EVALUATION OF A HIGH TEMPERATURE SOLAR THERMAL SEASONAL BOREHOLE STORAGE

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1. Introduction

A solar thermal system with seasonal borehole storage for heating of a residential area in Anneberg, Sweden, approximately 10 km north of Stockholm (59.4^{0}N; 18.0^{0}E), has been in operation since late 2002. Originally, the project was part of the EU THERMIE project “Large-scale Solar Heating Systems for Housing Developments” (REB/0061/97) and was the first solar heating plant in Europe with borehole storage in rock not utilizing a heat pump. Earlier evaluations of the system (Bernestål and Nilsson, 2007; Sweco Theorells, 2007) show lower performance than the preliminary simulation study, with residents complaining of a high use of electricity for domestic hot water (DHW) preparation and auxiliary heating. One explanation mentioned in the earlier evaluations is that the borehole storage had not yet reached “steady state” temperatures at the time of evaluation.

Many years have passed since then and this paper presents results from a new evaluation. The main aim of this work is to evaluate the current performance of the system based on several key figures (presented in 3.1), as well as on system function based on available measurement data. The analysis show that though the borehole storage now has reached a quasi-steady state and operates as intended, the auxiliary electricity consumption is much higher than the original design values largely due to high losses in the distribution network, higher heat loads as well as lower solar gains.

2. Description of the system

The residential area in question is compromised of 50 residential units with an average heated area of on average ~110 m^2 each and a total yearly design heating demand, including DHW, of 565 MWh. The heating is supplied from 2400 m^2 of flat plate solar collectors, a 60,000 m^3 seasonal borehole storage, and from electrical boosters when the solar collectors and borehole storage is not enough. The seasonal storage stores the collected solar energy at a relatively high temperature (27 - 42°C) and this, together with the low temperature heating system, eliminates the need for a heat pump. A schematic diagram of the system, without the seasonal storage, is seen in Fig. 1.

The system consists of 13 sub-units equipped with either one or two 750 litre DHW stores depending on the number of residential units connected. Each residential unit is equipped with a small DHW store, low temperature floor heating system and electrical boosters to both DHW and floor heating to ensure a working system even if the main heating system should fail, as this was one of the design requirements. Flat plate solar collectors cover the whole roof area of the residential units. All sub-units are connected through a culvert system to the main unit, which is situated between the sub-units and the borehole storage. An overview of the residential area is shown in Fig. 2 (left), showing the borehole storage, main unit and sub-units for the three apartment areas. The distance from the borehole storage to the main unit is ~35 meters and distance between the main unit and the sub-units is roughly 35 meters for the closest and 140 meters for the furthest (direct route meaning the pipe distances are longer).

The flow going through the borehole storage is connected as one loop circulating trough all sub-units in parallel, where it passes through the solar heat exchanger before entering the store in each sub-unit. The flow circulates through all sub-units even during times when the collector circuit is not in operation, meaning that during charging of the borehole storage (summer season) the store in each sub-unit is discharged every night and the energy stored in the stores is transferred to the borehole storage.

The borehole storage consists of 99 active holes drilled to 65 m depth with spacing of 3 m in between (one hole is inactive and contains a temperature sensor where the storage temperature in one point can be manually recorded). The configuration is square shaped and contains 2x10 parallel lines with 5 boreholes each. During charging, the store is charged from the middle and out meaning that the centre is hottest. During discharging, the flow in the store is reversed. See Fig.2 (right).

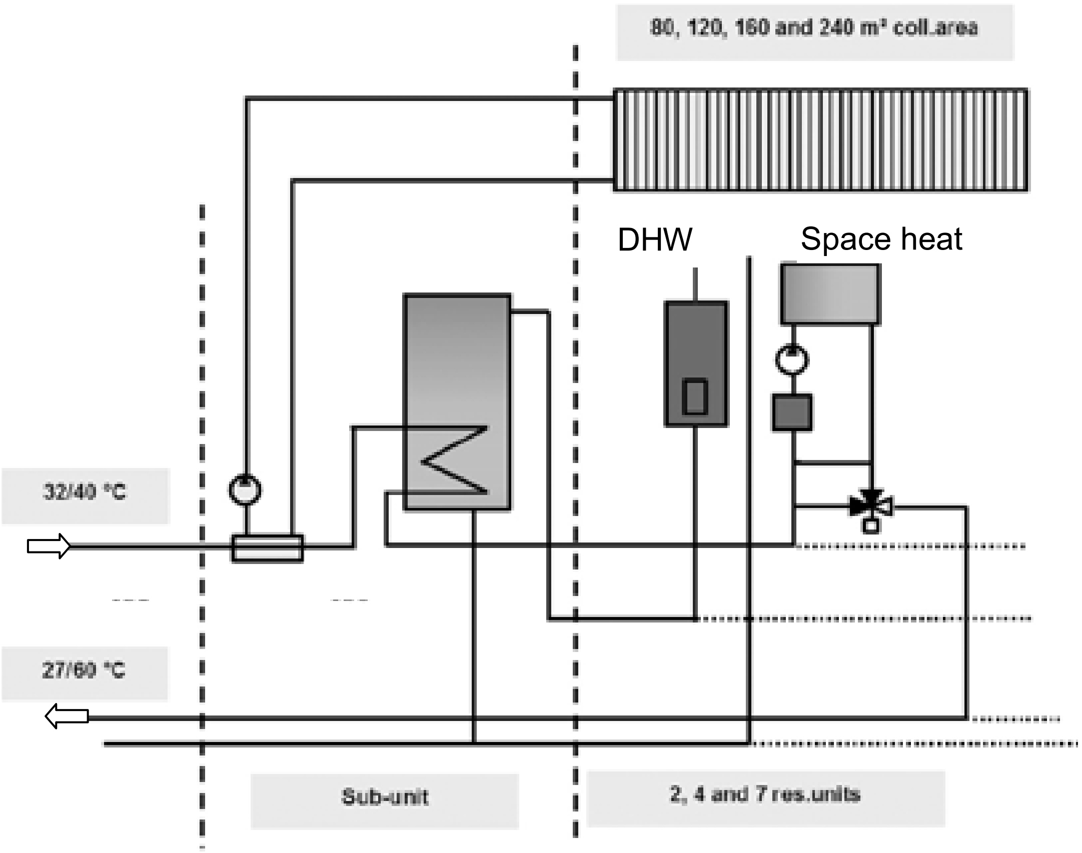

Fig. 1: System principle. Heat distribution system comprising sub-units with solar collector connection and DHW buffer storage. Residential unit with floor heating system and DHW tank, both with electric back-up heaters for supplementary heating. Design condition: flow 32 and return 27 °C. Collector design operation: flow 40 and return 60 °C (Lundh and Dalenbäck, 2008).

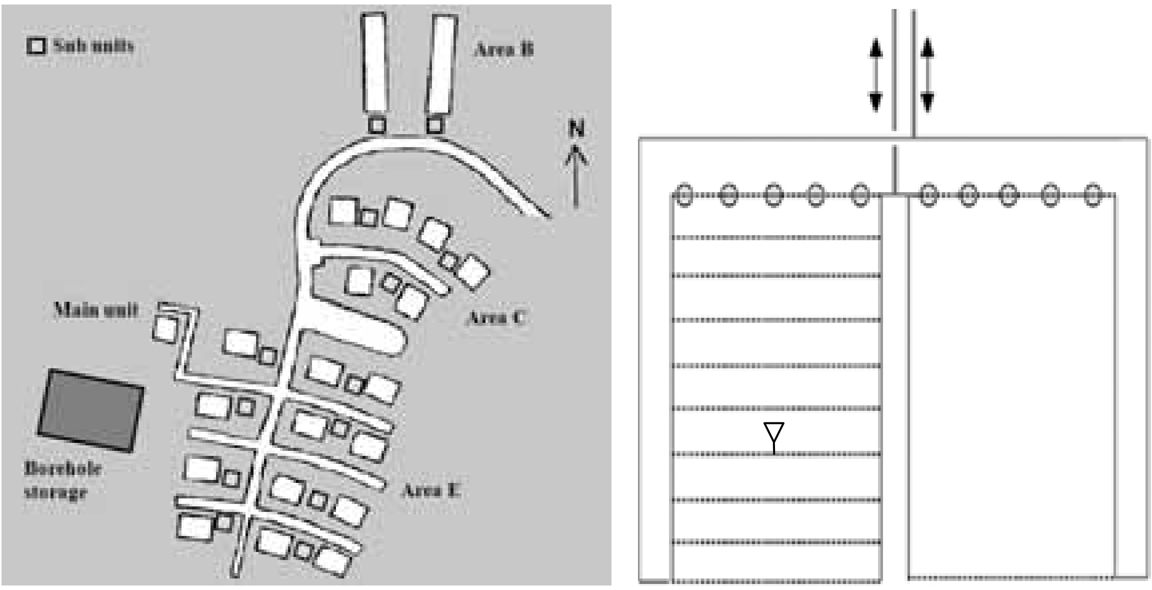

Fig. 2: An overview of the whole residential area (left) including the borehole storage, main unit and 13 sub units in three areas (B, C and E), and the borehole storage configuration (right) with ground sensor position marked (manual measurement only).

2.2. Available measurement data

Data from sensors used in the control system are saved at a 4 minute time interval, but due to restrictions of the controller when the system was taken into operation, the number of sensors for which data is saved is limited. For the borehole storage, the available data includes temperatures to and from the borehole storage as well as the flow rate, all measured at the main unit. Regarding the sub-units the data includes DHW temperature before (cold water) and after (pre-heated water) the sub-unit store and the flow rate, temperature of the flow from the borehole storage before and after the solar heat exchanger plus the flow rate as well as the temperature of the flow leaving the sub-unit to the borehole storage. This data is however only available for 3 out of 13 sub-units; B1, C1 and E7. Data for electricity consumption on the apartment level is available for the 4 apartments connected to sub-unit E7. This data includes auxiliary electricity to the electrical boosters for the space heating system and DHW as well as domestic electricity use. The sensors have been in place now for nearly 10 years and are not calibrated.

3. Method

The work is focused on the evaluation of the current system, based on measurement data for the year 2010-2011. The key figures described in Tab. 1 were chosen to assist in the system evaluation including both an analysis of the system performance as well as of the system function.

3.1. Definition of key figures

To as a large extent as possible, measured data was used directly in the calculation of the key figures but due to a lack of recorded measurement points, some values had to be estimated indirectly using the available data. Key figures concerning the sub-units and apartments had to be extrapolated to the whole area, as described in 3.2.

In the energy balance of a sub-unit, due to the lack of measured data, there are two unknowns, namely the sub-unit losses and the solar contribution to space heating. To estimate these two parameters, the month of July was chosen assuming no space heating during this month. With this assumption, the sub-unit heat losses could be calculated. The sub-unit losses for July were then used as a basis for estimating losses for the other months using a correction coefficient based on the operating temperature (highest during the summer). The solar contribution to space heating could then be calculated based on the energy balance.

Since no temperature in the borehole storage is recorded in the available measurement files, the storage temperature is evaluated by using the outlet temperature of the borehole storage during discharge when the heat transfer rate over the borehole heat exchanger is relatively small. The calculation is made during days when the temperature difference between inlet and outlet flow is low (small heat transfer rate). Temperature of the store is then estimated by using the outlet temperature during discharging and adding 4 °C for the temperature drop over the borehole heat exchanger, giving an estimate of the borehole storage core temperature.

For the borehole storage losses, an estimation of the net accumulated energy (change in internal energy) is necessary if there is a temperature difference in the borehole storage between the start and end of the year. This was the case in 2006 (~1°C rise in temperature from January – January) but not in 2010, showing that the borehole storage has reached a quasi-steady state.

Tab. 1: Key figures chosen for the evaluation of the current system.

Key figure	Definition	Unit
Solar fraction[1, 2]	The solar contribution to the total heat load, calculated as: 1 – (Total auxiliary use)/(Total heat load). Note that the sub-unit losses are included in the total load but not distribution losses.	%
Borehole storage losses	Calculated from the energy balance of the store, including change in internal energy, for a complete year.	MWh
Losses in distribution system[2]	The difference in energy that leaves the main unit and arrives at the sub-units during discharging of the borehole storage or vice versa during charging.	MWh
Losses in sub-units[1, 2]	Heat losses in the sub-units calculated through energy balance of the sub-unit.	MWh
Total heat load[2]	The sum of the auxiliary energy used and the solar contribution, either directly or through the borehole storage, calculated from the energy balance of the subunit and connected residences. Includes losses in sub-units.	MWh
Total auxiliary energy use[2]	Total electricity supplied for heating and DHW.	MWh
Solar energy from collectors[2]	The energy transferred to the borehole storage loop in the sub-unit solar heat exchangers.	MWh
Energy supplied to the borehole storage	Energy from the solar collectors entering the borehole storage, measured at the main unit.	MWh
Energy taken out from the borehole storage	Energy extracted from the borehole storage for delivery to the sub-units, measured at the main unit.	MWh
Temperature of the borehole storage (core)[1]	Temperature estimated by using the measured temperature of the borehole outlet during discharging at low heat transfer rate, and adding 4 °C to compensate for the heat exchanger temperature drop.	°C
Average winter temperature	The average ambient temperature from November to March reported for Stockholm main weather station.	°C
Annual horizontal solar radiation	Since no measurement of the solar radiation is logged at the site, this figure is based on public weather data for Stockholm.	kWh/year
Average annual collector efficiency	Calculated based on solar energy from collectors and horizontal radiation for the whole year	%

[1]Key figures calculated indirectly using available data. [2]Extrapolation involved in the calculation.

3.2. Extrapolation of results

As was mentioned earlier, measured data are available only for the main unit, 3 sub-units (out of 13) and 4 apartments (out of 50). Thus, results for the whole system need to be extrapolated.

There are three main assumptions which were made during the extrapolation. The first one is that all sub-units in one area have the same location relative to main unit. This has an influence on the pipe system losses. The second assumption is that in one area all energy values (loads, solar gains and energy transported to/from the borehole storage) for a sub-unit only depend on the number of buildings, their living area and collector area and are independent of the building location relative to the sub-unit, shading effects, building orientation, building geometry and number of inhabitants. The third assumption is that sub-unit losses were the same for all sub-units.

4. System evaluation

To evaluate the system the established key figures were calculated for 2010 and also compared with the design values from Lundh and Dalenbäck (2008), Dalenbäck et al. (2000) and a prestudy (Nordell and Hellström, 2000) as well as an earlier system evaluation for 2006 (Bernestål and Nilsson, 2007) carried out before the borehole storage had reached steady state. The key figure results are presented in Tab. 2. The solar fraction is considerably lower than the design values for both 2006 and 2010, indicating that the system does not work as well as planned. The borehole storage losses however are much lower for 2010 than for 2006, 387 and 527 MWh respectively. This can partly be explained by higher temperature in the surrounding rock, since the storage has been in operation for a longer time. However, the difference is too large for this factor on its own. The sum of the borehole losses and distribution network losses are quite similar, being 690 and 654 MWh for 2006 and 2010 respectively. Based on the measurement data available, it was not possible to identify why these figures are so different, whereas most other figures for the two years are quite similar. It should be noted that the figure for the energy transferred to and from the borehole storage is measured directly at the main unit, while the energy quantities for the other end of the distribution network is based on an extrapolation and thus more uncertain. For 2006, the storage had not reached steady state as the temperature at the end of the year was over 1°C higher than at the start, leading to an estimated accumulation of 50 MWh in internal energy of the store over the year (Bernestål and Nilsson, 2007).

The losses in the distribution system are much higher in the current evaluation, amounting to 267 MWh for 2010. Of this, 156 MWh were losses during discharging and 111 MWh were losses during charging. Although the temperatures during charging are higher than during discharging, the period of operation for charging is much shorter resulting in the cumulative losses for discharging being higher. Here it can be noted that the average winter temperature is almost 6 °C lower for 2010 than for 2006, which can partly explain the higher distribution losses. The average winter temperature for the design simulations is in between the two evaluations. The heat load is 10% higher in 2010 compared to 2006 and 11% higher than the design value.

The sub-unit losses are higher than the design values. In the evaluation in 2006 the sub-unit losses were not calculated and were instead included in the total load and for that reason, there is no value available for comparison. In this evaluation, the sub-unit heat losses were calculated as described in 3.1 and this resulted in roughly 6.5 MWh of heat losses for each sub-unit. This can be compared with values for existing solar combisystems for detached houses that have similar storage sizes and piping to those in the subunits. Results from the EU project CombiSol (Letz *et al.*, 2010) show that for the Swedish systems monitored, the heat losses are in the range of 2.5 and 5.6 MWh, indicating that the calculated sub-unit losses for Anneberg are very high indeed. It is however possible that the sub-unit losses calculated for Anneberg are somewhat overestimated. It was assumed that the space heating demand for the studied month (July) was zero but it is possible that this was not the case and any space heating during this month would have been included in the heat losses and due to the extrapolation process, also in other months. The number of stores in the sub-units can also be a cause for overestimation of the sub-unit losses. Only sub-units with 2 stores were used in the calculation as basis for extrapolation (since this was the only data available) while in reality 4 out of 13 sub-units only have 1 store.

The available radiation is lowest for the design case and at the same time the solar energy from the collectors is the highest, giving an average annual efficiency of 49%, based on the horizontal radiation and surface area of the collectors. The average efficiency is very similar for the measurement data for 2006 and 2010, but this is much lower than that for the design data (~39% compared to 49%). This indicates that the collectors are operating at a much higher temperature or are not as efficient as in the design study. Part of the decrease in efficiency is that the glass covers of several of the solar collectors are broken. Apparently this was the result of movements of the hardened glass covers over time and pressure from a sharp object in the frame resulting in the glass breaking. Since these modules had not been repaired, some degradation in performance is to be expected. The available radiation for 2006 was greater than for 2010 resulting in a higher collector output.

Tab. 2 Key figure comparison between design values (Dalenbäck et al., 2000), values calculated for 2006 (Bernestål and Nilsson, 2007) and values calculated for 2010.

Key figures	Design values	2006 evaluation	2010 evaluation
Solar fraction [%]	80	42[1,2] (45[3])	40[1,2] (41[3])
Borehole storage losses [MWh]	500	527	387
Losses in distribution system [MWh]	100	163[2]	267[2]
Losses in sub-units [MWh]	30	NA	85[1,2]
Total heat load (including sub-unit losses) [MWh]	565	574[1,2]	631[1,2]
Total auxiliary use [MWh]	120	334[2]	379[2]
Solar energy from collectors [MWh]	1075	980[2]	906[2]
Energy supplied to borehole storage (measured at main unit) [MWh]	NA	809	720
Energy taken out from borehole storage (measured at main unit) [MWh]	NA	232	333
Average winter temperature [°C]	-0.3	1.9	-3.8
Annual horizontal solar radiation [kWh/year]	922	1020	992
Collector efficiency	49%	40%[2]	38%[2]

[1] Key figures calculated indirectly using available data. [2] Extrapolation involved in the calculation.

[3] Based on the data for subunit E7 for which all energy quantities are measured and recorded. The main figure is for the whole system based on extrapolation of results from the data recorded for 3 subunits.

Regarding auxiliary electricity consumption for space heating and DHW, measurement data separately showing DHW and space heating electricity consumption was available from 4 apartments in sub-unit E7. Based on measurements on auxiliary energy and solar contribution to DHW together with calculated solar contribution to the space heating load, the heat supply to an average residential unit was calculated. Monthly values for solar and auxiliary energy for the average unit are shown in Fig. 3. Compared to a residential unit according to the initial design shown in Fig. 4, the auxiliary energy required is much higher for the real system. It should also be noted that for the real system, auxiliary energy is required even during the summer months, which has to do with the way the real system is designed (further explained in 4.1). No explanation for the peak in the design data for March, an unusual time for peak load in Sweden, was found in the references.

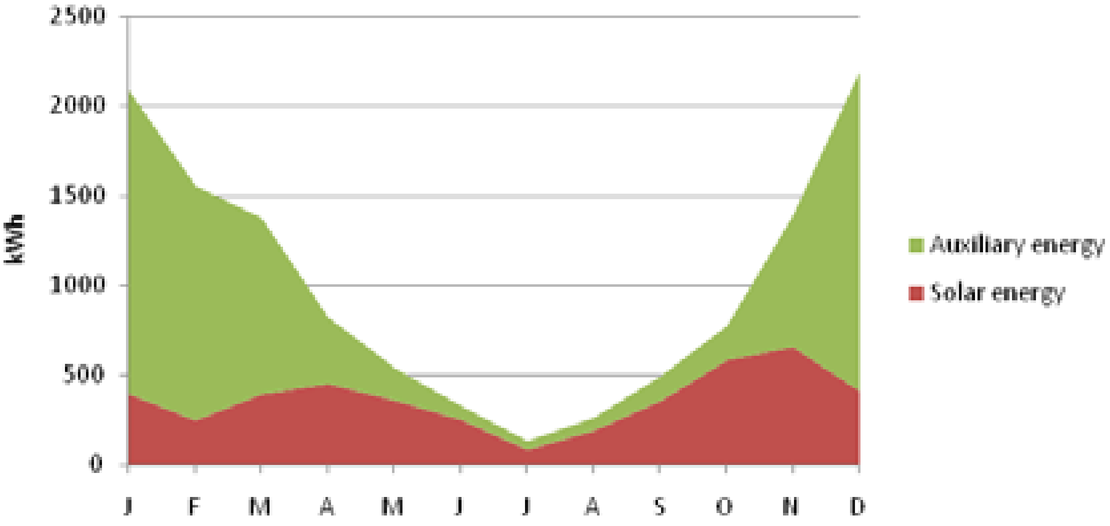

Fig. 3: Heat supply to one average residential unit in 2010.

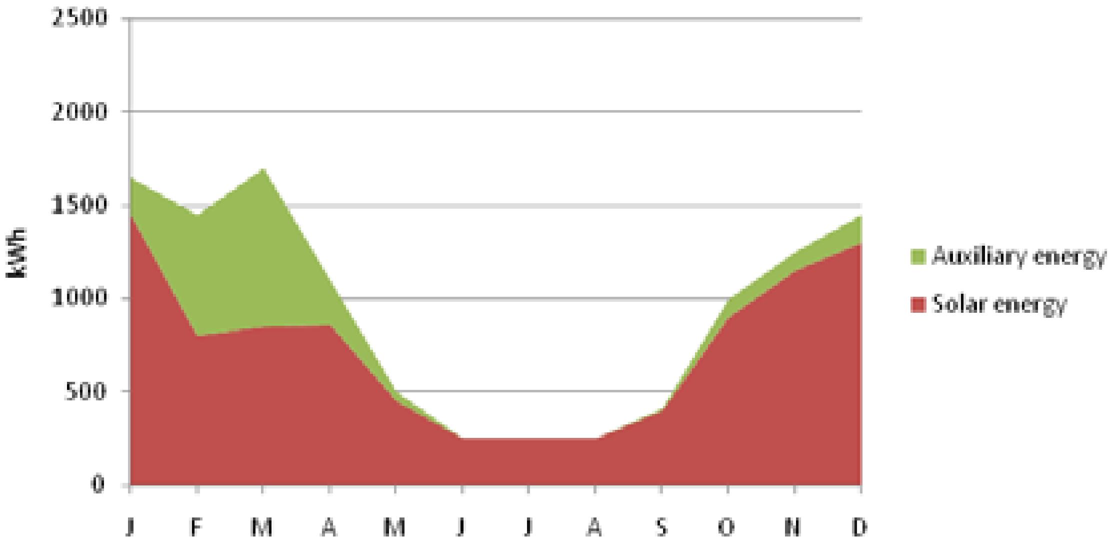

Fig. 4 Heat supply to a residential unit according to the initial system design in (Lundh and Dalenbäck, 2008).

Key energy figures for the borehole storage and distribution for 2010 are shown in Fig. 5. After 8 years of operation it is concluded to be the final borehole storage performance, since it should have reached the steady-state temperature by this time. A confirmation that the storage has reached steady state can be found in Fig. 6 where the temperature is more or less equal for January 2010 and 2011. Shown in the figure is the estimated maximum and minimum temperature of the borehole storage core for each month, calculated as described in 3.1. Also included are some values from manual measurements from a sensor in an inactive borehole. The manual measurements were performed and logged by one of the inhabitants in the area. The temperature sensor is located at a depth of approximately 45 meters and the borehole is in position H3, meaning the 7th row, 3 positions in from the outer edge or roughly somewhere in between the outer edge and the core of the borehole field (see Fig. 2). The manual measurement was done at the end of month in the evening or late afternoon, whereas the maximum and minimum temperatures were calculated based on the monthly average outlet temperatures during discharge.

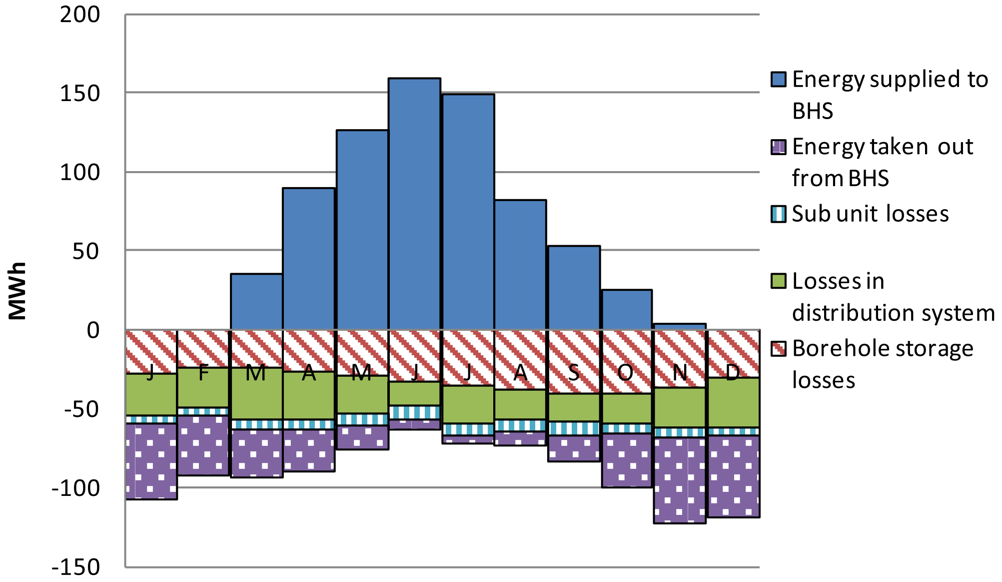

Fig. 5: Key energy figures for the borehole storage and distribution in 2010. Energy supplied and taken out from the borehole storage is measured at the main unit.

The cumulative annual energy supplied to the borehole storage during 2010 was 720 MWh and the energy taken out from the storage was 333 MWh (measured at the main unit). However, the amount of energy which was actually supplied to the sub-units was only 178 MWh (measured/extrapolated at the sub-units) because of losses in the store and high distribution losses as seen in Fig. 5.

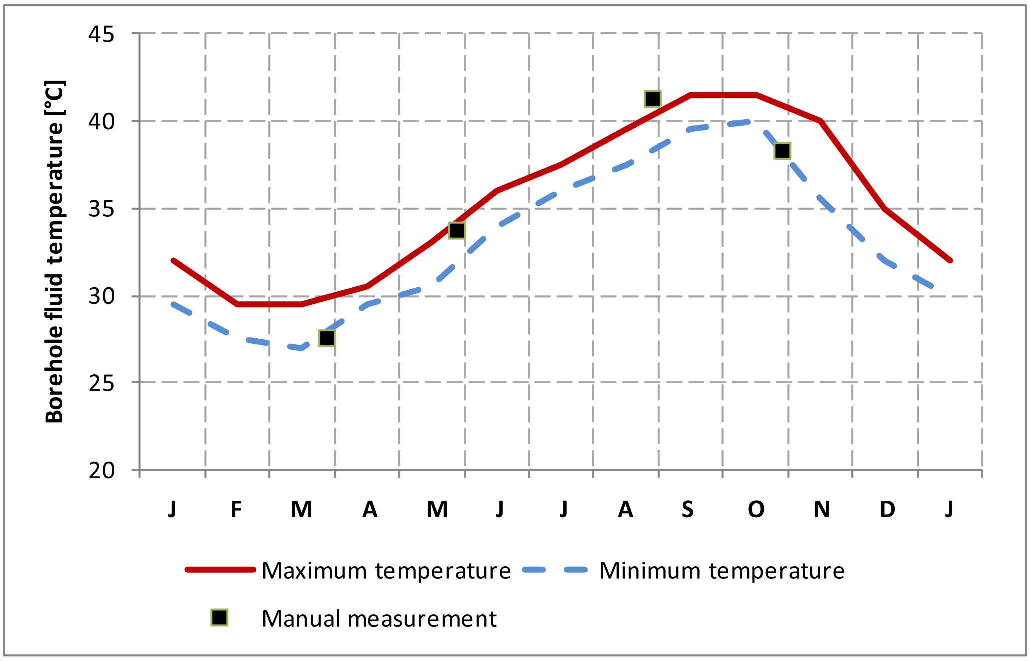

Fig. 6: Maximum and minimum temperatures for the borehole storage core between January 2010 and January 2011 estimated from the outlet temperature, as well as manual measurements at one point in the store.

It can also be discussed whether the solar fraction, 40 % for 2010, is calculated in a fair way from the perspective of the inhabitants. For the evaluation in 2006, since the sub-unit losses were not estimated, they were simply included in the heating demand and for the sake of comparison, the same was done in this evaluation. It can be argued however, that at least part of the sub-unit losses are introduced to the system due to its design, and could have been avoided with a different system design or a different heating system altogether. The extreme alternative would be if all buildings were equipped with electric wall panel heaters where the (local) losses are more or less negligible. As a comparison, the solar fraction was also calculated with the sub-unit losses regarded as not being part of the heat load. This resulted in a solar fraction of only 31%. The same calculation for the design case shows a reduction in the solar fraction from 80% to 78%. This clearly illustrates the difference in the assumed subunit heat losses for the design case, and the calculated heat losses for the real system as well as the importance of the heat losses.

4.1 System function analysis

The key figures calculated from the system evaluations show much lower values, mainly for the solar fraction, than was estimated and calculated during the initial design. Two possible reasons for this are firstly, that the initial simulations overestimated the performance of the system, or secondly, that the system function for some parts is not correct. A system function analysis of selected parts of the system is done to investigate the second reason. The analysis is made for four days during 2010; 2nd of February, 11th of April, 22nd of June and 4th of November, to represent different regimes of system operation (end of discharge, beginning of charging, high charging with good radiation and partly charged store and beginning of discharging respectively). Measurement data used for the analysis are temperatures and flow rates to and from the borehole storage as well as three sub-units and electricity consumption from four apartments.

The analysis shows that the operation of the borehole storage works as intended. However problems affecting the system performance were found in other parts of the system. One problem was found in the sub-unit heat exchangers between solar collector and sub-unit/borehole storage at a couple of the subunits studied. Here a temperature drop of up to over 2 °C was found on the sub-unit side of the measured heat exchangers both at nighttime during the summer and in wintertime when the solar collector is not in operation. Since the same phenomenon is observed in several sub-units, although the temperature drop is varying, the risk of faulty sensors can be assumed to be low. Bernestål and Nilsson (2007) also reported a temperature loss over the solar heat exchanger, proving that the problem also existed in 2006. A calibration of the temperature sensors is required to determine whether the drop is due to sensor error or a real heat loss in the collector circuit when the collector pump is inactive, presumably, which could be caused by natural convection in the circuit or individual pipes. A temperature drop of several degrees will also have a negative impact on the amount of heat the borehole storage can contribute to the floor heating in the buildings.

It was also discovered that the current system design requires a large amount of auxiliary electric heating of the domestic hot water even during the summer months, when there is excess solar energy available for the residences. There are two possible reasons for this. The first being long pipe distances between sub-unit and apartment. If the pipes between the small domestic hot water tank in each apartment and the sub-unit store are relatively long, longer periods without discharge will result in colder water in the pipes being introduced into the DHW store at the start of discharges and the need of electric heating to maintain the set temperature there. The second reason is the current sub-unit design. In the summer during the day, water from the borehole storage is heated up in the solar heat exchanger, passes through the sub-unit (DHW) store and then through the borehole storage and back to the solar heat exchanger. The sub-unit store is therefore charged during the day to a high temperature. After sunset the borehole storage loop continues to run however, leading to a discharge of the sub-unit store (and further charging of the borehole storage). The temperature of the sub-unit store therefore quickly reaches the temperature of the borehole storage, which is always lower than the set temperature in the small DHW stores in the residences. One reason for this design is that no buffer store for the borehole storage had been included in the original design and instead, the sub unit stores also work as buffer stores for the borehole storage in order to reduce peak charging power.

4.2 Uncertainties

The data have been gathered from the controller for the system, which has been in operation for 10 years, and it is not clear whether the sensors were calibrated in advance. Thus there are significant uncertainties in the measurement data. In addition there are several steps in the calculation procedure which introduce uncertainties to the figures. The first source of uncertainty is the extrapolation from available data. Even though data for one sub-unit from each typical building area (B, C and E) are available, there are still some differences between the sub-units of a particular area. Some differences are the number of buildings connected to the sub-unit, number of stores in the sub-units, roof and apartment area of the buildings and the distance between the sub-units and the borehole storage. The first three reasons influence the available solar energy from the collector field, space heating and DHW load, energy transported to and from the borehole storage and heat losses. The distance between the sub-units and the borehole storage affect the pipe losses in the distribution system. Extrapolation of the use of auxiliary electricity was even less accurate since electrical meters are only installed in apartments from area E7. In other apartments the heated floor is different which affected the auxiliary energy consumption for space heating. The number of inhabitants and their behavioral patterns are different in each apartment which also has an influence on auxiliary energy used. The assumptions made during the extrapolation procedure can have a large impact on the results.

The second source of uncertainty is estimation of key figures which could not be directly calculated from the available measured data. Some figures were difficult to separate from one another (e.g. sub-unit losses and space heating load) since there was not enough information in the measured data. Again, assumptions made during the calculation can affect the results.

The third source of uncertainty concerns the comparison between the current system evaluation and earlier evaluations, and this is possible differences in the assumptions and methods used in calculating the key figures. There was, however, a lack of information concerning the assumptions made in the previous works, which introduce a certain uncertainty in the comparison to the earlier studies.

5. Conclusions

From the current system evaluation as well as from the comparison with previous studies, it can be concluded that the borehole storage itself is operating as intended and has now reached a quasi steady state. The solar collectors also seem to be operating as intended with reasonable performance but for some of the collectors, the glass cover has broken and not been replaced, lowering the performance of the collector field. Also, a temperature loss over the collector heat exchangers is present even during nights and winter time when the collector circuit should be turned off. The reason for this could not be confirmed but might be possibility is self circulation in the collector loop.

The whole system also works in the sense that energy is transferred to and from the borehole storage and the supply of heat and DHW is working. The auxiliary energy consumption for heating and DHW is however higher than originally anticipated, for several reasons including high heat losses in the distribution system and sub-units, discharging of sub-unit stores during night and temperature loss over the solar heat exchangers. Another reason for the high auxiliary energy use is the indoor temperature, which can be set by the inhabitants. The original design assumed an indoor temperature of 20 °C in all apartments, but earlier evaluations (Bernestål and Nilsson, 2007; Sweco Theorells, 2007) discussed that this indoor temperature was only observed in a few apartments, and that the temperature was usually set at a higher setting, resulting in higher auxiliary use when the borehole storage is no longer warm enough to supply the required temperature. The resulting high electricity demand for heating and DHW is therefore a combination of high heat losses, system design and inhabitant behavior. The difference in auxiliary electricity demand between the original design simulations and the real system is also enhanced by a better collector performance in the design case.

To be able to make a more thorough evaluation with lower uncertainties, it is recommended that data from more sensors is recorded as well as sensor checks. With the progress in computers and data storage, the storage capacity should no longer pose any problems. It would be especially of value to record data for all sub-units and to include the space heating requirement to remove the need for extrapolation and to lower the uncertainty of the calculation of the sub-unit losses. It is also important to confirm the temperature loss over the solar heat exchangers by recording data for the flow and temperatures on the solar side on the heat exchanger.

6. Acknowledgements

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