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Techno-economic Analysis of Solar Options for a Block Heating System

Martin Andersen[1, 2], Chris Bales[1] and Jan-Olof Dalenbäck[2]

[1] Solar Energy Research Center (SERC), Dalarna University, Borlänge, Sweden

[2] Chalmers University of Technology, Gothenburg, Sweden

Abstract

An innovative small solar district heating system with one central heating plant and four solar substations has been built in Vallda Heberg, Sweden, to supply a new housing area with passive houses. The target solar fraction was 40% and the total system design, including heat distribution in the buildings, was based on previous experience and aimed to be simple and cost-effective. The main aim of this study was to determine whether the system can be designed in a more effective manner by change of distribution system and load density. TRNSYS models were calibrated against measured data and then used to predict the energy performance. Results indicate that lower distribution heat losses can be obtained by change to a distribution concept with lower operating temperatures, while potentially reducing cost. Changes in heat density cause reduced distribution losses and boiler supplied heat demand, with only minor effects on solar system yield.

Keywords: solar thermal, district heat, hot water circulation, simulation

1. Introduction

EKSTA Bostads AB (municipal housing company) has built and operates a number of solar assisted heating plants in small residential building areas, the first ones from the 1980's. The heat supply is managed via small district heating systems based on wood chips and/or wood pellet boilers and roof-integrated solar collectors of different generations, i.e. 100% heating by renewables. The buildings, commonly small multifamily buildings, have always had a bit lower heat demand than required by the Swedish building code.

The new residential area in Vallda Heberg comprises multifamily buildings, as well as single family buildings. All buildings are designed as passive houses according to the Swedish standards, i.e. well insulated buildings with air tight envelopes, and supply and exhaust ventilation with heat recovery is applied in all buildings. The whole area is supplied with heat from a small district heating system with pellet boiler and solar thermal, with a targeted solar fraction of 40% (Nielsen et al., 2014). This system (see Figure 2) comprises one central heating plant (HP) with a wood pellet boiler (and an oil boiler for back-up) and four sub-stations (SS1-4). Buffer storage tanks are installed in the central heating plant and in each sub-station. There are 108 m² evacuated tube solar collectors (ETC) on the heating plant and 570 m² flat plate roof-integrated solar collectors in connection to the sub stations. Heat is supplied from the sub-stations to the buildings with a so called GRUDIS 2-pipe system (Zinko, 2004) where hot water is circulated in plastic (PEX) pipes, similar to a standard DHW circulation system (Figure 1). This allows a very simple and inexpensive solution for transfer of heat in each building, reducing costs for the total heating system (Gudmundson, 2003): district heat and heat distribution within the buildings. However, as all buildings are passive houses, a large share of the supplied heat is lost in culverts and sub-stations, which adds to the running costs.

The main aim of this study is to determine whether it is possible to make the design of the whole heating system more efficient. In future work, costs will also be taken into account to determine the most cost-effective solution.

Figure 1 shows a schematic overview of the heating system at Vallda Heberg, with the boiler central to the right, substation in the middle and a passive single-family house to the left.

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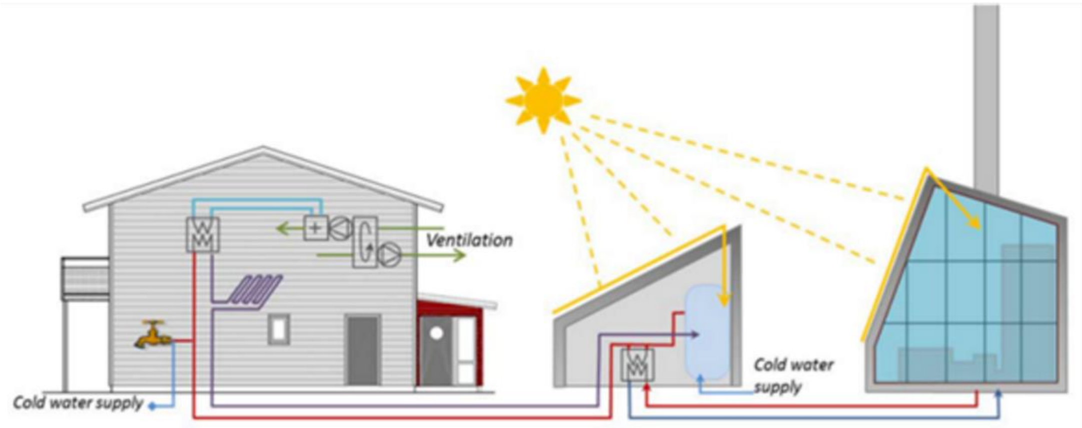

Figure 1: Simple schematic of the technical system in Vallda Heberg. (Based on figures from Markgren Arkitektur AB and Mats Abrahamssons Arkitektkontor AB).

2. Method

The main parts of the Vallda Heberg system, including buildings, have been modelled in TRNSYS and calibrated with measured data from the system. These include the single and multi-family houses, substation, primary and secondary distributions systems as well as the solar fields and central boiler plant. In order to simplify the overall system model, common "blocks" such as buildings and substations have been multiplied to give a heat load similar to that of the real Vallda Heberg system. Distribution pipes have also been lumped together to give the same heat losses as the real system. This system is then the benchmark for other system configurations where choice of culvert system and load density are varied.

3. System description

Figure 2 shows an overview of the Vallda Heberg residential area, including heat supply units and color-coded distribution pipelines. Flat-plate collectors (FPC) supply heat to storage tank through the solar heat culvert (SHC). This heat is used to pre-heat domestic hot-water (DHW) and its circulation (DHWC) flow.

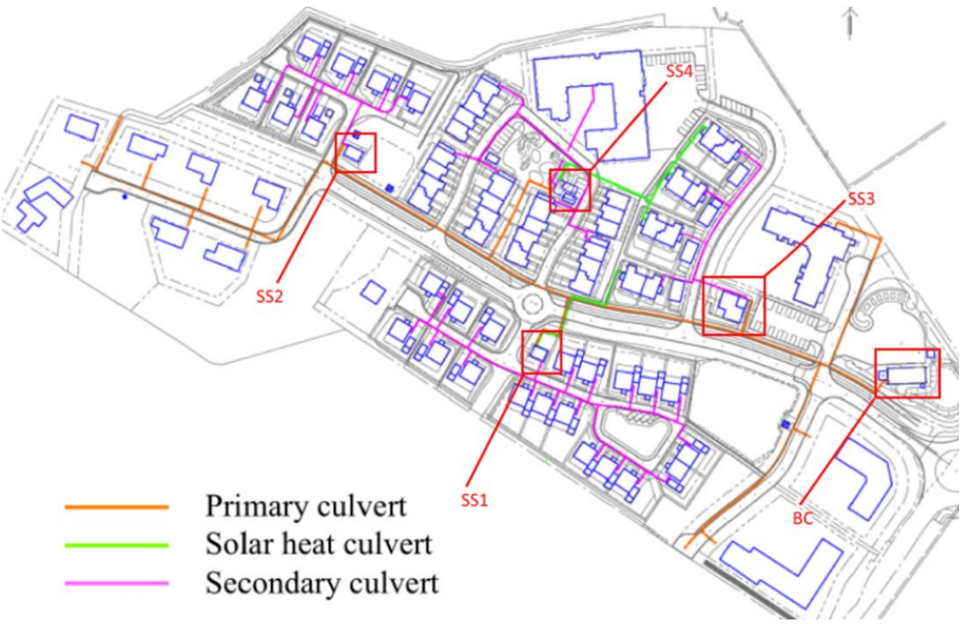

Figure 2: Residential area of Vallda Heberg with denoted substations (SS) and central heating plant (denoted BC) in red, together with color coded distribution pipelines.

Heat generated in the main heating plant (HP) by the wood pellet boiler (WPB) and evacuated-tube solar collectors (ETC) is distributed through the primary culvert (PC) to the substations. Here it acts as auxiliary heating for the DHW and/or DHWC to reach the target supply temperature to the building stock. The DHW and/or DHWC is then delivered to the residents through the secondary culvert (SC). More details on the heating system is given in the following sections.

3.1 Heat demand and distribution system

The system at Vallda Heberg supplies 128 living units, of which 16 are apartments in multi-family houses (MFH) and 64 are apartments in a senior (SEN) living facility. The remaining 48 living units are single-family houses (SFH) and row houses (RH). The heat demand of the different living units differ according to the building characteristics (Table 1), but all buildings are designed according to the Swedish passive house standard.

Table 1 shows the characteristic specific energy consumption of the buildings at Vallda Heberg, based on calculations and prognosis values as stated in a performance assessment made in 2014 (Fahlén et al., 2014).

Table 1: The characteristic specific energy consumption of the buildings at Vallda Heberg for the year April 2013 – 2014 March. The percentage value given refers to the share of total energy use in the building (including electricity).

Load	SH		DHW		Total	DHW/SH
Unit	[kWh m^{-2}]	[%]	[kWh m^{-2}]	[%]	[kWh m^{-2}]	[-]
SFH	30	58	17	32	47	0.55
RH	65	79	12	15	77	0.18
MFH	50	63	22	28	72	0.44
SEN	37	64	9	16	46	0.24

The table values have been read out of graphs for the most part and thus are somewhat uncertain. Specific demand for SH based on measurements varies significantly, as does that for DHW and the ratio of DHW to SH energy. An overview of the system characteristic demand based on measured heat consumption for 2015 and the ratio of specific energy demand presented above (Table 1), is presented below (Table 2), together with the respective collector area (CA) and storage volume (SV) for each substation:

Table 2: Characteristic demand, collector area and storage volume of the Vallda Heberg system for the year 2015

Quantity	SS1	SS2	SS3	SS4		System tot.
Load served	19 SFH	7 SFH	4 MFH (16 APT)	64 SEN APT	6 RH (22 APT)	128
Demand [kWh]	107647	44864	84599	204416	117623	559149
DHW [kWh]	38197	15919	25850	39994	18331	138292
SH [kWh]	69450	28945	58749	164422	99292	420857
CA [m^2]	142	48	64	316		570
Specific CA [m^2/MWh]	1.32	1.07	0.76	0.98		1.02
SV [m^3]	15	5	6	28		54
Specific SV [m^3/MWh]	0.139	0.111	0.071	0.087		0.10

The heat demand is supplied from the main HP to the substations through the primary culvert (PC) in regular district heating twin-pipes, but with an additional DC200 casing insulation made from expanded polystyrene (EPS) of density 30 kg/m^3 and thickness 100 mm. Pipe dimensions vary according to the load served in the different parts of the system, but the majority (~90%) of primary network pipe length is of dimension DN65, DN80 and DN100. The secondary distribution of heat from the substations to the living units is done in an EPSPEX-culvert, which consists of PEX-piping placed in an EPS-casing. These PEX-pipes are of dimensions DN32 – DN65, although the vast majority (~90%) are of dimension DN50 and DN65.

For the year April 2013 – March 2014, the losses attributed to secondary distribution were 25% and 30%, for SS1 and SS2, respectively. For the whole system, total losses were 28% for one single month (March 2014), of which about one third (10%-points) were attributed to the secondary distribution, including substations. The rest was attributed to the primary distribution and losses in HP (Nielsen et al., 2014). Two other studies estimate the heat losses during March 2014 to be around 10% each for the BC and PC (Fahlén et al., 2014; Olsson and Rosander, 2014). However, these values are highly uncertain, as the temperature difference at the heat meters used to calculate the quantities in the energy balance were small (occasionally very small, <3 °C).

3.2 Heating plant

The heat supply consists of a boiler central for which the details are listed below (Table 3). Further down, a schematic of the HP is shown in Figure 3, depicting the PC heat exchanger (HX), storage tanks, solar heat exchanger (HX), wood-pellet boiler (WPB) and oil boiler (OB). The installed solar system utilizes an ETC from Ritter XL Solar, with constant volume flow in both solar loop and charge loop. The anti-freeze system from Paradigma utilizes pure water and heat from the accumulator tanks to heat collectors and outside piping when water in loop gets near to freezing point, although the exact temperature control is unknown. The measured annual solar yield for the year April 2013 – March 2014, as well as for year 2015, was about 57 MWh/a, corresponding to about 8% and 10% of total heat demand, respectively.

Table 3: Details of the heating plant at Vallda Heberg

Boiler Central	
Installed storage volume	15 m^3
Installed collector area	108 m^2 (ETC)
Collector Slope (β)/Azimuth (γ)	70°/30°
PC design operating temperatures (S/R)	75°C/50°C
PC pipe diameter $Ø_{PC}$	100 mm
Load capacity biomass boiler	300 kW
Load capacity oil boiler (back-up)	500 kW

The installed storage volume consists of three buffer tanks of 5 m^3 each. These are connected top-to-bottom, to act as one large tank (Figure 3). The solar loop pump starts/stops when the temperature in the collector is >30°C/<25°C. When the temperature difference between the solar loop (S13) and the temperature in the bottom of the "cold" tank (S8) is >5K/<2K, the charge pump starts/stops.

Solar heat is delivered to the storage tanks according to temperature level, either through valve 1 to the "hot" tank (>75°C) or through valve 2 to the "warm" tank (<75°C).

There are two operating modes - one for winter and one for summer (boiler control sensors in parenthesis):

- Summer mode - valve 3 is open and 4 closed. The "warm" and "cold" tanks are mostly by-passed. The solar system is the preferred heat supply, with the boiler augmenting according to demand (S3, S4).
- Winter mode - valve 4 is open and 3 closed. All tanks are used, as the heat demand is larger and solar resource is less than in summer. The solar system acts as a pre-heater for the boiler (S4, S6).

The summer mode is chosen according to the availability of solar energy and the size of heat demand, and hence may commence/terminate in different months from year to year.

Figure 3 shows a schematic of the heating plant at Vallda Heberg, including all relevant temperature sensors (denoted S1 – S17) and control valves (denoted 1 – 4).

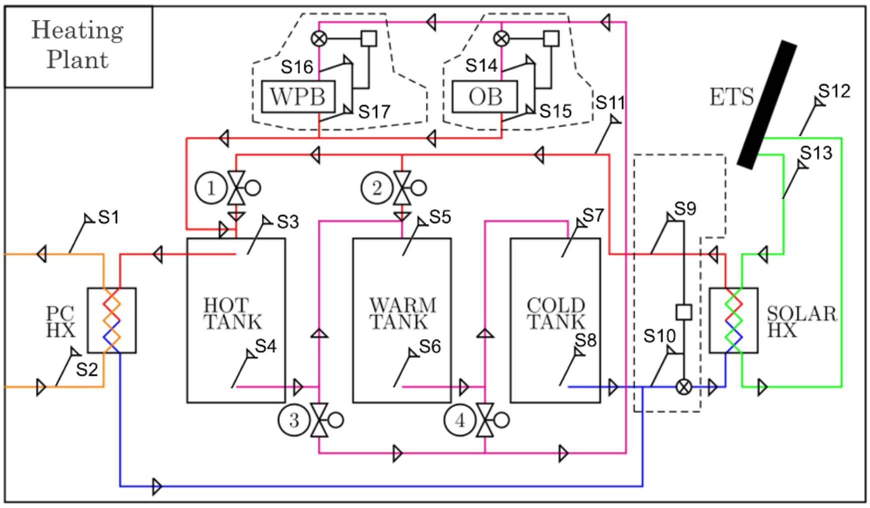

Figure 3: Schematic of the boiler central at Vallda Heberg (Olsson and Rosander, 2014)

A modulating WPB of 300 kW from Osby Parca (turndown ratio 13) supplies heat to the "hot" tank (Figure 3) when the temperature in the tank(s) falls below the target value. The flow rate of the boiler supply pump is adjusted to give an outlet temperature of maximum 95°C. There is an additional 500 kW boiler (OB) which works as reserve. Hot water supply from the tank to the PC HX is controlled to ensure a constant supply set-temperature of 70°C, increasing the flow rate if the outlet temperature to the PC (S1) is <70°C and vice versa. Note that this temperature differs from the design supply temperature (Table 3), and that the stated value is assumed based on the measured inlet temperature of SS3 and SS1). The control system is configured to start the boiler according to the temperature in the "top" and "bottom" of the tank(s), which refers to the placement of the temperature sensors in the storage. The placement of the sensors varies with operating mode, which will be explained further in the next section describing the monitoring system.

3.3 Sub-stations

The majority of sub-stations (SS1 – SS3) at Vallda Heberg have the same design, the differences being the connected load, collector area and storage volume (see Table 2). SS4 has a different design, as it supplies the senior living quarters, where SH is supplied by a radiator system, and thus is separated from DHWC.

A schematic of one of the sub-stations (SS1) used to supply a collection of 19 SFH is shown in Figure 4:

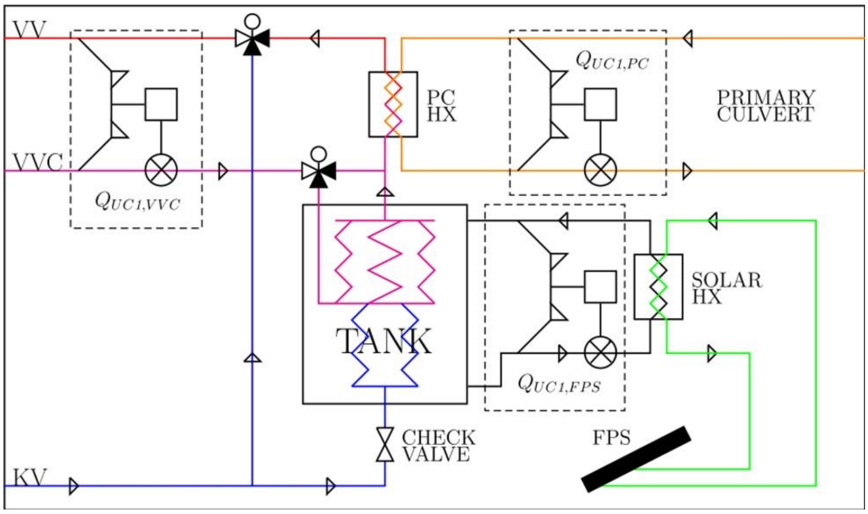

Figure 4: Schematic of SS1 at Vallda Heberg (Olsson and Rosander, 2014)

The sub-stations work as distribution units for the heat delivered by the PC and the FPC's, but also act as hydraulic separation between the higher pressure/-temperature primary distribution and the lower pressure/-temperature secondary distribution. This is important, as the pressure of the secondary distribution GRUDIS loop, must be low enough to allow for tapping of DHW.

Warm water is circulated between the buildings (the load) and the SS in the DHWC loop (denoted VVC). If storage is sufficiently warm (dT +5/+2 K), the flow is routed through the upper half of the storage through an internal HX, but only when the exiting temperature remains below a limit of 62°C. When DHW is tapped in the houses, make-up cold water (CW) enters the bottom half of the storage in an internal HX, where it is pre-heated. In the event of DHWC heating through storage, the pre-heated DHW is mixed with the DHWC flow, before entering the second internal HX. Auxiliary heat is supplied by PC HX when necessary to achieve a target supply temperature of 57°C.

3.4 Monitoring system

The monitoring system at Vallda Heberg uses flow meters from manufacturers Landis+Gyr and Kamstrup (Christensson, n.d.), with the majority coming from the former. In the HP, meters are installed at the boilers (S14 – S17) and in the charge loop (S9, S10) by the solar HX (see Figure 3). No measurements are made of the energy leaving the HP – the additional sensors (S1, S2) installed are used for system control purposes only. In SS1, they are installed in the PC loop, in the charge loop and in the circulation loop (Figure 4). SS4 monitors delivered heat to the radiator circuit in the SEN and heat from PC, whereas the remaining sub-stations (SS2, SS3) only monitor heat from PC. According to previous studies of the system, the flow meters installed in the system have large errors associated with the measured energy when the temperature differential (dT) is small between in- and outgoing flow (Fahlén et al., 2014; Olsson and Rosander, 2014).

The accuracy of heat meters is governed by European Standard EN1434, which states the methods for calculation of accuracy and their boundaries. According to EN1434, the calculated uncertainty of the heat meter is the arithmetic sum of part uncertainties - one part for the calculator, one part for the temperature sensors and one part for the flow meter. For the heat meter installed in conjunction with the WPB, about 25% of the logged temperature measurements for 2015 are below that of the operation threshold of the meter (3K < dT < 120K) (Landis+Gyr, 2015). The measurement uncertainty of the temperature component alone for these measurements is >3.5%. The average total error calculated for all measurements in the WPB is 7.5% for 2015, based on the logged temperature and flow values. This does not take into account any measurement errors in the charge loop.

For the substations, dT over the flow meter is relatively large for the majority of the values, compared to that of the lower threshold value, which means that the uncertainty is not as high as for the boiler. Nonetheless, calculations show that for SS1, about 15% of all measurements in 2015 had an uncertainty above 10%, which is still significant.

4. Model description

4.1 Overall system

Two models have been made in TRNSYS: one modelling SS1 supplying 19 SFH and one modelling the HP supplying SS1 – SS4. In order to simplify the system model when modelling the whole system, the total load was modelled as consisting of SFH only and that this load was supplied by sub-stations identical to SS1. This was done by connecting the model of SS1 (putting it in a macro) with the model of the HP in TRNSYS. By using a set of equations, the load on the SS1 model was scaled (multiplied) up by a factor giving the total system heat demand. This demand was then used to calculate the necessary mass flow in PC, depending on the inlet supply temperature and assuming a return temperature equal to that of the inlet flow in the PC HX of the SS (100% efficiency of HX).

In order to assess the differences between the demands in the different sub-stations, the demand of each sub-station was normalized to that of SS1, as shown below (Table 4):

Table 4: Overview of the heating demand of the different sub-stations at Vallda Heberg normalized to the demand of SS1. The given factor values represent the ratio between SH and DHW demand.

	SS1	SS2	SS3	SS4	Total
Load served [SFH]	19	7.9	14.9	56.8	98.7
Load factor	1.0	0.4	0.8	3.0	5.2
DHW factor	0.355	0.355	0.306	0.181	0.247
SH factor	0.645	0.645	0.694	0.819	0.753
DHW [l/day]	2630	1096	2067	7868	13676

The total heat demand of the whole heating system equals about 98.7 SFH or about 5.2 times that of SS1. In modelling the system, the number of houses modelled (24.6) were chosen so that the scale factor was exactly 4.0 with a specific collector area for the sub-station equal to the average specific collector area of 1.02 for the whole system (see Table 2).

4.2 Buildings

The SFH are modelled using a two-zone building model (type 56). One zone is heated, if necessary, by a water-air HX (with glycol anti-freeze) in the air supply duct of the mechanical ventilation system with heat recovery – the other by floor heating. Floor heating has a fixed flow rate, resulting in heating year round due to the supply temperature of around 57°C, whereas the air heating is controlled by a room sensor. The target inside temperature is 19.5°C.

The house is modelled to have low heat losses and infiltration, based on design information. Inputs for outer area of walls in different directions, air volume of different nodes etc. have been modelled based on drawings of the house. Windows and shading (provided by roof overhang and balcony) are accounted for. Internal gains are added to the main area (i.e. not bathroom) based on known electricity consumption (70 % is expected to be gained as heat) and the average number of inhabitants.

The floor heating in one zone of the building is modelled with a pipe heat load (type 682, TESS) with a 100W constant demand based on static calculation at design conditions, which are the conditions that are dominant throughout the year. The return temperature from this model is calculated and given as input to the SC.

Active SH is supplied by pre-heating of supply air by means of heat recovery (type 667, TESS) from exhaust air, in addition to auxiliary heating by an air-fluid HX (type 670, TESS) utilizing glycol as the heat transfer fluid. The glycol circuit is supplied with heat from the SC by a fluid-fluid HX (type 5b).

4.3 DHW

The DHW consumption profile is calculated with DHWcalc (Jordan and Vajen, 2003), using a 3 minute random distribution based on the annual monitored volume for the year April 2013 – March 2014 for SS1. The base of the profile is the statistical distribution profile of a SFH, the input being the total amount of water used in one day (11676 l/day) for the whole system and the day of maximum (monitored) water load (347). The cold water supplied to the residential area of Vallda Heberg is supplied from a nearby lake. The temperature of the inlet water thus is expected to follow an annual temperature curve corresponding to a sinus function, with an average temperature of 12°C and an amplitude of 4°C (January being the coldest).

The DHW consumption profile is used as input for a data reader (type 9). Two equations are dedicated to dividing the total flow in the SC into one SH component and one DHW component, directing the correct flow to the SH and subtracting the consumed DHW from the total flow before returning to the SC return pipe.

4.4 Sub-station

The substation is modelled using the following non-standard components:

- Storage (type 340, multiport model (Drück, 2006))
- Solar collectors (type 832 QDT multi-node model (Haller et al., 2012))

The parameters for the custom made storage have been supplied by technical drawings of the sub-substation and through communication with the engineering company in charge of its design (Andersson & Hultmark – A&H). The storage has been modelled with two internal HX, one in the top of the tank and one in the bottom, which is a simplification over the real system that has six in the top of the tank and three in the bottom. This has been taken into account by sizing the top heat HX volume to be double that of the bottom HX. The solar collector parameters were taken from the supplier of the custom made collectors in this system.

The DHWC pump, storage charge pump and solar loop pump are modelled using standard components (type 3b). Pump manufacturer brand and model name has been supplied by the engineering company in charge of design (A&H), allowing to derive pump operation curve parameters from the pump datasheet. Nominal volume flow rates originated from technical drawings of the substations, but were chosen to achieve harmony between measured and simulated values during calibration. Internal piping is modelled with standard components (type 31) and heat losses from these represent the whole substation, avoiding the need of a separate building model. The UA values have thus also been chosen to allow for harmony between simulated and measured values for the SS loss in the calibration phase. All pipes with negligible flows (i.e. < 0.02 l/s) and by-pass valves have been ignored as these are irrelevant for normal operation. The PC HX and the solar HX were modelled using standard components (type 5b), with parameters supplied from technical drawings. The UA value of these was assumed to be the nominal power of the HX divided by the design temperature difference over the HX (from "hot" side inlet to "cold" side outlet).

4.5 Heating Plant

The heating plant is modelled using the following non-standard components:

- Storage (type 340, multiport model, non-standard (Drück, 2006))
- Solar collectors (type 538, evacuated tube solar collector with modulating flow, TESS)
- Boiler (type 659, auxiliary heating, TESS)
- Boiler feeding pump (type 741, variable speed pump, TESS)
- PC HX- and PC supply pump (type 742, user specified flowrate, TESS)
- PC HX (type 805, domestic hot water HX, hot side flow is output, non-standard (Haller, 2006))

Storage is modelled as one large tank instead of three small, without internal HX. Charging is done through assigned double ports according to the principle explained earlier (see section *3.2 Heating plant*). The surfaceto-volume ratio of the original storage has been maintained in scale-up of storage. The double-port feature is also used to distinguish between ports used for boiler return according to operating mode, leaving a set of ports unused for parts of the year. The switching between summer and winter mode is done with a forcing function (type 14h) in combination with a flow diverter, flow being directed to ports according to the season.

Solar collectors parameters are taken from the summary of EN12975 test results by TÜV Rheinland, annex to the Solar KEYMARK Certificate. The listed incidence angle modifiers (IAM) are compiled in a file and used as input to the model.

Boiler parameters are derived from the datasheet from the boiler manufacturer, values utilized mainly being the rated power, set-point temperature and max temperature of the boiler. The minimum flow rate is ignored, as it is considered irrelevant for modelling purposes. The boiler control is ON/OFF, as opposed to in reality where it is modulating. The modulating behaviour is imitated by implementing differential boiler control with short on/off cycles, resulting from small temperature dead-bands, much in the same way as pulse-width-modulation (PWM). Boiler control target temperature is 82°C, one differential controller checking the tank bottom and one checking the tank bottom – if both are below dead-band (1.5°C and 2°C) the boiler is ON.

The boiler feeding pump is modelled as variable speed, making modulating operation possible at a later time by implementation of a PID-controller. At present it is modelled as running when boiler is on, with the flow rate being the nominal flow rate. The PC HX pump flow rate is given as an input from the PC HX, which calculates the necessary "hot side" inlet flowrate to achieve the target "cold side" outlet temperature of 70°C. For the PC supply pump, the flow rate is given as the return flow rate from the PC, equal to the "cold side" outlet of PC HX. All pumps are modelled with a maximum flow rate taken as the nominal flow rate found in technical drawings.

Heat losses in the HP are modelled by single pipe ducts using standard components (type 31), for which the DN has been derived from the technical drawings and the dimensions have been derived from EN1057 (European Comitee of Standardization, 2006). There is one pipe for the supply from boiler to storage and one from storage to PC HX. For the solar loop, there are four pipes: two pipes for collector supply and two pipes for collector return. There is one "inside" pipe and one "outside" pipe for each of the two-pipe segments, intended to model the solar pipe heat loss to ambient. Ambient outside temperature is given by the weather data, whereas the ambient inside temperature is assumed to be a constant 25°C, as this is the target temperature for the ventilation system in the HP according to control system description.

4.6 Distribution

According to previous studies, the PC route length is 1007 m, divided into the different pipe diameters. The route length of SC connected to SS1 is 469 m, and consisted of a mix between pipes of DN32 - 63 (Olsson & Rosander 2014). To estimate the remaining length of the secondary culvert, measurements were conducted using satellite images (i.e. Google Maps). Assuming that half of the SC connected to SS1 was DN63 pipes and assigning one fourth to DN50, with the remaining being DN40 (20%) and DN32 (5%) pipes, modeling the whole load at Vallda Heberg as consisting of SFH only, the length of distribution pipes will be divided as shown below (Table 5):

Table 5: Overview of measured and estimated culvert dimensions at Vallda Heberg

Culvert dimensions							
DN [mm]	32	40	50	65 (*63)	80	100	Total
PC Length [m]	15	20	44	602	187	139	1007
SC Length [m]	56	223	278	557*	0	0	1114

The modelled PC length is divided into four pipe sections (PC1 – PC4), serving the four different sub-stations (SS1 – SS4) in the original system (see Figure 2). As can be seen, the amount of PC culvert length of DN32 – 50 is small compared to the total PC length (~8%), so that it was chosen to model the PC as consisting of DN65 – 100 pipe sections only in order to simplify the model. The section serving SS2 is also serving an area of larger SFH not currently connected to the network, and thus the length of this element was dimensioned to account for heat losses in the section. It is further assumed that the pipe diameter decreases with distance from the HP, so that SS4 and SS2 are served by DN65 pipes (600 m in total), whereas SS1 and SS3 are served by DN80 (200 m) and DN100 (150 m) piping, respectively. For the simulations, however, the four pipe elements are modelled as one pipe connected to the load (SS) at the far end.

The consequence of this simplification is that the temperature of the flow delivered to the SS is a little lower than it would be in reality. This is made up for in the model by increasing the flow through the SS, to be able to deliver the required heat. Such a simplification is considered appropriate, as the focus of this study is on accumulated energy and does not consider energy flux specifically.

Distribution pipes are modelled by use of type 951 (buried horizontal pipe, twin-pipe system). For the PC, the pipe parameters were taken from the manufacturer datasheet (Powerpipe AB, 2016), including the insulation (rigid polyurethane - PUR) parameters. For the secondary culvert, the pipe dimensions were derived as explained earlier (Table 5). Following the assumption made for the mix of pipe dimensions for the SC, the average weighted DN would be 54 mm. The insulation parameters were taken from the manufacturer datasheet for the EPS casing (Elgocell AB, 2013). Because the original EPS casing has a square/rectangular cross-section and the pipe model takes cylindrical dimensions only, the casing diameter had to be calculated assuming that the cross-sectional area of the casing was circular.

4.7 Model calibration

The two models used in this study were developed separately and then calibrated towards measured data. The SS1-model was developed using meteorological- and monitored data for the sub-station and connected houses for the year April 2013 – March 2014. Optimally, the system heat losses would be modelled separately, but due to bad quality of measurements, the total losses from SS1 and SC1 were matched to difference between delivered energy to SS (PC HX and FPC) and end-use consumption. SH demand was calibrated by changing house UA value and house set-temperature. The PC delivered heat was calibrated mainly by adjusting losses in storage heat loss. The resulting deviation between measured and simulated values after calibration was in the range 0.4 – 1.2% (absolute values), for the energy consumption of SH, DHW, distribution losses, storage charged energy and PC delivered heat.

The HP model was developed using meteorological- and monitored for the calendar year 2015. Heat delivered from PC to the sub-stations (SS1 – SS4) was used as input to a pipe heat load (type 682, TESS), calculating the return temperature to the PC HX. Calibration was done mainly by adjusting the insulation parameters and UA values of pipes, to get the appropriate heat losses. The resulting energy balance showed negligible deviations, and most of the simulated values (solar heat, heat losses) deviated only slightly (<3%) from the measured. However, there were significant deviations in the simulated boiler energy (~9% lower than measured on annual basis). Attempts to calibrate the model by assuming tenfold thermal conductivity of the EPS and threefold thermal conductivity of the PUR could not reduce the discrepancy to an acceptable level (i.e. below 5%). Studies showed that the losses of the HP and PC appeared to be underestimated for the winter months, though no explanation for this could be found. Reducing the measured boiler energy by 10% gave good correspondence between simulated and measure values, implying that the discrepancy was a consequence of the large uncertainties in measurements by the installed flow meters in the HP (7.5%) and partly in the sub-stations (up to 8%), as the monitored values from these were used as input.

4.8 Model variations – parametric studies

The parametric studies made in this study are related to the type of distribution system and the load/linear heat density (LD). There has been two types of distribution system modelled:

- Original Vallda Heberg: PC distribution, substations, and SC distribution GRUDIS
- Modified Vallda Heberg: All GRUDIS system, DHW-circulation from the HP and to the load

In the modified Vallda Heberg, the sub-station is kept and the PC HX in the HP is removed, connecting the boiler directly to the PC HX in sub-station. This allows for a more direct comparison of the distribution pipe influence on the heat losses. This in turn influences the harvested solar energy and supplied boiler energy. The model has been altered by reducing the PC length from 950 m to 0 m, and increasing the SC by the same length. The length of the pipes supplying solar heat have been assumed to be one third of the original PC length (950 m), meaning that the solar collectors are modelled as placed on the house roofs as close to the HP as possible to minimize pipe heat losses. However, one major simplification is that the pipes are modelled as being above ground, and not buried as would often be the case.

By variation of the distribution pipe length, a parametric study was made for 0.5LD, 1LD and 2LD, to show how the parameter influences the system heat losses, supplied boiler energy and the harvested solar energy.

5. Results

5.1 Distribution concept

Figure 5 depicts the simulated annual energy balance for the system at Vallda Heberg according to choice of distribution concept, showing a significant reduction in heat demand for the two simulated cases. By choosing an all GRUDIS distribution system, the supplied boiler energy was reduced by 99.5MWh (13%) mainly due to a reduction in the total pipe distribution losses by 112MWh (43%). The heating plant (HP) loss also decrease by about 5 MWh (6%) which is mainly due to reduced storage heat loss, particularly during spring and autumn months. The change in stored solar energy from FPC (HP solar) was lower by about 27MWh (17%), assumed to be due to increased solar-pipe length and -losses. Heat from ETC on the HP is about the same in both cases. The sub-station (SS) loss is similar in both cases, with minor differences. It should be noted that the house heat demand is about 1.6% lower in the all GRUDIS case, which affects the results, but not by much.

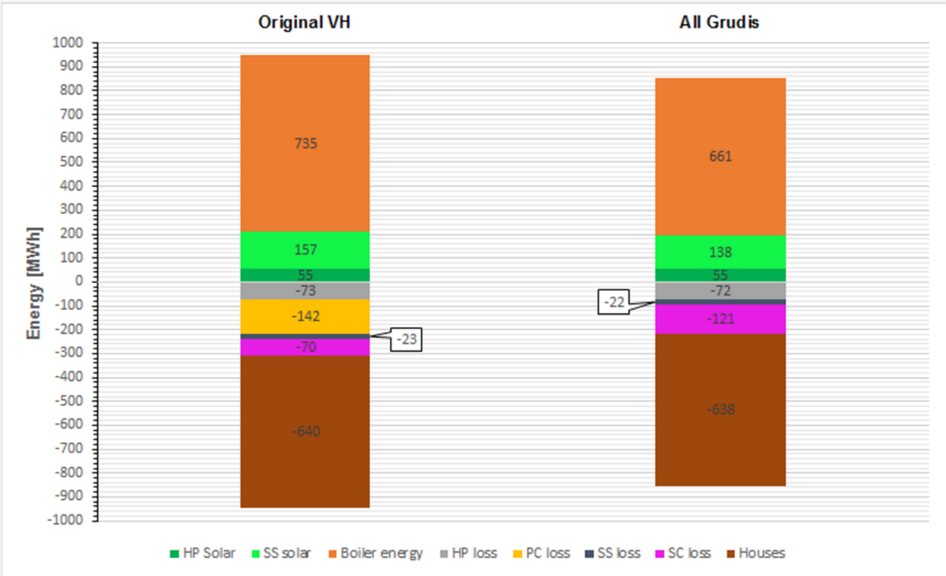

Figure 5: Simulated annual energy balance for the system at Vallda Heberg (VH) for two different choices of distribution concept. Abbreviations used: heating plant (HP), sub-station (SS), primary culvert (PC) and secondary culvert (SC).

5.2 Parametric study

Below (Figure 6) is an overview of the result from the parametric studies for the simulations conducted with the original distribution concept at Vallda Heberg, utilizing a combination of conventional DH twin pipes, sub-stations and GRUDIS.

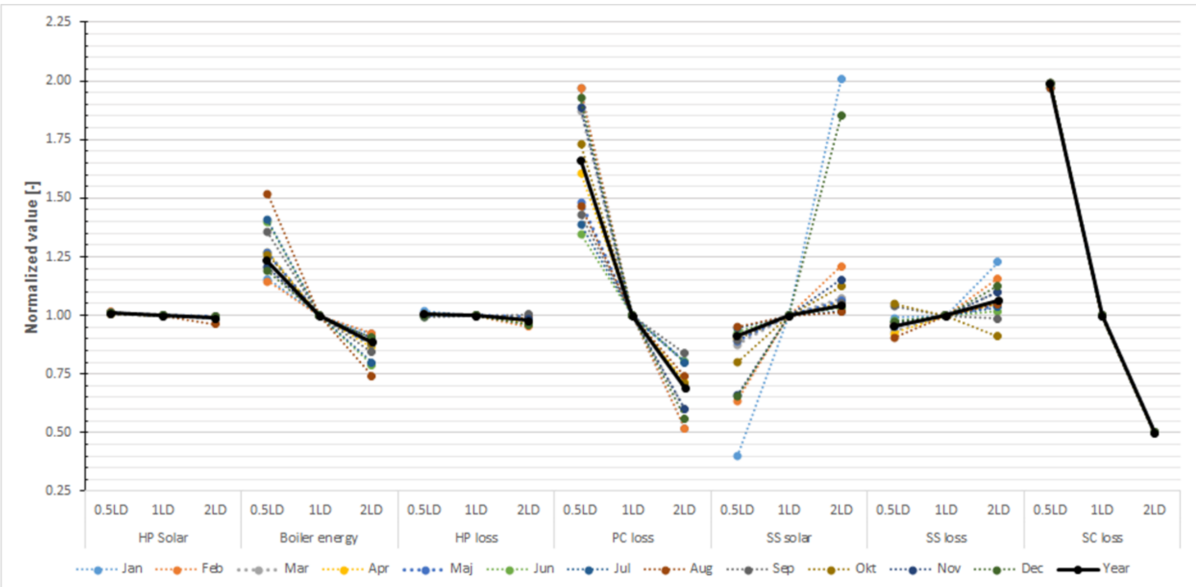

Figure 6: Influence of linear heat density on different parameters in simulation of the original distribution concept at Vallda Heberg. The values have been normalized to the simulated values for 1LD. Abbreviations used: heating plant (HP), sub-station (SS), primary culvert (PC) and secondary culvert (SC).

As can be seen, the boiler energy and distribution losses are the parameters most affected by the change in culvert length, and hence linear heat density. The SS solar energy (from FPC) varies moderately. This is expected as these parameters are directly dependent on the pipe length. The HP solar energy (from ETC) and HP loss is relatively unaffected, whereas SS loss varies moderately - mostly during winter due to higher loads and operating temperatures. For the All GRUDIS case, the influence of linear density is almost the same as that for the original system.

5.3 Discussion

In simulating the all GRUDIS system, some major simplifications were made in the model. For one, the substation was kept in the model, assuming that the available storage is divided between the HP and SS, instead of having larger stores in the HP. Doing this, the loss coefficients and stores are assumed the same for both simulated cases, instead of modelling the all GRUDIS system with a new design for a complete HP including all stores and DHWC connections. It is likely that the total losses would be lower if the HP was modelled as one unit. Secondly, the solar pipes from the FPC to the SS are not buried insulated twin pipes, but assumed to be above-ground, which overestimates the losses. Taking these two simplifications into account, the differences observed in choice of distribution concept would most likely be even greater.

Another simplification is modelling only one SS and assuming that the load is only made up of SFH. This means that the heat distribution in all buildings is the same and split between uncontrolled, year round floor heating and the heat to air supply is the same for the whole area. In the real system, there are different loads installed, many of which have a different characteristic heat demand (Table 1, Table 2 and Table 4). In contrast to the other dwellings in the system, the elderly home (SEN) has an installed radiator system with design operating temperatures of 60/40 which leads to a little lower return temperature from SS4 than for the other SS and this has not been taken into account. Furthermore, the lower ratio of DHW to SH in the RH and MFH means that the circulation flow to these buildings will be higher than in the case for SFH, which would influence the heat losses in SS3 and SS4 with associated distribution lines.

The observed pipe distribution losses in the simulations of an all GRUDIS distribution system are significantly lower than those in the original configuration. This may partly be attributed to the lower operating temperatures of the GRUDIS network and partly to the model of the SC. The modelled average ground temperature is 9°, which means that by assuming an average supply temperature of 56°C in SC and 70°C in PC, the difference in dT (47K/61K for SC/PC, respectively) is about 30%. In the twin-pipe model, the thermal conductivity of the *fill insulation* (PUR in PC and EPS in SC) surrounding the pipes is the most influential parameter for the heat losses, whereas the *gap material* (EPS for PC and clay for SC) is less influential. The PC model was calibrated to a fill insulation value 3-4% higher than that of the SC. Because the temperatures are higher in the PC, this might have a large influence on the heat losses.

The cost of distribution pipes is significantly different for PEX and conventional PUR coated steel pipes. As can be seen below (Table 6), the specific cost of SC is close to half that of the PC, whereas the trench cost is the same for both.

Table 6: Overview of the approximate costs for distribution pipes and trench work for the system at Vallda Heberg. All pipe costs are total costs including connections, welding and EPS insulation. (Andersson-Jessen, 2016; Magnus Klingheim, 2016)

		Length [m]	Price culvert [SEK/m]	Price trench [SEK/m]	Total price [10^6 SEK]
Original VH	PC	1007	1150	1600	2.8
	SC	1114	650	1600	2.5
	SUM				5.3
All GRUDIS	EPSPEX	2121	650	1600	4.8
	Solar culvert	336	1150	0	0.386
	SUM				5.2

In the all GRUDIS case, the solar culvert (SCU) length is assumed to be a third of that for PC and to be of same cost as the PC (i.e. same pipe type). It is furthermore assumed that the trench cost only applies once, with no additional trench costs for SCU going to the HP (i.e. EPSPEX and SCU in same trench). Thus, the total price of an all GRUDIS system would be about the same (-2%) as the original system cost, but with lower heat losses.

The cost of having an all-in-one HP is not calculated, but would be substantially lower than having a smaller HP and 4SS as is the present case.

The parametric study reveals it is mostly beneficial with a high linear heat density (LD), which is expected as it cuts distribution loss and consequently boiler energy. Changing the distribution pipe length has the effect of changing the LD, which is sufficient for simulation purposes, but has some practical issues in reality. Assuming that the total distribution pipe length (PC + SC) and total land area is kept the same, the implication of assuming that all living units (LU) are SFH means that more houses would need to fit in the same space. The LD would thus still be the same, but the built area would increase (i.e. higher building density). Now, if the LD is to increase, in order to get space enough for the same population living in SFH, a larger area would be needed. If the area is to be kept the same as in the original VH, increasing LD is equivalent of replacing SFH with MFH (although with the same demand characteristics as SFH). Conversely, decreasing the LD would imply having the houses further apart which, again, would require a larger area. If the space is to remain the same, then in effect, decreasing the LD implies having MFH (with the same demand characteristics as SFH) spaced further apart. Alternatively, the increase/decrease in LD can be seen as building SFH denser/sparser without limits on the area size.

5.4 Conclusions

The whole block-heating system of Vallda Heberg has been modelled in TRNSYS with some simplifications, utilizing one building model to simulate all buildings and one sub-station to simulate all sub-stations. Two distribution systems were modelled: the original system with primary culvert, substations and secondary culvert – and one all GRUDIS system using DHW-circulation piping for distribution. Results indicated a significant reduction in heat losses can be obtained by employing an all GRUDIS distribution system, while at the same time potentially reducing cost. Changes in heat density show that the distribution losses and supplied boiler energy decrease with increased heat density, and vice versa. This is as expected, as these parameters are directly related to the distribution network length. Future work should concentrate on investigating the influence of different load heat demand characteristics, as well as placement of solar collectors and type of solar collector technology.

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