Evaluation of the heat generation and distribution system in a Swedish passive house residential area

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SUMMARY

In Vallda Heberg, a residential area has been built consisting only of buildings certified as Swedish passive houses. This study focuses on the performance of the heating system in Vallda Heberg, which was designed to make the residential area self-sufficient in heat from solar thermal collectors and a wood pellet fuelled boiler. Heat measurements taken from the system were collected and used in the study. Heat generated from solar collectors during a seven month period (March-September 2014) represent about 43 % of the total heat input to the system. The measured period is not representative for an entire year and the annual solar heat fraction will be smaller. Losses in the heat distribution during the seven months were 32-53 %. Whether these losses were high or low was difficult to say, but high losses were expected since the residential area has a low heat use density.

KEYWORDS

Solar heating, heat losses, passive houses, district heating

INTRODUCTION

To meet increasingly stringent energy targets of the future, new thinking is needed in the design and construction of residential buildings, as well as other types of buildings. Focus should be lifted from the individual houses to a system perspective involving whole areas. Possibilities to take advantage of the interaction between different energy flows within the system will arise. Smart solutions for the integration of renewable energy can be found, and the amount of energy that goes to waste can be minimized.

In Vallda Heberg southwest of Gothenburg and close to Kungsbacka on the west coast of Sweden, a residential area entirely consisting of buildings certified as passive houses has been built. The houses, with a total heated floor area of about 14 000 m², are certified in accordance with the Swedish passive house definitions found in FEBY 09 and FEBY 12 (SCN, 2009 and 2012). Along with low energy demand in buildings, the area was designed to be self-sufficient in heat from renewable generation. Solar heat plays an important role in the local energy system, and the goal is that the measured annual solar heat generation should be at least 40 % of measured annual heat use (incl. domestic hot water) within the residential area.

For an evaluation of building energy performance and indoor climate in Vallda Heberg, see Fahlén et al. (2015).

This paper presents an evaluation of the heating system in Vallda Heberg. The objective is to analyse heat measurements to find the following:

- Performance of solar thermal collector units and their contribution to the system, in relation to total generation as well as to heat use in passive houses.
- Heat losses in primary and secondary parts as well as in the whole system.

A short description of the heat generation and distribution system is given here to provide the reader with some basic understanding of the system which the study is carried out on. A more detailed description can be found in the study by Olsson and Rosander (2014).

Heat is generated in a wood pellet fuelled boiler (backed up by an oil fuelled boiler) and from solar thermal collectors of two different types; flat plate collectors (FPC) and evacuated tube collectors (ETC). All heat generating unit locations are shown in Figure 1.

A small local district heating system distributes heat from the generating units to passive houses. The distribution system consists of a primary part (orange lines in Figure 1) and a secondary part (magenta lines in Figure 1). The primary system is a well-insulated district heating system with supply and return pipes, delivering heat from the boiler and ETC mounted on the boiler building to four substations (SS1-SS4) located throughout the system. In the substations there is an input of solar heat from FPC located directly on substations and on other buildings in the area and delivered to substations via a separate piping system (green lines in Figure 1). Heat is exchanged within the substations to the secondary system, which is a domestic hot water (DHW) circuit providing the passive houses with both DHW and heat for space heating.

Figure 1: The Vallda Heberg heat generation and distribution system.

METHODS

In order to evaluate the energy performance of the Vallda Heberg residential area, heat meters were installed at different locations in the system during construction. The general method or process used in this study can be summarized by the following steps; collection of measurement data, review of data and setting up system heat balances from data.

Measurement data with a monthly resolution has been collected from heat meters on three different system levels:

- Heat generated in boiler and ETC on boiler building
- Heat delivered to sub-stations from primary system and FPC
- Heat delivered to passive houses as space heating and DHW

In general, heat meters have been installed in the system so that they only measure ingoing heat to the boiler building and the substations. However, to estimate losses in underground piping there was a need to also have values on heat going out of these buildings. Assumptions on heat loss between ingoing and outgoing heat in the boiler building and substations were needed, and in this study the buildings were assumed to have a 5 % loss.

A review of the data was made to find and handle errors originating from bad measurements or from shortcomings in the recording and collection phase. All heat meters installed in Vallda Heberg were of high quality with ultrasonic flow sensors. An estimation of heat meter accuracy was not made in this study, but was carried out previously (Olsson and Rosander, 2014) for one of the heat meters in Vallda Heberg which was known to measure over small temperature differences. The maximum permissible error according to EN-1434 was determined for the heat meter over a range of different temperatures and volume flows.

When measurements had been collected and reviewed, the data was used to set up system energy balances. With the energy balances as a base, the following calculations were carried out:

- Performance and contribution of solar heat, from measurements on ETC and FPC
- Loss in the primary system, by comparing measurements from generation in boiler and ETC with delivered heat into sub stations
- Loss in the secondary system, by comparing heat delivered to sub stations with heat delivered to passive houses

Vallda Heberg was at the time of the study a newly constructed residential area, and thus not all buildings and system parts had been operational for more than a few months when measurements were collected. Energy measurements for system heat balance were taken for the period March-September 2014. Some other results, like performance of solar collectors, were determined for a full year when it was possible. Heat measurements from the two parts of the secondary distribution system originating from SS1 and SS2 have also been available for a full year.

RESULTS

Performance of solar thermal collectors

Performance of the two types of solar thermal collectors presented as heat per solar collector aperture area can be seen in Figure 2. ETC units have the highest performance, which is expected since this type of collector is less sensitive to cold surroundings thanks to an insulating vacuum layer (ASHRAE, 2011). A drop in solar heat generation during August and a new peak during September is evident in the results, especially for the ETC. This indicates that September was sunnier but might have been colder than August, which is confirmed by the mean outdoor temperatures for these months presented in Figure 5. ETC installed on the boiler building in Vallda Heberg are mounted at a steep angle close to the vertical line, to be more optimized toward winter conditions with low sun angle (Olsson and Rosander, 2014). Collector performance during summer was not as high as it would have been if the collectors were mounted at an angle optimized for maximum yearly heat generation. Measurements for the ETC were available for a whole year, and the yearly performance is 533 kWh/m² aperture area.

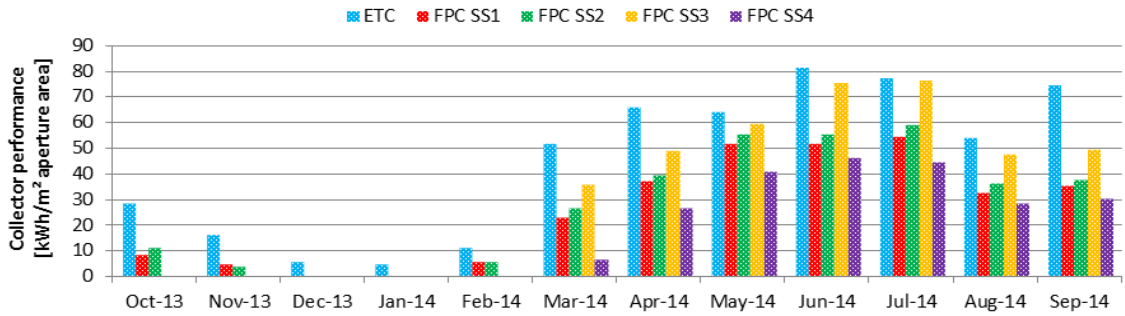

Figure 2: Performance of solar thermal collectors from October 2013 to September 2014.

Measurements from FPC units delivering heat to SS1 and SS2 were available for a year, and the yearly performances were 301 kWh/m² aperture area and 328 kWh/m² aperture area for SS1 and SS2 respectively. The lower performance of the FPC on SS1 can be due to heat loss originating from

underground heat transport, since many (73% of total aperture area) of the collector units connected to SS1 are mounted on the roof of a different building.

Other FPC units in Vallda Heberg, delivering heat to SS3 and SS4, have not been running and measured before March 2014. Results from March 2014 to September 2014 show that the FPC units connected to SS4 have a slightly lower performance than the ones on SS1 and SS2. A possible reason for this is that all collectors connected to SS4 are located on other buildings, giving rise to heat losses in distribution to the substation via underground piping. SS3 performance results are higher than for other FPC units, almost reaching the same performance as ETC. The reason for this high performance is unknown.

Contribution from solar thermal collectors

Total heat generated from all units (boilers and solar collectors) from March to September 2014 is presented in Table 1, and as fractions of the total heat contributed by each type of unit in Figure 3. Table and figure combined give the approximate amounts of energy from each type of generation unit.

Table 1. Energy generated from all sources March-September 2014.

Month	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14
Energy generated [MWh]	92,8	76,8	65,6	65,8	56,1	55,5	59,8

Solar fractions increase during the warm season and start declining again toward the autumn and winter. Note that the results presented in the figure somewhat contradicts this logic, with a higher solar fraction in September than in August. This effect could also be seen from the collector performance in Figure 2. Values of energy in Table 1 show a drop in total generation during August compared to July and September.

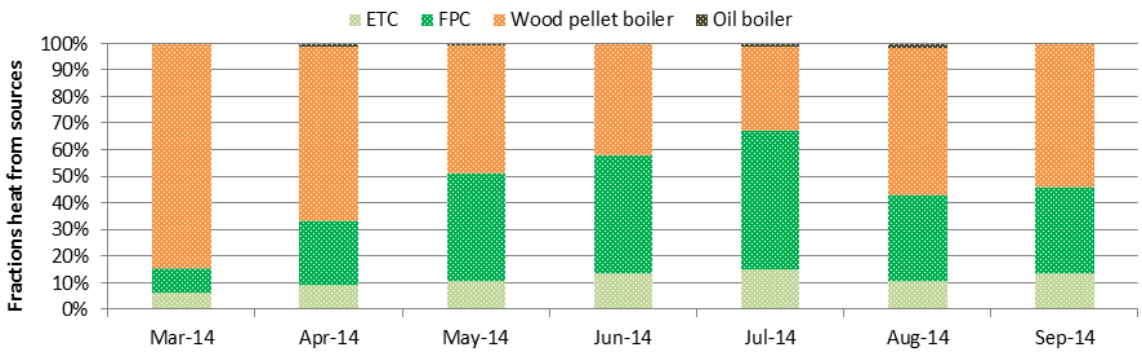

Figure 3: Heat generated from all units in Vallda Heberg as fractions of total heat generation.

The total amount of energy generated during the summer months highly depends on how much solar heat is available and how large of a mismatch there is between solar heat generation and heat demand. Solar heat is generated if the sun shines independent on if there is a demand for heat or not. When there is a good match between solar generation and demand there will be little need for the boiler to operate, since the solar heat can cover much of the demand. If the matching is poor, there will still be large quantities of solar heat generated but also a lot of heat from the boiler to fill in the gaps that the solar cannot cover. Another possibility is that the solar heat is not enough to cover the heat demand even when it is at its peak, but increased losses (see section Magnitudes and locations of heat losses) during the warm months suggest that more solar heat actually contribute to increase the heat loss. In other words, there is solar heat generated that cannot be used.

Figure 3 shows that there is a substantial amount of heat generation in the boilers even during the warmest months. This indicates that there could be a mismatch that the boilers have to even out. The system design, with a constant water circulation in the secondary system giving an ever present heat loss that has to be covered at all times, might also create a need for more heat from the boilers. Since the circulating water is used as DHW, there is a need to keeps its temperature at a certain lowest level (due to Swedish regulations), which the solar might not at all times manage to do. In these cases the boilers will come in and help. In a more conventional heating system there would not be a need to

keep high temperatures during summer, and the solar heat has a better chance to cover more of the heat demand.

Total heat generation from solar collectors during the time period was about 200 MWh, with about 150 MWh coming from FPC and 50 MWh coming from ETC. In addition to this, the heat coming from the two boilers reaches a level of around 270 MWh. Solar collectors thus provided about 43 % of the heat input during the period, but this is a summer case and the values are not representative for a full year.

Solar heat generated in the system can also be seen in relation to the amount of heat used for heating and DHW in the passive houses. A performance goal for the area during the design phase was that the solar coverage, defined as solar heat generation as a fraction of heat use in houses, should be at least 40 %. Unfortunately, all the required measurements for an entire year have not been possible to collect, so the goal cannot be validated in this study. A prognosis of the yearly solar coverage has been made in a previous study (Fahlén et al., 2014) by using measured values to as large extent as possible, and assumptions on missing values. Resulting coverage is around 33 %, indicating that the goal of 40% is not reached. Development of the area is not yet completed. Different dynamics of the final configuration of houses, with possibility of more solar collectors as well, might produce a different result when it comes to solar coverage.

A presentation of heat used in passive houses and heat generated from solar collectors as fractions of heat use can be seen in Figure 4. The figure tells of higher generation than use during June, July and September 2014. This, however, are some of the months with best performance of collectors and lowest heat use in houses. During the cold season the coverage drops rapidly due to both lower generation and larger heat use. Solar heat is able to cover the heat demand from houses during some months, but might not be able to cover heat losses as well. During the period presented here, solar heat was 70 % of the heat use in houses. If all solar heat was counted, including the portions going above the heat use in June, July and September, it would reach 79 % of the heat use.

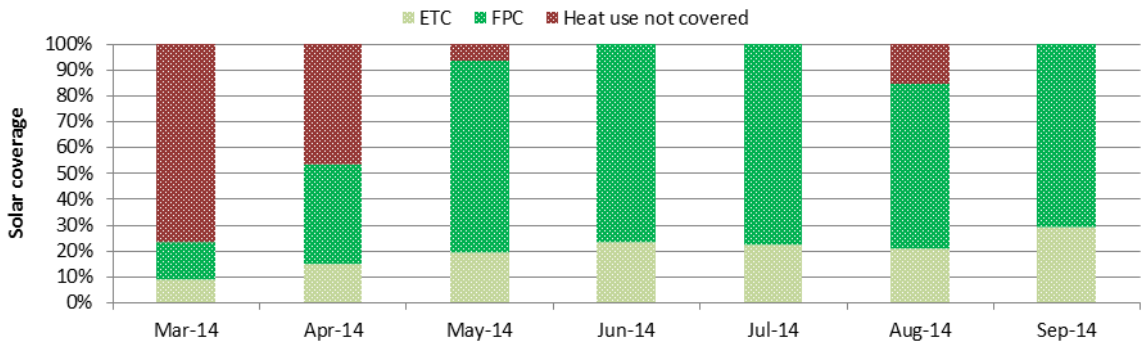

Figure 4: Coverage of heat use in passive houses by generated solar heat.

Table 2. Energy use in houses March-September 2014.

Month	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	Sep-14
Energy used [MWh]	62,7	47,8	36,0	29,7	24,1	28,4	27,0

Total energy use in all houses is presented in Table 2. Heat use reaches its lowest point during July, increases during August and decreases again during September. Its dependence on mean outdoor temperature from March to September 2014 is illustrated in Figure 5. All months except for September follow the pattern that a lower mean outdoor temperature results in a higher heat use. The drop during September is not extremely large, and can partly be explained by variations in user habits regarding DWH. This explanation is especially reasonable in a passive house area with a low demand for space heating, since the DWH can make up more than half of the total heat use. Indications of September being sunnier than August might also show in these results, assuming that the sunlight on buildings during September manage to decrease the demand for additional heating to a level below August in spite of a lower mean outdoor temperature.

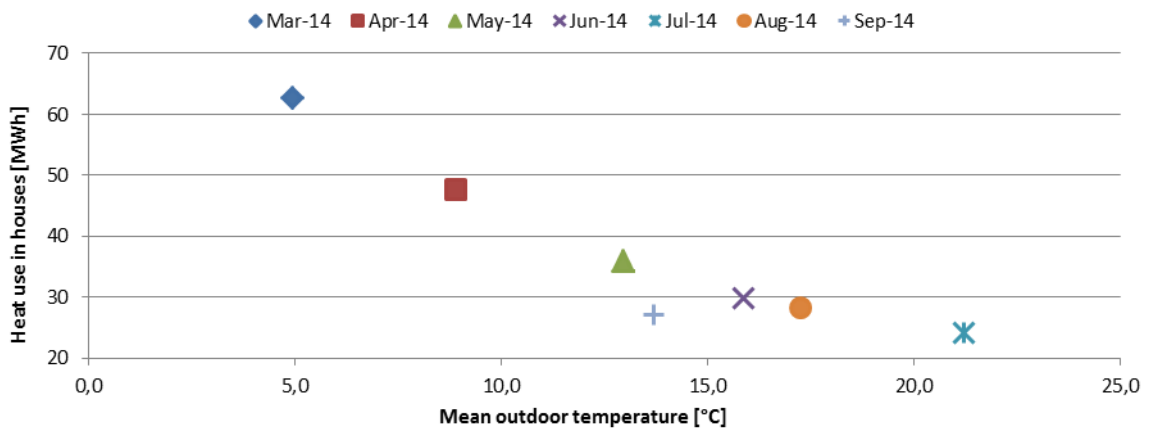

Figure 5: Heat use in houses and its dependence on mean outdoor temperature for March – September 2014.

Magnitudes and locations of heat losses

Since the residential area in Vallda Heberg consists to a large extent of singe family houses or smaller apartment buildings spread out over a quite large area, the pipes used in the heating system are long compared to the heated floor area that the system serves. In addition to this, the houses are passive houses, which among other special characteristics mean that they have a low heat demand. These factors combined give a low heat demand to pipe length ratio, corresponding to a large heat loss in relation to heat use in houses. To counteract this, the pipes have a high insulation standard with losses, estimated by pipe and insulation supplier, of 6-8 W/m depending on pipe diameter (Olsson and Rosander, 2014). Results regarding heat losses are presented in this section, and focus will be on losses in underground piping.

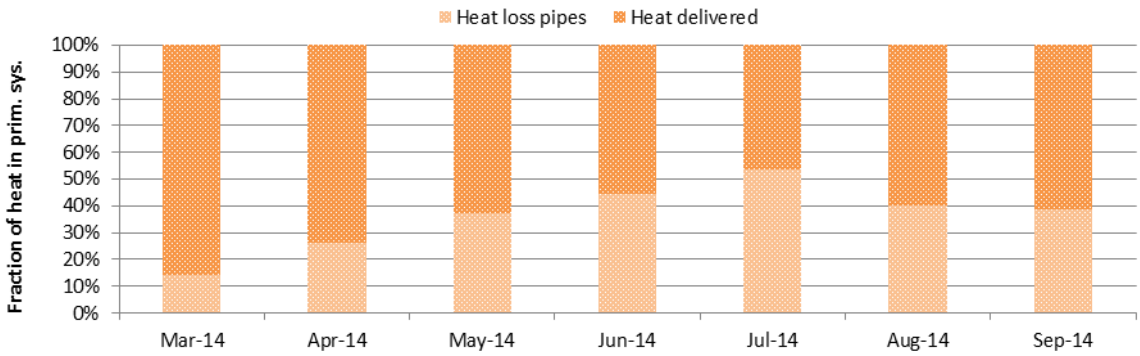

Figure 6: Heat loss in primary system underground piping and heat delivered to sub stations as fractions of total heat supplied to piping system.

Primary system underground piping heat loss is presented in Figure 6 from March 2014 to September 2014. The heat loss expressed in units of energy is quite constant over this time period, with values varying between about 15-17 MWh/month. Variation in lost energy during these months does not seem to have any seasonal dependence. Heat loss relative to heat delivered to sub stations (as shown in Figure 6) will however increase during the warmer months because of lower heat use. Losses during the whole period reach from 14 % to 53 %.

Heat loss results from the secondary system are presented in Figure 7, in the same manner and for the same time period as for the primary system. The secondary system consists of different parts connected to the four sub stations, and results presented here are the total for all parts.

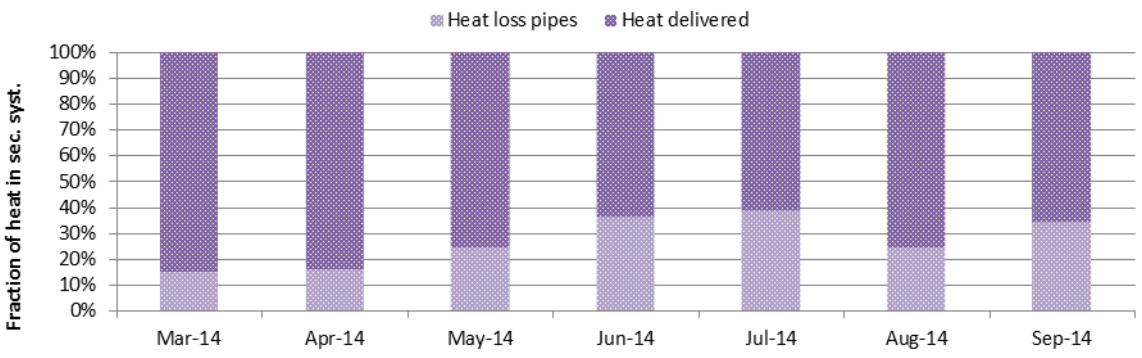

Figure 7: Heat loss in secondary system underground piping and heat delivered to passive houses as fractions of total heat supplied to piping system.

Contrary to the primary system, the secondary does not show a near constant loss expressed in units of energy over the time period. For the secondary system the loss increases during the warmer months both in absolute and relative terms, which suggests that an increased loss is linked to a higher generation of solar heat. A large part of the loss that comes from over-generation of solar heat should be counted as a loss within the substation, and not burden the piping heat loss. Assumption of a constant loss in the substation over the whole year is not accurate according to these results. The results also show a higher loss during September compared to August, following the same pattern as the solar heat generation. Heat losses in the secondary system are between 15 % and 38 %, but should probably be lower than this during summer because of solar heat over-generation.

Primary system heat loss was also affected by the solar over-generation, but the effect was not as apparent here because of the smaller amount of solar collectors relative to other heat sources.

Results for the whole system, from heat generation to heat use, are presented in Figure 8. Losses reach from 32 % to 57 %, and the effects described for primary and secondary systems are present in this figure as well. Absolute and relative heat loss in the whole system increase during the warm months when there is a surplus of solar heat generated. It is difficult to say anything about whether the heat loss in Vallda Heberg is high or low compared to other systems, since each system is different and most other district heating systems tend to be built in more densely populated areas. Total system piping losses of above 50 % can be regarded as high compared to more dense systems, but might be completely normal or even low seen in the context of low heat demand spread out over a large area.

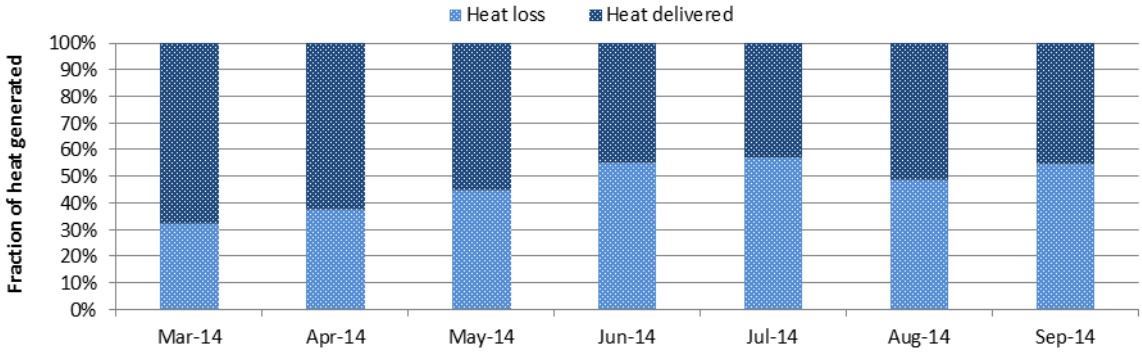

Figure 8: Heat loss and heat delivered as fractions of total generated heat

DISCUSSION

All results in this study are based on heat measurements, and must therefore be seen as somewhat uncertain because of possible measurement errors. An evaluation of errors has not been made in this study, but as mentioned in the Methods section there was an estimation made by Olsson and Rosander (2014) for one of the heat meters in Vallda Heberg. The heat meter in question was placed on the DHW circulation (secondary system) in one of the substations, and was expected to operate over small temperature differences. During warm months, the measured temperature difference could be as low as 1 K, giving a maximum permissible error of above 10 %. Because the secondary heating system was designed to operate with small temperature differences, all heat measurements taken here should be viewed as somewhat uncertain due to possible measurement errors.

Large efforts have been made to reach a high solar coverage in Vallda Heberg. Results from this study and from a previous one made (Fahlén et al., 2014) indicate that the target of 40 % of heat use covered by solar heat generation might be difficult to reach. There is a large over-generation of solar heat during the warm season at the same time as the solar collector annual performance is low in most of the units. A lot of heat is generated when there is no use for it, giving higher temperatures in the collector water circuit, which leads to lower collector efficiency (ASHRAE, 2011).

Heat losses in Vallda Heberg are difficult to put into perspective and compare to other known losses in district heating systems, since the area has a low density and a low heat demand. Total system losses of 30-50 % can be considered large in comparison with other, more conventional district heating systems. However, losses in this system are not relevant to compare with other systems if the conditions are not the same. More interesting would be to compare the heating system solution in Vallda Heberg with other possible solutions for providing heat to the passive houses.

Assumptions made in the study regarding heat losses in the boiler building and in substations might not be accurate since the results show that they might be linked to the generation of solar heat. It is reasonable that the absolute heat loss in underground piping is near constant over the course of a year and certainly not higher during the summer as the results from the secondary system show. The assumed heat loss in the boiler building has been shown to have a large impact on the calculated loss in the primary underground piping system (Olsson and Rosander, 2014). This gives another large uncertainty to the determination of heat losses.

CONCLUSIONS

A high solar coverage might be difficult to reach by adding more solar thermal collectors to this type of system, since there is a risk for large over-generation during the warm season. Over-generation gives higher heat loss and can also possibly lead to lower efficiency and performance of the solar collectors. This is especially true for flat plate collectors, with high performance during summer but not during winter. Evacuated tube collectors might be part of a solution to this problem, if they are installed at an angle close to the vertical plane like in Vallda Heberg. Performance will then be better in winter and worse during summer compared to the optimal angle, both decreasing losses during summer and increasing coverage during winter. Further possibilities to store the heat that is generated, ideally some time into the cold season, would be a way to reach higher coverage.

Possible errors in heat measurements and their effect on the calculation of heat losses need to be further evaluated to get better estimations on heat losses.

Heat losses in Vallda Heberg are large, which is expected in a residential area with a low density and low heat demand. Losses might be affected by the large amount of solar heat that cannot be used during summer. Highly insulated underground piping decreases the losses in the distribution, but other means to minimize them should be investigated. As the area is further developed, the heat demand will increase and the losses relative to demand will decrease. Still, the loss is likely to be large because of the way the area is built. If losses are to be even further minimized there might be other possible solutions for heating system design that could be evaluated. Other systems, like different types of electrical heating, could have lower losses in the local system but at the same time put more strain on the surrounding energy system.

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