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An integrated model for designing a solar community heating system with borehole thermal storage

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ABSTRACT

Borehole thermal energy storage (BTES) is found to be a favorable method for storing a large amount of thermal energy, and suitable for seasonal solar thermal storage, especially for large communities. Drake Landing Solar Community (DLSC), built in 2006, is the first such solar community in Canada. DLSC has achieved a 97% solar fraction after five years of operation. Although the DLSC project has been a success technically, the cost of the system is not attractive. In this study, an alternative design approach for a similar community is presented. The primary goal is to develop a system that not only achieves similar or better performance but also costs less. TRNSYS 17, along with a novel custom BTES component, is used for the system design and simulation. With the alternative design, the annual community thermal load of 2350 GJ is mostly met by solar thermal collectors via BTES and after five years of operation a 96% solar fraction is predicted. The simulation results are compared with published results for DLSC. It is estimated that the proposed system offers a 19% saving in initial cost in addition to reductions of BTES area of 38% and solar panel area of 25%.

Introduction

Solar thermal collectors with underground thermal storage system have been used to heat buildings and communities for many years. The first solar heating plants were constructed about 30 years ago. From 1979 to the middle of 2011, a total of 141 heating plants were built in Europe. Each plant has more than 500 m^2 of solar collector area or greater than 350 kW thermal capacities (Dalenback and Werner, 2012). Among these are several examples of large scale pilot solar plants in Germany and Sweden, each of which has achieved a solar fraction (SF) of at most 50 to 60% (Pavlov and Olesen, 2011a). The purposes of all these plants are storing heat at times when it is not required and using it at times when it is needed. Schmidt et al. have reviewed in detail advances in seasonal thermal energy storage in Germany (Schmidt et al., 2003).

Seasonal thermal energy storage normally stores heat in a sensible form. The main parameters for determining the heat transfer and losses for the storage are thermal properties of the storage medium, time of storage, storage temperature, storage geometry and volume. In community and district solar energy heat storage, the storage volumes are relatively large. Therefore, ground storage due to its low cost, as well as ability to deal with the large time scales, makes this storage technology the most promising (Nordell, 2000).

Four main types of seasonal storage have been presented by researchers (Schmidt et al., 2003, 2004; Socaciu, 2011; Pavlov and Olesen, 2011b). Those are: 1) hot water thermal energy storage, 2) aquifer thermal energy storage, 3) gravel-water thermal energy storage and 4) borehole thermal energy storage.

Schmidt et al. (Schmidt et al., 2004) provided an extensive study and some advice about how to design an optimized system to make the system more efficient and economical. Bauer et al. (Bauer et al., 2010) also described the different thermal storage types related to the solar district systems and compared the specific characteristics of different storage types. Hesaraki et al. (Hesaraki et al., 2015) conducted a comparative review of different types of seasonal energy storage systems integrated with the heat pumps for heating and to some extent cooling applications. The paper presented the systems with low temperatures suitable for running heat pumps to satisfy heating rather than cooling loads mostly. In their study, the implications of storing excess heat generated by the heat pumps in cooling season and the storage of solar heat at the same time, have not been investigated. Rad and Fung (Rad and Fung, 2016) also presented an extensive review of different types of thermal energy storage used for heating and cooling for solar communities, including the systems with a distribution system other than the heat pumps, e.g., fan coil, for both heating and cooling.

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In borehole thermal storage (BTES), the ground itself is the storage medium, and heat exchanges occur through a number of vertical boreholes in the ground. The storage volume is not exactly defined and separated. Geological formation plays a significant role in determining the thermal capacity of the storage. The vertical borehole lengths are usually in the range of 30 to 100 m with approximately 3 to 4 m separations (Schmidt et al., 2003). The borehole depths in recent installations can go up to 200 m (Pavlov and Olesen, 2011b).

In the borehole, heat is typically exchanged through double or single U-pipes or concentric pipes. The pipe material is commonly made of synthetic material like high-density polyethylene (HDPE). The fluid in the tubes is usually water although in some cases, to avoid freezing, the water is mixed with ethanol or glycol. The boreholes are often filled with grout, which normally is bentonite, quartz with sand or a water mixture (Northern Europe). Quartz gives the grout a higher thermal conductivity whereas bentonite provides sealing and plugging characteristics. The heat-transfer properties of grouted boreholes have been studied theoretically by Bennet et al. (Bennet et al., 1987) and Hellstrom (Hellstrom, 1991). They have also been tested in the laboratory by Paul (Paul, 1996) and using field measurements by Austin (Austin, 1998). The thermal conductivities of typical filling materials follow: stagnate water (0.6 W/mK), bentonite (0.8–1.0 W/mK), thermally enhance grout with quartz (1.0–1.5 W/mK), and water saturated quartz sand (1.5–2.0 W/mK).

For the thermal analysis of BTES, many tools have been developed. The main purpose of these tools is to design the requisite complex systems optimally, including cost effectively. The available tools vary from uncomplicated design tools to advanced simulation modeling with hourly climate data and detail load data. The model should consider a relatively high heat flow in the ground and the heat transfer in and adjacent to the boreholes. Therefore, with a suitable time resolution, the relation between the temperature of the heat-transfer fluid and the total storage heat-transfer rate is captured (Nordell, 2000).

Eskilson and Claesson proposed a model in finite-difference, a superposition borehole model (SBM), which is a detailed model that can accept arbitrarily placed vertical or horizontal boreholes (Eskilson and Claesson, 1988; Eskilson, 1987). This model is examined and validated in several field experiments (Hellstrom, 1991; Eskilson, 1987). It has been used to calculate the thermal performance of a heat pump-coupled system, with software such as EED (Hellstrom et al., 1997; Hellstrom and Sanner, 1997) and GLHEPRO (Manickam et al., 1997). This model calculates the dimensionless thermal response functions for various borehole configurations.

Hellstrom introduced another simulation model called, duct-ground heat storage (DST) (Hellstrom, 1989). This is a simulation model for multiple boreholes with uniform borehole spacing. It has been used extensively for both detailed design and field experiment evaluation. Both the SBM and DST models have been modified for use as a TRNSYS component. The TRNSYS version of DST can also investigate problems within the stored volume. It can check for radial stratification of the ground temperatures and assess the effect of the flow conditions in the borehole pipe on the thermal performance of the system (Pahud and Hellstrom, 1996).

In Canada, Drake Landing Solar Community (DLSC) in Okotoks, Alberta, the first large scale BTES designed as a part of a solar community, was built in 2006. DLSC has achieved a 97% solar fraction after five years of operation (Sibbitt et al., 2007). The primary objective of the DLSC project was to demonstrate that substantial energy cost savings are achievable compared to conventional systems by storing solar heat from summer for winter uses.

DLSC consists of 52 detached houses having a total annual heating demand of 2120 GJ (SAIC Canada, Science Applications International Corporation, 2012). From the central energy center, hot water is distributed through a two-pipe system to each of the 52 houses. Each house is equipped with an individual air handler with a water-to-air fan coil. All the houses, having an efficient building envelope, were built and certified based on the R-2000 standard developed by Natural Resources Canada (NRCan) (Natural Resources Canada Office of Energy Efficiency, 2012). A total of 2293 m^2 of flat-plate solar collectors was installed on the roof of the connected garages of the houses, facing south. The community energy center contains two short term storage tanks (STSTs) with a total 240 m^3 volumetric capacity, pumps, heat exchangers and controls. A borehole thermal energy storage (BTES), located next to the energy center, containing 144 boreholes of 35 m depth installed in 24 parallel circuits, is used as a seasonal thermal storage. Fig. 1 depicts the DLSC simplified system schematic (Sibbitt et al., 2007).

The DLSC maximum design borehole temperature is 80 °C. Sibbitt et al. describe how the high-temperature storage has two disadvantages, 1) during the charging time, the return fluid temperature to the solar panels is relatively high, which reduces the solar panel efficiencies, and 2) the storage heat loss is relatively high, calculated to be almost 60% (Sibbitt et al., 2007).

To minimize the thermal storage heat losses, Chapuis and Bernier, offered an alternative design approach for the Okotoks like system, to keep the storage temperature relatively low (Chapius and Bernier, 2009). The approach was based on using heat pumps to raise the temperature as per space heating demands. The proposed system was simulated using TRNSYS with its DST module. It was concluded that by keeping the average storage temperature slightly above the annual average ambient temperature, the return water temperature to the solar collectors would be relatively low. Therefore, higher efficiencies can be achieved from the solar collectors by solar collectors with correspondingly reduced areas. By considering heat pump electricity usage in the system, a 78% solar fraction could be obtained (Chapius and Bernier, 2009).

The DLSC's technical feasibility and system performance have been shown to be successful in terms of reducing energy costs (Sibbitt et al., 2011). However, the system's capital cost is substantially higher than conventional heating systems and does not offer any payback over the lifetime of the project.

The objective of this work is to use DLSC as a base case and then propose a new design with a similar, but more efficient, configuration. The proposed model can have different components and possibly smaller sizes, to achieve a lower initial cost and a better payback. The new design is constrained to produce the same solar fraction (SF) as DLSC and simulated with an integrated model using TRNSYS software (Klein et al., 2010).

System characteristics

System configuration and community thermal load

Fig. 2 shows the system configuration and equipment. The solar collectors transfer the harvested solar energy to a short term storage tank (STST) through a heat exchanger all year around. In the mid-spring and summer when there is no space heat demand from the community, the stored thermal energy is transferred to the ground for seasonal storage. The ground storage type is vertical borehole thermal energy storage (BTES). During the heating season, the stored heat in the Earth is extracted and transferred to the STST when the solar collectors cannot maintain the required temperature needed in the tank to meet the community heating load.

The selected community comprises a combination of single and multi-family residential units with 10% more heating load than the DLSC (Sibbitt et al., 2007, 2011). Fig. 3 shows the hourly thermal load profile for the selected community calculated by eQuest software (James J. Hirsch and Associates). The peak heating load is 457 kW and the total annual heating demand is 2350 GJ. Heat is supplied to the community through the distributed fan coils connected to the hot water distribution loop fed from the STST. The community water loop temperature is maintained on average at 40 °C. An auxiliary boiler is connected