are served by the BTES borehole field, and provide cooling and heating via two separate district loops that run throughout the campus: a 5°C cold water loop and a 65°C hot water loop.

The Akershus University Hospital in Ahus, Norway, was constructed in 2007 (Midttomme et al., 2010; Bäcklund, 2009). The borehole field, comprising 228 groundwater-filled boreholes of 200-m depth, drilled in hard rock, provides heat and cold to the hospital buildings supported by a combined ammonia chiller and heat pump system.

11.4.5 Low-temperature combined systems

There are many examples of BTES systems that are combined with other sources of heat and cold, such as lake or river water, ice storage, water tanks, biofuel, and so forth. Below are some examples.

For a long time the BTES at Richard Stockton College in Pomona, New Jersey (Stiles, 1998), built in 1994, was the largest BTES system in the world. The 400 boreholes, with a depth of 135 m, are fitted with U-tubes and penetrate three aquifers in saturated sands and clays. The borehole field is located under a 16,000 m^2 parking lot. The ventilation and air-conditioning system design, including heat pumps with a cooling capacity of over 5-MW, did not balance the thermal load, so the field was slowly heating up. A supplemental ATES was therefore added in 2008 to provide additional cooling and reduce the cooling demand on the BTES system.

Tianjing Cultural Center in Beijing was completed in 2011 and is, at present, the largest BTES system in the world. Placed below a lake in front of the building are 3789 boreholes of 120-m depth fitted with double U-tube heat exchangers (Yin et al., 2015). The BTES system is combined with ice storage cooling, a cooling tower, and district heating.

Lotte World Tower in Seoul, South Korea, is the second-tallest skyscraper building in the world and was scheduled for completion in 2015 (Viessmann, 2012). The tower is 555-m high and has 123 floors above ground and six floors below ground, hosting private apartments, offices, retail stores, and a hotel. The hybrid BTES system consists of 720 boreholes, 200-m deep, serving six heat pumps providing 1.7-MW heating and 1.9-MW cooling. Another six heat pumps provide 2-MW heating and 1.7-MW cooling from river water outside the building.

The Näsby Park hybrid BTES system was built in 2004, for the Näsby Castle buildings close to Stockholm, Sweden. The 48 boreholes of 200-m depth are recharged with 15−20°C surface water from a nearby lake during the summer. A 400-kW heat pump is used for heat load operation (Lund et al., 2004).

China Academy of Building Research is a net-zero energy building (NZEB) in Beijing, China, built as a demonstration building for NZEB in 2014 (Yu et al., 2015; Li et al., 2015). It has several storage systems for heat and cold; BTES, solar heat, thermal storage in the building material, and heat and cold storage in water tanks. The BTES system consists of two borehole fields on each side of the building. The smaller field has 20 boreholes of 100-m depth, arranged in two rows, fitted with double U-tube heat exchangers. The larger field consists of 50 boreholes of 60 m depth, arranged in five rows, and fitted with single U-tube heat exchangers. The BTES system is charged with solar heat from solar panels on the roof.

The Polish office building Atrium 1 in Warsaw (Skanska, 2014a) and the Swedish Skanska headquarters office building Entré Lindhagen in Stockholm (Skanska, 2014b) are two buildings with high-temperature cooling and low-temperature heating provided by BTES systems. The construction company Skanska has patented a special BTES concept called "Deep Green Cooling." It provides office cooling in the summer and preheating of incoming air in the winter without the use of heat pumps, and operates at temperatures close to undisturbed ground temperature. Free-cooling with outdoor air is used in combination with the BTES system, and additional winter heating demand is provided from the district heating network. Atrium 1 was completed in January 2014 and consists of 50 boreholes, 200-m deep, providing 232-MWh cooling and preheating annually. Entré Lindhagen was built in 2014 and has 144 boreholes of 220-m depth.

SOK Sibbo Bastukärr Logistics Center in Finland (Huusko and Valpola, 2014) is a hybrid BTES system built in 2012 and is the largest BTES system in Finland and the third largest BTES system in Scandinavia. The borehole field is part of a so-called GeoBio hybrid system and consists of 150 closed-loop boreholes drilled to 300-m depth. It covers 100% of the cooling demand and 50% of the heating demand for the logistics center building. The other 50% heating demand is covered by wood-pellet boilers. Temperatures in the storage vary between 18 and 32°C. In the summer the borehole field is charged with solar heat from horizontal pipes under a 2.5 ha parking lot. The BTES system provides free-cooling in the summer and, if needed, reversible heat pumps are used for peak load cooling. Two 1-MW heat pumps provide maximum 50°C heat to a low temperature heating system, and two 2-MW wood-pellet burners provide maximum 120°C heat to the local district heating net.

11.5 Conclusions

Low-temperature BTES systems provide efficient heating and cooling of large buildings, such as office buildings, commercial, and institutional buildings. The technology has a great potential to contribute significantly to energy efficient and sustainable energy systems in most regions in the world. In cooler climates, it offers significant reduction of costs for cooling and low costs for heating. With increasing demand for energy efficiency, buildings tend to be built with improved insulation. These well-insulated buildings, combined with increasing internal heat gains, create an increased demand for comfort cooling in cooler climates. BTES systems can take advantage of the increased demand for cooling and provide both heating and cooling in a very elegant and cost-effective way. Since the 1990s the number and types of buildings using BTES for combined heating and cooling has increased steadily as experience and proof of cost effectiveness has grown.

After the first decades of enthusiastic development of high-temperature seasonal storage, the interest in such systems has faded in favor of less complex low-temperature BTES. However, in recent years a renewed interest in high-temperature BTES applications with seasonal storage of solar heat or waste heat from industries and cogeneration plants has emerged. The number of such applications worldwide is still small, but the success of the moderate-sized district heating project Drake Landing Solar Community in Canada, and the industrial waste heat storage system in Emmaboda, Sweden, show definite potential for such applications.

The heat buffering ability of BTES systems has potential for improving the efficiency and robustness of district heating systems on city scales as district heating providers adjust to a building stock refurbished with low-temperature heating systems and thermally active building systems.

Several very large BTES systems with more than a 1000 boreholes have been constructed in recent years (see Table 11.2), indicating a trend toward larger BTES systems. Top five largest BTES systems in the world to date, counted in number of meter boreholes drilled in total, are:

- Tianjin Cultural Centre, Beijing, China: 3789 boreholes of 120 m (total 454,680 m)
- Ball State University, Indiana, United States: 1806 boreholes of 135 m (total 243,810 m)
- Lotte World Tower, Seoul, South Korea: 720 boreholes of 200 m (total 144,000 m)
- ELI-NP Marguele, Bucharest, Romania: 1080 boreholes of 125 m (total 135,000 m)
- Zhungguancon International Center, Beijing, China: 1060 boreholes of 123 m (total 130,380 m)

While the first BTES systems constructed in the 1980s were drilled to a modest depth, less than 100 m, today's boreholes are typically drilled to a depth of 120−200 m, or even deeper. Especially in the Scandinavian countries, borehole depths down to 300 m are not uncommon for new BTES projects.

It is yet to be seen if the potential for use of BTES for infrastructure applications can be economically feasible in practice. Keeping roads, bridge decks, platforms, and parking areas free from ice by storing solar heat in a BTES system deserves more attention in the future.

As long as BTES systems compete economically in a favorable way with systems that are less efficient, and have lower CO_2 emissions, there is a bright future for its application and development.

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