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Feasibility of underground seasonal storage of solar heat in Finland

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Abstract

The global challenge of climate change is urging for renewable energy sources to reduce greenhouse gas emissions. One of the applications of renewable energy is the solar district heating plant, which uses solar heat for space heating on a community scale. Seasonal storage of solar heat is crucial in solar district heating plants as a solution to the mismatch between the energy supply and demand. This is especially important in countries located in high latitudes with high levels of solar insolation and low heating demand in the summer, and low sun insolation and high heating demand in winter time. This study investigates selection of the most feasible method for seasonal storage of solar heat at high latitudes. The aim is to identify the key aspects of method selection and design of underground solar heat storage. Practices of underground thermal energy storage in Finland and other countries with similar ground conditions are reviewed. Five heat storage methods are evaluated based on their efficiency, cost, construction method, and suitability for typical ground conditions in Finland. The available methods of seasonal heat storage are compared, and the most promising method for solar heat storage in Finland is proposed. In addition, the potential provided by a combination of two or more methods is examined. The borehole storage method is proposed for storing solar heat in Finland. The combined method with a rock pit used for short term heat storage and boreholes for long term storage is also an attractive and technically feasible option for Finnish ground conditions.

Keywords: *Seasonal thermal energy storage, Solar district heating, Method selection, Finland*

Introduction

The intermittency problem of some renewable energy sources derives from their excess supply during the low season and insufficiency during the peak season. The solution is to accumulate and store the surplus energy that can be used in times of high demand and low supply. Energy can be stored in the form of electrical (e.g. hydroelectric, compressed air, hydrogen or liquid organic hydrates) or thermal energy (e.g. solar heat, waste heat, heat from cooling). One of the common applications of renewable energy is solar heat, where energy from the sun is used to heat up water and space in buildings. The storage of solar heat is a crucial aspect in adopting the solar energy for heating purposes. This is especially important in high latitudes, where sun insolation is highest in the summer, when the heating demand is low and lowest in winter when the demand is high, so not enough energy is produced (Barnes & Levine, 2011). This requires seasonal storing of solar heat produced during the summertime months that can be extracted and used during the wintertime months. The main advantages of energy storage include (1) less pollution of the environment by reduction of greenhouse gases emissions, (2) enhanced system performance and reliability of an energy system, (3) more efficient use of energy, and (4) finally better economics by reducing capital and operational costs (Lee, 2013).

To harness the solar energy that varies seasonally, a long-term storage solution is needed that can provide large storage volume. The most desirable storage medium for thermal energy storage is required to have good heat transfer, mechanical stability, large change of internal energy per unit volume, mass and unit cost, as well as low toxicity and corrosiveness (Barnes & Levine, 2011). The desired parameters of the materials include high energy density and heat capacity, high volumetric thermal capacity, good thermal conductivity and low cost (Cabeza, 2015). This implies the advantage of sensible heat storage, where water and bedrock are favourable choices as a medium for energy storage, because of suitable properties and large storage volumes that can be obtained at a relatively low cost (Nordell & Hellström, 2000).

The research on seasonal heat storage was conducted in Finland mostly during the 1980s and 1990s, when the first storage facilities were in the planning phase (Nordell *et al.*, 1994). Lund (1983) concluded that

seasonal storage of solar heat is feasible in typical southern Finnish weather conditions and solar fraction (*i.e.* energy obtained from the sun divided by the total energy required) above 70% may be achievable. A recent investigation by Flynn & Siren (2015) revealed that the performance of seasonal solar heat storage depends largely on local environmental conditions, including ground properties. This confirms the need for a thorough investigation of feasible alternatives to store energy underground in Finnish bedrock conditions.

This study is part of a project “Tackling the Challenges of a Solar-Community Concept in High Latitudes (SCC)”, which aims to develop a solar community in a high-latitude location, such as Finland, basing its energy management on renewable sources, proving economically feasible for all stakeholders, and being acceptable from the customer, society and environment points-of-view. The objective of this paper is to evaluate the potential for seasonal solar storage in Finland. This study evaluates the key aspects of method selection and design of underground solar heat storage, and aims to identify the most feasible method for seasonal storage of solar heat in high latitudes.

Methodology

Solar Community

One of the possibilities for the implementation of solar energy is the so called solar community, where the solar heat is stored seasonally and used for district heating on a community scale. According to the European Solar-district-heating (SDH) platform database there are 131 SDH plant across Europe, with 47 in Denmark, 21 in Sweden, and 2 in Finland (Solar District Heating, 2015). The existing underground thermal energy stores in Finland and countries with similar climatic and ground conditions are described briefly in this study. Sweden is used as the main reference country, as it has very similar ground and climatic conditions, and has successfully developed many heat stores.

One of the examples of a solar community with seasonal storage of energy that was constructed in Finland is the Kerava solar village (Lund & Mäkinen, 1982). It was constructed as a community of 47 houses with a plan to achieve 75% of the heating energy from solar heat. The solar energy was stored seasonally in 1500 m³ water tank excavated in rock with 54 borehole heat exchangers surrounding it to recover the escaping heat. The project was monitored during the years 1983-1985 and despite the fact that the seasonal storage system achieved an excellent efficiency of 85% the overall project did not reach its goal and the solar fraction equalled to 38%. One of the issues was that the storage tank was too small and it was fully charged after two months. It was concluded that increasing the tank volume by a factor of ten would result in an increase the solar fraction to 63% (Kauppa- ja teollisuusministeriö, 1986). After few years of operation the collection and storage of solar heat was terminated and the building was connected to a district heating network. This example illustrated that it is technically feasible to construct a solar community with seasonal ground heat storage in Finland, but the effectiveness depends on the proper design of the storage component.

Large scale heat storages can be found in Sweden. According to Hellström (2013) there are 50 borehole storage systems with the total drilling larger than 5000 m each, 40 aquifer storages and 3 cavern storage systems. The large number of heat storage systems and its rapid development, especially in 1980s, can be attributed to the favourable subsidy policy for renewable energy sources in Sweden.

One example of a successful implementation of seasonal solar energy storage at high northern latitudes is the Drake Landing Solar Community (DLSC) in Okotoks, Canada. Although the DLSC is located at the 51°N latitude compared to 60°N of Helsinki, the weather in Okotoks is cooler than on the southern coast of Finland. In DLSC the heat is stored in a large volume of soil with an array of 35m deep, evenly spaced 144 boreholes drilled into it. Boreholes are filled with a grouting material of high thermal conductivity to provide good thermal contact with the surrounding soil. The DLSC has reached a very high solar fraction of 98% in heating energy, which means that almost all heat used by the community is produced using the solar energy. It is one of the best result in the world and a record in its climatic region (Sibbit *et al.*, 2012). However, the concept implemented in the DLSC cannot be directly utilised in Finland, because of different ground conditions in Finland such as thin cover of soil over crystalline bedrock, higher thermal conductivity, and shallow groundwater table.

The Solar Community Concept (SCC) investigated in this study is planned to consist of 50 houses (100 m² floor area per unit) with total heat demand of 288 MWh a⁻¹ for both domestic hot water and space heating. The preliminary concept of SCC consists of two water tanks (hot and medium temperature) for diurnal storage of heat and one underground seasonal store. The size of the community is flexible and can be expanded in the future to increase the storage effectivity. Storage capacity should be as large as technically and economically possible to achieve high performance by decreasing the storage heat loss, which depends on the surface-area-to-volume ratio. Increasing the storage size can also have a positive influence on system economics, because the unit cost decreases (Lund, 1983). The seasonal store for the SCC project is regarded

as a general solution for typical environmental conditions in Finland to prove the feasibility of solar community. In the next stage, the final system will be designed according to the specific site conditions.

Environmental conditions in Finland

Finland is located between 60° and 70° latitude in the Northern Hemisphere and shows characteristics of both maritime and continental climate with yearly average temperatures reaching more than 5°C in the southern part of the country. The horizontal solar irradiation in Finland (measured in the capital city Helsinki) is 2.60 kWh m⁻² per day and is comparable to values measured in London, Amsterdam or Hamburg (Mauthner *et al.*, 2015).

Finland is located in the Fennoscandian shield. The bedrock is Precambrian in age, low-porosity crystalline rock comprising mostly granitic and metamorphic rocks. The crystalline bedrock is overlain by a thin layer of Quaternary glacial and postglacial sediments. Due to mechanically favourable properties the bedrock is stable, and thus suitable for hosting various underground facilities, such as energy storage constructions. The average overburden thickness in Finland is 8.5 meters, but it can reach values of up to 100 meters. The thickness of overburden affects the storage method selection as a thick soil layer may prevent some of the thermal energy storage methods being feasible. For example, rock caverns cannot be built in area where the soil layer is considerably thick, as reaching the bedrock would become extremely expensive. The groundwater level in Finland is located usually at depths of 1 to 4 meters from the surface, but it can be as deep as 20 meters in Quaternary eskers and bedrock with topographic variations (GTK, 2005). The groundwater flow can cause heat loss in storages that are in direct contact with the groundwater if the flow is substantial. The crystalline bedrock also hosts zones of weakness due to fracturing and brittle deformation. These zones may act as flow channels for groundwater. Most of the Finnish bedrock has generally relatively low fracture frequency and the heat transfer by groundwater flow is practically negligible. Kukkonen and Peltoniemi (1998) measured thermal properties of Precambrian bedrock in Finland. In most rock types the mean thermal conductivity was between 2 and 4 Wm⁻¹K⁻¹. The mean value of all samples was 3.24 ± 1.00 Wm⁻¹K⁻¹. This value is controlled by the mineral composition of the rock, but also by rock texture, rock porosity and, pore filling fluids. Specific heat capacities of the individual minerals and the relative amounts of these minerals control the heat capacity of the crystalline rock. Typical range for crystalline bedrock is between 770 and 830 J kg⁻¹K⁻¹ (Kukkonen & Lindberg, 1998).

Underground thermal energy storage methods

The underground thermal energy storage methods (Figure 1) suitable for seasonal storage of solar heat are the aquifer thermal energy storage (ATES), the borehole thermal energy storage (BTES), the tank thermal energy storage (TTES), the pit thermal energy storage (PTES), and the cavern thermal energy storage (CTES) (Novo *et al.*, 2010; Pinel *et al.*, 2011; Pavlov & Olesen, 2012; Schmidt & Miedaner, 2012). Furthermore, Hellström and Larson (2001) proposed a concept for storage of heat in artificially fractured bedrock (HYDROCK). There is a possibility to combine two methods (Combi or Hybrid store), for example a rock cavern and boreholes (Nordell *et al.*, 1994), or tank and boreholes (Reuss *et al.*, 2006). Such combination can join the advantages of each method to increase the efficiency of district heating systems, or to provide a higher power output.

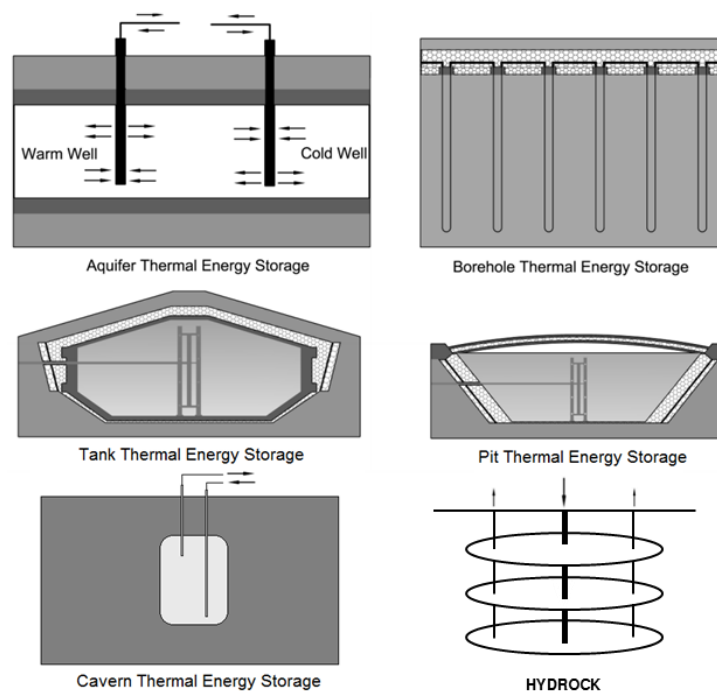


Figure 1. Underground thermal energy storage (UTES) methods (modified after Pavlov & Olesen, 2012)

From the technical and economic point of view, borehole storage is one of the most favourable storage systems for seasonal storage of solar heat (Cabeza, 2015; Gao *et al.*, 2015). However, it requires specific conditions, for instance, drillable ground, high heat capacity, high thermal conductivity, low hydraulic conductivity and natural ground water flow through the medium less than 1 meter per year (Novo *et al.*, 2010; Schmidt *et al.*, 2004). It is important to note that all of those conditions are satisfied by typical Finnish bedrock, so constructing borehole store in Finland is technically feasible.

There are certain guidelines regarding the method selection and design of seasonal underground thermal energy stores. All applicable boundary conditions need to be considered when choosing the storage method. This includes thermogeological conditions, size of the storage, temperature levels in the system, and legal requirements. One of the most important aspects in the pre-design phase are the geological site investigations that should consist of appropriate number of test drillings (Schmidt & Miedaner, 2012). Properly performed investigations help to identify the existing geological structures, like extensive fracture zones that can cause unexpected drilling problems and may require grouting. In cold climates, construction activities, such as drilling and excavations, should be performed during the summer season to decrease the cost by even as much as 10% (Andersson & Rydell, 2012).

In this study different heat storage methods are evaluated in the context of the SCC project. The feasibility is investigated against seven criteria on a scale from 1 (poorest) to 3 (best):

- Simplicity of construction process - evaluates how easily the required storage volume is obtained in the construction process.
- Cost efficiency for a small scale system - measures the amount of initial costs of different methods.
- Storage efficiency - measures how much of the charged energy can be discharged in one season.
- Site requirements - measures how high are the requirements for a particular site to be selected as a location for the store. This is especially important when choosing a general solution for typical conditions in Finland.
- Adaptability - measures the possibility to expand the size of a store due an increasing energy demand.
- Small scale feasibility - measures how easy is to construct a small scale system using different methods.
- Reliability of the storage system - measures the reliability of a store as whole system, taking into account all aspects from the construction phase to the beginning of the first charging phase.

Furthermore, the potential for combining two or more methods is assessed. In addition, specific storage costs are calculated for different storage methods, based on the information gathered by interviewing Finnish contractors, researching costs on supplier websites and by investigating previous projects. The cost consists of drilling, soil removal, administrative, excavation (only for CTES), and material costs. The ground conditions are assumed as average values described in the previous subsection.

Results and discussion

Evaluation of solar thermal storage methods

The evaluation of the available seasonal thermal storage methods was performed according to the seven criteria described in the previous section. The results of evaluation are presented in Table 1. The aquifer thermal energy storage (ATES) method and the borehole thermal energy storage (BTES) method are easier to construct compared to other methods, hence their score in the first criterion is higher. The cavern thermal energy storage (CTES) method and the pit thermal energy storage (PTES) method require large volumes to be economically feasible, so their cost efficiency for a small scale system is low. The tank thermal energy storage (TTES) method is an expensive solution at any scale of the system and should only be used when other methods are not feasible. The ATES is the cheapest solution for a small scale system followed by the BTES. In terms of storage efficiency, the TTES system has the highest value and the BTES system the lowest because of high heat loss. The ATES scores the highest in the criteria for site requirements, as it needs an aquifer to be present that can be used for storage of heat. The TTES can be constructed practically at any site. In term of adaptability, the BTES and the ATES systems can be easily expanded by adding more boreholes or well pairings. The storage volume for other methods cannot be increased easily, hence their low score in this criterion. The ATES, the BTES, and the TTES are easily constructed as a small scale system, therefore their score in the small scale feasibility criterion is high. In terms of reliability of the storage system, the ATES and the BTES are outperforming other methods.

Table 1. Evaluation of the available seasonal thermal storage methods for solar district heating in Finland

	ATES	BTES	CTES	PTES	TTES
Simplicity of obtaining sufficient storage volume	+++	+++	++	++	++
Cost efficiency of a small scale system	+++	++	+	+	+
Storage efficiency	++	+	+++	++	++
Site requirements	+	++	++	++	+++
Adaptability	+++	+++	+	+	+
Small scale feasibility	+++	+++	+	+	+++
Reliability of the storage system	+++	+++	++	+	+

Based on the overall evaluation, the recommended method for seasonal solar heat storage for the SCC project is the borehole thermal energy storage (BTES). The storage capacity criteria, combined with cost efficiency requirement, rules the CTES and the PTES out as these methods require larger scale of the system to achieve better system economics. This indicates that increasing the size of the community could change the result of the evaluation, and different method could be more appropriate. As the SCC is still in its pre-feasibility phase and the location of the village is not defined, the storage method must be suitable for as many sites as possible. For this reason the ATES is ruled out as it requires a suitable aquifer. The main argument for choosing the BTES over the TTES was reliability of the storage, cost effectiveness, and favourable ground conditions in Finland. The BTES system has also an advantage in terms of the adaptability in case of an increased heating demand for heating energy. The existing store can be expanded by drilling additional boreholes next to the existing borehole field.

Choosing the BTES as storage method opens up a possibility to combine the borehole storage method for seasonal storage and water tank (or rock pit) for short term storage. Placing the short term storage in the middle of the borehole field is technically feasible in favourable ground conditions in Finland and can be more cost effective, as the insulation of the short term store can be reduced. The optimal design of the solar community with seasonal underground storage of heat in Finland is required to select the most feasible storage method. The underground heat store should be modelled numerically to simulate and optimise its long-term performance. Hence, the results presented here should be only taken as indicative, and not as a solution for the final design of the solar community in Finland.

Costs

Summary of the specific storage costs of different underground thermal storage methods is presented in Table 2. The volume of borehole storage was normalized to water equivalent using the volumetric heat capacity ratio of water and granite. The storage method with the lowest cost of construction is the borehole thermal energy storage (BTES) method and the tank thermal energy storage (TTES) method is the most expensive alternative. Costs depend highly on the final size of the storage and the specific location.

Table 2. Summary of storage costs for borehole, tank, cavern and pit thermal energy storage methods calculated for preliminary-sized solar community in Finland (SCC)

Storage method	Volume in water equivalent (m ³)	Cost (€)					Specific cost per m ³ water equivalent
		Drilling	Overburden removal	Material	Excavation	Total	
BTES	31 000	175 000	2000	135 000	-	312 000	10
TTES	7 000	-	260 000	625 000	-	885 000	127
CTES	7 800	-	250 000	-	370 000	620 000	80
PTES	9 000	-	235 000	200 000	-	435 000	49

The calculated specific storage costs are plotted in Figure 2. The cost curve of seasonal solar storage projects and studies located in Germany and Denmark is modified after Schmidt *et al.* (2011). In addition, costs of several project located in Sweden are plotted for comparison, because of their low specific storage cost and similar environmental conditions to those present in Finland (Giordano *et al.*, 2016): Lyckebo CTES, Sodertuna BTES, Anneberg BTES, and Stora Skuggan (S.S.) BTES. It can be seen that the cost of the SCC storage falls in the range of seasonal solar stores in other countries. The borehole storage method is the most economically attractive option, as it falls in the lowest part of the cost curve, within the range of borehole stores in Sweden. This can be attributed to favourable geology of the Precambrian bedrock in both countries. The final cost of the system should be analysed using detailed life-cycle cost analysis to find a proper balance between the seasonal performance and the cost.

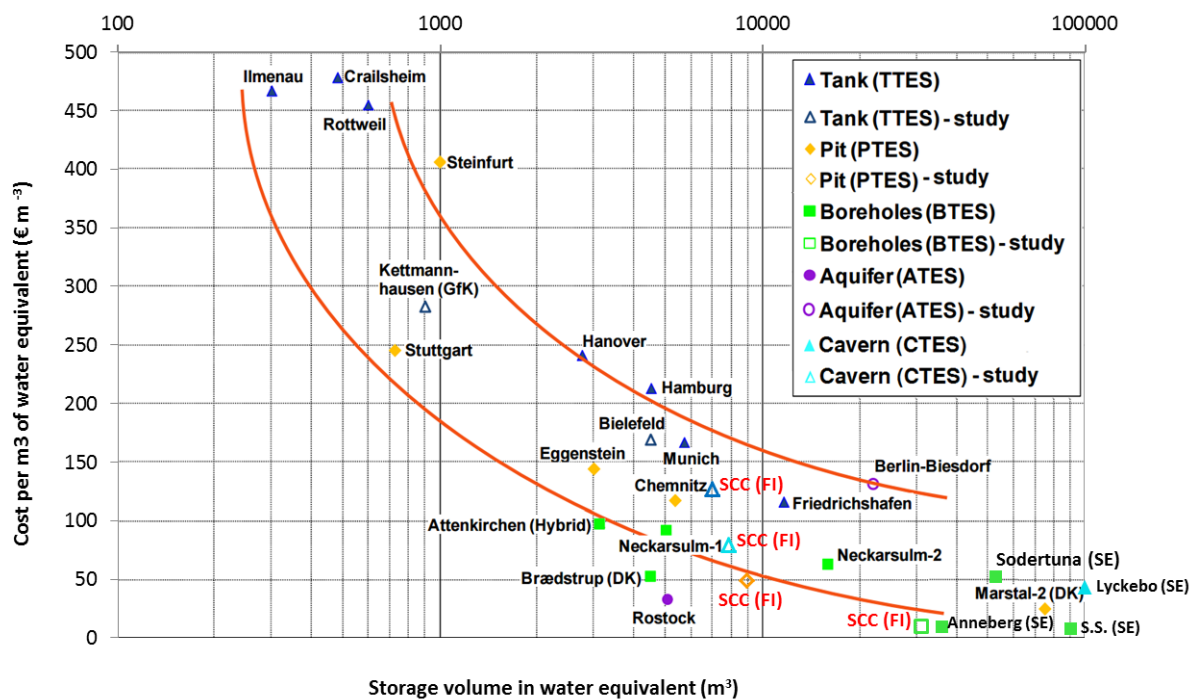


Figure 2. Specific storage costs (without VAT) of existing and planned solar thermal energy stores in Germany, Sweden (SE) and Denmark (DK); in addition costs calculated for SCC project in Finland (FI) are plotted (adapted from Schmidt *et al.*, 2011)

Conclusion

In conclusion, the borehole thermal energy storage method is suggested for the Solar Community Project (SCC) in Finland, because it is simple to build, cost effective, feasible on small scale, and suitable in Finnish ground conditions. The specific storage costs of different methods calculated for the SCC project show that the seasonal store falls within the typical cost range (e.g. tank, cavern, and pit thermal storage methods), or can be as cost effective as borehole thermal stores in Sweden.

Further research is required on site-specific tailoring and numerical simulation of the underground storage systems for comprehensive understanding of the capacity, time-dependent behaviour of the storage, and the role of different affecting variables.

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