# Simulations of a Solar-Assisted Block Heating System

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## Abstract

Two types of simulation software TRNSYS and Polysun are studied to check their suitability for solar district heating system planning. A reference case, a part of the Vallda Heberg district heating system is modelled in both tools and results are compared with available measured data and with each other. Models are successfully calibrated. TRNSYS and Polysun models have deviations in main key figures compared to the reference case less than 2% and less than 8% respectively. A sensitivity analysis of key parameters shows that the two tools give similar results.

*Keywords: solar thermal, district heat, dynamic simulation, TRNSYS, Polysun,*

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## 1. Introduction

Approximately 10% from EU heat market is covered by district heating (Dalenbäck, 2011), thus giving solar district heating a good potential to also be implemented in existing networks.

Furthermore, there are examples where the employment of solar thermal technology in combination with biomass combustion can supply 100% renewable district heating (Faninger, 2000). However, there are a number of obstacles for the wide spread implementation of solar district heating (SDH) systems, namely: high investment costs, technological difficulties and lack of engineering experience (Dalenbäck, 2011).

Considering complexity of the systems, usage of new technologies and the lack of engineering experience, computer modeling of the solar district heating systems is a key to successful system implementation. It is achieved through market available computer simulation software or self-developed tools. Several studies have been made employing such tools, of which the scope and purpose vary.

Considering the wide implementation of simulation software for the design and the optimization of solar district heating systems, it is important to investigate how applicable available tools are. In the present study two different tools are compared TRNSYS 17 (Klein, 2012), originally developed at SEL, and Polysun (Rezaei et al., 2009), developed by Vela Solaris. The base case for this investigation is a part of the solar-assisted block heating system for a new building area in Vallda Heberg, Sweden.

### *1.1. Aims*

The main aim of the study is to determine how applicable Polysun and TRNSYS are for simulation of block heating solar systems, which include advanced controlling strategies and/or complex hydraulics. In order to do this, different aspects should be considered. Available component models should be detailed and robust enough to build such system in the given boundary conditions. It should be possible to calibrate the model with the real system. Changing of the boundary conditions and sensitivity analysis of different components should lead to well-explained changes in the system model performance.

### *1.2. Methodology*

As a base case, sub-station 1 (SS1) of the Vallda Heberg district heating system was chosen. The models, in TRNSYS 17 and Polysun, were constructed based on drawings, known properties and operational strategies of

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the sub-station. The whole study is performed taking into perspective the boundary conditions, assumptions and limitations of the available data and models.

The system has been monitored to evaluate and fault-find the system. Based on data of the monitoring system and weather data of the Swedish Metrological and Hydraulic Institute (SMHI) for the monitoring period, input files have been constructed for the models in order to calibrate them using the measured energy, flows and temperatures. For the calibrated models, sensitivity analyses for key parameters were performed using Meteonorm weather data. The process and results of calibration as well as the models` reactions in sensitivity analyses were used to determine applicability, usability and limitations of the tools for the given case.

## 2. Description of the system

The local district heating system comprises one central heating plant (HP) for which the details are listed below in table 1 (the left part). It features a 250 kW wood pellet boiler (and an oil boiler for back-up) and four substations (SS1-4) connected to the primary culvert (PC).

Buffer storage tanks are installed in the central heating plant and in each substation. There are 108 $m^2$ evacuated tube solar collectors (ETC) on the heating plant and 570 $m^2$ flat plate roof-integrated solar collectors (FPC) in connection to the substations. Solar heat is targeted to cover 40% of the end-use of space heating and domestic hot water.

The focus of this study is SS1 with secondary distribution culvert and connected houses, of which the details are shown below in table 1 (the middle part).

**Tab. 1: Details of the central heating plant (HP) and of substation 1 (SS1) at Vallda Heberg, Sweden**

| **Heating plant (HP)** | | **Substation 1 (SS1)** | | **Load (SS1)** | |
|---|---|---|---|---|---|
| **Key characteristics** | **Values** | **Key characteristics** | **Values** | **Key characteristics** | **Values** |
| Installed storage volume | 15 $m^3$ | Installed storage volume | 15 $m^3$ | Single family houses | 19 |
| Installed collector area | 108 $m^2$ (ETC) | Installed collector area | 142 $m^2$ (FPC) | Heating area per house | 140 $m^2$ |
| Collector Slope (β)/Azimuth(α) | 70°/30° | Collector Slope (β)/Azimuth(α) | 27°/30° | Heating area total | 2660 $m^2$ |
| PC design operating temperatures (S/R) | 75°C/50°C | Load capacity solar HEX | 85 kW | Specific demand heat | 59 kWh/($m^2$·yr) |
| PC pipe diameter ØPC | 100 mm | Load capacity auxiliary HEX | 165 kW | Specific demand electricity | 34 kWh/($m^2$·yr) |
| Load capacity solar HEX | 65 kW | PC connection pipe diameter ØCP | 50 mm | SC length (total) | 938 m |
| Load capacity biomass boiler | 250 kW | | | SC target temperature | 58°C |
| Load capacity oil boiler (backup) | 500 kW | | | SC pipe diameter Øsc | 63 mm |
| Load capacity PC HEX | 1000 kW | | | | |

The secondary heat distribution system between the substation and the buildings is 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. The pipes are located in an insulating (styrofoam) box buried in the ground, with fig. 1 showing the distribution to the houses and the placement of the sub-station as well as heat meter points.

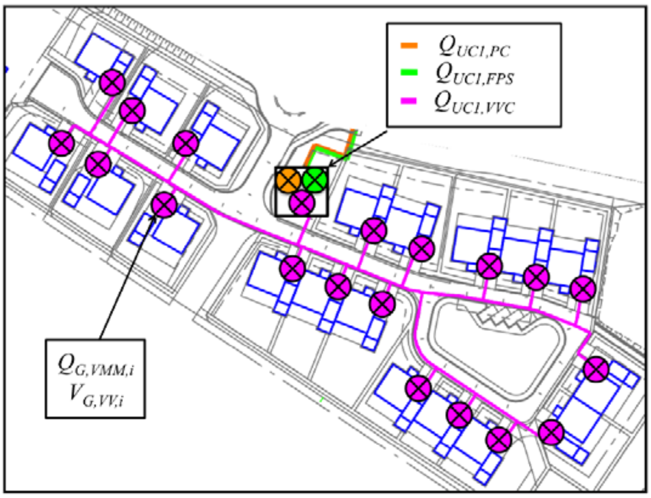

**Fig. 1: Drawing of distribution network and houses connected to SS1 (Olsson and Rosander, 2014)**

142 m$^2$ aperture area of flat plate collectors are connected to SS1. 38 m$^2$ on the roof of the substation, while the second field 104 m$^2$ located on multi-family buildings. The solar collectors deliver heat to the storage tanks via an external heat exchanger, as the collector loop fluid is a water-glycol mixture. One pump is controlled on each side of the heat exchanger by matched flow rate. The fixed solar collector flow rate is 0.38 l/min per m$^2$ aperture area. The pumps are controlled based on "sensors" in storage, collector outlet and heat exchanger outlet. To obtain stratification, two inlet heights to the storage are possible from the charging loop. Fig. 2 shows how the different loops are connected by heat exchangers.

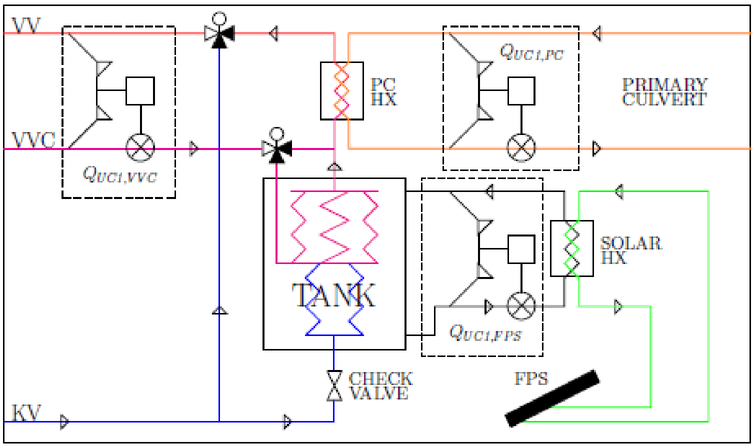

**Fig. 2: Schematic drawing of SS1 with installed heat meters (Olsson and Rosander, 2014)**

The circulation pump is running at constant flow. The cold water inlet of the loop is supplied through the storage to be pre-heated. If the storage temperature is high enough, the DHW circulation will pass through the storage as well. The primary culvert delivers heat to the secondary distribution loop via a heat exchanger when the solar heat of the sub-station is not sufficient to maintain 58°C outlet temperature. If the temperature after this heat exchanger is more than 60°C (due to high temperatures in the storage tank), cold water is mixed to lower the supply temperature.

The load is represented by a group of single-family houses and the DHW-circulation in the secondary culvert (SC). Details of the load are shown in table 1 (the right part).

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 (Jimmefors and Östberg, 2014). Roof overhang and balconies provide sun shading to reduce solar gains in the summer period.

Each house has two floors, and a total heated area of 140 m$^2$. The hot water circulation of the secondary culvert is connected to each individual building. The hot water is delivered directly for tapping and for heated appliances (e.g. washing machines). The circulating flow is passing through the floor heating loop in the bathroom and utility room without control (ie all year) as well as through a heat exchanger coupled via a thermostat controlled water-glycol loop that delivers heat to an air heating coil. Space heating is provided by the air heating coil to the supply air, which is pre-heated by the exhaust air using a rotating heat recovery unit.

### 2.1. Monitoring system

The monitoring system is logging every hour. Temperatures, flow rates and energy rates (and total quantities) are measured to evaluate the system performance of houses, distribution network and heating plant/substations. Incoming solar energy and auxiliary energy from heating central and hot water circulation losses are monitored at the substation, as shown in fig. 2. The DHW and space heating loads are measured in all houses. Temperature to and from houses are measured as well.

In 2014 the whole area of Vallda Heberg had a low heat demand, corresponding well to the design values. The measured yearly load of sub-station was 59 kWh/(m$^2$ living area) including circulation losses. Distribution losses are a large share of the yearly load (25 %), especially due to the low space heating demand of the buildings.

Solar fraction of SS1, SF (eq. 1), is calculated by the supplied solar (Qsolar) compared to load (Qload) as the relative saving of energy from the main heating plant:

$$SF = \frac{Q_{solar}}{Q_{load}} \qquad \text{(eq. 1)}$$

The actual solar utilization and solar fraction are larger than what is measured in the sub-station directly, due to the evacuated tubular collectors installed at the main heating plant. The specific collector performance of the flat plate collectors connected to SS1 was 297 kWh/(m$^2$·yr).

## 3. The models

The system models have been created based on known system properties and the available monitored data. Measured temperature levels and flow rates were used as a guideline when setting the controls of the model. Monitored data concerning energy consumption of the area has been used to calibrate the load parts of the model (space heating and distribution losses) and to create a load input file (domestic hot water). The monitored data for energy to the substation from heating plant and flat plate solar collectors are used to calibrate the supply parts of the models.

A hot water pattern input file has been constructed using DHWCalc (Jordan and Vajen, 2003) so that it matches the measured monthly demand data for all 19 houses of the network. The cold water inlet temperature variation during the year is based on information from the provider (8 to 16°C – January coldest) as this temperature is not measured.

Weather data of 2014 from SMHI has been collected on hourly basis as input file for the calibration process. This includes direct and global solar radiation data for horizontal surfaces for the area constructed by SMHI based on interpolation of values of other Swedish locations (SMHI, 2015).

The calibration itself has been based on monthly energy balances, due to the large uncertainties when combining short time interval interpolated weather data, limited measurement points and general assumptions.

### 3.1. TRNSYS and Polysun models

TRNSYS is a component based dynamic simulation tool, where the user combines component models and user defined equations and controls. The timestep used is 3 minutes. Integration and convergence tolerances are 0.001 relative.

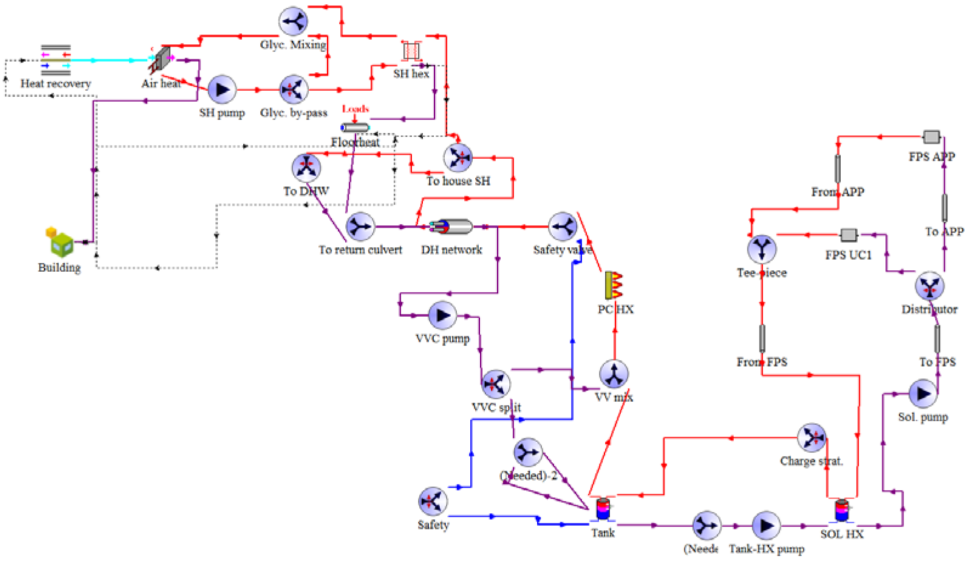

**Fig. 3: System model in TRNSYS**

Polysun is a dynamical simulation tool, which is used principally for design and planning of renewable energy systems. Polysun uses variable timestep. The largest timestep is chosen which satisfies convergence criteria, but not larger than 3 min and 12 min for day and night respectively.

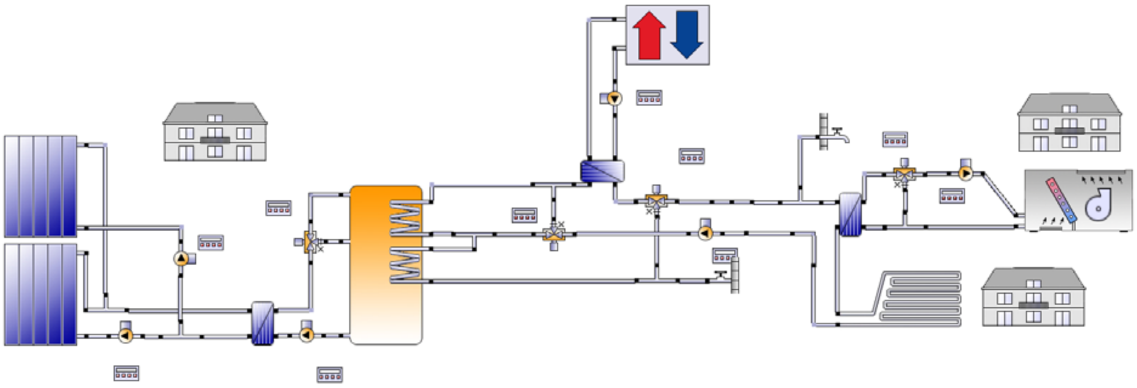

**Fig. 4: System model in Polysun**

The main components of SS1 are storage, heat exchangers and solar collectors. Other modelled components include pumps, valves and collector loop pipes.

The solar collectors are modelled as two flat plate collector components using the parameters for the installed collectors from Solar Keymark certificates. The pipe lengths to the two fields are included to simulate thermal capacity, time dependency and heat losses. The flow is distributed to the two fields dependent on collector area, so that the area specific flow rates are the same for both fields.

Even though the storage is cubic in reality, it is modelled as a vertical cylinder. Real inlet and outlet heights are used both for tank charge- and discharge.

In TRNSYS the distribution pipe is simulated using Type 951 buried twin pipe in the ground (Thornton 2012), comprising supply and return pipe inside one shell of insulation. In Polysun an existing pipe model was extended to simulate buried pipes. Each pipe has a separate shell. The models assume circular shape while the real twin pipe has rectangular insulation. The part of the flow which is due to DHW tapping is withdrawn from the flow at the end of the secondary culvert. The rest of the flow is for space heating with no flow bypassing the houses.

In TRNSYS one two-zone building is modelled to simulate an average of the 19 space heating loads of the 19 buildings. The flow rate to the building is thus one nineteenth of the total flow in the secondary culvert, after

DHW has been extracted. When the hot water returns to the network pipe the flow rate is multiplied by 19 again, while assuming that the return temperature is valid for the whole flow. In this way the space heating demand of the simulated building acts as average of all buildings in the network.

In TRNSYS inputs for outer area of walls in different directions and air volume of the two zones 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 (4 seated at rest). The yearly measured average electricity consumption is 4700 kWh per house. One zone is bathroom including floor heating, and the other zone comprises all other indoor areas, which are heated by mechanical ventilation only. All of the hot water circulation initially passes through a glycol heat exchanger, then through the floor heating. The glycol loop heatsup the inlet air via a heat exchanger after it is pre-heated by ventilation heat recovery unit. There is a bypass valve in the glycol circuit that is controlled by a room thermostat, and thus varies the addition of heat to the inlet. The heat recovery efficiency is a function of the ambient air, and the unit is turned off at ambient temperatures above 16°C.

In Polysun the space heating load is modelled as two one-zone buildings. The first building model represents the living area with a fan-coil heating system. The second building model represents a bathroom and a floor heating system. There is no flow separation since the first building represents total load of living areas of all 19 buildings, the second building represents total load of bathrooms of all 19 buildings.

In Polysun the same boundary conditions for building as in TRNSYS are considered, but since one building represents 19 buildings it is scaled down. The actual size is chosen during model calibration. For the living room internal gains are increased. These gains represent gains from bathroom, since there is no connection between the living area and the bathroom in the model.

### 3.2. Assumptions / simplifications in the models

Pressure drops are generally neglected, as pressure is not the driving force of flows in the models. This causes issues when controlling valves, as the flows rates are controlled upstream. Thus hydronic diverting valves are controlled based on equations, which are working ideally. Pipes and valves without flow during normal operation have been neglected. The primary culvert heat exchanger is modelled to give constant outlet temperature (perfect flow control on primary side).

In TRNSYS external heat exchangers are modelled without thermal capacity and heat loss coefficients. Heat losses of the solar heat exchanger lumped together with the return pipe of the solar loop. The UA value is constant for the solar heat exchanger. Pipes in solar loop have constant loss coefficient.

In Polysun, the main simplification is the use of two one-zone building models instead of one two-zone building model. So heat gains from bathroom to living area are not modelled. Heat exchangers are modeled without thermal capacity. Two independent buried pipes are used to model secondary culvert, therefore pipe thermal interaction is not considered.

Only modelling one house and one distribution pipe is a big simplification, and it is only possible in this study because the dynamic effects of the space heating elements are not the focus of this study.

### 3.3. Calibration

A few unknown properties were found by parameter identification based on comparison with monthly heat balances.

For TRNSYS model room set-point temperature of air heating, maximum heat recovery efficiency (80 %) and maximum external shading share (80 %) were estimated in this way. External shading is activated when solar radiation on the wall surface is above 200 W/m$^2$ until it decreases to less than 120 W/m$^2$. Floor heating was simulated using an active floor layer. The parameters of the floor were calibrated to reach around 200 W all year from water circulation to bath zone. Heat loss coefficient of pipe in solar loop was calibrated to monthly values of solar gains.

For Polysun model sizes of buildings which represent living area and bathroom were defined by parametric identification. Set-point temperature of air heating was also estimated in this way. Thickness of insulation of buried pipe was defined based on losses in distribution system. Thickness of insulation of pipes in solar loop was calibrated to monthly values of solar gains.

### 3.4. Simulated versus measured

Fig. 5 shows how the measured loads and solar gains of the block-heating system correspond to the simulated values on a monthly basis. Solar gains correspond very well, which is partly due to the calibration process. Considering loads, simulated values correspond well with measured values for simulations performed with TRNSYS. The simulated values obtained in simulations with Polysun show minor deviations due to the application of the one-zone model, as mentioned earlier.

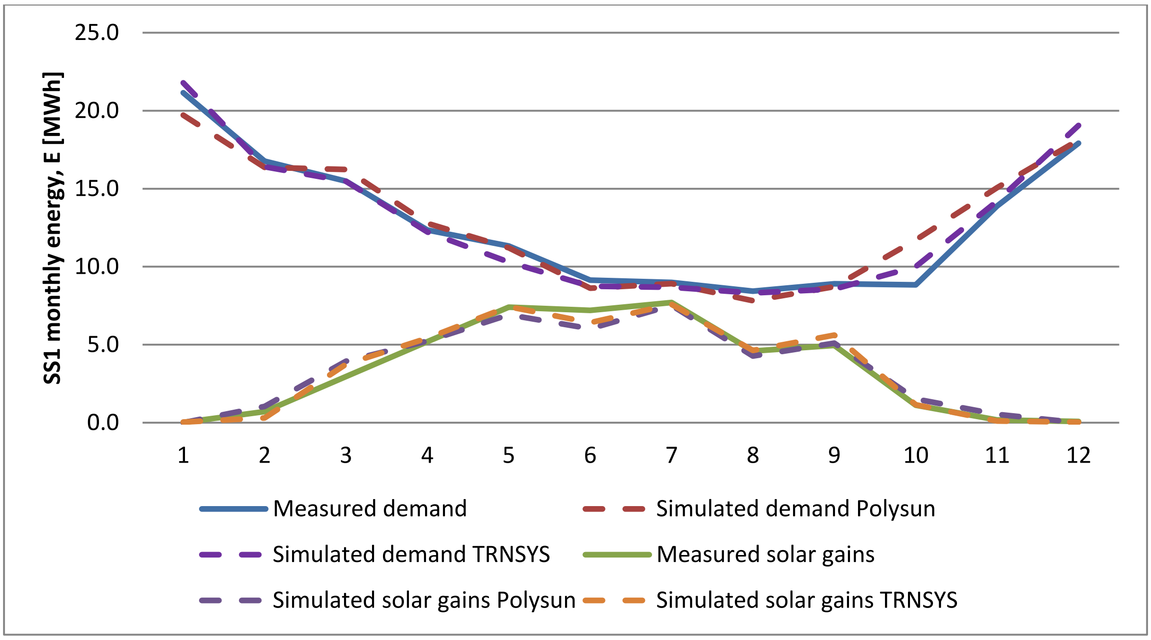

**Fig. 5: Measured vs. simulated in TRNSYS and Polysun heat loads and solar heat to storage for SS1 in 2014**

## 4. Model comparison

Table 2 and 3 below show comparison between measured and simulated values of key figures. The simulation results obtained with TRNSYS show very good agreement at production and load sides. Relative deviation on an annual basis for each key figure is lower than 1.5 %.

Polysun model has the highest deviation from measured value for space heating, which was partly compensated by calibrating distribution losses to achieve expected solar performance. Therefore, production side has very good agreement with measured data. Relative deviation on an annual basis is lower than 1.5 %.

**Tab. 2: Monitored and simulated in TRNSYS yearly key figures, and the deviation between these values**

| Parameter | Monitored [MWh] | Simulated [MWh] | Deviation [MWh] | Deviation, % |
|---|---|---|---|---|
| Space Heating | 71.9 | 72.6 | 0.7 | 1.0 |
| DHW | 45.2 | 44.7 | -0.5 | -1.2 |
| Distribution losses | 36.1 | 36.5 | 0.4 | 1.2 |
| Solar to storage | 42.1 | 42.5 | 0.4 | 0.8 |
| Primary culvert heat | 111.1 | 110.6 | -0.5 | -0.4 |

**Tab. 3: Monitored and simulated in Polysun yearly key figures, and the deviation between these values**

| Parameter | Monitored [MWh] | Simulated [MWh] | Deviation [MWh] | Deviation, % |
|---|---|---|---|---|
| Space Heating | 71.9 | 77.5 | 5.6 | 7.8 |
| DHW | 45.2 | 44.4 | -0.8 | -1.6 |
| Distribution losses | 36.1 | 33.5 | -2.6 | -7.3 |
| Solar to storage | 42.1 | 42.1 | 0 | 0 |
| Primary culvert heat | 111.1 | 113.1 | 2 | 1.2 |

## 5. Sensitivity analysis

For the sensitivity analysis weather data for a standard average year shall be used. For this purpose, Meteonorm data for this location is chosen. Therefore, the first study is sensitivity of the models to different weather data. Figure 6 and 7 show how simulated values for energy demand and solar gains vary according to the choice of weather data.

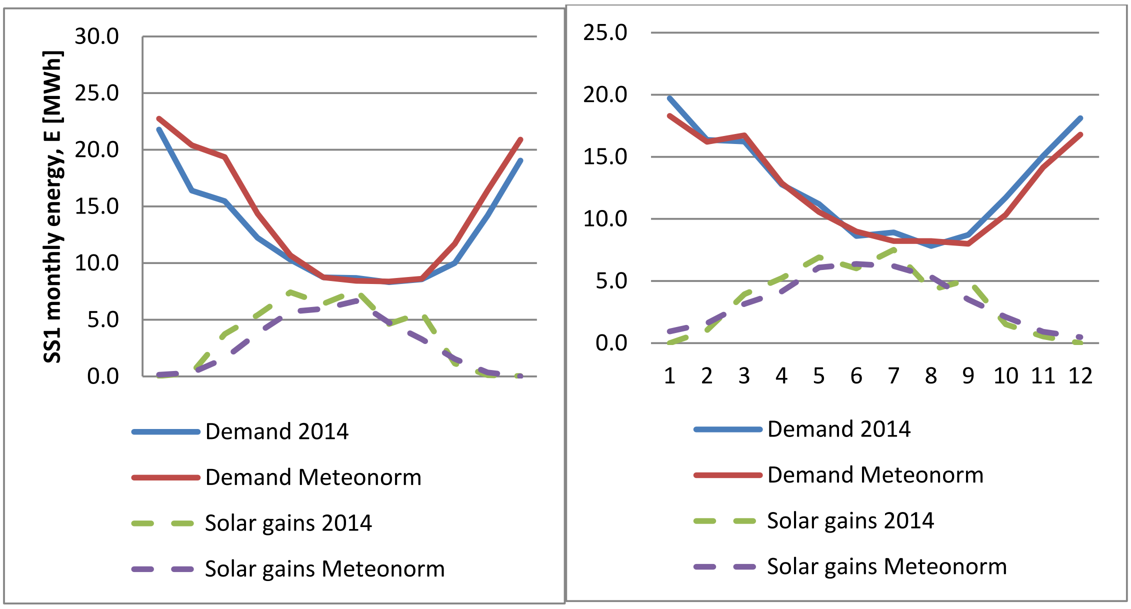

**Fig. 6 and 7: Comparison of Polysun (left) and TRNSYS (right) simulated 2014 data with Meteonorm data: heat loads and solar heat to storage for SS1.**

The Meteonorm average year is colder and has lower solar radiation level than 2014. It corresponds very well with TRNSYS results: annual total demand is higher and annual solar gains are lower with the weather data of the Meteonorm average year.

Polysun shows that even though shapes of the curves are similar to ones from TRNSYS, the absolute values do not reflect adequately the change of weather data. The main reason for it is an uncertainty in the building model, namely thermal performance of the one-zone model the size of which was calibrated according to thermal behavior of 19 multi-zone buildings.

Since the main focus of this study is to evaluate how Polysun can simulate the collector field and the substation as well distribution network and how close it can get to TRNSYS results, further sensitive analysis is done based on key figures normalized to the basic case simulated with the Meteonorm average year. In this way an influence of the uncertainty of the building model can be eliminated and other parts of the model can be studied.

Thus sensitivity analysis consists of two parts. The first part is a study of an influence of density of the heating network on the solar fraction of the sub-station and distribution losses in the system. The density of a distribution network is a relationship between the number of houses and the length of the distribution network. For the present study the number of building is constant and equal to the actual number of buildings at the site. The length of the distribution network is varied from 0.5 to 2.5 times of the actual length. The study showed a good agreement between both tools, as shown in the fig. 8.

The second part of the sensitivity analysis is a study of the influence of different collector field sizes and storage tank sizes on performance of the system in terms of solar energy supplied to the system from the store. Collector field size is varied from 0.5 to 2 times of the basic case. A relative storage volume (storage volume / collector aperture area) is varied for each collector field size from 0.5 to 2 times of the basic case. In this way a matrix of 25 systems is built.

In the fig. 9 matrix results for solar energy supplied to the system from storage are shown. For all cases Polysun results are close to TRNSYS showing consistency between tools.

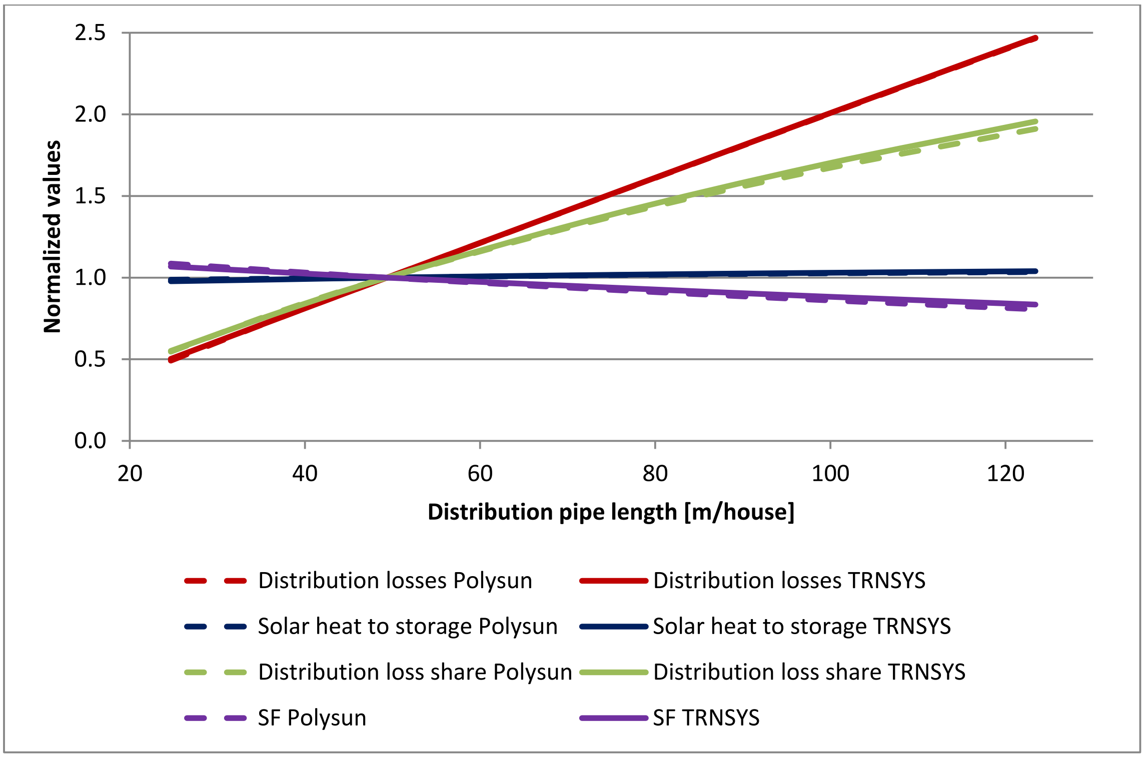

**Fig. 8: Sensitivity analysis of influence of heating network density on district heating system performance (solar fraction, value of distribution losses, solar energy to the system and share of distribution losses in total demand) for TRNSYS and Polysun models**

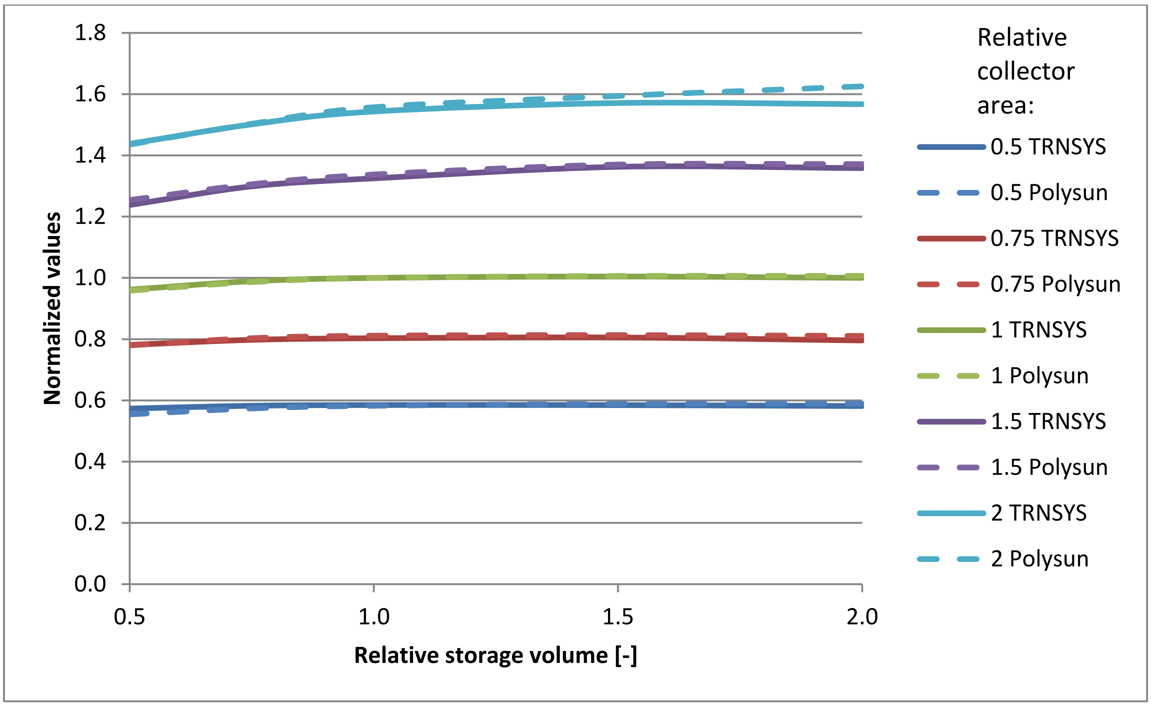

**Fig. 9: Sensitivity analysis of influence of collector and storage sizes on system performance for Polysun and TRNSYS models.**

## 6. Conclusion

Applicability of Polysun and TRNSYS for simulation of block heating solar systems was studied by comparison with measured data and performing a parametric study. As a reference case Vallda Heberg decentralized solar district heating system was chosen. It was proven that if enough measured data is available and controlling strategy as well as main system parameters are known it is possible to calibrate models in Polysun and TRNSYS with high degree of accuracy. Relative deviations of all annual key figures of both tools compare to the real case are low and monthly values are also in good agreement. Relative deviations of annual key figures for TRNSYS and Polysun are < 2% and < 8% respectively.

In order to compare model behaviors a sensitivity analysis was performed. First of all, instead of actual weather data Meteonorm average year data was used. With the new weather data TRNSYS showed expected performance. Since the year 2014 was rather warm, total demand for the average year is higher than for 2014. For the same changes in boundary conditions Polysun showed poor agreement – total demand for the average year approximately equals to the one in 2014 and is significantly higher than TRNSYS. It means that the building model in Polysun does not respond adequately to change in the weather data. The main reason is that the one-zone building model is not suitable to simulate such complex case (multi-zone building with complex interaction between zones).

Then two cases were studied; influence of a density of the heating network on a solar fraction of the sub-unit and distribution losses in the system; and influence of different collector field sizes and storage tank sizes on performance of the system in terms of solar energy supplied to the system and a solar fraction. In order to eliminate influence of the building model, key figures were normalized to the base case and plots were built based on these normalized values (fir. 8 and fig. 9). The plots show very good agreement between Polysun and TRNSYS. It means that Polysun simulates the changes in the same way as TRNSYS for collector and store sizes as well as pipe length/energy density of the network.

## Acknowledgement

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