Subject:	Seasonal Borehole Thermal Energy Storage
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Description:	Guidelines for design of seasonal borehole thermal energy storages.
Author:	Bruce Sibbitt and Doug McClenahan, Natural Resources Canada – bsibbitt@nrcan.gc.ca; dmcclena@nrcan.gc.ca
Download possible at:	http://task45.iea-shc.org/fact-sheets

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Introduction

Borehole thermal energy storage (BTES), which is also referred to as duct storage, has been successfully used for seasonal heat storage in a number of large solar systems. Some of these systems utilize a heat pump to upgrade the stored energy to the load temperature while others use the stored heat directly without upgrading. Borehole thermal energy storages have also been used for storing cold.

BTES use the heat capacity in a large volume of native soil to store thermal energy underground. The soil itself is a very good medium for large heat storage systems since it is no-cost, already on-site, involves minimal excavation, is non-toxic and has a reasonable heat capacity. Much of the cost of a BTES is in the heat exchanger used to transfer heat to and from the soil, the drilling of boreholes in which to install the heat exchanger and in the insulation which is placed over the top of the store. For smaller storages (up to 5 000 m^3) typically an insulated steel tank is used but for large storages a BTES can be considerably cheaper per unit volume of water-equivalent storage.

The purpose of this document is to provide useful guidelines for BTES design and implementation including information on how BTES performance and solar system performance are affected by a wide range of soil properties and by the shape of the BTES field, in terms of the ratio of its diameter to its depth. This information can be beneficial to the designer since in the early stages of system planning and design, soil conditions and water table depth are often unknown. In all cases, it is assumed that a BTES would not be utilized if there is a significant water movement through the bore field since the result would likely be unacceptably high heat loss.

The sensitivity results in this Tech Sheet are based on more than 1000 TRNSYS simulations of solar systems designed to meet a large fraction of the heating load at supply temperatures that are less than 40 C for most of the winter and always less than 55 C, without heat pumps. However, the results may also provide guidance for systems using heat pumps and those with higher delivery temperatures. The same systems were also simulated in 5 different Canadian climates.

Description of the storage

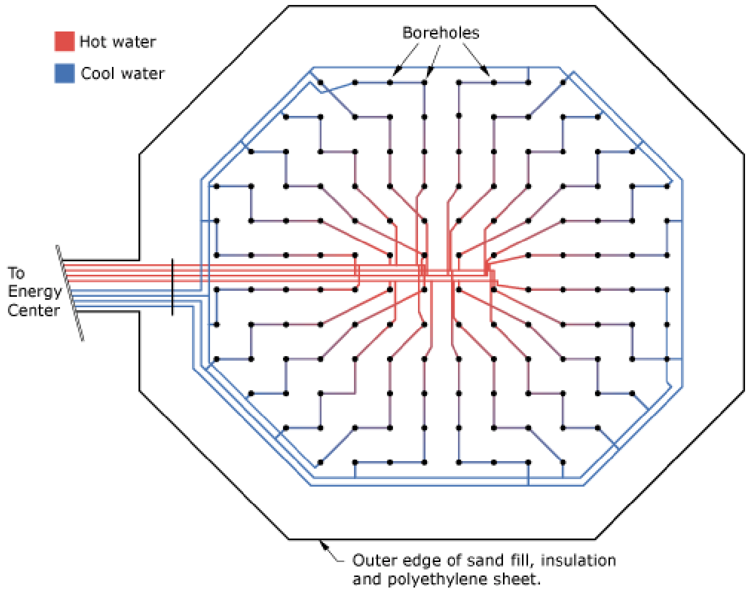
A borehole storage consists primarily of a large volume of earth that has a matrix of regularly spaced vertical holes drilled into it, each one usually containing one or two u-tubes that have been grouted in place. The top of the bore field is covered with insulation and earth which can be landscaped, covered with a playing field or a parking lot, etc. Water flow through the heat exchangers is used to charge and discharge the BTES, at different times. The BTES design can significantly affect the performance of the entire system so when deciding on the type of storage and its design, it is important to accurately model the storage within the system design model so that the whole system may be optimized. The following sections are intended to facilitate accurate assumptions and effective design decisions.

Shape and configuration considerations

The BTES is generally designed to be approximately cylindrical in shape in order to maximize the volume to surface area ratio, however, other three dimensional shapes may also be used. The influence of different cylindrical aspect ratios (length to diameter) on storage efficiency and system performance is addressed in the section on Site Variables.

Since a significant portion of the cost of a BTES is related to the design heat exchange capacity, least cost BTES solar system designs often incorporate a relatively small buffer water storage tank to work with the primary BTES storage. The buffer is able to accept and deliver sufficiently high heat transfer rates to meet peak solar collection and load events and work effectively with the lower heat transfer capability of the BTES by distributing peak inputs and loads over longer periods of time. This approach permits lower total borehole length and reduced heat exchanger length without sacrificing system performance. The cost of the buffer storage is traded-off against the cost of more heat exchanger length in the BTES. Simulations are necessary to correctly account for all of the interactions when identifying the optimum system component sizes.

Several heat exchanger u-tubes are connected in series to make a circuit following an approximately radial path halfway through the storage. The flow direction for charging is from the BTES centre to the outer edge and from the outer edge to the centre, for discharging, to maximize temperatures available to the load, to minimize BTES heat loss and to minimize the collector inlet temperature. A number of parallel circuits are used to distribute the flow throughout the entire storage volume. An example of a BTES layout and a borehole and u-tube cross-section is shown in Figure 1. Figure 2 is a cross-section through the top portion of one circuit in the same BTES.



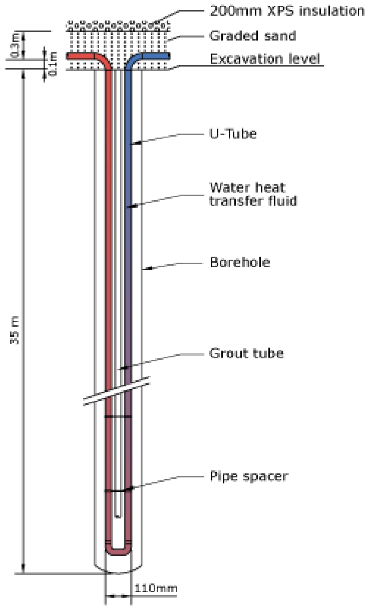


Figure 1. Layout of a borehole thermal energy storage and cross-section of a single borehole and u-tube

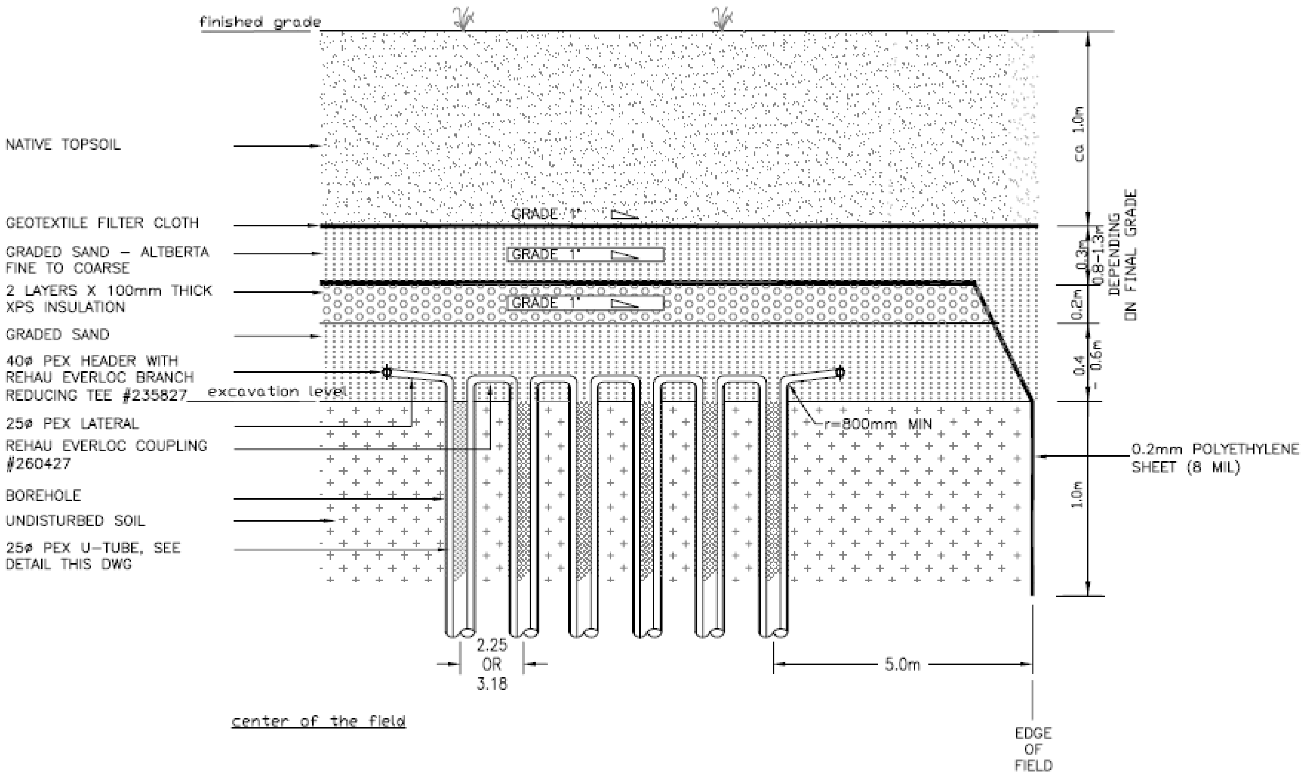


Figure 2. Cross-section of the top portion of one BTES circuit

Location of storage and geotechnical conditions

Ground water conditions

Before designing the system and selecting the type of storage to be used, some very important initial investigations have to be carried out. To avoid excessive heat loss from a BTES it is important that the storage is not implemented in an area where there is significant movement of groundwater at a depth near or above the bottom level of the boreholes. If there is significant movement of groundwater, the storage must be placed above the level of that moving ground water. If the ground water is stationary or with negligible flow, the storage can be implemented but the ground water level must be lowered during the construction phase until the u-tubes are installed and the boreholes grouted.

Geotechnical investigations

A preliminary geotechnical investigation based on existing well records for the area of the planned storage can typically provide a reasonable idea of the expected stratigraphy including depths and types of soil and rock that are typical in that location, the likelihood of encountering moving water and the depth of the water table. If the results of the preliminary work justify further investigation, test wells are drilled in the target area to more accurately assess details of the underground at the test location. The test wells may also be used for thermal response testing to better define the effective thermal properties in that location, which are needed for modelling BTES performance. Even if the investigation suggests that another type of storage would be more appropriate for that location, it is of course important to be aware of this before construction begins.

Underground heat exchanger piping

Heat storage in the soil is achieved by placing a significant surface area of water-to-ground heat exchanger in thermal contact with the ground. A u-tube is inserted into each borehole, usually with an additional tube which is open at the bottom, used for grouting. Once the assembly has been fully inserted, grout is pumped through the open tube to completely fill the space between the u-tube and the native soil. The grout tube is generally slowly withdrawn during the grouting process as the space is filled. The grout provides a reasonably high conductivity thermal connection between the u-tube and surrounding soil. The grouted u-tubes constitute most of the heat exchange surface area with the soil volume. A small additional heat exchange area is achieved through the horizontal interconnections between u-tubes and the piping running underground connecting the BTES to the remainder of the system. A high quality cross-linked high density polyethylene (PEX) tubing is normally used for this underground heat exchanger since it is strong, chemical resistant and is able to withstand the pressures and temperatures encountered with a long expected service life. PEX-a tubing is available with a claimed 50 year durability (1.25 safety factor) for continuous operation at 70 C and 8.5 bar and 15 year durability for continuous operation at 90 C and 6.9 bar (SF=1.25 also). Factory made PEX-a U-tube heat exchangers comprised of a single piece of tubing (without connections) are available and are often used for this application since they avoid the potential for a connection failure at the bottom of a borehole. The necessary connections between adjacent u-tubes and from u-tubes to headers, are typically made with corrosion resistant metal fittings and clamps. Durability is paramount since the connections become very difficult to access, once buried and any connections at the bottom of a borehole should be considered inaccessible. Figure 3 shows a borehole being drilled next to a number of boreholes with protruding u-tubes. In Figure 4 one of the u-tubes is moved to the borehole for insertion and Figure 5 shows the top ends of the inserted u-tubes interconnected on the surface which will ultimately be 2 metres below finished grade.

For BTES systems that will only be operated at lower temperatures, the designer may consider lower-cost non-cross-linked polyethylene tubing, as is sometimes used with geothermal heat pumps, however, greater care must be exercised in handling and protecting the non-cross-linked PE tubing since it is much easier to damage.

Figure 3. Drilling boreholes

Figure 4. U-tube ready for insertion into borehole

Figure 5. U-tubes connected into 24 near-radial strings and into 4 circuits

BTES top insulation

The interconnected u-tubes and headers are first covered with a layer (approximately 0.5 m) of graded sand which is covered with an insulation layer. Extruded polystyrene (XPS) rigid insulation is often used since it is not damaged by moisture or water and can be obtained with a sufficiently high crush strength to withstand the pressure exerted by another 0.5 metre of sand and 1 metre of native topsoil placed above it. A geotextile cloth is placed on top of the sand before the topsoil is put in place. The insulation layer generally extends somewhat beyond the outer ring or row of boreholes. The total resistance and thickness of the insulation layer will normally depend on the operating climate, the BTES operating temperature and the cost of the insulation and the cost of the solar energy delivered by the system.

Landscaping

The area above the BTES is available for almost any use. It may be covered with grass for a park or a playing field or paved for a parking lot, tennis court or other sports surface. It is also possible that small structures be built over it. Depending on the load, the material above the sand layer described above, would be designed for the particular use.

Figure 6. BTES covered with grass

Impact of site variables on performance

Soil properties and BTES shape

The performance of borehole thermal storages and the solar systems that they are part of must depend to some degree on the thermal properties of the native soil in which they store the heat. Also, since insulation is placed only over the top surface of the BTES, it would be expected that the shape or aspect ratio (diameter/depth) of the BTES volume would also influence its efficiency and system performance. More than 200 detailed TRNSYS simulations were performed to examine how much soil type and BTES shape affect both the annual efficiency of the BTES and the system solar output, measured in terms of solar fraction, for systems sized to serve Drake Landing . Four soil types (dense rock, heavy saturated soil, heavy dry soil and light dry soil), 3 collector areas, 6 borehole depths (17.5 to 210 metres) and 3 total borehole lengths (3780, 5040 and 6300 metres) were included. Table 1 summarizes the thermal properties for 7 soil types; the 4 used in the simulations appear in bold type.

Soil Type	**Density** **kg/m³**	**Thermal Conductivity** **kJ/hr.m.K**	**Specific Heat** **kJ/kg.K**	**Thermal Diffusivity** **m²/day**	**Density x Specific Heat** **kJ/m³.K**	**Alpha** **m²/h**
Dense Rock	**3,200**	**12.46**	**0.84**	**0.11**	**2,683**	**0.0046**
Average Rock	2,800	8.72	0.84	0.09	2,347	0.0037
Heavy Saturated Soil	**3,200**	**8.72**	**0.84**	**0.08**	**2,683**	**0.0032**
Heavy Damp Soil	2,100	4.67	0.96	0.06	2,012	0.0023
Heavy Dry Soil	**2,000**	**3.12**	**0.84**	**0.04**	**1,677**	**0.0019**
Light Damp Soil	1,600	3.12	1.05	0.04	1,677	0.0019
Light Dry Soil	**1,500**	**1.25**	**0.84**	**0.02**	**1,238**	**0.0010**

Table 1. Thermal properties of soils

Figure 7 illustrates some of the key results for the simulated systems which all have the same number of collectors and all have a BTES with the same total borehole length as Drake Landing has. The 4 solid lines near the top of the graph show the solar fraction delivered by the solar system for each of the 4 different soil types examined and lower on the graph, the 4 broken lines show the BTES efficiency for each of the same 4 soil types. The horizontal axis covers the range of the number of boreholes in the simulated systems; since the total borehole length is constant, the BTES shapes near the left side of the graph tend to be “pencil shaped” (aspect ratio<< 1) while those on the right are more like “pancakes” (aspect ratio>> 1). In this graph, the BTES aspect ratio (depth/diameter) is equal to 1 when there are 144 boreholes and this location is labelled.

Probably the most important result from Figure 7 is that soil type has a relatively modest impact on overall system performance for aspect ratios greater than 0.3 (> 70 boreholes in the plot), at least for the system design and climate simulated. Similarly, for the range of relatively normal BTES aspect ratios (0.3 to 3), BTES shape has only a moderate impact on overall system performance. These results also show that the soil conditions which result in maximum BTES efficiency do not produce the maximum solar contribution to the load (maximum solar fraction). The light dry soil delivers the highest BTES efficiency but that BTES is generally not very good for solar system performance. In other words, a light dry soil can provide high storage efficiency by having relatively small losses, however, the same soil properties that minimize heat losses also significantly restrict the ability of the storage to accept heat inputs and to deliver heat as required, while forcing collector operating temperatures to increase and collector efficiency to drop.

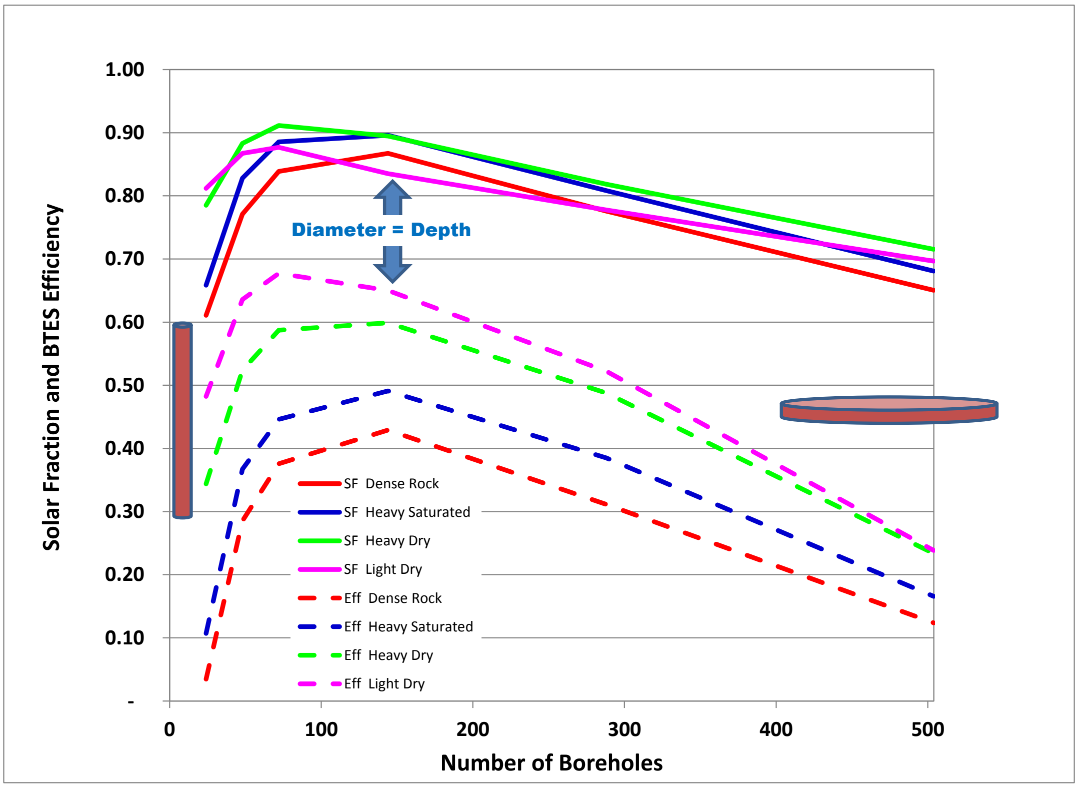


Figure 7. Impact of soil type and BTES shape on solar fraction and storage efficiency for a 52 home community

Figure 8 shows the results for another set of detailed simulations for a very similar but significantly larger system used to supply 400 apartment units and 654 houses rather than the 52 houses at Drake Landing. The system has 22,200 m^2 of collector (gross area), a 1250 m^3 buffer tank and a BTES with 60,000 m of borehole length. While the results show very similar trends to those in Figure 7, there are some important differences. First, the annual storage efficiency tends to be much higher for the larger systems, as would be expected with the increase in storage volume to surface area ratio. Also, the curves for overall performance, in terms of system solar fraction, tend to be flatter with high performance being available over a broader range, including relatively squat cylindrical shapes. Finally the difference in solar fraction between heavy saturated soil or dense rock versus both the heavy and light dry soils appears to be somewhat more pronounced.

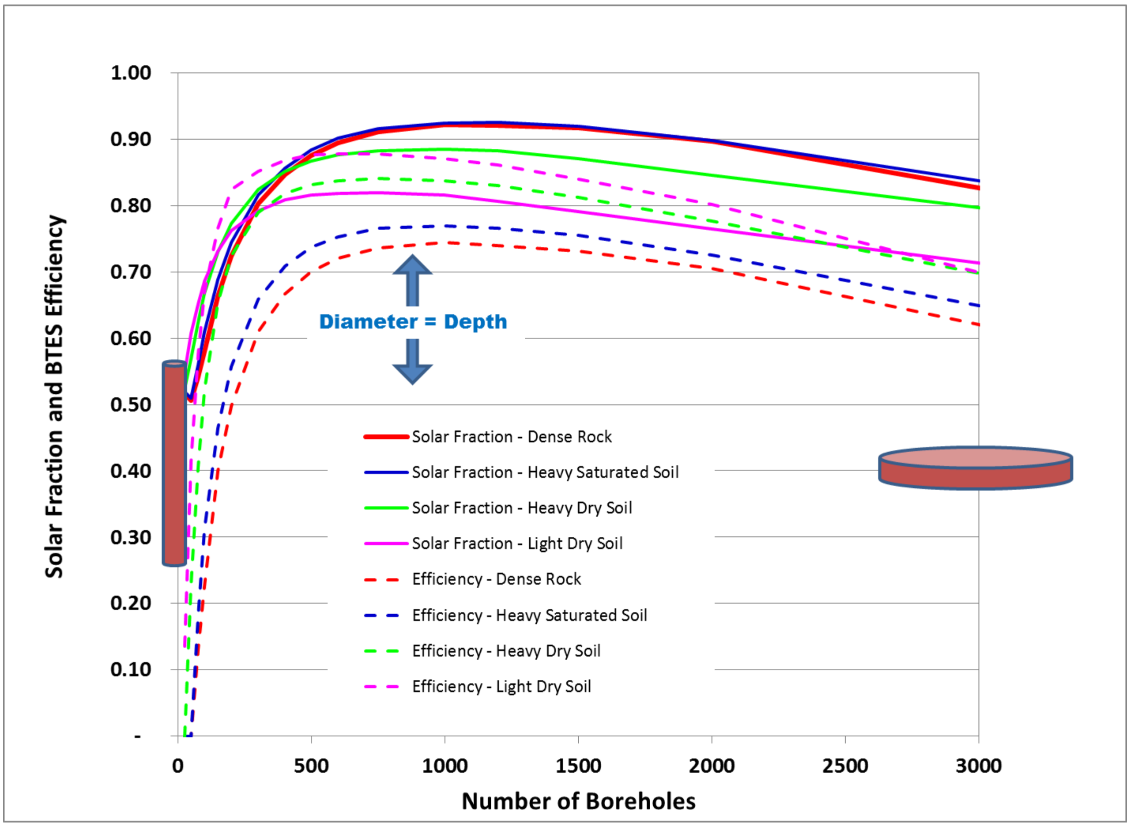


Figure 8. Impact of soil type and BTES shape on solar fraction and storage efficiency for a 1054 home community

Climate

The systems simulations performed to obtain the results presented in the previous section used Calgary, Alberta weather data. To assess the influence of climate on the BTES performance and system performance, the same systems were simulated in 4 additional Canadian locations. Table 2 shows how the available solar radiation and the heating loads compare for all 5 locations.

	Vancouver	Calgary	Toronto	Montreal	Shearwater
Heating Load (GJ)	1015	2677	2015	2440	1920
Heating Degree Days (C-days)	2818	4980	3873	4363	4116
Incident Irradiation (MJ/m²)*	5023	6343	5275	5296	5188
Latitude (N)	49.2	51.1	43.7	45.5	44.6
Longitude (W)	123.2	114.0	79.6	73.8	63.5

Table 2. Heating load and climate data for 5 locations used to assess the impact of climate on solar fraction and BTES efficiency

In general, for the shape of the BTES efficiency curves and system solar fraction curves for the other 4 climates looked similar to those for Calgary, the city with the highest heat load and the highest available solar radiation. Vancouver showed the greatest differences, since the heating load was smallest at less than 40% of that in Calgary and the incident radiation there was also the lowest, at 79% of the highest city.

In Vancouver, the system was over-sized with all soil types and a range of BTES shapes allowing the system to provide 100% of the heating load with solar energy. BTES efficiencies were all lower despite the milder climate, again suggesting over-sizing of the system.

In Shearwater and Toronto the solar fractions were higher than in Calgary with very similar BTES efficiencies in Toronto but slightly lower in Shearwater. In the Montreal climate, the solar fractions tended to be 10-15 percentage points lower with the most effective BTESs having similar efficiencies to those in Calgary.

While it is highly unlikely and definitely not recommended that a design optimized for one location would be constructed without re-optimization in significantly different climates, these results suggest that the climate isn't likely to have a very large impact on BTES performance.

Simulation, cost and optimization of borehole storages

To predict the behavior and performance of a BTES in an energy system it is necessary to account for performance of all of the subsystems and their interactions with each other and with the load and the weather. Mathematical models representing each of the components are connected together to simulate the whole system. Several different simulation tools are available, however, TRNSYS has probably been used most often for simulating large solar seasonal storage systems in many countries.

Simulation tool (TRNSYS)

TRNSYS is a very flexible software tool used for simulating the behavior of transient systems, including the dynamic solar thermal energy systems described here. It is based on a robust algebraic and differential equation solver and is supplied with a large library of component models. It includes a powerful graphical interface that greatly simplifies the assembly and interconnection of the component models necessary to represent a system. Successful modelling in TRNSYS demands knowledge of the software and a good understanding of the systems being simulated.

When designing a BTES it is usually necessary to simulate the system that it interacts with. This typically includes parameters such as the heat load imposed by a district heating system, the heat supply from each source e.g. a solar collector array and meteorological data. The simulation is typically carried out using a time step of from 1 to 10 minutes, to simulate how the components interact and how the system behaves and performs for at least one year. With seasonal storages, the warm-up period can be several years so 5 and 10 year simulations may be required to achieve quasi-steady operation.

The BTES can be modelled in TRNSYS with type 557 (Duct Ground Heat Storage Model). This type models the storage volume geometrically as a cylinder with a vertical axis of symmetry and uniformly placed heat exchanger boreholes or ducts. If the shape of the real BTES will not be cylindrical, inputs may be selected to represent the actual shape with a cylinder having the correct borehole depth, number of boreholes and total borehole length. The borehole spacing should also be represented correctly whenever possible. This means that some of the BTES outer surface areas will not be represented accurately, but this is of less importance. It is also necessary to define parameters such as the conductivity, heat capacity and diffusivity of the soil and the thickness and conductivity of the top insulation.

The graphical user interface representation for a simplified version of the TRNSYS model prepared to model the Drake Landing Solar Community (DLSC) in Alberta, Canada is shown in Figure 9. A more detailed version of the model with multiple collector array components and multiple district heating loop branches was used during the system design to size and optimize the solar system, including the solar collector array, a short-term water tank storage and a seasonal BTES.

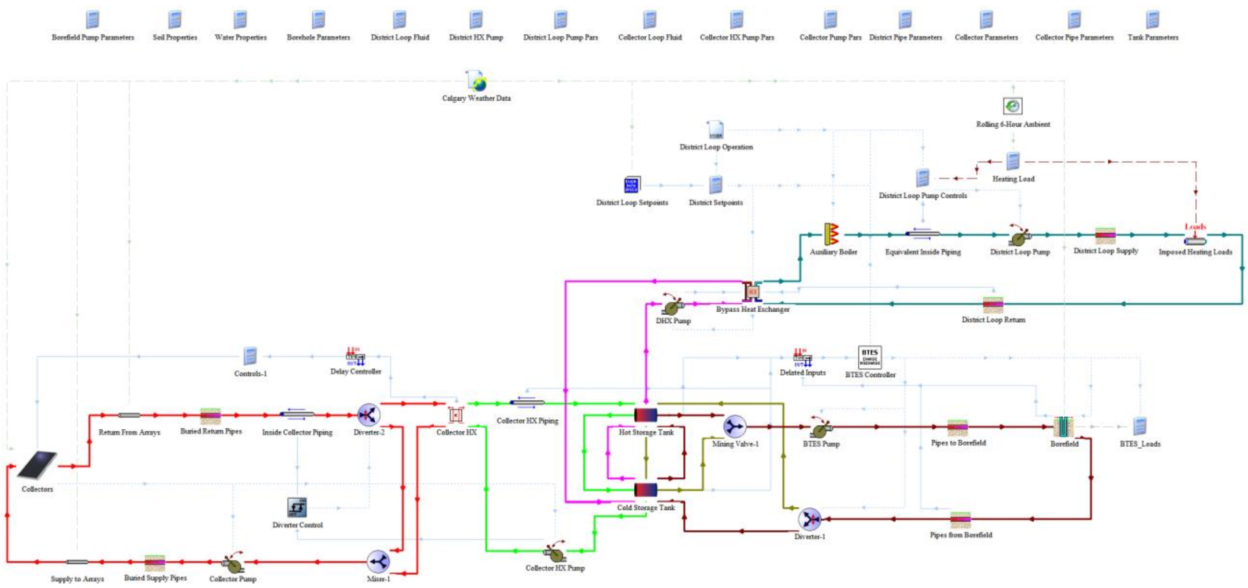


Figure 9. Graphical interface representation of the simplified TRNSYS model of the seasonal solar district heating system at Drake Landing using a BTES.

BTES cost

Only a limited amount of cost data is available for the implementation of borehole thermal energy storages, however, it may be useful in the planning and design of new systems. Figure 10 shows the specific cost for installed BTES that have been implemented as well as some that are only conceptual. It is clear that like other large storages, the specific cost drops significantly as the size increases. The curve shown is a fit to the Canadian data only.

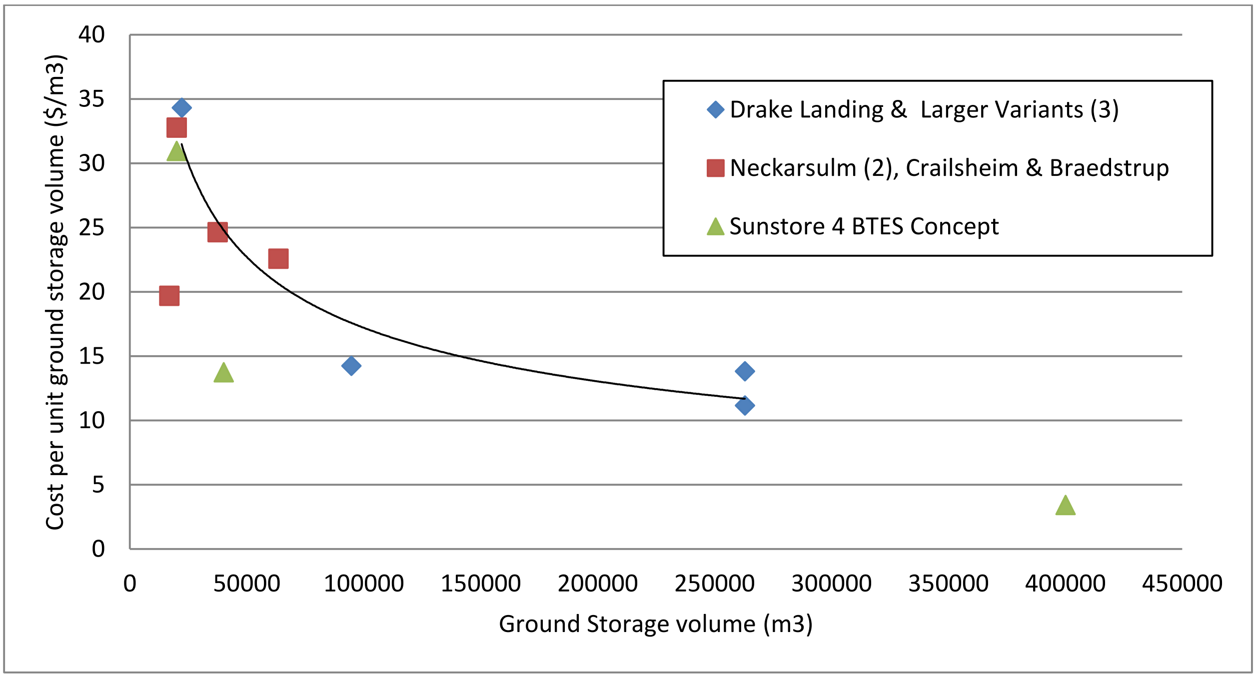


Figure 10. Specific installed cost for several borehole thermal energy storages

Optimization of storage size and shape

For any heat storage, including BTES, to work well within a system it is important to find the best or optimum sizing for the individual parts of the system. This can be done by systematically running a series of simulations to identify the best (generally the least cost) combination of major component sizes to achieve the design objectives. Since the goal is often to minimize the cost of achieving a particular outcome, optimization can sometimes make the difference between a profitable and an unprofitable investment. A generic optimization program like GenOpt® may be used with the TRNSYS system model to automatically perform numerous runs with varied parameters to minimize a specific target function. As an example, the system shown in Figure 9 was optimized by varying the size of the solar collector array, the size of the seasonal BTES and the size of the short-term storage to identify the lowest cost system that would deliver 90% of the heat load. When the energy being displaced by the solar system is inexpensive, optimization for minimum delivered energy cost is likely to identify the zero-solar option as optimum.

Information on systems utilizing BTES

Eight large solar heating systems utilizing borehole thermal energy storages have been identified. Three are located in Germany (Attenkirchen, Crailsheim and Neckarsulm) one each in Sweden (Anneburg), Denmark (Braedstrup), Canada (Drake Landing), Finland (Kerava) and the Netherlands (Groningen).

The Crailsheim and Drake Landing projects are described in Project Example Fact Sheets, which are also available on the Task 45 site: http://task45.iea-shc.org/fact-sheets .

Information on 6 of the European systems listed above is also available through the Solar District Heating website: http://www.solar-district-heating.eu/tabid/575/Default.aspx and on the Canadian system at: http://www.dlsc.ca/ .

ANNEX A Data sheet for PEXa for u-tube heat exchangers

2.0 PROPERTIES OF PE-XA AND PE 100

REHAU offers RAUGEO pipes made of high-pressure crosslinked polyethylene (PE-Xa) and non-crosslinked polyethylene (PE100).

The most important advantages of PE-Xa over PE100 are:

- No spreading through pipe wall of grooves, notches and puncture loads
- Small bending radii possible even at low temperatures
- No sand backfill necessary
- Applicable even at temperatures over 40°C, therefore ideal for heating and cooling purposes
- Rugged, rapid and weather independent compression sleeve jointing technique can be used

The differences are listed in detail in Table 1:

Properties of illustrations of pipe types	PE-Xa				PE 100		
							
Material	High-pressure crosslinked polyethylene				Polyethylene		
Compliant with standard	DIN 16892/16893				DIN 8074/8075		
Durability (Safety factor SF = 1.25))	Pipes SDR 11 (25 x 2.3, 32 x 2.9, 40 x 3.7)						
20 °C	100 years/15 bar				100 years/15.7 bar		
30 °C	100 years/13.3 bar				50 years/13.5 bar		
40 °C	100 years/11.8 bar				50 years11.6 bar		
50 °C	100 years/10.5 bar				15 years/10.4 bar		
60 °C	50 years/9.5 bar				5 years/7.7 bar		
70 °C	50 years/8.5 bar				2 years/6.2 bar		
80 °C	25 years/7.6 bar				-		
90 °C	15 years/6.9 bar				-		
Constant operating temperatures	-40 °C to 95 °C				-20 °C to 30 °C		
Minimum laying temperature	-30 °C				-10 °C		
Minimum bending radii	20 x 1.9	25 x 2.3	32 x 2.9	40 x 3.7	25 x 2.3	32 x 2.9	40 x 3.7
20 °C	20cm	25cm	30cm	40cm	50cm	65cm	80cm
10 °C	30cm	40cm	50cm	65cm	85cm	110cm	140cm
0 °C	40cm	50cm	65cm	80cm	125cm	160cm	200cm
Notch impact strength	very high				high		
Crack growth at FNCT (full notch creep test)	no failure				failure after 200-2000 h		
Backfilling material	surrounding soil				Sand		
Pipe roughness	0.007mm				0.04mm		
Average thermal coefficient of longitudinal expansion t	0.15mm/(m*K)				0.20mm/(m*K)		
Building material class to DIN 4102	B2				B2		
Chemical resistance	see annex 1 of DIN 8075				see annex 1 of DIN 8075		
Density	0.94 g/cm³				0.95 g/cm³		
Strength	extremely strong (no growth of grooves and notches occurring during transport and installation)				strong (slow growth of grooves and notches occurring during transport and installation)		
Requirement on material for piping zone	excavated material (usually has higher thermal conductivity than sand)				sand filling		
Suitability for heat storage	unrestricted (operating temperature up to 95 °C)				no (maximum operating temperature 30 °C)		
Suitability for cooling with refridgeration machine	yes (operating temperature up to 95 °C)				(maximum operating temperature 40 °C)		
Applicable fluid	to VDI guideline 4640						
Melting index MFR	-				0.2-0.5 g/10 min		
MFR group	-				003. 005		

Table 1

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