



## Seasonal solar thermal energy storage through ground heat exchangers –Review of systems and applications

**Pavlov, Georgi Krasimiroy; Olesen, Bjarne W.**

*Published in:*  
Proceedings

*Publication date:*  
2011

*Document Version*  
Early version, also known as pre-print

[Link back to DTU Orbit](#)

*Citation (APA):*

Pavlov, G. K., & Olesen, B. W. (2011). Seasonal solar thermal energy storage through ground heat exchangers –Review of systems and applications. In Proceedings

## DTU Library

Technical Information Center of Denmark

---

### General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

# **Seasonal solar thermal energy storage through ground heat exchangers – Review of systems and applications**

Georgi K. Pavlov\*

International Centre for Indoor Environment and Energy  
Department of Civil Engineering  
Technical University of Denmark, Lyngby, Denmark  
e-mail: gpav@byg.dtu.dk

Bjarne W. Olesen

International Centre for Indoor Environment and Energy  
Department of Civil Engineering  
Technical University of Denmark, Lyngby, Denmark  
e-mail: bwo@byg.dtu.dk

## **ABSTRACT**

Energy demands in buildings vary on daily, weekly and seasonal basis. These demands can be matched with the help of Thermal Energy Storage (TES) systems that operate synergistically and are carefully matched to each specific application.

Solar energy is an important alternative energy source for heating applications. One main factor that limits its application is that it is a cyclic, time-dependent energy source. The use of seasonal thermal energy storage can substantially reduce the cost of solar energy systems that can supply up to 100% of buildings energy needs. Such systems are designed to collect solar energy during the summer and retain the stored heat for use during the winter. The application requires large inexpensive storage volumes and the most promising technologies were found underground, using ground heat exchangers (GHE). Although such systems have been constructed and demonstrated, it is challenging to make them cost effective. Economically justified projects can be designed using annual storage on a community-wide scale, which could reduce cost and improve reliability of solar heating.

In this work, a review of monitoring campaigns and/or simulation studies of seasonal solar energy storage systems through ground heat exchangers is presented. It reveals important design considerations related to cost effectiveness and thermal performance of the ground storage and the connected systems. Integrated approach evaluating the performance of all system components should be used during the design process and determination of system control strategies.

## **INTRODUCTION**

The building sector accounts for about 40% of the total energy use in the European Union (EU) countries (International Energy Agency, IEA 2009). However, at the same time the building sector has a documented cost-effective saving potential of up to 80%, which can be effected over the next 40 years. In order to ensure these considerable energy conservations and at the same time to apply renewable energy in an optimal way, the development of integrated, intelligent technologies for buildings is needed.

---

\* Corresponding author

Increasing energy demands, shortages of fossil fuels and environmental concerns are increasing the interest in the development of renewable energy sources. Such sources, as solar energy, have intermittent nature and their effective utilization is dependent on the availability of efficient and effective energy storage systems. Efficient TES systems minimize thermal energy losses and attain high energy recovery during the extraction of the stored thermal energy with little degradation in temperature.

Seasonal storage of solar thermal energy for space heating purposes has been under investigation in Europe since the mid 1970s within large-scale solar heating projects. The objectives of such systems are to store solar heat collected in summer for space heating in winter. Most large-scale solar systems have been built in Sweden, Denmark, The Netherlands, Germany and Austria [1]. The first demonstration plants were developed in Sweden in 1978/1979, based on results from a national research programme [2]. The seasonal storage concept research work continued within the IEA “Solar Heating and Cooling” programme. Experiences have been gained and exchanged in Task VII “Central Solar Heating Plants with Seasonal Storage (CSHPSS)” since 1979 in many countries. In the past decade, the main activities have been within the work initiated in the CSHPSS Working Group, IEA Solar Heating and Cooling Programme as well as the work carried out in Europe within the EU/APAS-project “Large-Scale Solar Heating Systems” [3]. Figure 1 shows a scheme of a central solar heating plant with seasonal storage.

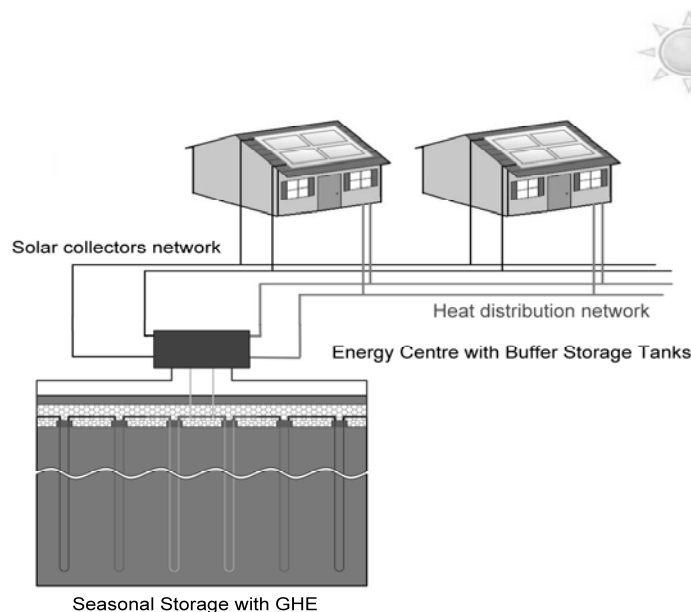


Figure 1. Scheme of a CSHPSS using ground heat exchangers

For seasonal or long-term storage, low temperature concepts with the use of heat pumps, to raise the temperature of the water used for space heating to a suitable level, seem to be an appropriate option. This technology becomes possible in large-scale central solar heating systems and it enables to reduce the solar collector area required achieving nearly 100% of the total heating demand. The difficulty associated with this technology lies in making it cost effective [4].

In this paper, an attempt to summarize developments during the last decades in seasonal solar thermal energy storage in the ground using ground heat exchangers is done.

## DESCRIPTION OF STORAGE TECHNOLOGIES

Storage of sensible heat results in energy losses during the storage time. These losses are function of storage time, storage temperature, storage volume, storage geometry, and thermal properties of the storage medium. Since seasonal thermal energy storage requires large inexpensive storage volumes the most promising technologies were found underground. Such systems are called Underground Thermal Energy Storage (UTES) systems [5]. Among the UTES systems developed since 1970s, four different types of storages turned out as main focus for the ongoing engineering research: Water tank, Water-gravel pit storage, Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), Figure 2.

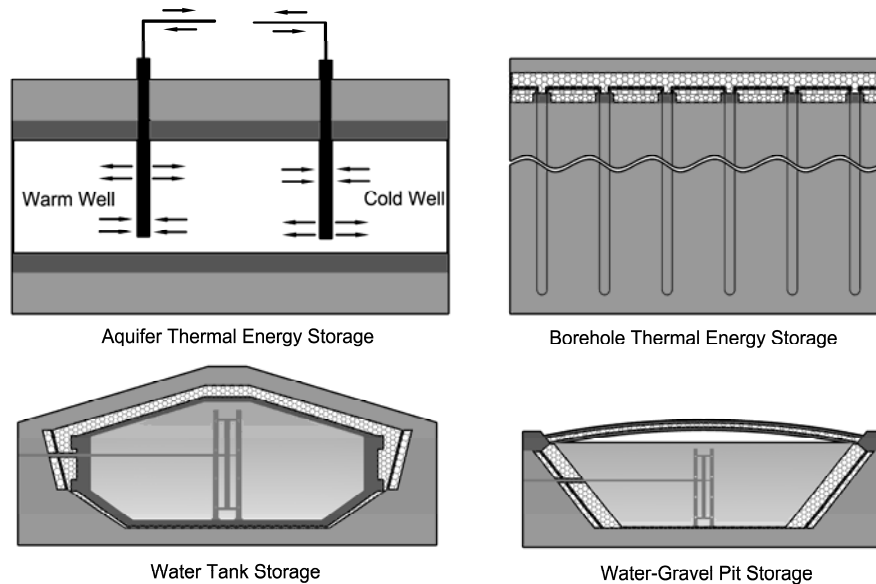


Figure 2. Underground thermal energy storage concepts

Water tank thermal energy storage is usually built as a steel or reinforced pre-stressed concrete tank, fully or partially buried in the ground. Due to high specific heat of water, and the possibility for high capacity rates for charging and discharging, this technology seems to be the most favorable from a thermodynamic point of view.

Gravel-water pits are normally buried in the ground and need to be waterproofed and insulated at least at the side walls and on the top. Heat is charged into and discharged out of the store either by direct water exchange or by plastic piping installed in different layers inside the store. The gravel-water mixture has lower specific heat capacity than water alone and for this reason the volume of the whole basin has to be higher compared to hot water tank heat storage to obtain the same heat storage capacity.

Aquifers are below-ground widely distributed sand, gravel, sandstone or limestone layers with high hydraulic conductivity which are filled with groundwater. If there are impervious layers above and below and no or low natural groundwater flow, they can be used for heat storage. In this case, two wells or groups of wells are drilled into the aquifer and serve for extraction or injection of groundwater. During charging periods cold groundwater is extracted from the cold well, heated up by the solar system and injected into the hot well. In discharging-periods the flow direction is reversed. Especially for high temperature heat storage a good knowledge of the mineralogy, geochemistry and microbiology in the underground is necessary to prevent damage to the system caused by well-clogging, scaling etc.

In borehole thermal energy storage the heat is directly stored in the ground. Suitable geological formations are e.g. rock or water-saturated soils. U-pipes, so called ground heat exchangers, are inserted into vertical boreholes, into a depth of 30-200 m, to build a huge heat exchanger. The boreholes are usually filled with groundwater (Northern Europe), or with bentonite, quartz sand or thermally enhanced grouts (North America, Central Europe). While water is running in the U-pipes heat can be fed in or out of the ground. The heated ground volume comprises the volume of the storage. At the top of the store there is a heat insulation layer to reduce heat losses to the surface. One advantage of this type of storage is the possibility for a modular design. Additional boreholes can be connected easily and the store can grow with e.g. the size of a housing district. The size of the store has to be three to five times higher than that of a hot water heat store to obtain the same heat capacity. Because of the lower capacity at charging and discharging usually a buffer store is integrated into the system.

So far, the development of seasonal storage has been aimed at heating large district system stores instead of single house solutions, in order to fulfill technical viability and cost effectiveness by using large storage volumes. Fisch et al. [3] reviewed large scale solar plant development in Europe during the 1990s. The work refers to two large-scale solar heating applications: systems with short-term (diurnal) storage designed to supply 10–20% of the annual heating demand or 50% of the domestic hot water; and systems with long-term (seasonal) storage capable of supplying 50–70% of the annual heating demand. Within the findings of that work was that large-scale solar applications benefit from the effect of scale. Compared to small solar domestic hot water systems for single-family houses, the solar heat cost can be cut at least in third. Long-term storage systems prove being more effective in reducing fossil fuels use and complying with CO<sub>2</sub> emission policies. Among the main results of the evaluation of the existing projects was the need to reduce the cost-benefit ratio for CSHPSS.

The experimental plants built in some European countries involve the development of new concepts of seasonal storage such as duct storage, natural aquifer, and pit storage concepts using high performance concrete and new construction technologies. Lottner et al. [6] reviewed long-term national monitoring programme Solarthermie-2000 of large-scale solar heating plants, with and without seasonal storage, in Germany. The study reveals that at present the specific storage costs for seasonal storage of solar energy are still too high and many efforts must be made to achieve technical and economic feasibility. Schmidt et al. [7] reviewed detailed results of the same monitoring program. The technology of central solar heating plants is described and advices about planning and costs, for improving and optimizing the installations in order to make such concepts more economic, are given. In Bauer et al. [8] monitoring results of CSHPSS of the same program and its continuation Solarthermie-2000plus are reviewed. The different types of thermal energy stores and the affiliated central solar heating plants and district heating systems are described. The operational characteristics, of the CSHPSS under investigation, are compared using measured data.

Which of the technologies described above is selected depends very much on the local hydro-geological site conditions. Water tank and pit thermal energy stores are technically feasible and work well. However, construction costs and thermal losses are still too high. The main cost for hot-water storage tanks is caused by the concrete construction, ground works, insulation, and the use of steel liners to reduce water permeability. Considerable cost

reductions can be obtained with the development of high-density concrete materials. For gravel-water stores, sealing of the pit, insulation and ground works account for significant part of the costs. Moisture protection of the insulation is important for both concepts. Natural aquifers are a cost effective seasonal storage concept but require water saturated sand layers with high permeability without ground water movement. Well construction is the predominant part of the costs for aquifer heat stores. The installation work for borehole heat exchangers, including material and drilling works, causes nearly half of the costs for borehole heat stores [9] [7] [10] [11].

## THERMAL PERFORMANCE OF GROUND HEAT EXCHANGERS

Long term storage of high quantities of thermal energy is one of the key problems for a widespread and successful implementation of solar district heating. Seasonal storage in the ground, using ground heat exchangers, seems to be favorable from technical and economical point of view. Depending on the temperature level, the thermal energy is extracted either by a heat pump (low temperature ground storage  $< 40^{\circ}\text{C}$ ) or directly (high temperature ground storage,  $40\text{-}80^{\circ}\text{C}$ ) and delivered to the customers. The thermal performance of such systems is influenced by the heat and moisture movement in the area surrounding the heat exchangers.

An important issue in the design of underground seasonal storage systems using borehole heat exchangers is to find cost-effective methods to construct the BTES field so that heat can be injected or extracted from the ground without excessive temperature differences between the heat carrier fluid and the surrounding ground. As a result of the limited thermal conductivity the heat losses are rather moderate and storage efficiencies of 70% can be reached. In contrast good thermal contact between the heat exchangers and the ground is required to allow a good heat transfer rate per unit area of the heat exchanger tube.

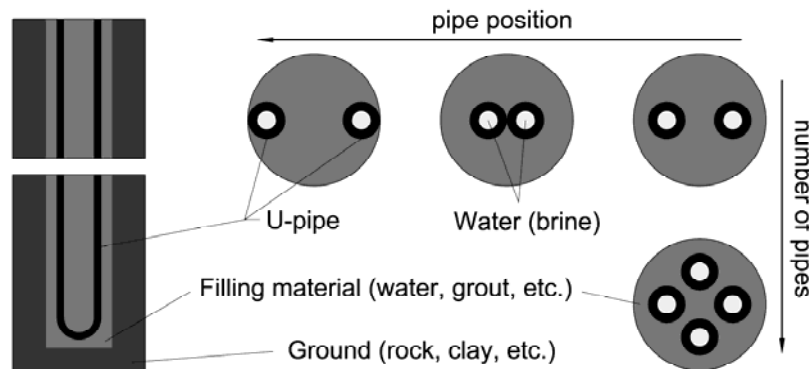


Figure 3. Ground Heat Exchanger – single/double U-pipe in a borehole

The heat transfer between the heat carrier fluid and the surrounding ground depends on the arrangement of the flow channels, the convective heat transfer in the ducts, and the thermal properties of the materials involved in the thermal process. The two major thermal resistances associated with these different parts are the thermal resistance between the heat carrier fluid and the borehole wall, borehole thermal resistance, and the thermal resistance of the surrounding ground from the borehole wall to the some suitable average temperature level, often chosen to be the local average ground temperature. The influence of the borehole thermal resistance may in conventional designs become relatively large. Especially crucial are applications with high demands on heat injection rates and high temperatures such as solar heating systems and other low temperature applications with high demands on achieving high heat transfer rates at small temperature differences.

The most important parameters influencing the borehole thermal resistance are the thermal conductivity of filling material, the number of pipes, pipe position and the pipe thermal conductivity, Figure 3. Paul [12] have completed a study that reveals significant advantages of thermally enhanced grouts on design, costs and heat pump performance in ground-coupled heat pump systems. The thermal resistance of the pipe material and the convective heat transfer inside the pipe have to be kept low. The contribution to the total borehole thermal resistance is quite large for single U-pipes of polyethylene, but usually decreases with number of pipes in the borehole. Bose et al. [13] showed results from five thermal response tests with the use of spacers and different grout materials, pointing out a 30% borehole length reduction possibility when using spacers and thermally enhanced grout.

Hellström [14] presented how the thermal performance of a U-pipe borehole heat exchanger changes as a function of the filling material thermal conductivity for three different pipe positions in the borehole. Moreover, Hellström et al. [15] shows a performance comparison at different temperature levels and heat rates, indicating the influence of free convection heat transfer in the groundwater.

In the case of a water-filled borehole, the heat transfer will induce natural convection. In a laboratory experiment by Kjellsson and Hellström [16] has been investigated the influence of different pipe materials (polyethylene and copper) and pipe geometry, at high fluid temperature levels (15-45°C) and large specific heat transfer rates (50-100 W/m), on the convective heat transfer in a borehole. The experiment shows that natural convection has a small effect at low temperatures and low heat injection rates, which agrees with field experiences from heat extraction boreholes. However, the influence has a large effect at high temperatures and large heat injection rates. The convective heat transfer has been up to about 3-5 times higher than the estimated heat transfer for pure conductive heat transfer through stagnant borehole water. The results imply that the borehole thermal resistance for U-pipe heat exchangers may become relatively low at high temperature applications.

The ground thermal resistance depends on the borehole spacing. Usually the spacing is intended to be uniform throughout the storage volume; however, in practice deviations from the intended drilling directions result in an irregular distribution of the boreholes in the store. Analytical studies show that the influence of irregular borehole spacing should be small if the storage volume is about the same [17].

Ground water movement through the storage region may significantly increase the losses of thermal energy. There may be both regional flow, caused by hydraulic gradients at the site of the store, and natural convection induced by the increased temperatures in the storage region. A numerical study by van Meurs [18] concerning a porous medium with homogeneous hydraulic properties indicates that a heat store requires a protecting hydraulic screen if the ground water flow exceeds 0.05 m/day (~20 m/year).

The heating of a water-saturated ground material will induce natural convection due to the temperature-dependent density of water. Buoyancy flow will cause warmer water with lower density to flow upwards. For a ground heat store in a porous medium the natural convection currents will be most pronounced at the vertical boundaries of the store. The magnitude of the buoyancy flow depends primarily on the temperature levels of the store and the surrounding ground, the horizontal and vertical permeability of the ground material, and the vertical extension of the store [19]. Numerical studies [18] [20] show that the thermal performance of

the store will be affected if the intrinsic permeability of the ground exceeds  $10^{-12} \text{ m}^2$ . However, the presence of impermeable horizontal layers will reduce the natural convection.

In unconsolidated soils like clay, silt, or sand, heat capacity and thermal conductivity are strongly dependent on the water content especially at higher temperatures ( $> 60^\circ\text{C}$ ). In this region water losses due to vapor diffusion along the temperature gradient can lead to dry-out and cracking in the area surrounding the heat exchanger tubes. This additional resistance may reduce the heat transfer rate significantly. In that relation, Reuss et al. [21] studied numerically and experimentally the heat and moisture transfer in ground storage systems with vertical heat exchangers in unsaturated soil. The effective heat transfer coefficient and the heat capacity of the soil depending on water content, mineral composition, dry bulk density and shape of soil components have been determined by computer simulations and validated through laboratory and field experiments. The model was used for the design of a pilot plant of a high temperature ground store for seasonal storage of waste heat from a heat and power cogeneration unit.

### **STATUS OF SEASONAL STORAGE OF SOLAR ENERGY USING GHEs**

Different heat stores integrated in CSHPSS have been developed in Germany as part of the R&D programmes Solarthermie-2000 and Solarthermie-2000plus. The common objective in all demonstration plants has been to achieve solar fraction of 50% of the stored solar heat being utilized for heating applications.

Since 1997, pilot borehole thermal energy storage is in realization in Neckarsulm. After several upgrade stages the BTES presently contains a volume of  $63360 \text{ m}^3$  with 528 borehole heat exchangers in a depth of 30 m. The installed solar collector area is  $5670 \text{ m}^2$ . The CSHPSS operates in the following manner: the heat from the solar collectors is delivered to the solar plant and collected in buffer stores which are used for short-term heat storage to balance peak heat deliveries from the collectors. The heat distribution network is supplied either by the buffer tanks or the BTES, depending on the temperature level. A gas condensing boiler is used for additional heat supply if none of the thermal energy stores is able to cover the heat demand at the requested temperature level. Due to the fact that the storage can only be heat insulated on top, heat losses might be quite high when the storage is heated noticeable above ground temperature. This matter is in observation in Neckarsulm because the maximum design temperature of the storage is  $85^\circ\text{C}$ .

Results from monitoring campaign, in the period 1999-2007, show that the design solar fraction of 50% of the plant has not been reached yet (highest 44.8% in 2007) which could be due to the 10% smaller solar collector area than planned; and mainly due to the about 10K higher than expected net return temperatures in the district network. Computer simulation for the system in Neckarsulm showed an increase of the solar fraction of 6% with a decrease of the net return temperatures by 5K compared to the 1999 measured values [22]. The net return temperature gives the lowest temperature level in the system and respectively the minimum discharge temperature of the BTES. Therefore, the high return temperatures reduce the heat capacity of the ground store. The main reason for the high return temperatures is improper design of the heat distribution system. To reduce the possible consequences of that problem, the second generation of CSHPSS are designed with low-temperature heating systems.

The small solar collector area results also in about 20K lower maximum temperature in the store ( $65^\circ\text{C}$  measured during the last years of operation,  $85^\circ\text{C}$  maximum design temperatures). The measurements show also that in the first five years of operation no heat



has been discharged from the BTES since it had to be heated up to a usable temperature level. The duct store needs 5-8 years of operation until steady state conditions are reached (long heating-up period of the store). Further details of the CSHPSS in Neckarsulm can be found in [8] and [23].

The borehole thermal energy storage built in Crailsheim indicates the next generation of this kind of storages. The project description and design prerequisites are given in Mangold [24]. The BTES has a total volume of 37500 m<sup>3</sup> with 80 borehole heat exchangers in a depth of 55 m. The total solar collector area installed is 7300 m<sup>2</sup>. A buffer storage tank of 480m<sup>3</sup> is added to the system because of the high capacity rates of the solar collectors during summer. Since the high capacity rate cannot be charged directly to the BTES during the day, it is distributed over longer period of time with the help of the buffer storage tank.

The heat from the seasonal store is transferred to a diurnal storage tank of 100 m<sup>3</sup> either directly or via a heat pump. The heat pump allows higher usability and increases the storage capacity of the seasonal heat store. In addition the temperature level in the BTES is reduced which results in lower storage heat losses. Furthermore the efficiency of the CSHPSS becomes more robust against high return temperatures from the heat distribution network. A feasibility study for the whole heat supply system has been done in order to determine the lowest solar heat cost for the system concept. According to computer simulations the BTES will be heated up to 65°C at the end of September, the lowest temperatures at the end of the heating period will be 20°C. Maximum temperatures during charging will be above 90°C.

Different type of CSHPSS is built in Attenkirchen [7]. The heat store is a combined hot-water and borehole heat store. A central concrete tank with a volume of 500 m<sup>3</sup> is surrounded by 90 GHEs (30 m deep). Depending on the temperature levels in the two parts of the store, heat pumps use the GHEs as heat source and deliver heat into the hot-water tank or use the hot-water tank as heat source and supply heat into the district heating network.

A preliminary study of a solar-heated low-temperature space-heating system with seasonal storage in the ground has been performed for a planned residential area with 90 single family houses with 1080 MWh total heat demand in Anneberg, Sweden [25]. The suggested heating system with a solar fraction of 60% includes 3000 m<sup>2</sup> solar collectors. A BTES in crystalline rock of 60000 m<sup>3</sup> (99 borehole heat exchangers, each having a depth of 65 m) is used as a seasonal store. The temperature of the seasonal store varies between 30°C and 45°C over the year. The floor heating system is designed for 30°C. Electrical heaters are used to produce peak heating.

The system performance has been evaluated using the simulation models TRNSYS and MINSUN together with the ground storage module DST (*Duct Storage Model*) [26] [27] [28] [29] [30] [31]. The study implies an economically feasible design for a total annual heat demand of about 2500 MWh. The total annual heating costs have been investigated for three different systems, assuming a 25 years pay-back period: solar heating (1000 SEK/MWh), small-scale district heating (1100 SEK/MWh) and individual ground-coupled heat pumps (920 SEK/MWh). The heat loss from the Anneberg storage system has been estimated to 42% of the collected solar energy. This heat loss would be reduced in a larger storage system. For a case where the size of the proposed solar heating system would be enlarged by a factor of three, the total annual cost of the solar heating system would be reduced by about 20% to 800 SEK/MWh, lower than the best conventional alternative.

The partly solar heated building area in Anneberg, Sweden, has been built in 2002 [32]. The final design has been carried out for 50 residential units (about 120 m<sup>2</sup> each) with an annual heat demand of 550 MWh. The heating system is designed for low-temperature heating (32°C/27°C) and individual electric heaters. The solar heating system has been built with a total solar collector area of 2400 m<sup>2</sup> and 60000 m<sup>3</sup> rock store volume (100 boreholes, 65 m depth). The mean temperature of the seasonal store has been 30-45°C and the working temperatures of the single-circuit heat distribution network 20-60°C.

Evaluation of the system performance has been done using the simulation models TRNSYS and MINSUN together with the ground storage module DST. The solar heating system resulted with a solar fraction of about 70% after 3-5 years of operation, required for initial heating of the store and the surrounding ground. Monitoring and evaluation of the system performance after 2 years of operation (2003/04) has been performed. It shows that the collectors will have favorable working conditions but the store is rather small. Although problems have occurred and several components have worked less efficient than expected, the overall system idea works as intended.

In Canada, the first seasonal solar thermal energy storage was built in 2006 in the residential area in Okotoks as borehole thermal energy storage. The BTES volume of 35000 m<sup>3</sup> consists of 144 vertical boreholes, each having a depth of 37 m. During the warmer months of the year, the system will primarily be charging the BTES field. In the colder months, each home will draw energy from the BTES field into their homes. During intense summer sunshine, the BTES field cannot accept energy as quickly as it can be collected; thus heat is temporarily stored in short term energy storage tanks (located in an Energy Centre), with transfer to the BTES continuing through the night. This situation is reversed in the winter, when heat cannot be extracted from the BTES field quickly enough to meet peak heat demands, typically in the early morning hours.

Results from computer simulations indicate that the system will reach about 90% solar fraction for space heating after an initial 5 years charging period [33]. The predicted end of summer BTES temperature is around 80°C. Such a high storage temperature has two drawbacks. First, the return temperature to the solar collectors is relatively high which leads to relatively low solar collector efficiencies. Second, heat losses from the borehole storage are relatively high as they represent 60% of the injected heat [34].

Chapuis and Bernier [35] proposed a new seasonal storage strategy based on the concept of the system at Okotoks. First, the storage temperature is kept relatively low in order to limit heat losses and improve solar collector efficiencies. Second, the seasonal borehole storage is designed in such a way as to enable simultaneous charging and discharging of the ground using four pipe boreholes with two independent counter-current circuits. Finally, the temperature level is raised using heat pumps to supply heat at an acceptable temperature for space heating. The proposed configuration is simulated with TRNSYS using the DST model. Results from simulations indicate that it is possible to keep the seasonal storage temperature at an annual average slightly above the annual mean ambient temperature using a relatively small solar collector area leading to relatively high solar collector efficiencies. Combined with a heat pump, it is shown that this system can reach a solar fraction of 78%.

## **EXPERIENCES FROM PILOT PROJECTS AND DEMONSTRATION PLANTS**

Seasonal heat storage needs large volumes of storage to supply the energy stored during summertime along winter. Those large stores require the development of technologies capable

of minimizing heat losses in order to preserve the thermal performance and life time of the solar heating plant. These approaches must be coupled with low investment, at least lower than conventional heating systems.

In Tables 1 are summarized the technical characteristics of some demonstration plants in central solar heating systems with borehole seasonal storage described in this article. The experimental projects mentioned have been selected as they are large-scale pilot plants. An overview of the effectiveness of diverse configurations of these systems, including solar heat systems costs are provided.

Table 1. Technical data of CSHPSS [6] [7] [10] [36]

<i>CSHPSS</i>	Heated living area	Total heat demand, GJ/a	Solar collector area, m <sup>2</sup>	Storage volume, m <sup>3</sup>	Solar fraction, %	Maximum design storage temperature, °C	Solar heat cost at analysis date, MWh <sub>i</sub>
Neckarsulm, DE	20000 m <sup>2</sup>	1663	5000	63400	50*	85	172 EUR
Crailsheim, DE	260 houses, school and gymnasium	14760	7300	37500	50*	85	190 EUR
Attenkirchen, DE	6200 m <sup>2</sup>	1753	800	10000	55*	85	170 EUR
Anneberg, SE	9000 m <sup>2</sup>	3888	3000	60000	60*	45	1000 SEK
Okotoks, CA	52 houses	1900	2293	35000	90*	80	

CA = Canada, DE = Germany, SE = Sweden.

\* Calculated values for long-time operation

The economy of CSHPSS depends not only on the storage costs, but also on the thermal performance of the storage and the connected system. Before starting the design of a new plant the geological conditions of the location, the characteristics of the heat source and the demands of the consumers have to be analyzed thoroughly. Important parameters are the maximum and minimum operating temperatures of the storage and of the district heating network. In order to achieve high solar energy efficiency, the solar plant has to be operated at low temperatures. Low storage temperature limits heat losses and improves solar collector efficiencies.

Heat from the storage can only be used without a heat pump as long as the storage temperature is higher than the return temperature of the district heating system. If the temperature level in the ground storage is high enough to meet the demand of the heating system, direct use is possible. Suitable techniques are low-temperature heating systems (typical range: 25°C-35°C) like floor and wall heating. Thus the ground storage can be operated in the range 40°C-80°C. In other cases an additional heat pump is required to adjust temperature levels of the storage and the heating system.

Obviously direct use is the most advantageous technique from the economic point of view as the investment for a heat pump can be avoided. In contrast high temperature systems must be built in a much bigger scale than low temperature systems because of the higher losses caused by the large temperature gradient. In general the size of high temperature ground storage systems should exceed a minimum size of 10000 m<sup>3</sup> [21].

The major investment is the cost of building the storage; e.g. drilling of boreholes, construction of heat exchangers, refill of boreholes and labour [7] [9] [10] [11]. As drilling costs increase with the depth of the borehole, the length and the number of ducts are important. Thermal properties (heat capacity, thermal conductivity) of the ground determine the spacing of the heat exchangers. Number, length and spacing of ducts taken together allow the storage volume to be calculated.

## CONCLUSIONS

Borehole thermal energy storage systems for seasonal storage of solar heat are technically feasible and work well. However, the annual utilization factor of these systems needs to be increased. For this purpose decreasing the net return temperatures and developing enhanced heat pumps is required. The operation of the BTES is only reasonable in combination with a buffer store due to the limited charging and discharging power of the ground store. Hence, the improvement of buffer storage technology has to be advanced as well.

The seasonal energy storage technologies for solar energy applications are characterized by many factors such as solar collectors, annual sun exposure, heat distribution networks, heat demand and insulation of the buildings, and volume of the store. Once these technologies have been well developed, the main effort consists in reducing costs in order to make them market competitive against conventional energy sources. To determine the economy of a storage, the investment and maintenance costs of the storage have to be related to its thermal performance (the cost of the usable stored energy).

## REFERENCES

1. Dalenbäck, J.O., Large scale solar heating and cooling systems in Europe, *Proceedings of ISES Solar World Congress: Solar Energy and Human Settlement*, VOLS I-V, pp 799-803, 2007.
2. Dalenbäck J.O. and Jilar T., Swedish solar heating with seasonal storage-design, performance and economy. *International Journal of Ambient Energy* 1985;6(3); pp 123-128.
3. Fisch M.N., Guigas M., Dalenbäck J.O., A review of large-scale solar heating systems in Europe. *Solar Energy* 1998;63(6); pp 355-366.
4. Dincer I., Evaluation and selection of energy storage systems for solar thermal applications. *International Journal of Energy Research* 1999;23; pp 1017-1028.
5. Nordell, B., Large-scale Thermal Energy Storage, *Proceedings of Winter Cities'2000*, Luleå, Sweden.
6. Lottner V., Schulz M.E., Hahne E., Solar-assisted district heating plants: Status of the German programme Solarthermie-2000. *Solar Energy* 2000; 69(6); pp 449-459.
7. Schmidt, T., Mangold D., Müller-Steinhagen H., Central solar heating plants with seasonal storage in Germany. *Solar Energy* 2004; 76; pp 165-174.
8. Bauer, D., Marx R., Nußbicker-Lux J., Ochs F., Heidemann W., Müller-Steinhagen H., German Central solar heating plants with seasonal heat storage. *Solar Energy* 2010; 84; pp 612-623.
9. Schmidt T., Mangold D., Müller-Steinhagen H., Seasonal Thermal Energy Storage in Germany. *Proceedings of ISES Solar World Congress 2003*, Göteborg, Sweden.
10. Schmidt T., Mangold D., New steps in seasonal thermal storage in Germany. *Proceedings of Ecstock 2006*, Richard Stockton College of New Jersey, USA.
11. Lehtmetts, M., Parameter Study of Solar Heating Systems with Seasonal Ground Storage in Moraine. *Swedish Geotechnical Institute, Report 51*, Linköping, Sweden, 1995.
12. Paul, N.D., The Effect of Grout Thermal Conductivity on Vertical Geothermal Heat Exchanger Design and Performance, *M.Sc. thesis, South Dakota University*, 1996.
13. Bose, J., Smith M., Spitler J., Advances in Ground Source Heat Pump Systems - An International Overview. *Proceedings of 7th IEA Heat Pump Conference 2002*, 1; pp 313-324, Beijing.
14. Hellström, G., Thermal Performance of Borehole Heat Exchangers. *Proceedings of The Second Stockton International Geothermal Conference 1998*, New Jersey, USA.

15. Hellström, G., Kjellsson, E., Laboratory measurements of heat transfer properties of different types of borehole heat exchangers, *Proc. Terrastock Conference 2000*, Stuttgart.
16. Kjellsson, E., and Hellström, G., (1997). Laboratory Study of the Heat Transfer in a Water-Filled Borehole with a Single U-pipe, *Proceedings of 7th Int. Conf. on Thermal Energy Storage, Megastock'97*, June 18-21, 1997, Sapporo, Japan, pp 509-514.
17. Hellström, G., Ground Heat Storage, Thermal Analyses of Duct Storage Systems, Part I: Theory, *Thesis, Dept. of Mathematical Physics, University of Lund*, Sweden, 1991.
18. van Meurs, G.A.M., Seasonal Heat Storage in Soil, *thesis, Dept. of Applied Physics, University of Technology Delft*, Netherlands, 1986.
19. Hellström, G., Tsang C.F., and Claesson J., Buoyancy Flow at a Two-Fluid Interface in a Porous Medium: Analytical Studies. *Water Resources Research* 1988, Vol. 24, No.4, pp 493-506.
20. Lund, P., Effect of Ground Water Flow on the Performance of Long-Term Pipe Heat Storage in the Ground. *Report TKK-F-A586* (1985), *Helsinki University of Technology*, Finland.
21. Reuss, M., Beck M., Muller J.P., Design of Seasonal Thermal Energy Storage in the Ground, *Solar Energy* 1997, Vol. 59, No. 4-6, pp 247-257.
22. Seiwald, H., Bericht zum Projekt Neckarsulm-Amorbach, *internal report, ITW, University of Stuttgart (Report to the project in Neckarsulm, in German)*, 2000.
23. Nußbicker, J., Mangold D., Heidemann W., Müller-Steinhagen H., Solar Assisted District Heating System with Duct Heat Store in Neckarsulm-Amorbach (Germany). *Proceedings of ISES Solar World Congress 2003*, Göteborg, Sweden.
24. Mangold D., Seasonal storage – a German success story. *Sun & Wind Energy*, 2007; 1; pp 48-58.
25. Nordell, B., Hellstrom G., High temperature solar heated seasonal storage system for low temperature heating of buildings, *Solar Energy* 2000, 69, pp 511-523.
26. Claesson, J., Efring, Hellström G., Johansson, Duct storage model. *Dept. of Mathematical Physics, University of Lund*, Sweden, 1981.
27. Hellström, G., Duct Ground Heat Storage Model: Manual for Computer Code. *Dept. of Mathematical Physics, University of Lund*, Sweden, 1989.
28. Mazzarella, L., Duct storage model for TRNSYS 1989 version. *ITW, Stuttgart Univ., Dipartimento di Energetica, Politecnico di Milano*, Italy, 1989.
29. Mazzarella, L., The MINSUN Simulation and Optimization Program. *User' s Manual, Dipartimento di Energetica, Polytecnico di Milano*, Italy, 1990.
30. Pahud, D., Duct storage model for TRNSYS 1996 version. *LASEN-EPFL*, Lausanne, Switzerland, 1996.
31. Klein, S. A., TRNSYS 16 – A TRAnSient SYstem Simulation program, *Solar Energy Laboratory, Univ. of Wisconsin*, USA, 2004.
32. Lundh, M., Dalenbäck J.-O., Swedish solar heated residential area with seasonal storage in rock: Initial evaluation. *Renewable Energy* 2008, 33, pp 703-711.
33. McDowell, T.P., Thornton J.W., Simulation and model calibration of a large-scale solar seasonal storage system, *3rd National conference of IBPSAUSA*, Berkeley, USA, 2008.
34. Sibbitt, B., Onne T., McClenahan D., Thornton J., Brunger A., Kokko J., Wong B., The Drake Landing Solar Community Project – early results. *2-nd Canadian Sol. Build. Conf.*, Calgary, Canada, 2007.
35. Chapius, S., Bernier M., Seasonal storage of solar energy in borehole heat exchangers, *Proc. of the IBPSA Conf. Building Simulations 2009*, Glasgow, Scotland, pp 599-606.
36. Wong, W.P., McClung J.L., Snijders A.L., Kokko J.P., McClenahan D., Thornton J., First large-scale solar seasonal borehole thermal energy storage in Canada. *Ecstock 2006 Conference*, Stockton, NJ USA.