Experimental investigations on solar heating/heat pump systems for single family houses

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Preface

In the period 2013-2017 the project “Experimental investigations on solar heat pump systems for single family houses” is carried out at Department of Civil Engineering, Technical University of Denmark. The aim of this project is to increase the knowledge of the heat and mass transfer in the combined solar heating/heat pump system type when the heat pump makes use of a horizontal ground source heat exchanger. The knowledge is gained by experimental investigations on a solar heating/heat pump system and forms the basis for improved marketed combined solar heating/heat pump systems.

The project is financed by the Bjarne Saxhof foundation.

Background and objective of the project

Combined solar heating/heat pump systems for single family houses have become very popular. The systems can provide all the needed heat for domestic hot water and space heating and the system concepts are very promising.

Why are the systems concepts promising? Because solar energy can be used to increase the inlet temperature to the evaporator and thereby decrease the temperature lift the heat pump has to provide in order to meet the required flow temperature towards the consumer resulting in better performance of the heat pump system. Solar energy can be directly used to cover the consumption and the heat pump will not be activated and solar energy can be used to recharge the ground source resulting in stable ground source temperature over many heating seasons which gives the heat pump stable operation conditions and keeps the performance high. The heat pump can also be used for cooling purposes.

The main components of the solar heating/heat pump system are the solar collector, the storage tank and the heat pump. There are many ways of designing and combining all the different components of the solar heating/heat pump systems and controlling the systems. The most widely used energy sources for the heat pumps are the ambient air, ground source heat exchanger or borehole heat exchanger. In cold winter periods, heat pumps that make use of ambient air as heat source run with low efficiency when the ambient air temperature gets low. When the ambient temperature gets below the freezing temperature, ice will build up on the cold side heat exchanger, the evaporator. The heat pump uses a portion of the produced heat to melt the ice on the heat exchanger. At a certain temperature level, the heat pump will provide all the needed heat from a build in electrical heater. The heat source temperature is more stable with ground source heat exchanger or borehole heat exchanger. In systems with ground source heat exchanger or borehole heat exchanger, excess energy production by the solar collectors can be used to recharge the ground heat source and prevent the system from overheating.

Until now, a large number of these promising combined solar heating/heat pump systems have been installed. Unfortunately, the experiences from the systems put in operation are often not as positive as expected. The efficiency of the systems is low and the systems are relatively costly and complicated.

Hence there is a large need to increase the knowledge of the heat and mass transfer in these combined solar heating/heat pump systems and based on that knowledge to assist the manufacturers to improve the systems.

This project will establish the basis for understanding and improving combined solar heating/heat pump systems with ground source heat exchangers for single family houses by detailed experimental investigations on such a system.

The experimental investigations on the system are carried out at the Technical University of Denmark, Department of Civil Engineering in the period 2013-2017.

Details of the solar heating/heat pump system and the horizontal ground source heat exchanger

The solar heating/heat pump system consists of a tank-in-tank storage with domestic hot water in the inner tank and still water for space heating in the outer tank, flat plate solar collectors and a ground-to-water heat pump. The heat pump is connected to a horizontal ground source heat exchanger. Domestic hot water and space heating water are distributed to the heat distribution system from the tank-in-tank storage. To the right in Figure 1, a picture of the test facility can be seen. The roof is facing south and has a tilt of 45°. The three solar collectors are installed on the south facing roof and can be seen in the upper left corner of the roof. The ground source heat exchanger is installed in the ground in front of the roof.

The different parts of the complete system are described below.

The horizontal ground source heat exchanger

Figure 1 shows a horizontal layout of the ground source heat exchanger and a picture of the location of the installation.

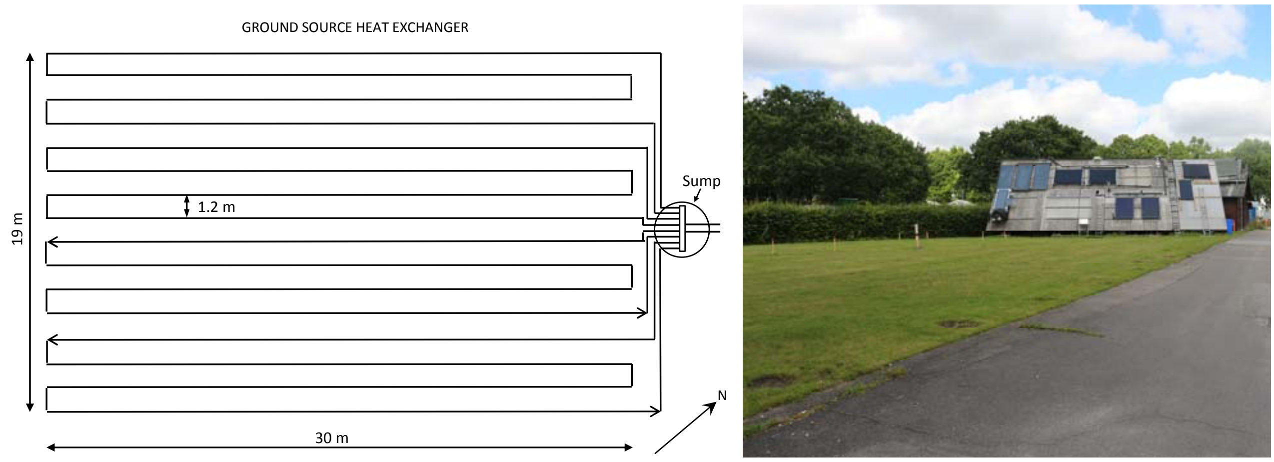


Figure 1. Layout of ground source heat exchanger and the location of the installation.

The ground source heat exchanger has 4 slings, each with a length of 120 meter. The total pipe length is 480 meter. The slings are laid 1 meter below the soil surface with a pipe distance of 1.2 meter. In this way, each sling has 4 connected pipes in which the fluid flows back and forth and the individual pipes are being referred to as hoses. The whole heat exchanger has 16 hoses. The pipes are connected to a manifold located in a sump. The four slings are identical and it is assumed that the flow will be equally distributed in the slings. Feeding tubes connect the manifold to the heat pump in the indoor test facility. The heat ground source heat exchanger pipes are PE80 with an outer diameter of 40 mm and an inner diameter of 35.4 mm. The feeding tubes between the manifold and the heat pump are PE80 with an outer diameter of 50 mm and an inner diameter of 44.2 mm. The fluid used in the ground source heat exchanger is a mixture of 50 % isopropyl alcohol (IPA) and 50 % water. The ground source heat exchanger covers an area of 19 m x 30 m.

As a rule of thumb, the ratio between the total length of the heat exchanger and the heating power of the heat pump should be between 20 – 40 m/kW. In this investigation the used heat pump has a maximum heating power of 12 kW corresponding to a ratio of 40 m/kW heating power of the heat pump.

Figure 2 shows some pictures taken during the construction of the ground source heat exchanger.

Figure 2. Pictures taken during the construction of the ground source heat exchanger.

Two boreholes are drilled to the depth of 10 meter. The first borehole (B1) is located 10 meters away from the edge of the ground source heat exchanger and the second borehole (B2) is located in the centre of the ground source heat exchanger, see Figure 3. The marking pole seen in the left picture marks the location of B2 in the middle of the ground source heat exchanger. The tile in the right picture marks the location of B1 next to the white container building which can be seen in all three pictures. The marking pole can also be seen in Figure 1. As it can be seen in the figures, the ground with B2 receives solar radiation all day while the ground with B1 is mostly shaded from solar radiation.

Figure 3. Location of boreholes B1 and B2.

The two boreholes revile the soil types and the boreholes are subsequent used to place temperature sensors in order to study the temperature distribution in the ground below and next to the heat exchanger. Table 1 shows the soil types in the boreholes and the vertical extend of the soil type. The relative kote of the location is 10 meter and the ground water level is 15 meter below the soil surface.

Table 1. Soil types.

Depth below the soil surface, B1 [m]	Soil type in borehole, B1	Depth below the soil surface, B2 [m]	Soil type in borehole, B2
1.6	Mulch, sandy, clay, black	1	Gravel, mixed with mulch, brown
3.2	Clay, fat, sandy, brown	3	Clay, sandy, brown
7.8	Sand, fine-grained, brown	10	Sand, fine-grained, brown
10	Sand, fine-grained, silty, brown		

The solar heating/heat pump system

Figure 4 shows the layout of the solar heating/heat pump system. Also the measurement points used by the control system to operate the system can be seen in the figure.

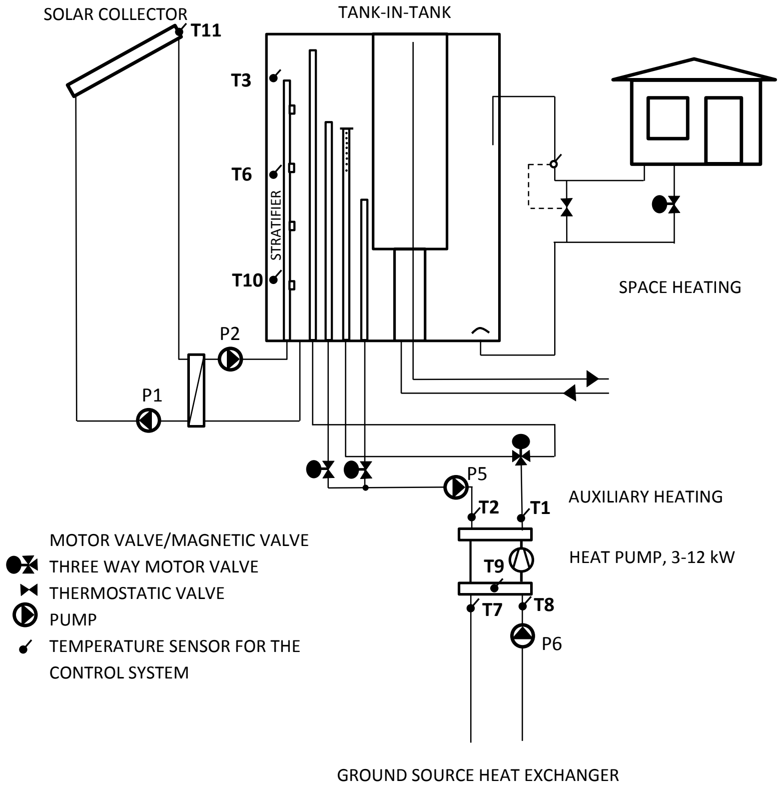


Figure 4. Schematic drawing of the Layout of the solar-heat pump system.

The storage

The storage is a tank-in-tank with a total volume of 725 liter where the inner domestic hot water tank has a volume of 175 liter.

In the still water tank, there is a stratification pipe from the German company Solvis GmbH & Co. KG for charging the tank with heat from the solar collector. The stratification pipe is made of polypropylene (PP) with an outer diameter of 60 mm and a wall thickness of 3 mm and with lockable openings acting as "non-return" valves. The distance between the centres of each opening is about 292 mm. Another 4 specially fabricated pipes are used for charging the tank with heat from the heat pump. The specially fabricated pipes are made of polyoxymethylene (POM) with an outer diameter of 80 mm and an inner diameter of 35 mm. The thick pipe wall minimizes heat transfer between the hot water in the pipe and the colder water in the storage tank during operation of the auxiliary heating loop. With the arrangement of pipes, the storage tank can be charged with domestic hot water at a high temperature level in the top of the storage tank and with space heating water at a lower temperature level in the middle part of the storage tank. The auxiliary heated volume for domestic hot water is 183 litres with 124 litres in the outer storage tank and 59 litres in the inner storage tank. The auxiliary heated volume for space heating is 189 litres with 128 litres in the outer storage tank and 61 litres in the inner storage tank. Figure 5 shows pictures of the two pipes used to charge the storage tank with space heating water. The hot water inlet from the heat pump to the storage tank is through holes in the long pipe and the outlet from the storage tank to the heat pump is through the short pipe.

Figure 5. Pictures of the two pipes used to charge the storage tank with space heating water.

Heat for domestic hot water is taken from the top of the domestic hot water tank and lead out at the bottom of the tank via a crosslinked polyethylene (PEX) pipe that stretches from the bottom to the top of the tank. Domestic cold water is lead into the bottom of the domestic hot water tank via a direct inlet.

The outlet for the space heating loop is located in the domestic hot water volume. Therefore, heat for the space heating loop is taken from the space heating volume in the tank and lead to the outlet via a bended pipe inserted into the tank. The pipe is made of a composite of plastic (cross-linked polyethylene) and aluminium (ALUPEX). The return from the space heating loop is lead into the tank via a direct inlet located under a half ball baffle plate with a diameter of 200 mm, in order to avoid mixing in the storage tank. Except for the outlet for the space heating loop located in the upper hot part of the storage tank, all other in- and outlets are located at the bottom of the storage tank.

The storage tank is manufactured by the Danish company Ajva ApS. Figure 6 shows the engineering drawing of the tank-in-tank storage and pictures of the tank-in-tank storage in the test facility without and with insulation.

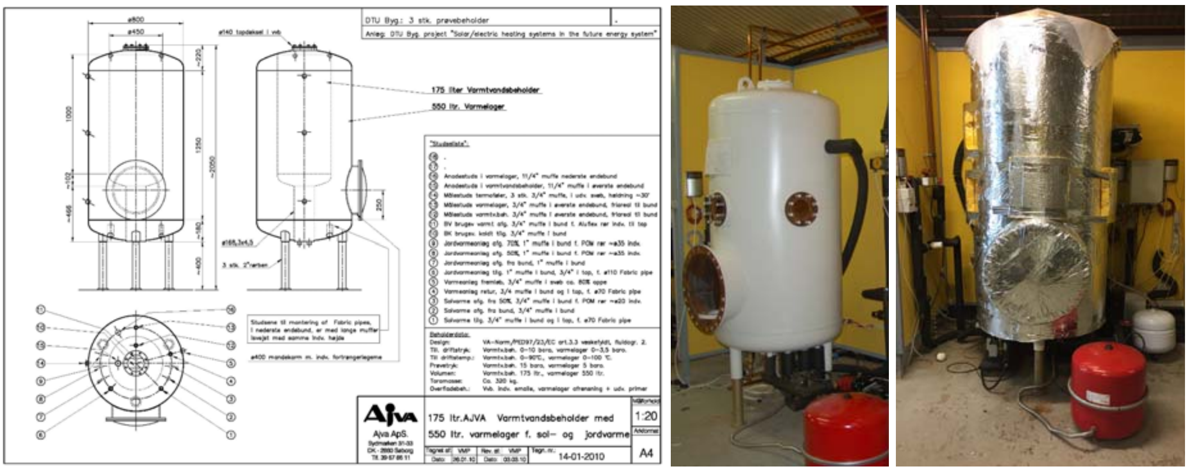


Figure 6. Engineering drawing (in Danish) and pictures of the tank-in-tank storage.

The solar collector

From three flat plate solar collectors with a total transparent area of 9 m^2, solar energy is transferred to the storage tank via an external plate heat exchanger. The solar collector type is BA30 and the solar collectors are manufactured by the former Danish company Batec A/S. The solar collector has an absorber made of cupper with manifold pipes in the top and the bottom of the collector and 8 parallel strips. The outer dimensions of the solar collector are 2.82 m x 1.12 m x 0.085 m. Figure 7 shows a picture and schematically illustration of the solar collector design. All three solar collectors can also be seen in the picture in Figure 1.

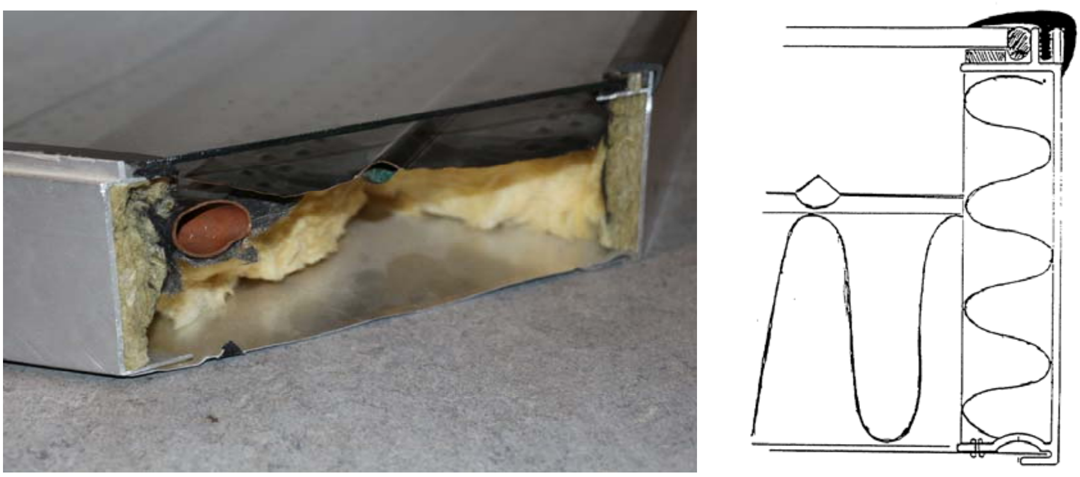


Figure 7. Picture and schematically drawing of the solar collector design.

The circulation pumps in the primary and the secondary solar collector loops are type NMT Plus 25-80-180 from IMP PUMPS and type UPS 25-40-180 from Grundfos respectively.

The solar collector is operated with start and stop temperature differentials of 5 K and 3 K respectively. The pumps will be stopped if the temperature in the solar collector reaches 120 °C or the temperature in the top of the tank reaches 90 °C.

There have been operational problems with the solar collectors and the amount of solar energy delivered to the storage tank has been less than expected. Therefore new identical solar collectors are installed. The new solar collectors came in operation from June 2 2017 and they work as expected.

The heat pump

A ground-water heat pump based on a Bock HG single stage piston compressor, Type HGX 12P/110-4 S with a heating capacity of 3-12 kW is used as auxiliary energy source. The coolant is R134a. The heat pump is manufactured by the Danish company Salling vaske- og køleservice A/S. Figure 8 shows pictures of the heat pump installed in the test facility. In the right picture, the heat pump is open and some of the individual components can be seen.

Figure 8. Pictures of the heat pump.

The pumps to circulate the flow to the storage tank and to the ground source heat exchanger are built into the heat pump cabinet. The circulation pump between the heat pump and the storage tank is type Alfa 1 25-60-180 from Grundfos and the circulation pump used between the heat pump and the ground source heat exchanger it type Magna 25-60-180 from Grundfos. The control system is type LMC 320 from the company Lodam Electronics A/S. The control system controls the solar collector loop and the supply of auxiliary energy from the heat pump to the tank based on input from temperature sensors, see Figure 4. The temperature sensors are located in the outlet from the solar collector and in the bottom, in the space heating volume and in the domestic hot water volume of the storage tank. The temperature sensors used by LMC 320 are type NTC with an accuracy of ±1 K. A 3-way motor valve directs the heat from the heat pump towards the domestic hot water volume or the space heating volume in the storage tank depending on the measured temperatures in the respective volumes. Figure 9 shows the two pumps and the 3-way valve in the heat pump cabinet.

Figure 9. The two pumps and the 3-way motor valve in the heat pump.

Domestic hot water production has higher priority than space heating water production.

The settings for the heat pump operation are set by the user. Table 2 shows three different control modes for the heat pump used in the test period.

The compressor is designed to operate on a nominal compressor frequency of 50 Hz in on/off mode. In modulating mode, a frequency inverter allows the compressor to be operated with a frequency between 30 Hz and 70 Hz. The power consumption of the compressor is a function of the compressor frequency and higher frequency means higher power. Hence the frequency inverter allows the heat pump to increase the compressor power in order to satisfy the heating demand. For example will the compressor power increase gradually until the set point temperature is reached or until the maximum power is reached in case the set point temperature cannot be reached before the maximum power is reached.

During domestic hot water production in modulating mode, the heat pump runs with a user defined fraction of full power. The used defined fraction is 80 % during the whole test period. In on/off mode, domestic hot water is produced with the nominal power.

During space heating water production, the power of the heat pump is either controlled by the frequency inverter in modulation mode or by the nominal frequency in on/off mode.

As it will become obvious later in the report, the frequency available in on/off mode is only 30 Hz and not the nominal frequency of 50 Hz. Unfortunately the frequency for the compressor in on/off mode is the last used frequency on the frequency inverter which is the lowest frequency that the compressor can operate on. This means that the heat pump cannot always reach the set point temperatures and operates in domestic hot water preparation mode most of the time.

The settings for domestic hot water preparation are determined by a set point temperature (T3) and a neutral zone. When the temperature T3 is below the set point temperature – neutral zone, the heat pump starts. When the temperature T3 is above the set point temperature the heat pump stops.

The operation conditions for space heating preparation are determined by the set point temperature (T6) and the neutral zone. When the temperature T6 is below the set point temperature – 0.5 · neutral zone, the heat pump starts. When the temperature T6 is above the set point temperature + 0.5 · neutral zone the heat pump stops.

Table 2. Control modes used for the heat pump in the test period.

Control mode	Description
Sup Modul.	Speed control of compressor via a frequency inverter based on supply water temperature to the storage tank. During space heating water preparation, a PI controller keeps the flow temperature from the heat pump as close as possible to the set point temperature + 0.5 · neutral zone. During domestic hot water preparation, the compressor power is 80 % of maximum power.
HTank On/Off.	On/Off control of the heat pump based on fixed power of the compressor and the temperature of the heating accumulator tank (T3 and T6). During space heating water preparation, the compressor starts when T6 is below the set point temperature – 0.5 · neutral zone. The compressor stops when T6 is above the set point temperature + 0.5 · neutral zone. During domestic hot water preparation, the compressor power is 100 % of the fixed power.
HTank Mod.	Speed control of compressor via a frequency inverter based on the temperature (T6) in the storage tank. During space heating water preparation, a PI controller aims to reach the set point temperature + 0.5 · neutral zone temperature of T6. During domestic hot water preparation, the compressor power is 80 % of maximum power.

The space heating loop and the domestic hot water loop

A big uninsulated buffer tank and a cooling system combined with an insulated storage tank act as heat sink for both the space heating loop and the domestic hot water loop, see Figure 10.

Large circulation pumps drive the flow in these loops for the whole test facility. Motorized valves, type Honeywell are used to activate the space heating and the domestic hot water loops of the solar heating/heat pump system. In the space heating loop also a thermostatic valve from Danfoss is built in between the flow and return pipe to the space heating loop. In this way, cold water from the return from the space heating loop can be mixed with the hot water to the space heating loop.

Figure 10. Cooling system and heat sink in the test facility.

The different operation stages during charge and discharge

Figure 11 shows the hydraulic loops in operation in the different charge operation stages which are: auxiliary heat to the domestic hot water volume (left), auxiliary heat to the space heating volume (middle) and solar energy to the whole storage tank volume (right).

Figure 12 shows the hydraulic loops in operation during domestic hot water draw off (left) and space heating water draw off (right).

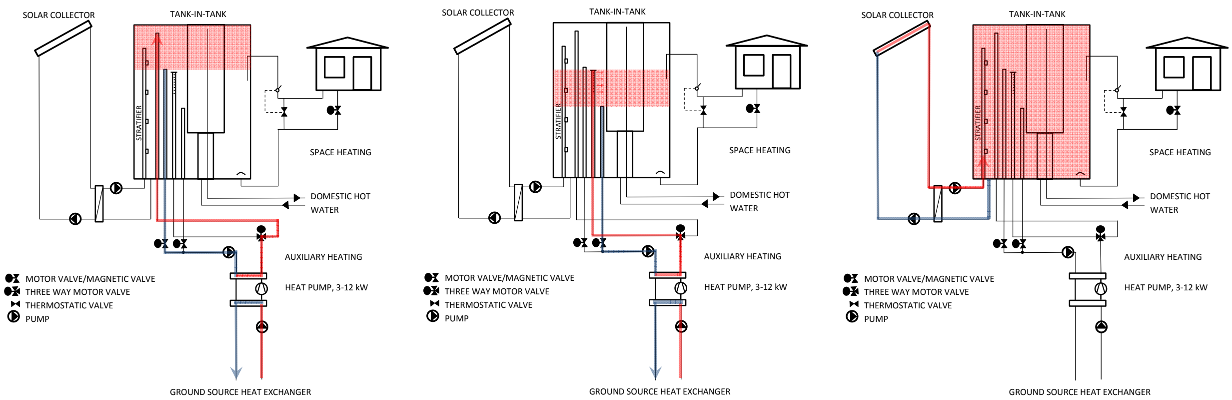


Figure 11. Charge operation stages of the solar heating/heat pump system. Left: Auxiliary energy from heat pump to domestic hot water volume in the storage tank. Middle: Auxiliary energy from heat pump to the space heating volume in the storage tank. Right: Solar energy to storage tank.

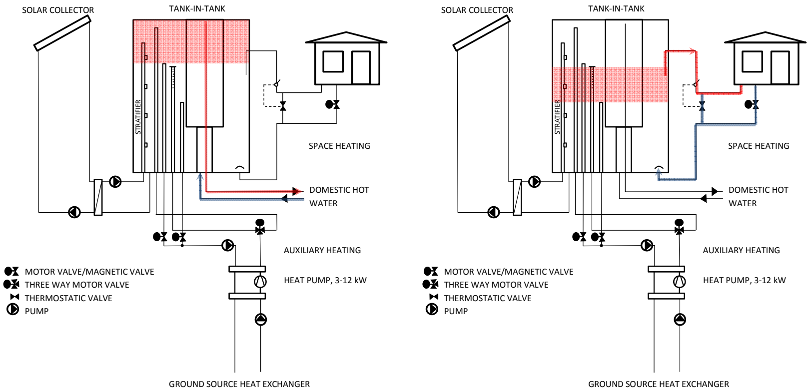


Figure 12. Discharge operation stages of the solar heating/heat pump system. Left: Domestic hot water draw off. Right: Space heating water draw off.

The experimental set up

For detailed monitoring of the whole system, temperatures and volume flow rates are measured in all loops. Temperatures are measured both in the still water volume and in the domestic hot water volume in the tank-in-tank storage and temperatures are measured in the ground above, below and next to the ground source heat exchanger. Also the ambient temperature, the indoor temperature in the test facility and the total solar irradiance on the solar collectors are measured. The time resolution of the measurements is 1 minute.

The solar heating/heat pump system

Figure 13 shows the design of the solar heating/heat pump system and all the measurement points.

Table 3 shows the actual position of the temperature sensors in the storage tank. The total inner height of the storage tank is approximately 1568 mm, see Figure 6. Note also that T28 is only located 14 mm into the storage tank. Consequently, sometimes T28 is located in air in the top of the storage tank.

Table 4 shows the location of charge and discharge loops in the storage tank.

All the measurement points which are part of the monitoring system are shown in orange. The control system makes use of its own set of sensors which are not a part of the monitoring system, although these temperatures can be accessed manually via the control system at a time resolution of 2 minutes. All the measurement points which are part of the control system are shown in bold black.

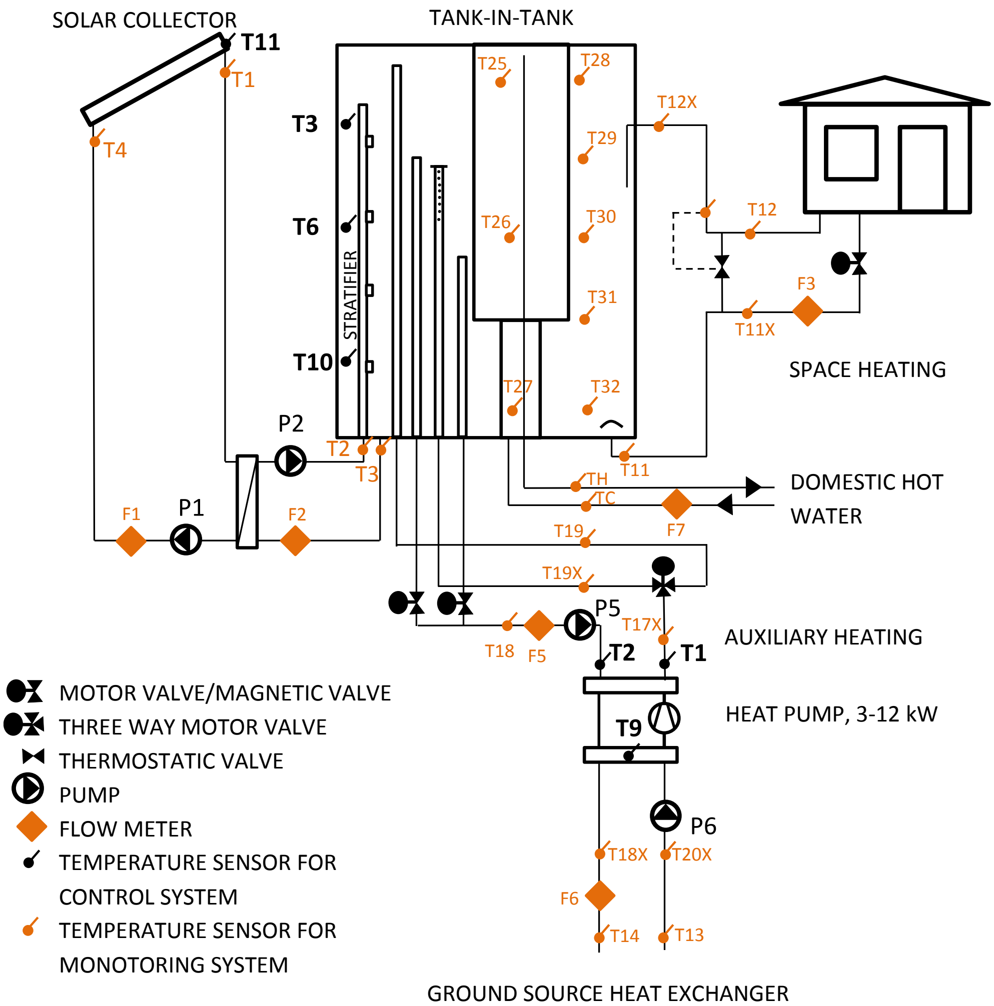


Figure 13. The solar heating/heat pump system with measurement points.

Table 3. Position of temperature sensors in storage tank.

Temperature sensors in storage tank	Position from bottom of storage tank [mm]
Control system	
T3	1255
T6	835
T10	320
Monitoring system	
T25	1528
T26	873
T27	231
T28	1554
T29	1233
T30	898
T31	577
T32	258

Table 4. Position of pipes in the storage tank

Pipes in the storage tank	Upper position measured from bottom of storage tank [mm]
Auxiliary heating loop	
DHW volume inlet from HP	1400
DHW volume outlet to HP	1115
SH volume inlet from HP	1085
SH volume outlet to HP	715
Domestic hot water loop	
DHW outlet to consumer	Top of tank
DCW inlet from utility	Bottom of tank
Space heating loop	
SH outlet to consumer from SH volume	1000
SH outlet to consumer from storage tank	1250
SH inlet from consumer	Bottom of tank
Solar collector loop	
Stratification pipe	1335

The ground source heat exchanger

Temperatures are measured in the ground below the hoses in the 10 meter deep borehole, B2 with temperature sensors every meter. B2 is located in the middle of the ground source heat exchanger. The whole surface area above the ground source heat exchanger is exposed to solar radiation during the day. The identical borehole, B1 is located 10 meter away from the edge of the ground source heat exchanger. B1 is located in a shaded area and does not receive much solar radiation, see Figure 1 and Figure 3. The temperature sensors in the boreholes are referred to as B1_Z and B2_Z. The Z refers to the depth of the temperature sensor below the soil surface and can assume the values 1 corresponding to -1 m, 2 corresponding to -2 m, …and 10 corresponding to -10 m.

The hoses are numbered 1, 2, …, 16 from east to vest. Along the hoses, temperature sensors measure the ground temperature in the level of the hoses, 0.5 m above the hoses and 0.5 meter below the hoses. The temperature sensors are located in two lines perpendicular to the flow direction. The temperature sensors are only mounted in one half of the ground source heat exchanger, as symmetry in the temperature distribution is assumed. The first row of temperature sensors is located in the first fourth of the ground source heat exchanger and the second row of temperature sensors is located in the middle of the ground source heat exchanger. The temperature sensors in the first row are referred to as Hx_1_z. The x refers to the hose number and can assume values from 1 to 8. The 1 refers to the measurement line. The z refers to the depth of the sensor and can assume the values 1 corresponding to -0.5 m, 2 corresponding to -1 m and 3 corresponding to -1.5 m. The temperature sensors in the second measurement line are referred to as Hx_2_z. The x and z are as explained above.

Also the inlet and outlet temperatures in the feeding tubes are measured.

Figure 14 shows a top view of the ground source heat exchanger and the location of the temperature sensors in the horizontal direction and Figure 15 shows the cross section A-A and the location of the temperature sensors in the vertical direction. The location of the measurement points makes it possible to measure the ground temperatures at the inlet and the outlet of both an outer sling, located at the edge of the ground source heat exchanger and an inner sling, located in the middle of the ground source heat exchanger.

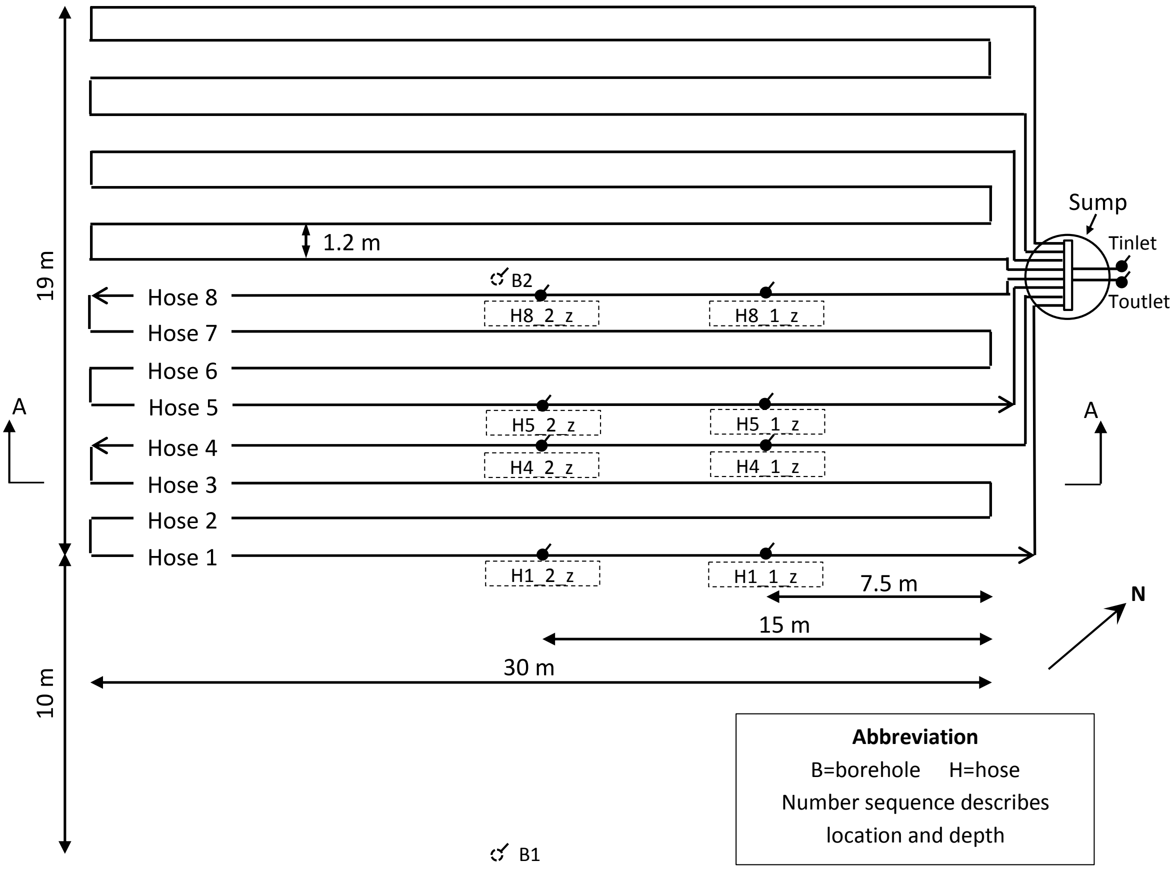


Figure 14. Top view of the ground source heat exchanger and the location of the temperature sensors.

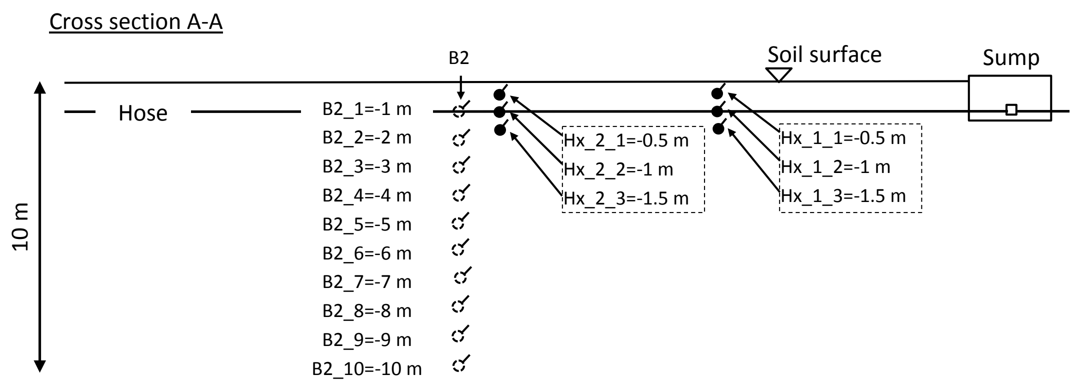


Figure 15. Cross section of the ground source heat exchanger and the location of the temperature sensors.

The measurement equipment

The measurement equipment used is shown in Table 5. The flow meter in the primary solar collector loop is calibrated with a glycol/water mixture.

Table 5. Measurement equipment.

Equipment	Type	Location	Accuracy
Flow sensor	Brunata HGS5-R4	HP-Ground loop	± 5 %
	Brunata HGQ1-R3	HP-Tank loop	± 5 %
	Brunata HGQ1-R0	Solar and SH loops	± 5 %
	Clorius Combimeter 1.5 EPD	DHW loop	± 2-3 %
Temperature sensor	Copper/constantan, type TT		± 0.5 K

Test conditions and system configurations in the test period

The measurements of the ground temperatures are started on August 23 2013. On November 26 2014 the solar heating/heat pump system is put in operation. The system covers only domestic hot water consumption until September 30 2015 where also the space heating loop is activated.

The Settings for the temperature levels in the domestic hot water volume and in the space heating volume in the storage tank are varied during the test period. Also different control strategies and operation conditions for the heat pump have been investigated during the test period.

Further, more measurement points have been added during the test period in order to determine all necessary energy amounts. Also, the tank design has been changed during the test period in order to avoid mixing between the domestic hot water volume and the space heating volume in the storage tank.

Test conditions

Domestic hot water is drawn three times a day in the morning, at noon and in the evening. The tappings are carried out in three equal energy amounts of 1.5 kWh. This corresponds to a daily hot water consumption of 100 litres heated from 10 °C to 50 °C. In total, 4.5 kWh are tapped every day. The volume flow rate during tapping is around 7.5 l/min.

Space heating is not adjusted to cover a specific space heating demand. Space heating water is drawn from the storage tank every day during the whole year and the number of daily periods with heat demand and the flow temperatures are varied. The volume flow rate is always around 5 l/min. Figure 16 shows the monthly space heating consumption for the solar heating/heat pump system in the test period, see also Table 13. The figure also show the monthly space heating demand for a single family house of 140 m^2 with a yearly space heating demands per m^2 floor area of 30 kWh (SFH 30) corresponding to a yearly space heating demand of about 4 700 kWh. The single family house does not use space heating in the period May - September. It can be seen that the monthly space heating consumption of the solar heating/heat pump system is similar to the consumption of SFH 30 during the period October – April.

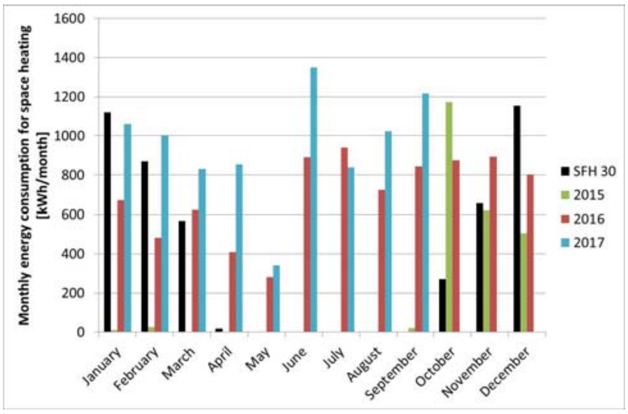


Figure 16. Space heating consumption in test period and space heating consumption for a single family house with a space heating demand of 30 kWh/m^2/year.

Table 6 shows the control and operation conditions in the test period. The table also shows the storage tank design used. The storage tank design is explained in the next section about different system configurations tested.

Table 6. Control and operation conditions for the solar heating/heat pump system in test period.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Nov 5 2015 – Nov 9 2015	Sup modul	50.5 °C / 4 K	25 °C / 4 K	a)
Nov 10 2015 – Mar 16 2016	Sup modul	50.5 °C / 4 K	25 °C / 4 K	b)
Mar 17 2016 – May 10 2016	Sup modul	50.5 °C / 4 K	35 °C / 4 K	b)
May 11 2016 – Jun 14 2016	Sup modul	50.5 °C / 4 K	35 °C / 4 K	c)
Jun 15 2016 – Nov 16 2016	Sup modul	55 °C / 4 K	35 °C / 4 K	c)
Nov 17 2016 – Feb 3 2017	HTank on/off	55 °C / 4 K	35 °C / 4 K	c)
Feb 4 2017 – Mar 8 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	c)
Mar 9 2017 – Mar 22 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	d)
Mar 23 2017 – August 28 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	e)
Aug 29 2017 – Sep 7 2017	HTank mod	55 °C / 4 K	45 °C / 15 K	e)
Sep 8 2017 – Sep 18 2017	HTank mod	55 °C / 4 K	35 °C / 5 K	e)
Sep 19 2017 – Sep 30 2017	HTank mod	52 °C / 4 K	35 °C / 5 K	e)

Different system configurations tested

A number of different system configurations have been tested during the project. The differences are mainly in how auxiliary energy is transferred to the tank. In all cases, the thick walled POM pipes are used and they all have in- and outlet at the bottom of the storage tank. The heat pump supplies domestic hot water to the storage tank when the temperature sensor T3 drops below the threshold value and space heating water to the storage tank when temperature sensor T6 drops below the threshold value. The threshold values are set in the controller. Supply of domestic hot water has a higher priority than supply of space heating water.

The system configurations and the location of the sensors used by the control system can be seen in Figure 17. The configurations are named a), b), c), d) and e).

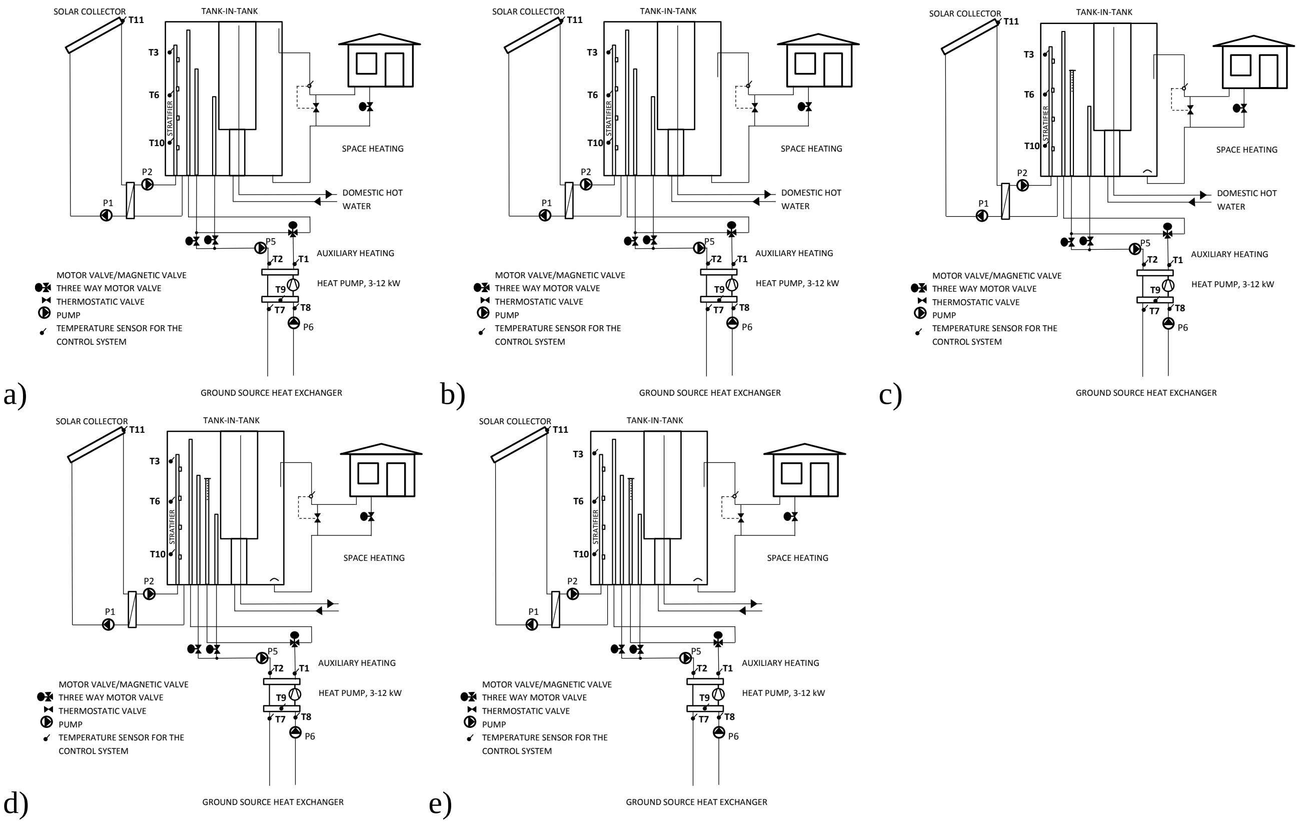


Figure 17. Different system configurations tested.

Configuration a): Three pipes are used to supply both domestic hot water and space heating water to the storage tank. When supplying domestic hot water to the storage tank, hot water is lead in through the longest pipe and colder water is lead out through the middle pipe. When supplying hot water for the space heating volume, hot water is lead in through the middle pipe and colder water is lead out through the shortest pipe. The drawback of this configuration is mixing when space heating water is supplied to the tank. Further, the flow pipe for the space heating loop is mounted wrong. It is pointing upwards instead of downwards and water for the space heating loop is taken from the domestic hot water volume instead of from the space heating volume. Finally, the return from the space heating loop is lead directly into the storage tank and is in this way causing mixing.

The heat pump starts and stops continuously during discharge periods because all the heat is taken from the top of the storage tank. T3 is often cooled below the required temperature level in the top of the storage tank and this causes the heat pump to start up in domestic hot water production mode every time.

Configuration b): same as configuration a) except for the flow pipe for the space heating loop which is turned 180°.

The number of heat pump starts and stops is reduced. The heat pump still operates in domestic hot water mode most of the operation time. The reason is that mixing during space heating operation mode causes the temperature T3 to drop below the required temperature level in the top of the storage tank. This causes the heat pump to switch to domestic hot water production mode.

Configuration c): Same as b) except for the changes of the middle pipe, the shortest pipe and the return inlet from the space heating loop. The middle pipe is closed at the top and 96 holes with a diameter of 10 mm are drilled in the upper part of the pipe along the circumference, see Figure 5. The inlet velocity is in this way reduced to 3 cm/s when supplying space heating water to the storage tank. In this way the degree of mixing is reduced. The shortest pipe is shortened by 9 cm. In this way, the distance between the pipe outlet and the temperature sensor T6 is increased from 3 cm to 12 cm. The return inlet from the space heating loop is also equipped with a half ball baffle plate with a diameter of 20 cm. In this way the degree of mixing is reduced. The drawback of this configuration is mixing when domestic hot water is supplied to the storage tank because the return from the storage tank to the heat pump is through the holes in the middle pipe which are located in the space heating volume. In this way, the space heating volume is heated by the water from the domestic hot water volume.

The heat pump is now operating in space heating water preparation mode in more and longer periods. The heat pump still switches to domestic hot water preparation mode during operation of the space heating loop. This happens because T3 in the domestic hot water volume is cooled during draw off for the space heating loop and possible due to mixing during space heating water supply from the heat pump. The pipe between the space heating volume and the outlet from the storage tank, located in the domestic hot water volume contribute to the cooling of T3. Of course, the heat pump also switches to domestic hot water preparation mode after domestic hot water draw off.

Configuration d): Four pipes are used to supply domestic hot water and space heating water to the storage tank. The two longest pipes are used as in- and outlet when domestic hot water is supplied to the storage tank while the two shortest pipes are used when supplying space heating water to the storage tank. In the storage tank, the outlet from the domestic hot water volume to the heat pump is located 3 cm above the inlet to the space heating volume from the heat pump. The drawback of this system is the location of the temperature sensor T3 in short distance from the inlet to the space heating volume from the heat pump. The sensor may be cooled during heating of the space heating volume and thereby force the heat pump to switch to domestic hot water heating. Also the pipe where the water flows from the space heating volume to the space heating loop via the outlet located in the domestic hot water volume contributes to the unwanted cooling of the domestic hot water volume.

The heat pump is now able to stay in space heating preparation mode during longer periods without switching to domestic hot water preparation mode during space heating discharge. The heat pump still switches from space heating water preparation to domestic hot water preparation during space heating water draw off. The reason is most likely that T3 is cooled when the space heating is drawn from the tank and also due to possible mixing when the space heated volume is heated by the heat pump.

Configuration e): Same as d) except for the temperature sensor T3 which is moved 10 cm up. The distance between the domestic hot water outlet from the storage tank to the heat pump and the temperature sensor T3 is in this way increased from 7 cm to 27 cm and T3 is now located just above the outlet from the storage tank to the space heating loop.

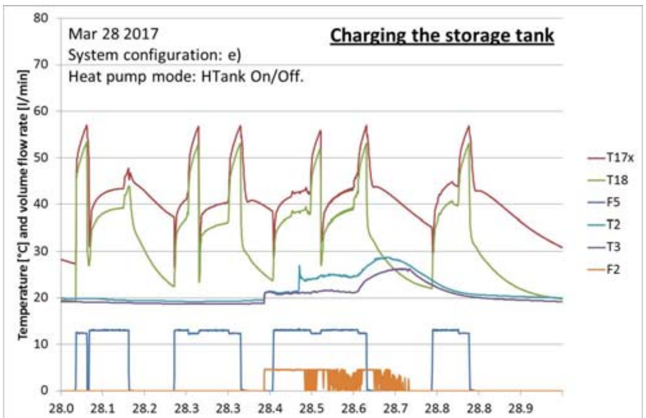
Temperature and flow distribution, power consumption of the heat pump compressor and temperatures in the ground are shown on March 28 2017 where the heat pump is in HTank on/off mode and on August 30 2017 and September 23 2017 where the heat pump is in HTank mod mode. Table 7 shows the operation conditions during the three days. Table 7 is an extract of Table 6.

Table 7. Control and operation conditions for the solar heating/heat pump system in test period.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Mar 23 2017 – August 28 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	e)
Aug 29 2017 – Sep 7 2017	HTank mod	55 °C / 4 K	45 °C / 15 K	e)
Sep 8 2017 – Sep 18 2017	HTank mod	55 °C / 4 K	35 °C / 5 K	e)
Sep 19 2017 – Sep 30 2017	HTank mod	52 °C / 4 K	35 °C / 5 K	e)

Figure 18 shows the temperature and flow distribution in the charging loops and the storage tank and Figure 19 shows the power consumption of the heat pump compressor and the temperature and flow distribution in the discharging loops on March 28 2017.

The figures show that the heat pump switches to domestic hot water preparation mode a few times during heating of the space heating volume and simultaneously space heating draw off. It is most likely due to unwanted cooling by the pipe where the water flows from the space heating volume to the space heating loop via the outlet located in the domestic hot water volume. Therefore, it is expected that the operation conditions will be further improved by improving the design of the space heating draw off for the space heating loop. The outlet from the tank to the space heating loop should be moved down to the space heating volume in the tank or the pipe which is presently used should be insulated much better.



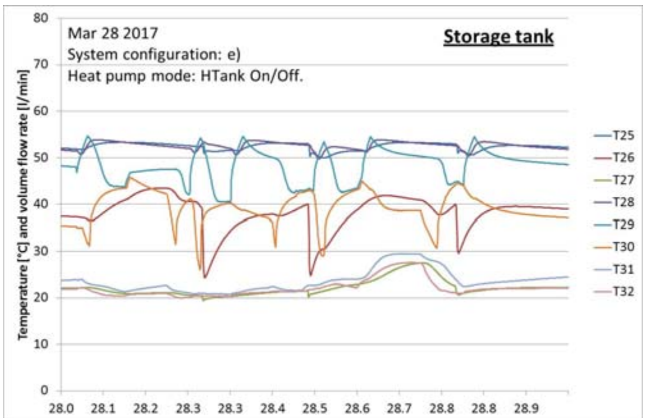


Figure 18. Temperatures and flows in the system on March 28 2017.

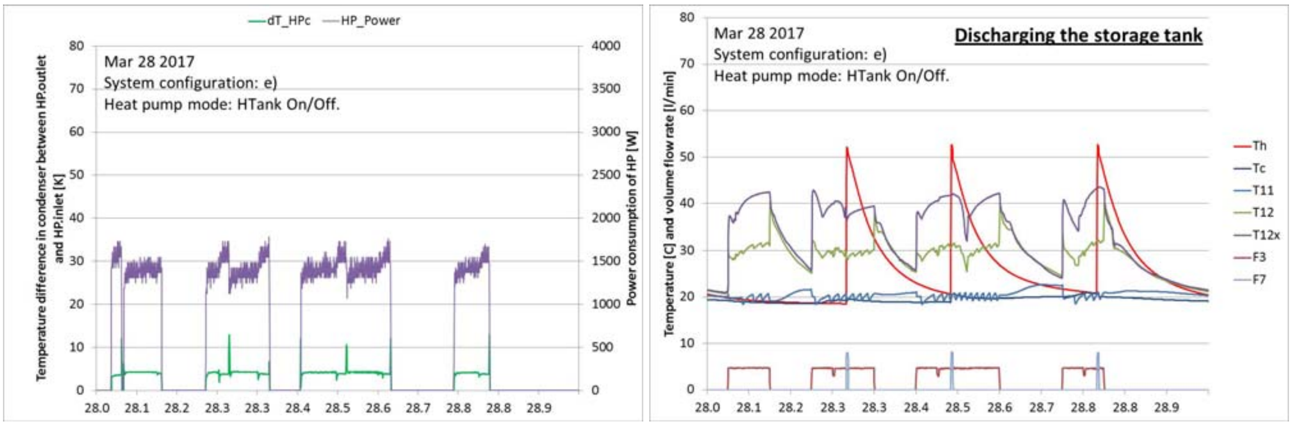


Figure 19. Power consumption of heat pump compressor, temperatures and flows in the system on March 28 2017.

Figure 20 and Figure 21 show the temperatures in the ground 0.5 meter above, next to and 0.5 meter below the ground source heat exchanger, the in- and outlet temperatures and the temperature difference between the in- and outlet temperatures to the ground source heat exchanger on March 28 2017.

The temperature sensors that measure the temperatures between the ground source heat exchanger and the heat pump increase quickly when the heat pump is not in operation. The reason is that the fluid in the pipes and the temperature sensors are heated by the indoor temperature in stand still periods.

The figures show that return temperature to the heat pump from the ground source heat exchanger is similar to the ground temperature in both the outer sling and the inner sling. In the outer sling, a small temperature gradient in the flow direction between measurement line 1 and 2 is present in the inlet hose H4 while no temperature gradient in the flow direction can be observed between measurement line 2 and 1 in the outlet hose H1. Exactly the same picture can be observed in the inner sling, although the temperature gradient in the inlet hose H8 is larger than the same temperature gradient in the inlet hose H4 in the outer sling. It can also be observed that the temperature level in the ground next to the outlet hose H1 at the edge of the ground source heat exchanger is higher than the temperature level in the ground around the other hoses, H4, H5 and H8. The reason is that heat from the surrounding ground is heating up the ground temperatures around the outer sling. The measurements show that the length of the ground source heat exchanger is sufficient with the current heating demand.

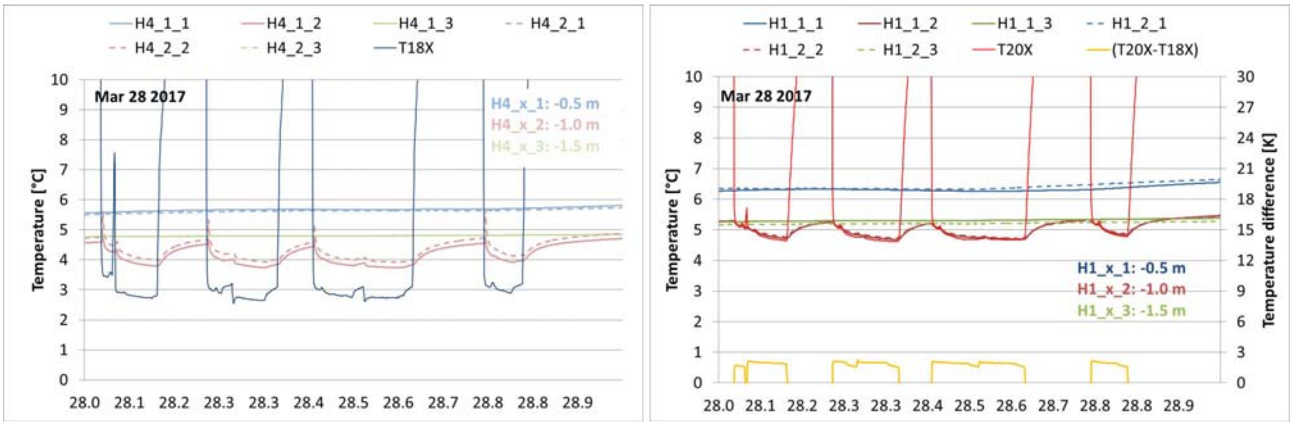


Figure 20. Temperatures in the ground above, next to and below the hoses in the outer sling on March 28 2017. H4_1_z and H4_2_z show the temperatures at the sling inlet and H1_2_z and H_1_1_z show the temperatures at the sling outlet.

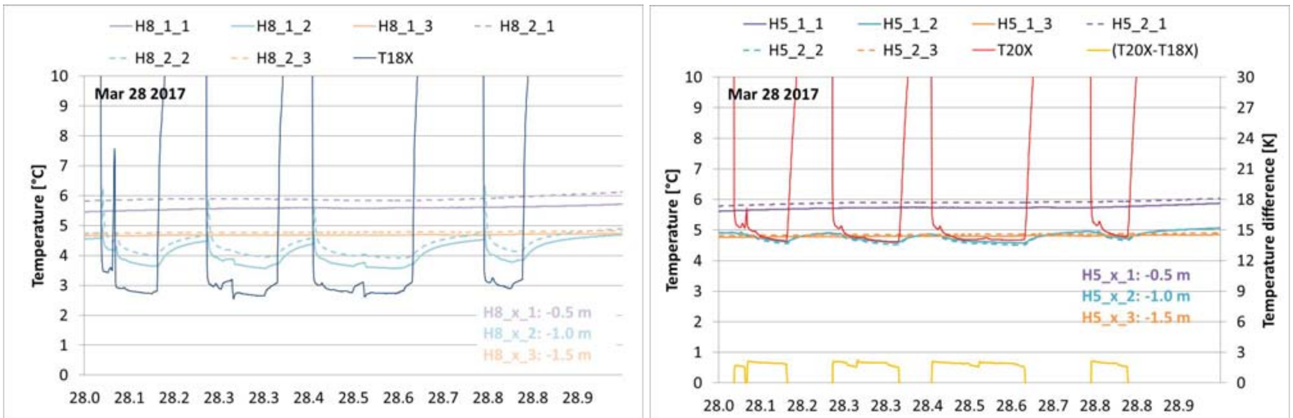


Figure 21. Temperatures in the ground above, next to and below the hoses in the inner sling on March 28 2017. H_8_1_z and H_8_2_z show the temperatures at the sling inlet and H_5_2_z and H_5_1_z show the temperatures at the sling outlet.

Figure 22 shows the temperature and flow distribution in the charging loops and the storage tank and Figure 23 shows the power consumption of the heat pump compressor and the temperature and flow distribution in the discharging loops on August 30 2017.

By now, new solar collectors are installed and the thermostatic valve between the flow and return temperature to/from the space heating loop is closed. Cold water returning from the space heating loop is no longer mixed with the hot water from the storage tank going to the space heating loop. For the same reason, the space heating consumption is increased since the set point temperature in the space heating volume and the flow in the space heating loop are unchanged.

The figures show that the number of starts and stops of the heat pump when the heat pump is producing space heating water are increased when the operation mode of the heat pump is changed from HTank On/Off to HTank mod. The number of starts and stops of the heat pump when the heat pump is producing domestic hot water for the storage tank are reduced and the length of the periods are much shorter due to higher heat production from the heat pump in HTank mod mode than in HTank on/off mode. The heat pump has many starts and stops when it produces space heating water. Most likely it will be better to reduce the neutral zone to 0 K and allow the heat pump to modulate and find the needed heating power for the situation and thereby reduce the number of starts and stops.

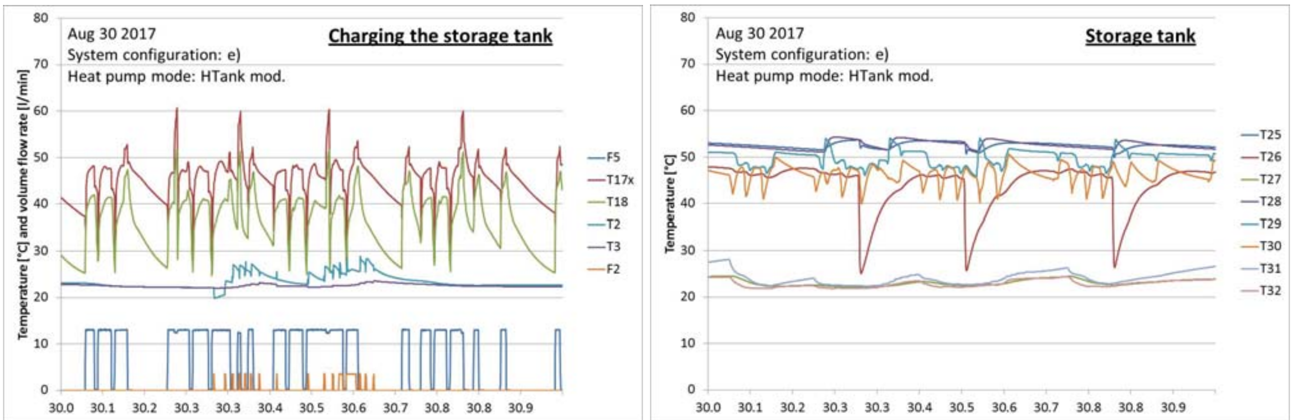


Figure 22. Temperatures and flows in the system on August 30 2017.

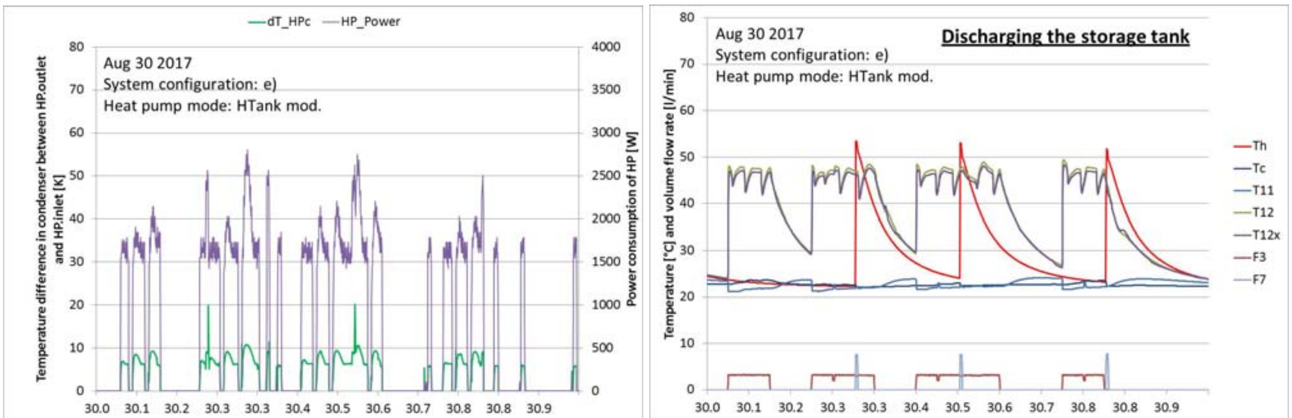


Figure 23. Power consumption of heat pump compressor, temperatures and flows in the system on August 30 2017.

Figure 24 and Figure 25 show the temperatures in the ground 0.5 meter above, next to and 0.5 meter below the ground source heat exchanger, the in- and outlet temperatures and the temperature difference between the in- and outlet temperatures to the ground source heat exchanger on August 30 2017.

The figures show that return temperature to the heat pump from the ground source heat exchanger is lower than the ground temperature in the outer sling and similar to the ground temperature in the inner sling. Also the temperature gradient is larger in the inner sling than in the outer sling. The reason is that heat from the surrounding ground is heating up the ground temperatures around the outer sling. A small temperature gradient in the flow direction between measurement line 1 and 2 is present in the inlet hose H4 while no temperature gradient in the flow direction can be observed between measurement line 2 and 1 in the outlet hose H1. Exactly the same picture can be observed in the inner sling, although the temperature gradient in the inlet hose H8 is larger than the same temperature gradient in H4 in the outer sling. This shows that the length of the ground source heat exchanger is sufficient with the current heating demand.

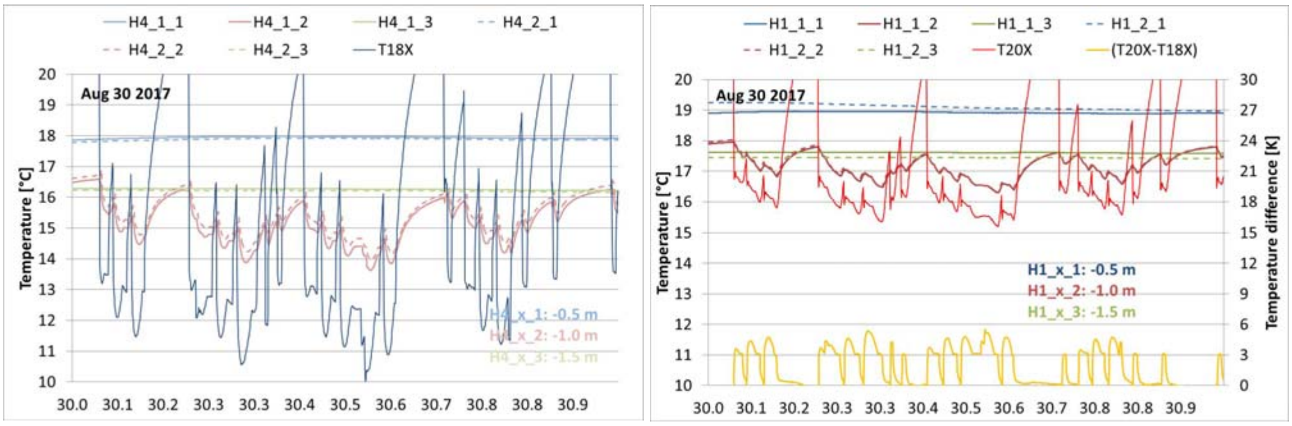


Figure 24. Temperatures in the ground above, next to and below the hoses in the outer sling on August 30 2017. H4_1_z and H4_2_z show the temperatures at the sling inlet and H1_2_z and H_1_1_z show the temperatures at the sling outlet.

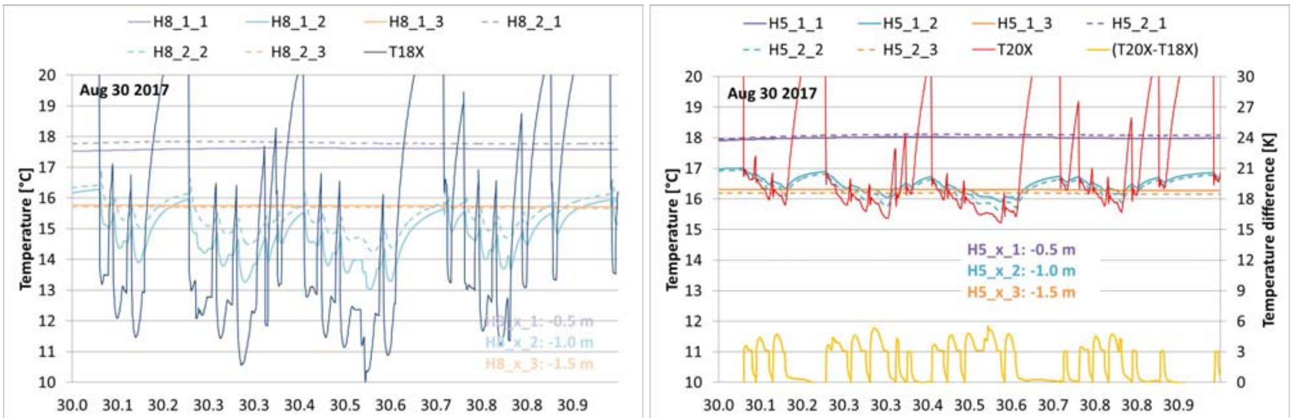


Figure 25. Temperatures in the ground above, next to and below the hoses in the inner sling on August 30 2017. H_8_1_z and H_8_2_z show the temperatures at the sling inlet and H_5_2_z and H_5_1_z show the temperatures at the sling outlet.

Figure 26 shows the temperature and flow distribution in the charging loops and the storage tank and Figure 27 shows the power consumption of the heat pump compressor and the temperature and flow distribution in the discharging loops on September 23 2017.

The figures show that the number of starts and stops of the heat pump when the heat pump is producing space heating water are increased as the set point temperature and the neutral zone are changed from 45 °C and 15 K respectively on August 30 2017 to 35 °C and 5 K respectively on September 23 2017.

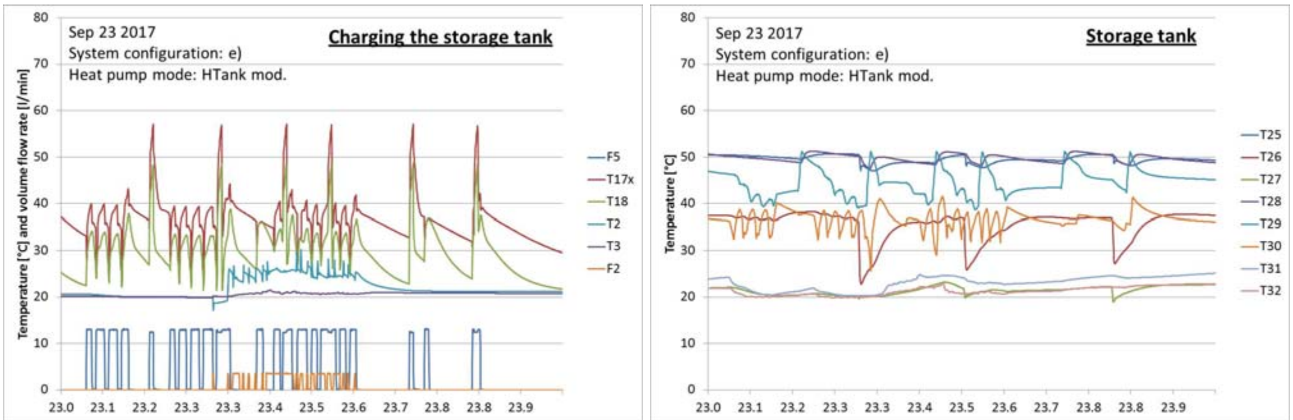


Figure 26. Temperatures and flows in the system on September 23 2017.

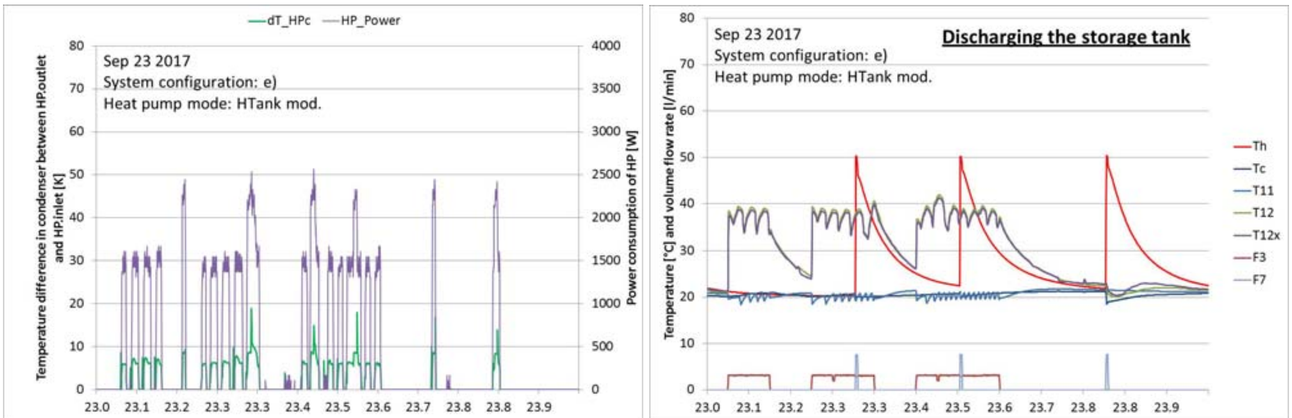


Figure 27. Power consumption of heat pump compressor, temperatures and flows in the system on September 23 2017.

Figure 28 and Figure 29 show the temperatures in the ground 0.5 meter above, next to and 0.5 meter below the ground source heat exchanger, the in- and outlet temperatures and the temperature difference between the in- and outlet temperatures to the ground source heat exchanger on September 23 2017.

The figures show that return temperature to the heat pump from the ground source heat exchanger is lower than the ground temperature in the outer sling and similar to the ground temperature in the inner sling. Also the temperature gradient is larger in the inner sling than in the outer sling. The reason is that heat from the surrounding ground is heating up the ground temperatures around the outer sling. A temperature gradient in the flow direction between measurement line 1 and 2 is present in the inlet hose H4 while no temperature gradient in the flow direction can be observed between measurement line 2 and 1 in the outlet hose H1. Exactly the same picture can be observed in the inner sling, although the temperature gradient in the inlet hose H8 is larger than the same temperature gradient in H4 in the outer sling. This shows again that the length of the ground source heat exchanger is sufficient with the current heating demand.

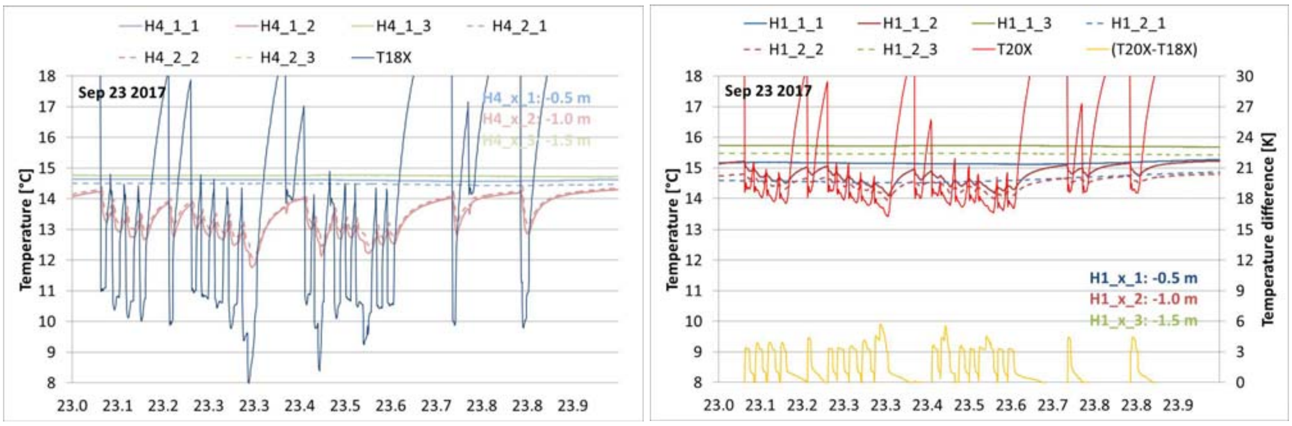


Figure 28. Temperatures in the ground above, next to and below the hoses in the outer sling on September 23 2017. H4_1_z and H4_2_z show the temperatures at the sling inlet and H1_2_z and H_1_1_z show the temperatures at the sling outlet.

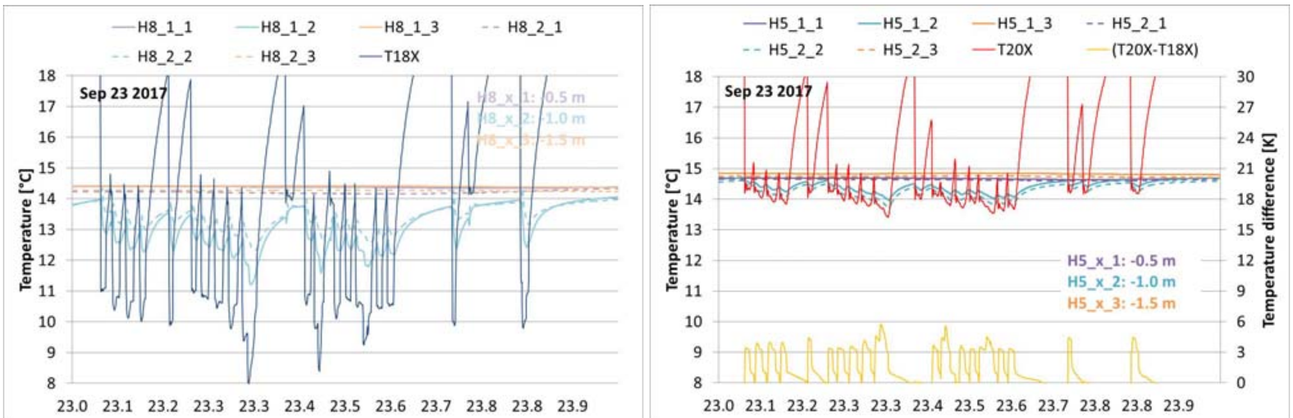


Figure 29. Temperatures in the ground above, next to and below the hoses in the inner sling on September 23 2017. H_8_1_z and H_8_2_z show the temperatures at the sling inlet and H_5_2_z and H_5_1_z show the temperatures at the sling outlet.

Test period

Measurements from the solar heating/ heat pump system

Table 8 shows all the periods with measurements.

Table 8. Periods with measurements from the solar heating/heat pump system.

Month	2014	2015	2016	2017
January	-	5.-6., 8.-31.	1.-31.	2.-31.
February	-	1.-28.	1.-29.	1.-28.
March	-	1.-31.	1.-31.	1.-6., 8.-31.
April	-	1.-30	1.-30.	3.-30.
May	-	1.-31.	1.-9., 11.-31.	1.-16., 18.-31.
June	-	1.-30.	1.-30.	1.-28.
July	-	1.-31.	1.-31.	12.-30.
August	-	1., 3.-18., 21., 24.-31.	1.-31.	3., 6.-31.

September	-	1.-30.	1.-30.	1.-30.
October	-	1.-31.	1.-31.	
November	26.-30.	1.-30.	1.-29.	
December	1.-30.	1.-31.	8.-31.	

The measurements are considered to be good and usable for evaluation of the performance of the solar heating/heat pump system if the system has been in operation and if the domestic hot water tapping is correctly performed, that is three daily tapings of an energy amount of 1.5 kWh per tapping and with a domestic hot water temperature > 45°C.

In the period November 26, 2014-November 5, 2015 it is not possible to determine the performance of the solar heating/heat pump system. The reason is that the flow temperature from the heat pump during domestic hot water preparation is not measured. Only the flow temperature from the heat pump during space heating operation is measured.

In Table 9 the periods with good measurements which can be used for evaluation of the performance of the solar heating/heat pump system are shown.

Table 9. Periods with good measurements from the solar heating/heat pump system.

Month	2014	2015	2016	2017
January	-	-	1.-31.	2.-19., 21.-23., 25.-31.
February	-	-	1.-6., 17.-29.	1.-22., 24.-28.
March	-	-	1.-7.	1.-5., 22.-25., 28.-30.
April	-	-	-	4.-30.
May	-	-	4.-8., 12.-21., 24.-31.	1.-14.
June	-	-	1.-12., 15.-30.	2.-27.
July	-	-	1.-6., 10.-31.	13.-18., 20.-29.
August	-	-	1.-11., 24.-31.	7.-23., 29.-31.
September	-	-	1.-4., 7.-30.	1.-5., 7.-16., 19.-20., 22.-25., 28.-30.
October	-	-	1.-10., 12.-31.	
November	-	6.-8., 11.-30.	1.-21., 24.-28.	
December	-	1.-7., 10.-14., 16.-31.	8.-21., 23.-31.	

Measurements from the ground source

In Table 10 the periods with measurements are shown. There are no usable measurements from January to July 2014. The reason for this is problems with a new data acquisition system which is installed in January 2014. The problem is finally solved in July 2014 and the measuring of the ground temperatures goes on.

Table 10. Periods with measurements from the ground and the ground source heat exchanger.

Month	2013	2014	2015	2016	2017
January		-	1.-31.	4.-31.	1.-31.
February		-	1.-28.	1.-29.	1.-28.
March		-	1.-31.	1.-31.	1.-31.
April		-	1.-13., 15.-30.	1.-11., 13.-30.	1.-6., 10.-30.
May		-	1.-31.	1.-21., 23.-31.	1.-15.
June		-	1.-30.	1.-26., 28.-30.	-

July		-	1.-30.	1.-14., 18.-31.	19.-31.
August	23.	28.-31.	-	1.-31.	1.-31.
September	1.-30.	1.-30.	-	1.-30.	
October	1.-23.	1.-13., 30.-31.	31.	1.-31.	
November	1.-27.	1.-27., 30.	1.-30.	1.-30.	
December	13.-14., 20.-25.	1.-31.	1.-29.	1.-31.	

Measurement results

Daily energy flows in the solar heating/heat pump system in the test period

Figure 30 shows the daily energy amounts transferred to the storage tank from the solar collector loop and from the heat pump for the whole measurement period.

Figure 31 shows the daily energy amounts drawn from the storage tank for domestic hot water and space heating for the whole measurement period.

Figure 32 shows the electrical energy consumption of the heat pump compressor and the total daily electricity consumption for the solar heating/heat pump system for the whole measurement period. The total electricity consumption comprises energy consumption for the heat source pump, the pump between the heat pump and the tank, the solar pumps and the control system.

The energy transferred from the heat pump to the storage tank and the electrical energy consumption of the heat pump are only shown from November 6 2015 from where the auxiliary energy transferred to the tank is measured correctly. There are also periods where the data acquisition system for one or another reason is not collecting data. During most of these periods, the solar heating/heat pump system has been in operation, that is: energy is charged and discharged to/from the storage tank and the ground source heat exchanger. For these reasons, not all the measurements are suitable for evaluation of the system performance.

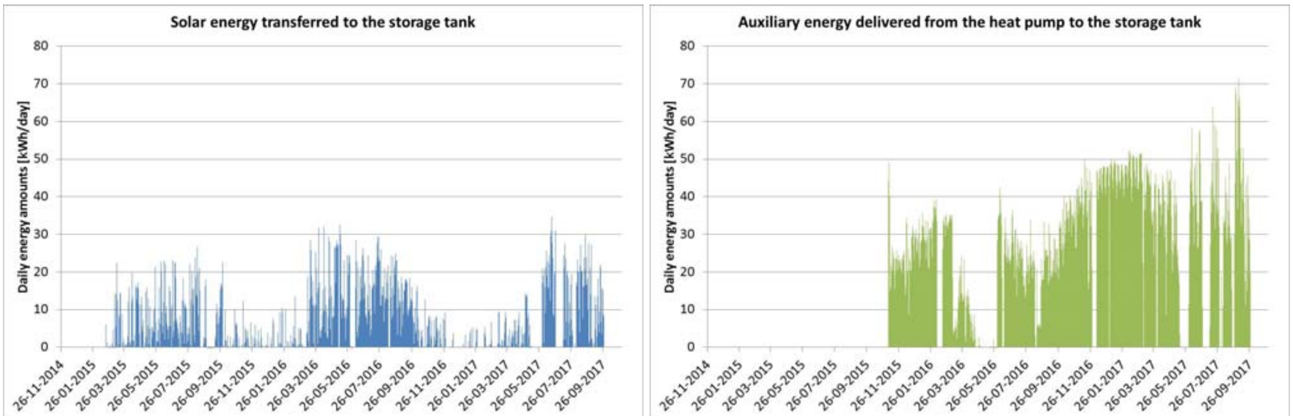


Figure 30. Daily energy amounts charged to the storage tank in the test period.

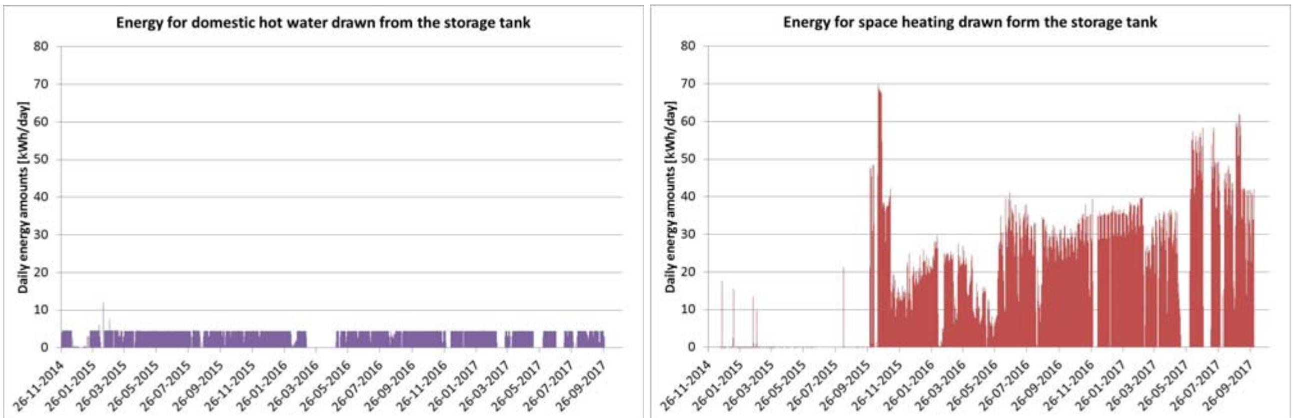


Figure 31. Daily energy amounts discharged from the storage tank in the test period.

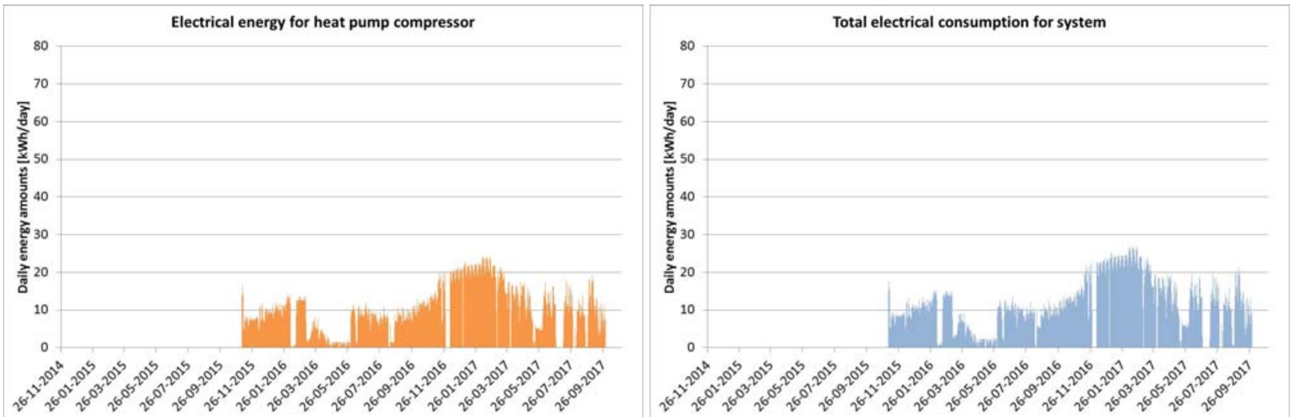


Figure 32. Daily electricity consumption of heat pump compressor and total daily electricity consumption for solar heating/heat pump system.

In Table 11, the power consumption of pumps and control system is shown.

Table 11. Power of pumps and control system.

Power of pumps in primary and secondary solar collector loop	Power of pump in heat pump – storage tank loop	Power of pump in heat pump – ground source loop	Power of control system
[W]	[W]	[W]	[W]
60	40	80	12.5

In the following, the operation conditions for the heat pump and the ground are studied during two days. The days are August 29 2017 with high amount of solar radiation and August 30 2017 with low amount of solar radiation.

The energy flows on the two days are shown in Table 12.

Table 12. Daily energy flows.

Date	Solar energy to tank [kWh]	Auxiliary energy from HP to tank [kWh]	Space heating consumption [kWh]	Domestic hot water consumption [kWh]
August 29, 2017	28	44	60	4.5
August 30, 2017	1	69	59	4.5

In Figure 33 - Figure 38 the operation conditions on the source side of the heat pump are shown on the two days. It is clear to see that the inlet temperature to the evaporator and the outlet temperature from the evaporator are higher on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation. It is also clear to see that the higher temperatures occur during the afternoon and evening. The temperature difference in the evaporator and the power consumption of the heat pump compressor are lower on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation.

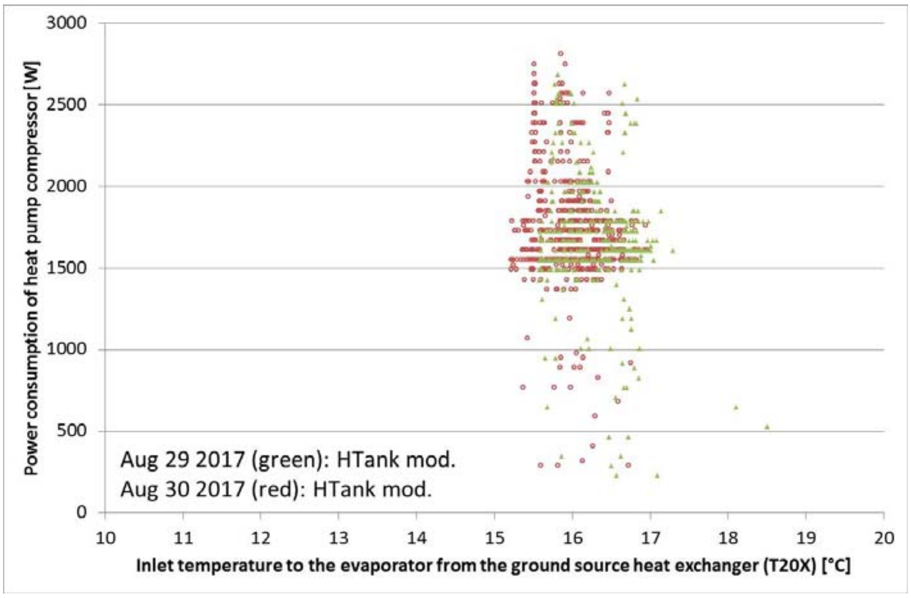


Figure 33. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

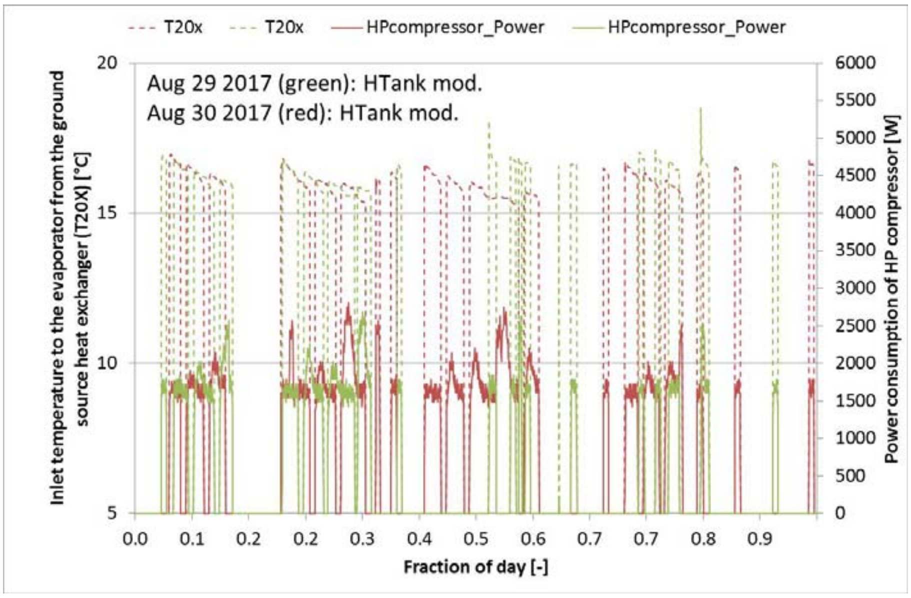


Figure 34. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

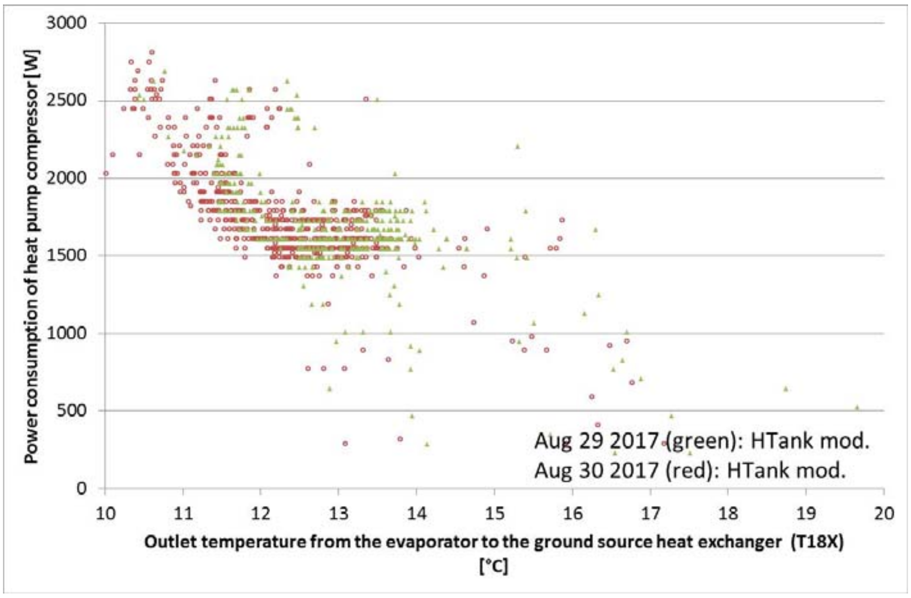


Figure 35. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

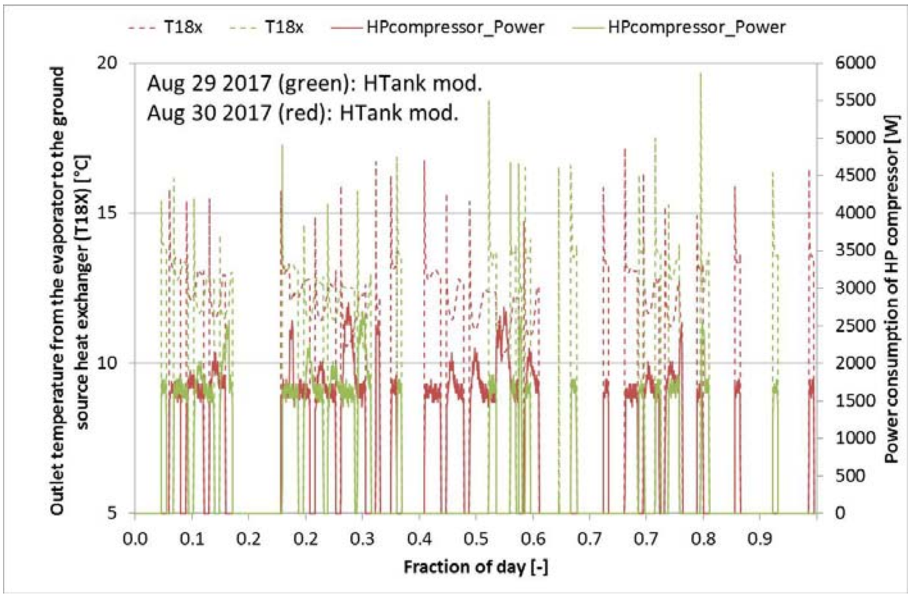


Figure 36. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

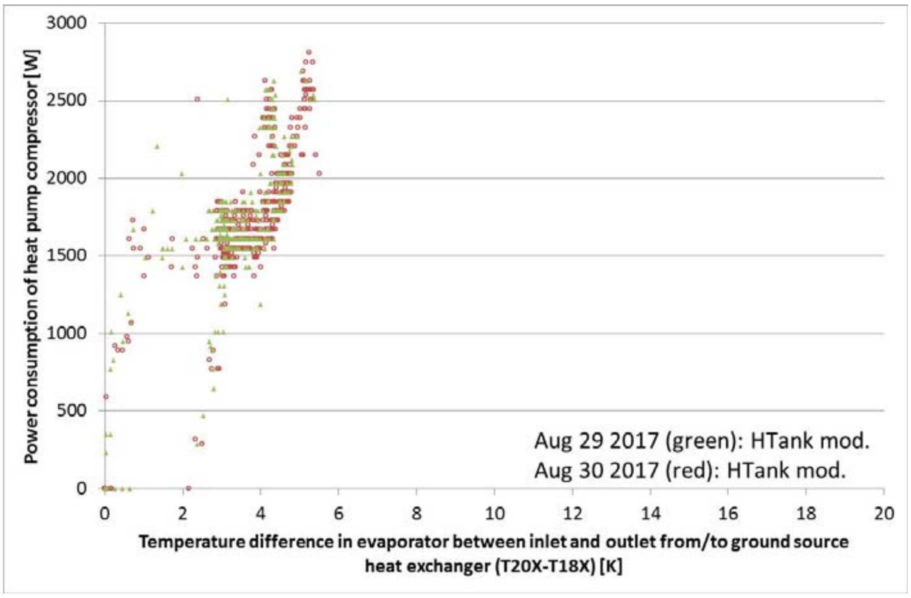


Figure 37. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

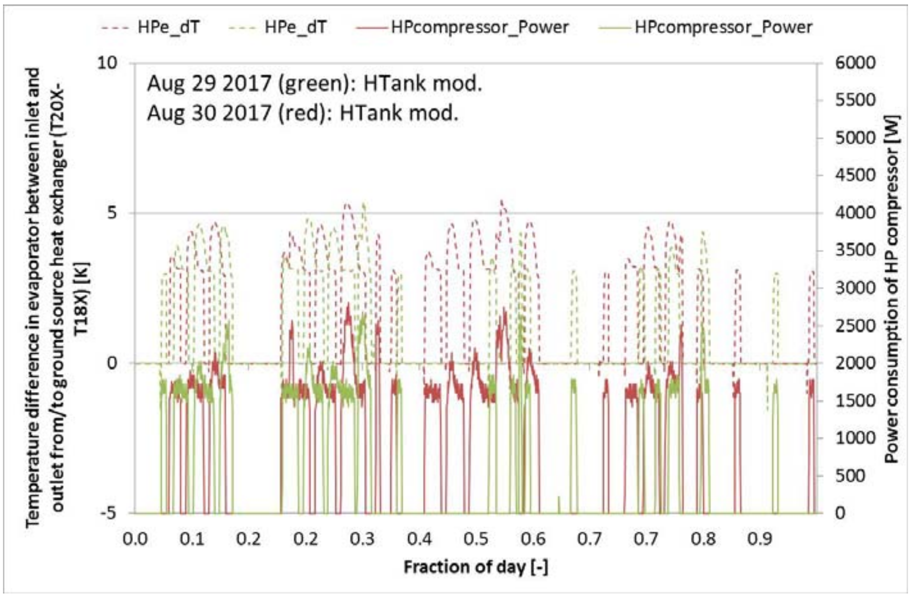


Figure 38. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

In Figure 39 - Figure 44 the operation conditions on the load side of the heat pump are shown on the two days.

It can be seen that the inlet temperature to the condenser and the outlet temperature from the condenser are slightly higher on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation. The slightly higher temperatures occur during the afternoon and evening and result in lower heating power from the heat pump condenser.

The benefit of solar radiation is found on both the source side and load side of the heat pump in form of higher temperature levels of inlet- and outlet temperatures and lower power consumption of the heat pump compressor.

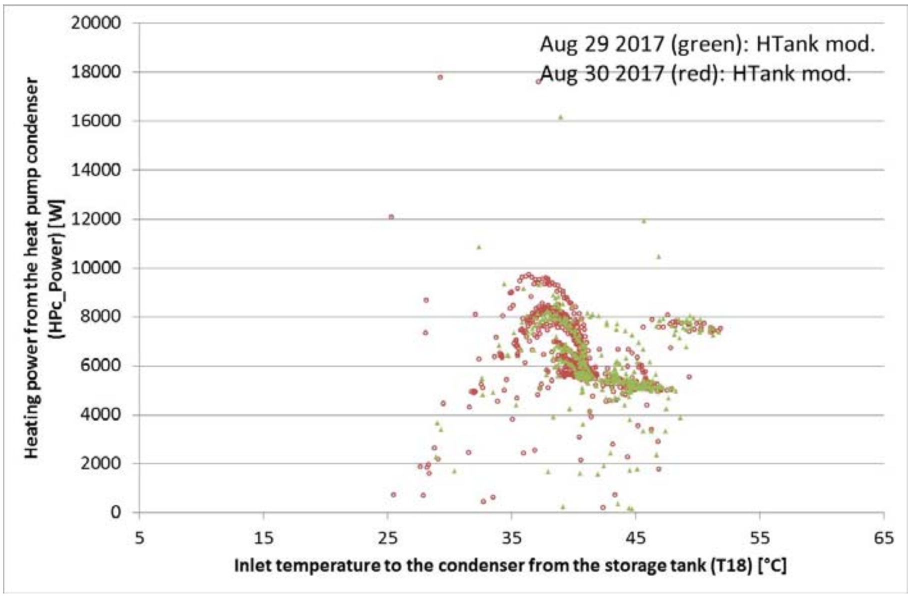


Figure 39. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

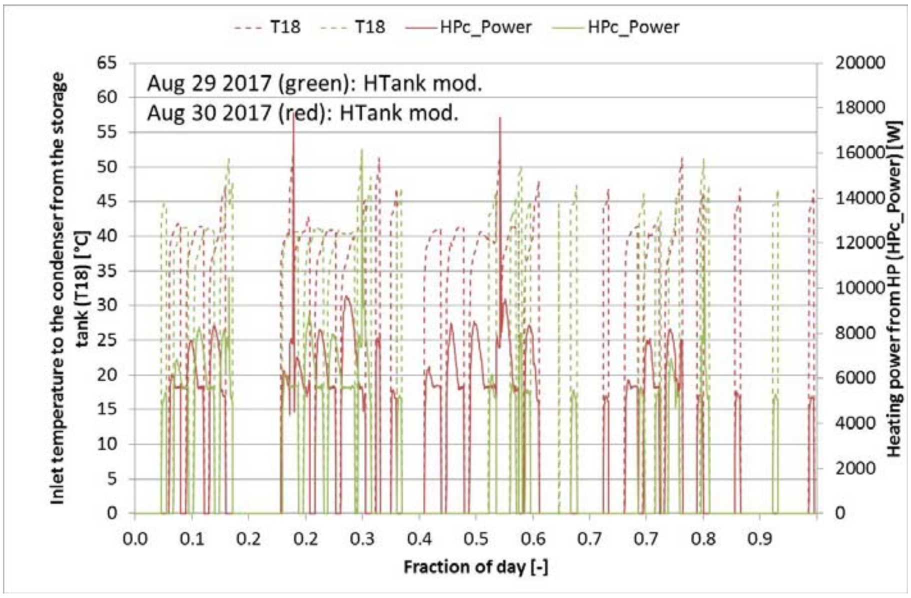


Figure 40. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

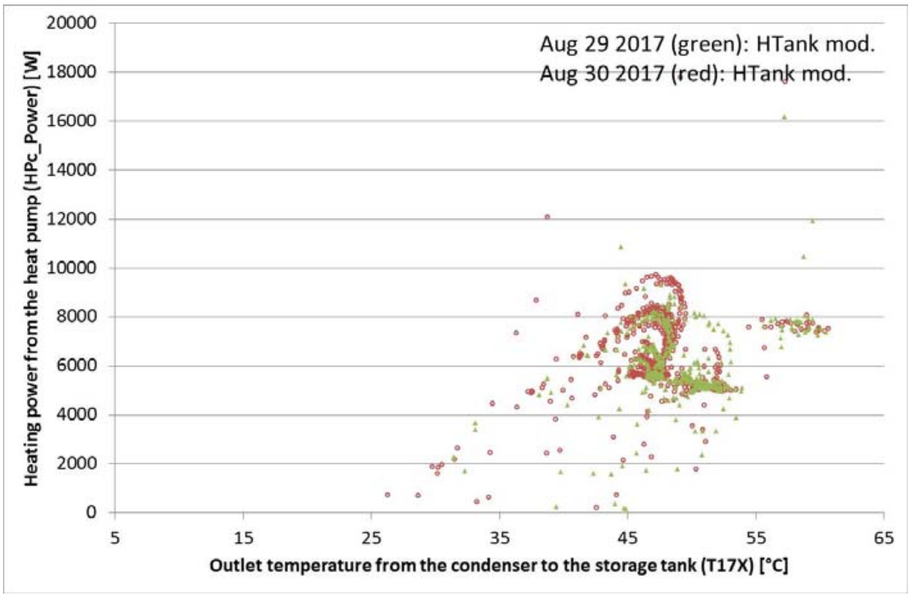


Figure 41. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

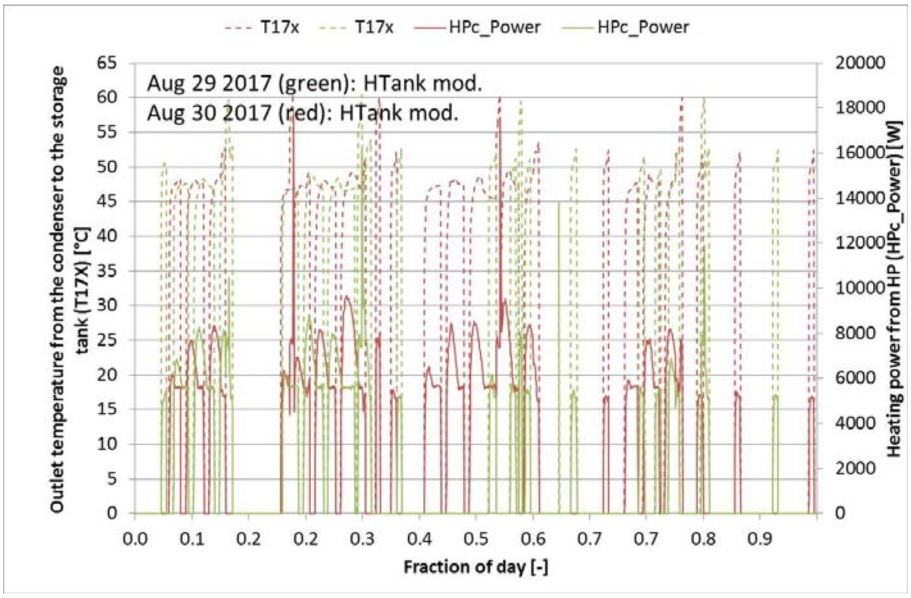


Figure 42. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

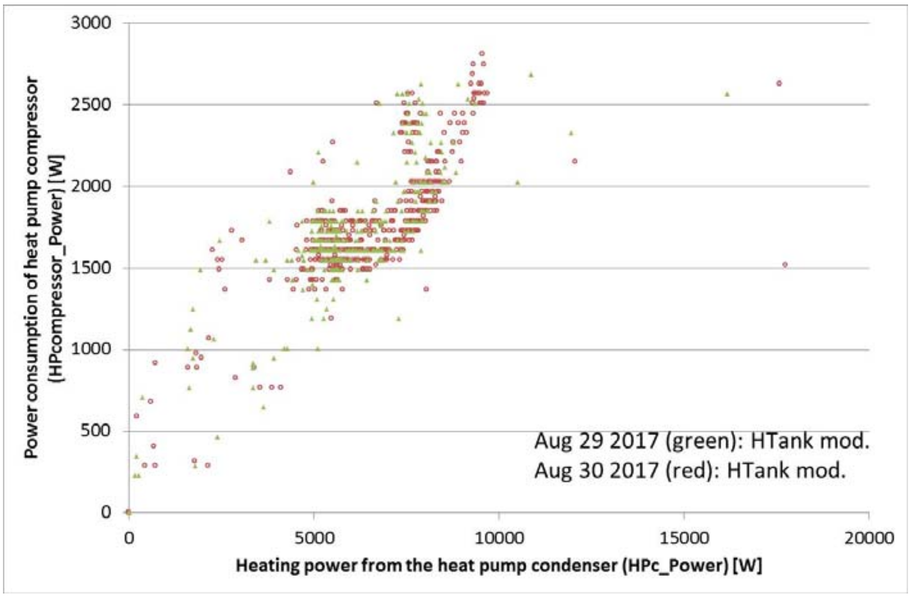


Figure 43. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

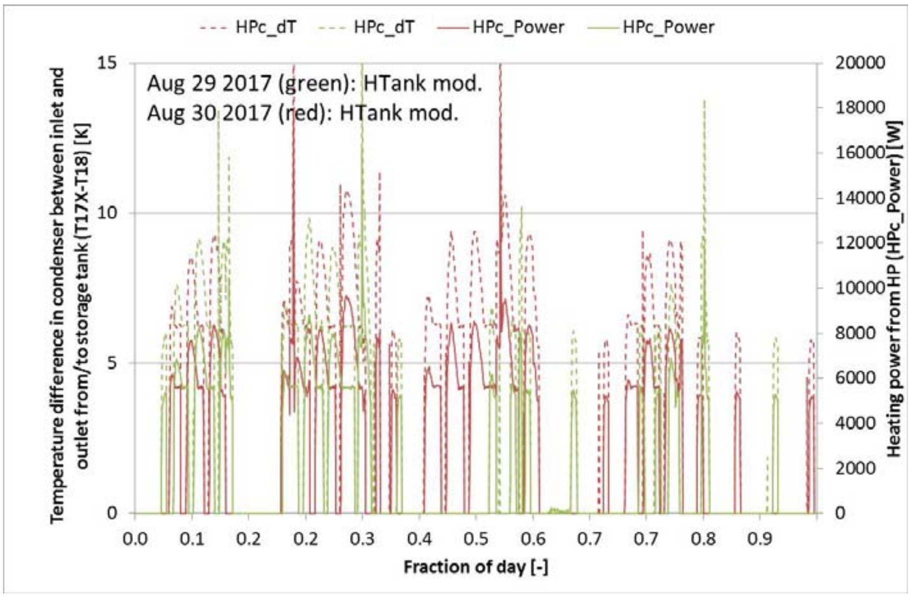


Figure 44. Operation conditions in the heat pump compressor on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

Figure 45 and Figure 46 shows the temperature conditions on the source and load side of the heat pump on August 29 2017 with high amount of solar radiation and August 30 2017 with low amount of solar radiation and the global solar radiation. Note that the temperatures on the source side increase and the temperatures on the load side decrease when the heat pump is not in operation. This is because the temperature sensors are heated/cooled by the indoor temperature in stand still periods.

From these figures, it is very clear to see that inlet and outlet temperatures on the source side are higher and the temperature difference is lower in the afternoon and evening on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation. It is also clear to see that the heat pump is in operation less time with high amount of solar radiation.

It can also be seen that the inlet and outlet temperatures on the load side of the heat pump are slightly higher in the afternoon and evening on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation, especially the temperature from the tank to the heat pump.

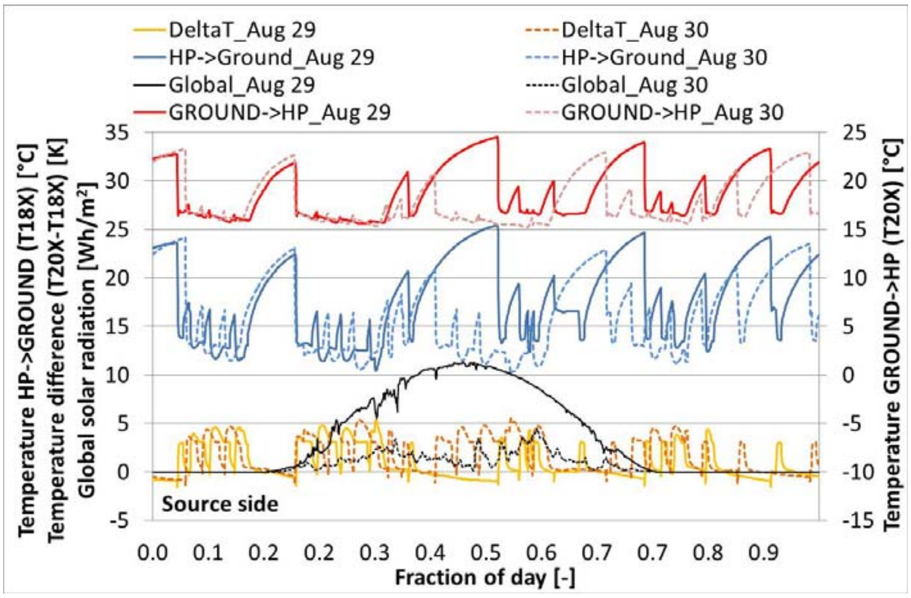


Figure 45. Operation conditions on the source side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation and global solar radiation.

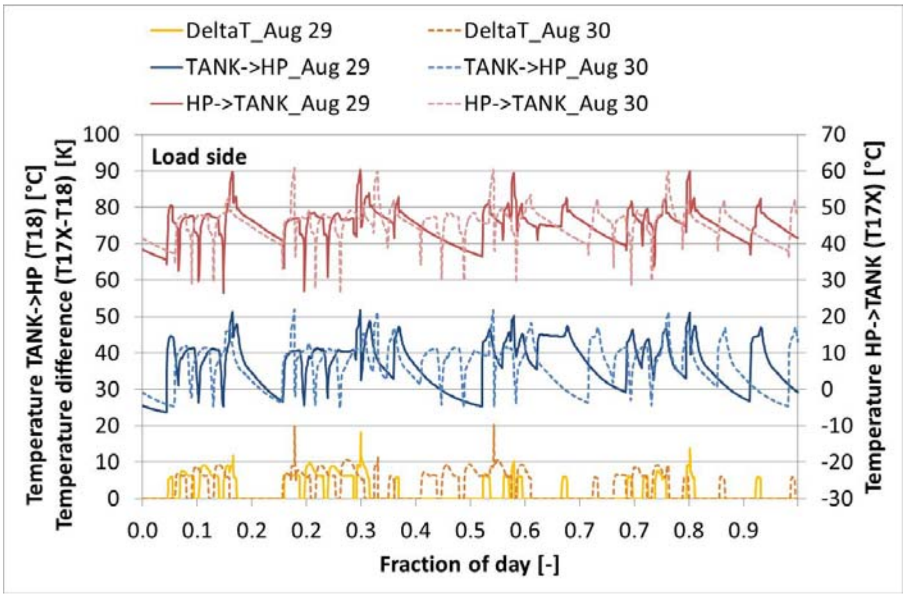


Figure 46. Operation conditions on the load side of the heat pump on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

Figure 47 show the operation conditions in the ground source heat exchanger on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation. The figures also show the inlet temperature from the heat pump to heat exchanger (T18X), the outlet temperature from the heat exchanger to the heat pump (T20X), the global solar radiation and the total volume flow rate in the ground source heat exchanger (F6). The volume flow rate in each sling is a fourth of the total volume flow rate.

Figure 48 - Figure 51 show the temperature conditions in the ground 0.5 meter above, in level of and 0.5 meter below the ground source heat exchanger on August 29 2017 and August 30 2017. The figures show the temperature conditions at the inlet and outlet of both the outer and the inner slings.

It can be seen that the ground temperatures next to the ground source heat exchanger (-1.0 m) are higher on August 29 with high amount of solar radiation than on August 30 with low amount of solar radiation. It can also be seen that the ground temperatures 0.5 meter above the heat exchanger (-0.5 m) increase after a sunny day while the temperatures 0.5 meter below the heat exchanger (-1.5 m) are not directly affected.
The figures show that the ground temperature level is lower in the inner sling (H8 and H5) than in the outer sling (H4 and H1). It can also be seen that the temperature gradient in the inner sling is higher than in the outer sling. Temperature gradients can be seen in the ground around the heat exchanger both in the flow direction and perpendicular to the flow direction.

The inlet and outlet temperatures to/from the heat exchanger increase during August 29 with high amount of solar radiation. The reason is mainly because solar energy supplied to the tank is directly utilized for space heating and domestic hot water and the heat extraction from the ground therefore is reduced.

It can be seen that the inlet and outlet temperatures to/from the heat exchanger are also high during the night both on August 29 and August 30. This is because there is no space heating and domestic hot water consumption during the night and the heat extraction from the ground therefore reduced. The figures show that highest inlet and outlet temperatures to/from the heat exchanger occur in periods when the heat extraction from the ground is low. The heat extraction from the ground is low when solar energy is directly used to cover the space heating and domestic hot water consumption.

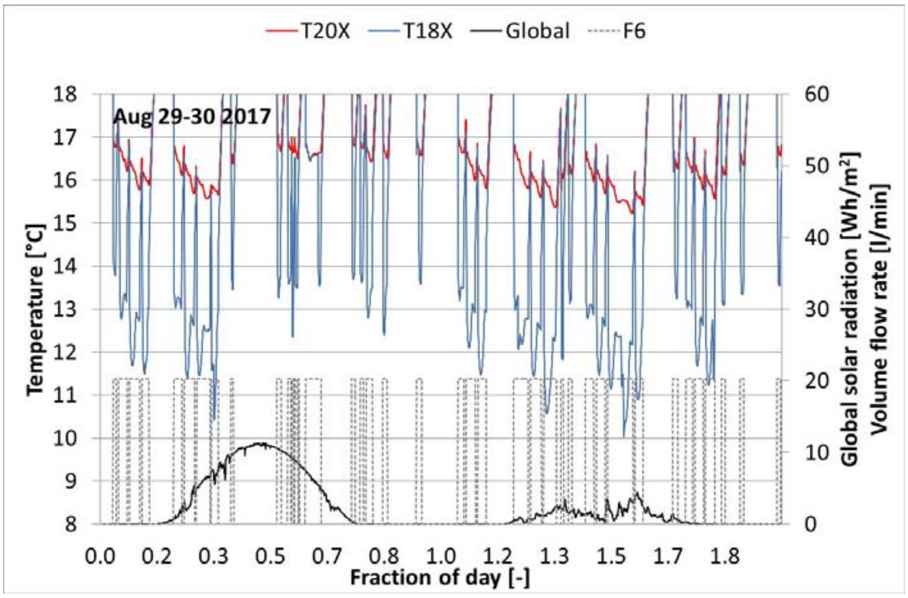


Figure 47. Operation conditions in the ground source heat exchanger on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

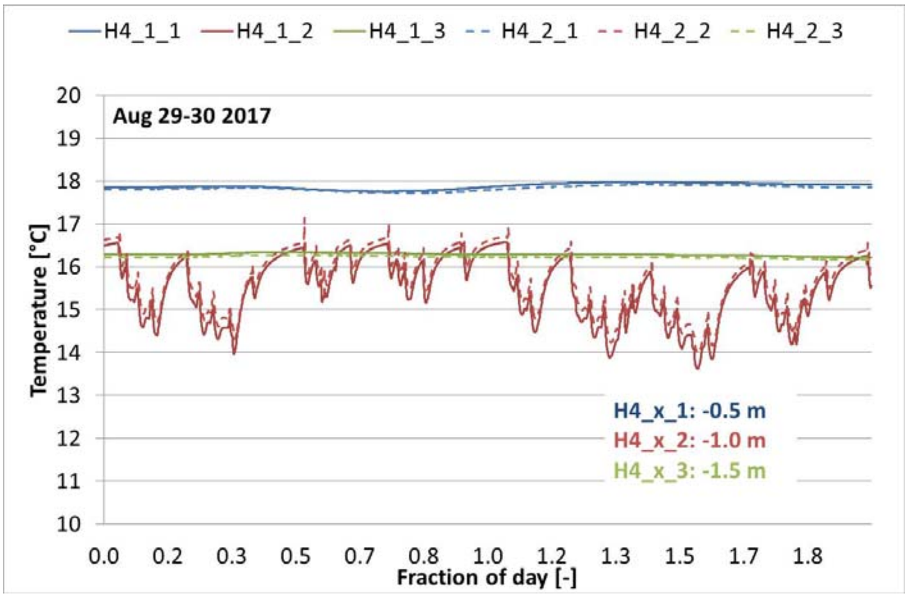


Figure 48. Temperature conditions in the ground at the inlet to the outer sling on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

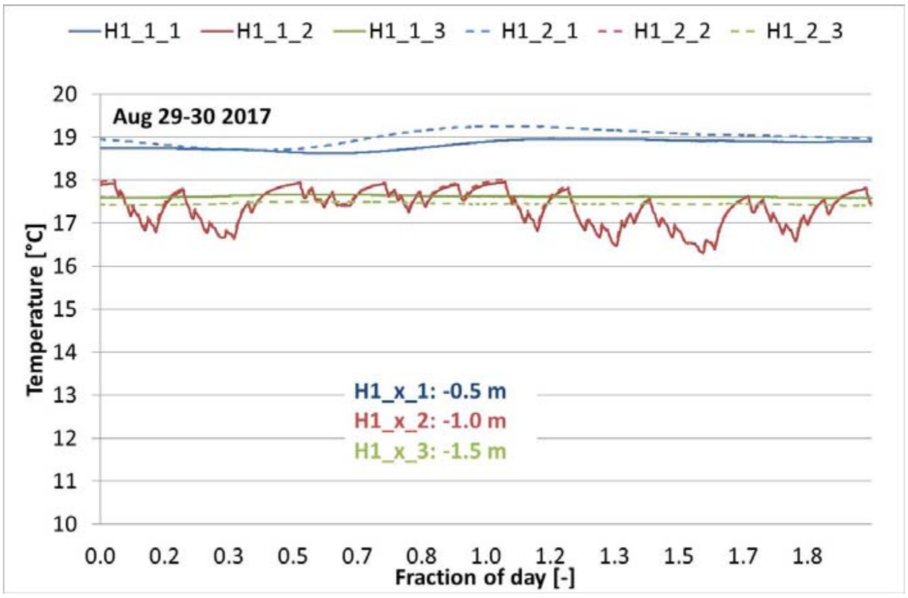


Figure 49. Temperature conditions in the ground at the outlet from the outer sling on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

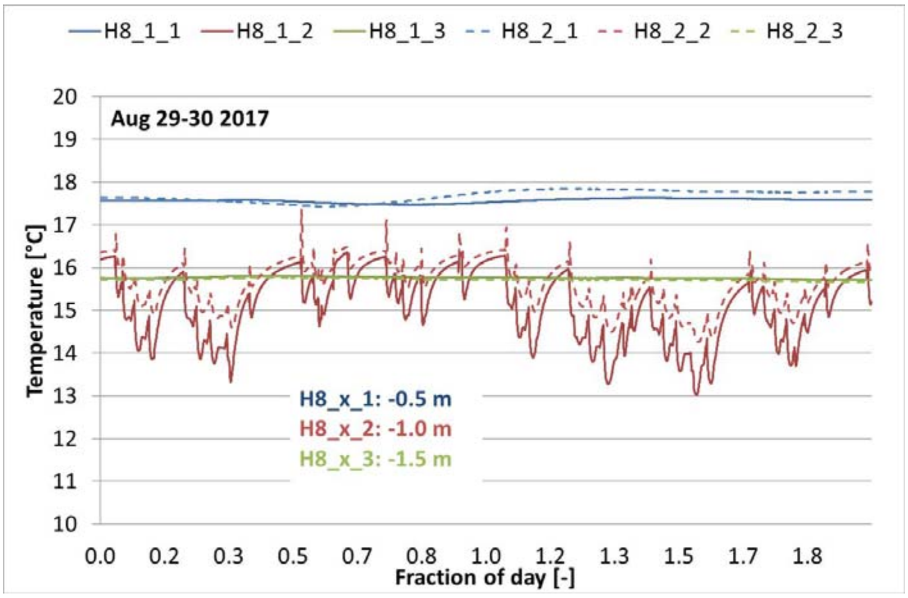


Figure 50. Temperature conditions in the ground at the inlet to the inner sling on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

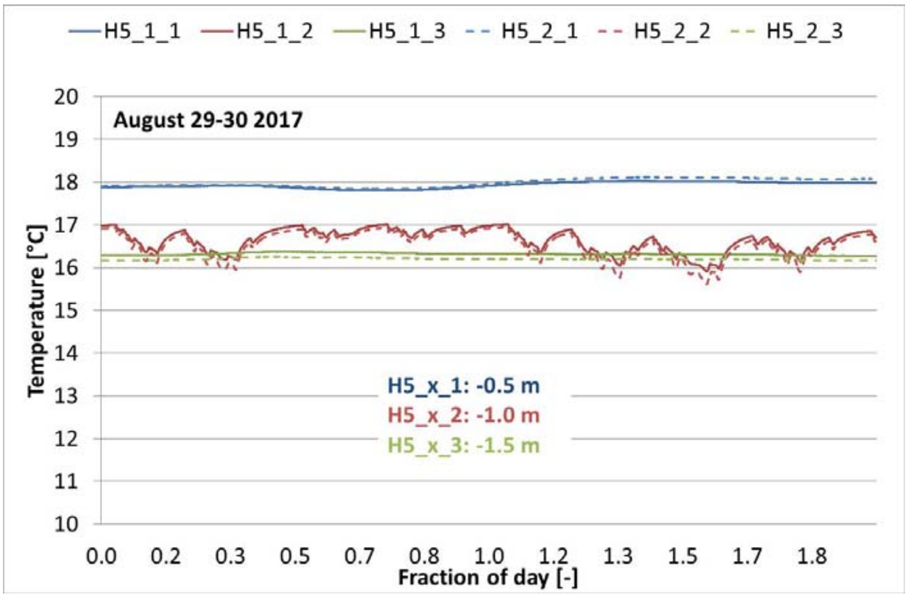


Figure 51. Temperature conditions in the ground at the outlet from the inner sling on August 29 2017 with high amount of solar radiation and on August 30 2017 with low amount of solar radiation.

In Table 13, monthly energy amounts in the test period are shown. The shown energy amounts are: total electricity consumption of heat pump, pumps and control system, electricity consumption of heat pump compressor, solar energy to storage tank, auxiliary energy to storage tank, space heating consumption, domestic hot water consumption and energy from ground source. The energy amount from the ground source is estimated as: auxiliary energy to storage tank – electrical energy consumption of heat pump.

Table 13. Monthly energy amounts in the test period.

Period	Total electricity consumption of HP compressor, pumps and control system [kWh]	Electricity consumption of HP compressor [kWh]	Solar energy to tank [kWh]	Auxiliary energy from HP to tank [kWh]	Space heating consumption [kWh]	Domestic hot water consumption [kWh]	Energy from ground source to HP [kWh]
Nov 14	-	-	0	-	0	18	-
Dec 14	-	-	0	-	18	80	-
Jan 15	-	-	1	-	9	66	-
Feb 15	-	-	9	-	25	113	-
Mar 15	-	-	134	-	0	126	-
Apr 15	-	-	231	-	0	128	-
May 15	-	-	163	-	0	140	-
Jun 15	-	-	305	-	0	135	-
Jul 15	-	-	229	-	0	140	-
Aug 15	-	-	228	-	0	109	-
Sep 15	-	-	35	-	21	131	-
Oct 15	-	-	60	-	1172	133	-
Nov 15	-	-	0	-	189	23	-
Nov 15	220	196	49	613	431	108	417
Dec 15	293	262	30	763	505	137	501

Jan 16	352	316	63	913	671	140	597
Feb 16	262	230	51	643	481	96	413
Mar 16	224	180	275	527	622	35	347
Apr 16	72	47	339	153	408	0	106
May 16	21	0.2	543	2	281	113	2
Jun 16	265	228	328	795	890	132	567
Jul 16	256	206	515	705	940	135	499
Aug 16	197	137	452	516	724	123	379
Sep 16	258	219	361	738	844	130	519
Oct 16	365	326	131	1041	874	140	715
Nov 16	458	411	91	1098	892	122	687
Dec 16	524	471	6	1088	801	108	617
Jan 17	694	623	30	1387	1029	135	764
Feb 17	675	606	24	1330	999	126	724
Mar 17	573	510	65	1245	831	67	735
Apr 17	446	394	95	1049	854	125	655
May 17	257	223	68	409	341	63	186
Jun 17	379	328	530	1093	1348	120	765
Jul 17	260	226	238	789	839	78	563
Aug 17	269	229	452	808	1024	95	579
Sep 17	360	312	300	1195	1215	113	883

Evaluation of the performance of the solar heating/heat pump system

As previously mentioned, not all the measurements are suitable for evaluation of the performance of the system. In the following, only measurements where the solar heating/heat pump system has been in operation and where the domestic hot water tapping is performed with three daily tapings of an energy amount of 1.5 kWh per tapping and with a hot water temperature > 45°C are used.

Figure 52 shows the daily energy amounts transferred to the storage tank from the solar collector loop and from the auxiliary heating loop.

Figure 53 shows the daily energy amounts drawn from the storage tank for domestic hot water and space heating.

Figure 54 shows the electrical energy consumption of the heat pump compressor and the total electricity consumption of the solar heating/heat pump system. The figure also shows the fraction of electricity consumption of the heat source pump and of all the pumps and the control system. The fraction of electricity consumption is defined as the electrical energy consumption by the component in question divided by the total electrical energy consumption of all the components and the control system in the solar heating/heat pump system.

The periods which the measurements are divided into correspond to the periods shown in Table 6. In the period Mar 23 2017 – Aug 28 2017, new solar collectors are installed and the thermostatic valve in the space heating loop is closed. The valve is closed and the new solar collectors put in operation on June 2. The closed valve results in an increased the space heating consumption. The new solar collectors result in more solar energy transferred to the storage tank than with the old identical solar collectors with problems. Regardless of this, the measurements are considered as one period.

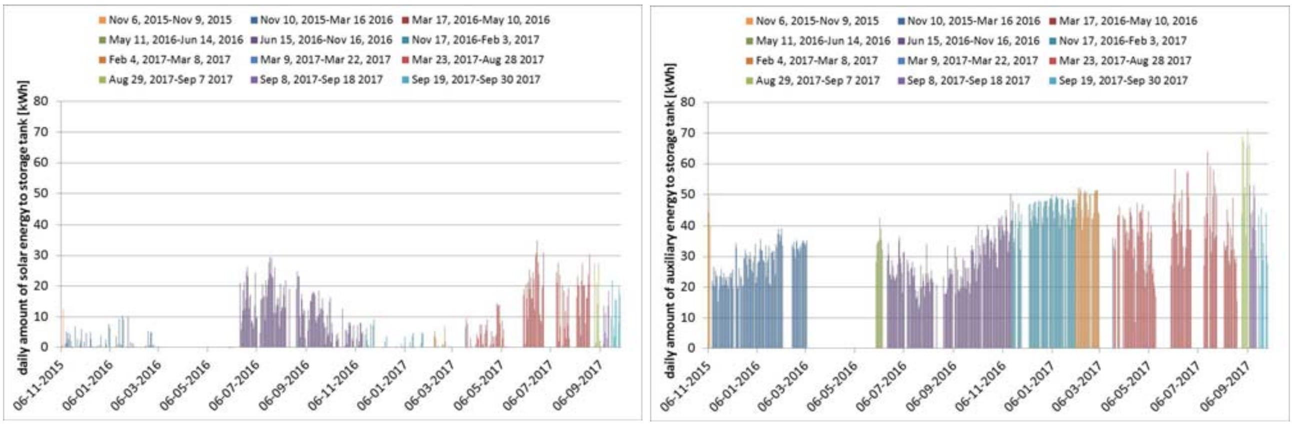


Figure 52. Daily energy amounts charged to the storage tank in the test period with good measurements.

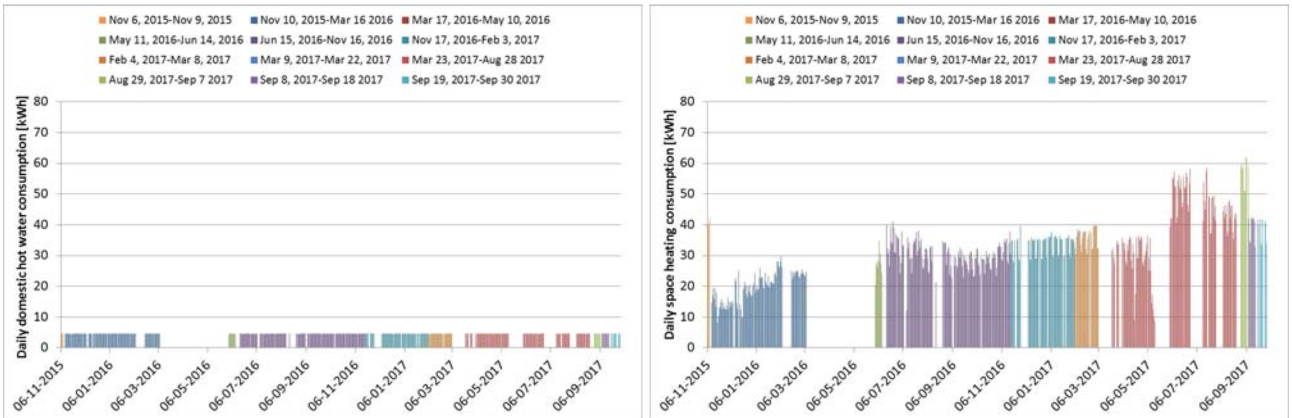


Figure 53. Daily energy amounts discharged from the storage tank in the test period with good measurements.

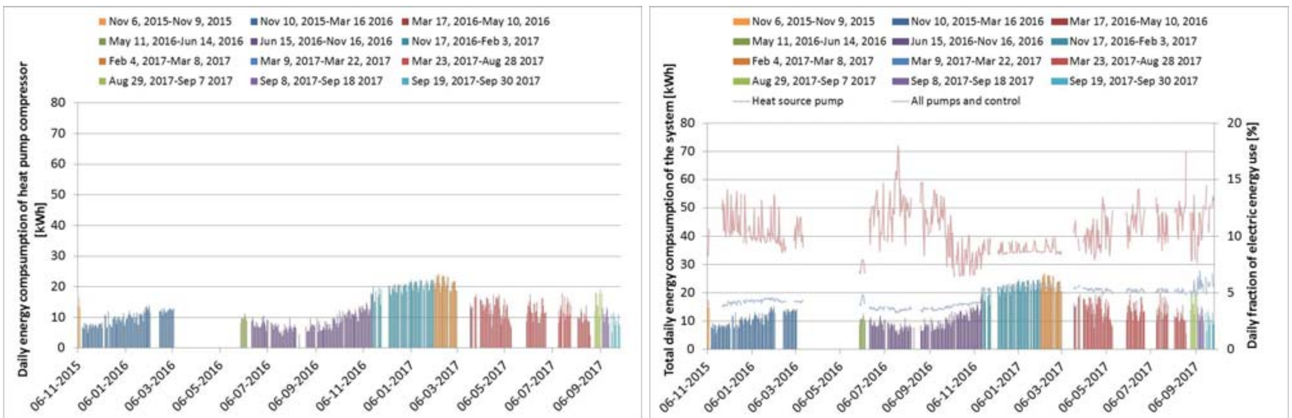


Figure 54. Daily electricity consumption of heat pump compressor (left) and solar heating/heat pump system (right) in the test period with good measurements. Daily fraction of electrical energy consumed by the heat source pump and by all pumps and control system in the solar heating/heat pump system (right).

The performance of the solar heating/heat pump system is expressed by monthly seasonal performance factors.

$$SPF_{HP} = \frac{\sum Q_{HP}}{\sum (E_{HP} + E_{ctr})} \quad (1)$$

$$SPF_{HP+HS} = \frac{\sum Q_{HP}}{\sum (E_{HP} + E_{ctr} + E_{CPHS})} \quad (2)$$

$$SPF_{bst} = \frac{\sum (Q_{HP} + Q_{Solar})}{\sum (E_{HP} + E_{ctr} + E_{CPHS} + E_{CPSolar})} \quad (3)$$

$$SPF_{SHP} = \frac{\sum (Q_{DHW} + Q_{SH})}{\sum (E_{HP} + E_{ctr} + E_{CPHS} + E_{CPHPTank} + E_{CPSolar})} \quad (4)$$

$$SPF_{ST} = \frac{\sum Q_{Solar}}{\sum (E_{ctr} + E_{CPSolar})} \quad (5)$$

Equation (1) and (2) express seasonal performance factors of the heat pump system without giving any information on the seasonal performance factors for the solar heating/heat pump system. Equation (3) expresses the seasonal performance factor for the solar heating/heat pump and can be compared to equation (2) and shows the added value to the seasonal performance factor by the solar heating/heat pump system. Equation (4) gives the seasonal performance factor for the complete solar heating/heat pump system including energy consumption and heat losses of all components, and expresses the ratio between the useful energy output and the corresponding energy input needed. Equation (5) gives the seasonal performance factor of the solar collector and thus shows how beneficial it is to operate the solar collector in different periods.

Figure 55 shows the seasonal performance factors SPF_{HP} and SPF_{HP+HS} according to equation (1) and (2) respectively. Figure 56 shows the seasonal performance factors SPF_{bst} and SPF_{SHP} according to equation (3) and (4) respectively.

It can be seen that SPF_{bst} reaches values above 4 when high amounts of solar energy are transferred to the storage tank. It can also be seen that SPF_{bst} is similar to SPF_{HP+HS} in periods with no or small contributions of solar energy to the storage tank.

Figure 57 shows the seasonal performance factor for the solar thermal collector SPF_{ST} according to equation (5). The figure also shows the total amount of energy transferred from the solar collector to the storage tank, the utilization of solar energy and the energy consumption of the pumps in the solar collector loop. The utilized solar energy is defined as the amount of solar energy transferred to the storage tank divided by the amount of solar energy on the solar collector.

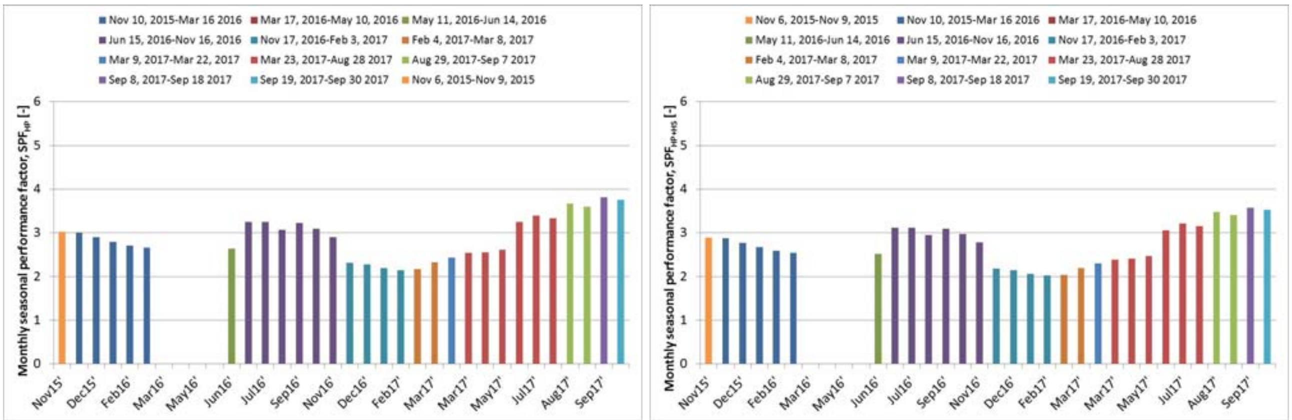


Figure 55. Seasonal performance factors.

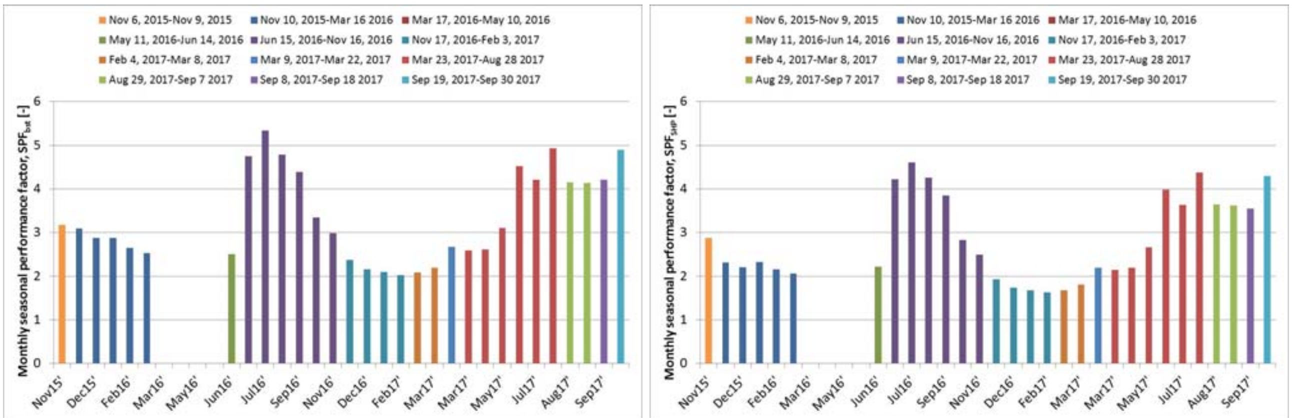


Figure 56. Monthly seasonal performance factors for the solar heating/heat pump system without considering the heat loss of the storage tank (left) and with heat .

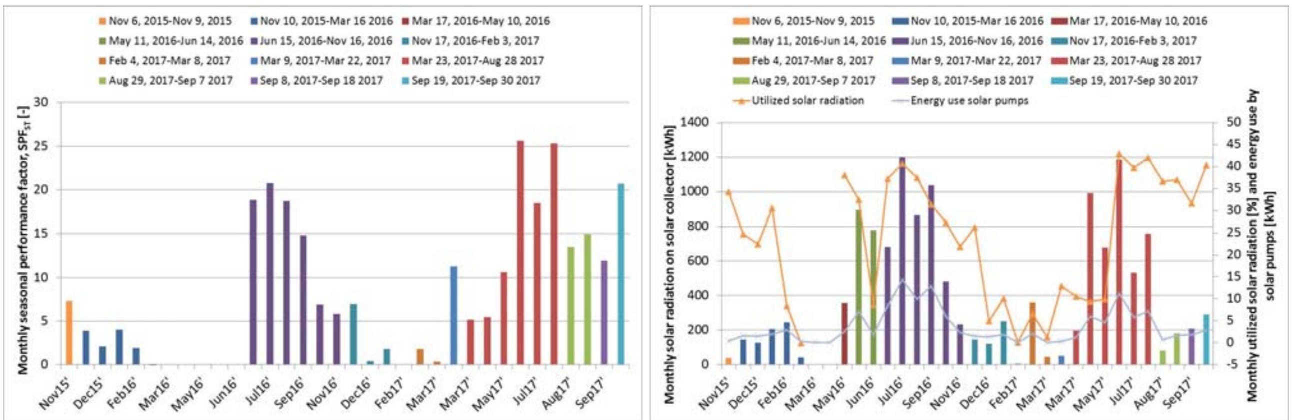


Figure 57. Monthly seasonal performance factor for the solar collector (left) and monthly solar radiation on the solar collector and the utilization of the solar radiation and the electricity consumption of the solar pumps (right).

What influences the performance of the heat pump?

Figure 58 shows daily values of electricity consumption of the heat pump compressor as function of energy supplied to the storage tank from the heat pump. The measurement points are divided into periods corresponding to the periods shown in Table 6. In the figure, it is clear to see that each period of measurement points form an almost linear curve between the daily electricity consumption of the heat pump compressor and the daily energy supplied to the storage tank from the heat pump. The tilts of the curves depend on the system design and the operation conditions of the heat pump. This shows that the efficiency of the heat pump is constant for the same system design and operation conditions.

From Figure 58 it is also clear to see that the system configuration e) results in the most efficient operation conditions of the heat pump. In the period Mar 23 2017 – Jun 2 2017, the thermostatic valve in the shunt between the flow and return to/from the space heating loop is open and cold water coming from the space heating loop is mixed with hot water from the storage tank going to the space heating loop. Hereafter the valve is closed leading to an increased space heating consumption. Further and much more important is that new solar collectors are put in operation on June 2 2017 resulting in increased amounts of solar energy transferred to the tank. The measurement points from this period are now divided in two groups of points which are a group of points located high in the graphs from before the changes and a group of points located low in the graphs from after the changes. From the figure it can be seen that the energy consumption of the heat pump compressor increases as the total consumption of space heating and domestic hot water increases for all the curves. Since the two groups of points not only represent an increased space heating consumption, but also a large increase in the amount of solar energy transferred to the storage tank it is concluded that the efficiency of the heat pump compressor is influenced in a very positive way if the amount of solar energy supplied to the system increases.

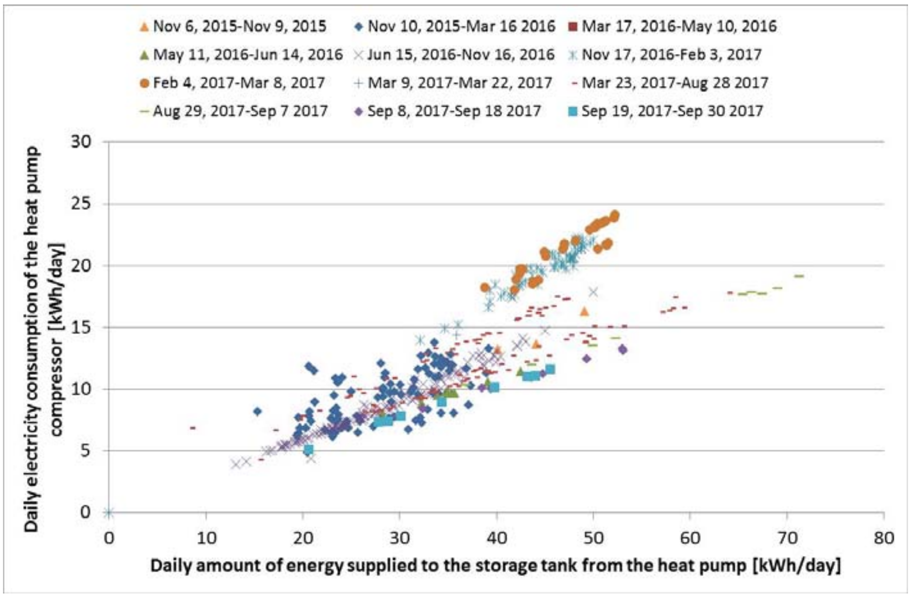


Figure 58. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump.

By focusing on the different periods shown in Figure 58, the following observations on what influences the efficiency of the heat pump are made:

Going from system configuration a) to b), se control and operation conditions in Table 14:

Table 14. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Nov 5 2015 – Nov 9 2015	Sup modul	50.5 °C / 4 K	25 °C / 4 K	a)
Nov 10 2015 – Mar 16 2016	Sup modul	50.5 °C / 4 K	25 °C / 4 K	b)

- Low set point temperature level in SH and DHW volume in storage tank
- Similar solar energy supply to storage tank
- Lower SH and DHW consumption in b) than in a)
- The points from the two measurement periods lay in one curve indicating that the improved system design and total consumption does not influence the efficiency of the heat pump compressor, see Figure 59

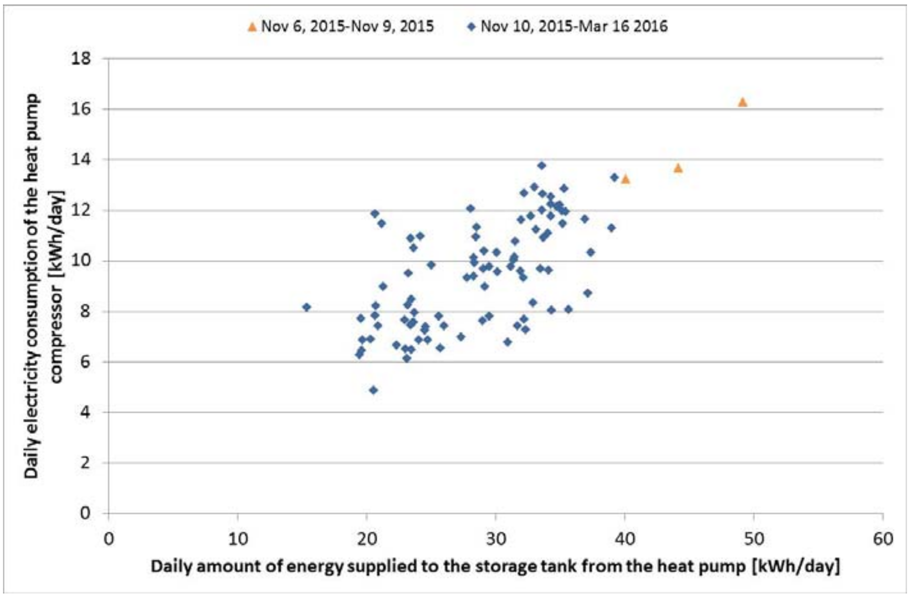


Figure 59. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration a) to b).

Going from system configuration b) to c), se control and operation conditions in Table 15:

Table 15. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW	SH	

		Set point temp. / Neutral zone	Set point temp. / Neutral zone	
Nov 10 2015 – Mar 16 2016	Sup modul	50.5 °C / 4 K	25 °C / 4 K	b)
May 11 2016 – Jun 14 2016	Sup modul	50.5 °C / 4 K	35 °C / 4 K	c)

- Low set point temperature level in SH and DHW volume in storage tank
- No solar energy supply to storage tank in c)
- Similar SH and DHW consumption
- The points from the two different measurement periods lay in two curves, one curve with b) points and one curve with c) points. The tilt of the curve with b) points is higher than the tilt of the curve with c) points indicating that the improved system design influences the efficiency of the heat pump compressor in a positive way, see Figure 60

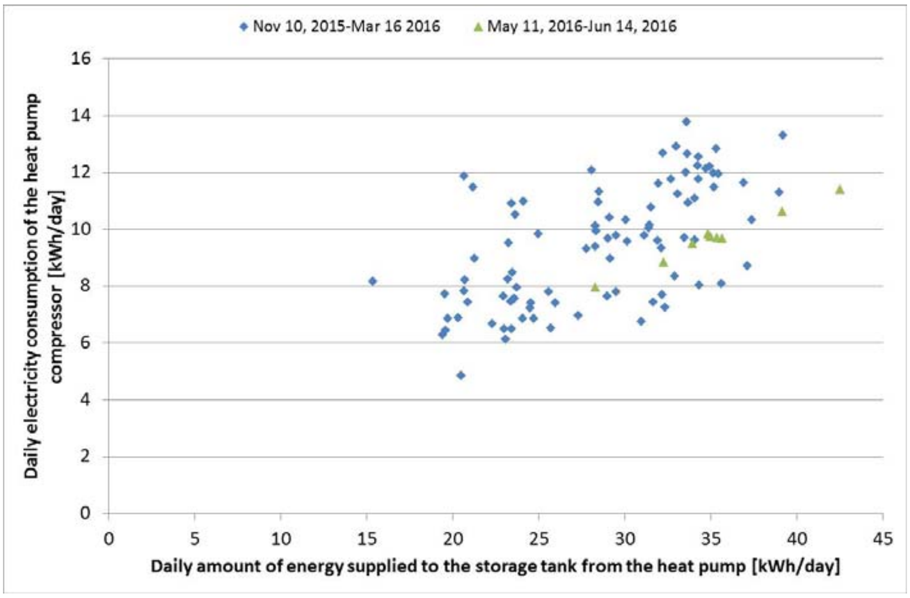


Figure 60. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration b) to c).

Going from system configuration c) with low DHW set point temperature level to c) with high DHW set point temperature level, se control and operation conditions in Table 16:

Table 16. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
May 11 2016 – Jun 14 2016	Sup modul	50.5 °C / 4 K	35 °C / 4 K	c)
Jun 15 2016 – Nov 16 2016	Sup modul	55 °C / 4 K	35 °C / 4 K	c)

- Similar solar energy supply to storage tank
- Similar SH consumption

- The points from the two measurement periods lay in two curves, one curve with c) points with low DHW temperature level and one curve with c) points with high DHW temperature level. The tilt of the curve with c) points with high DHW temperature level is higher than the tilt of the curve with c) points with low DWH temperature level indicating that high temperature level influences the efficiency of the heat pump compressor in a negative way, see Figure 61

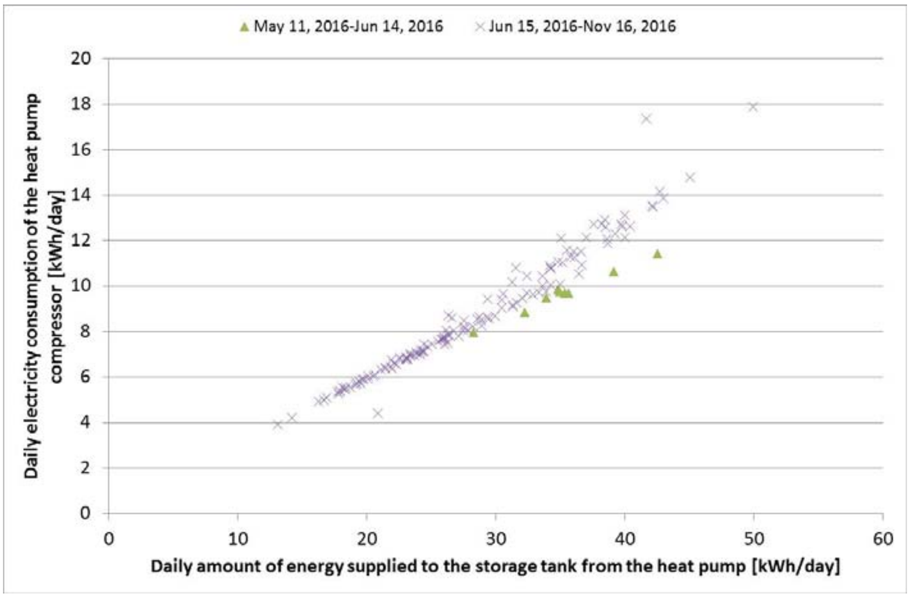


Figure 61. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration c) with low DHW temperature level to c) with high DHW temperature level.

Going from system configuration c) in Sup modul heat pump mode to c) in HTank on/off heat pump mode, se control and operation conditions in Table 17:

Table 17. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Jun 15 2016 – Nov 16 2016	Sup modul	55 °C / 4 K	35 °C / 4 K	c)
Nov 17 2016 – Feb 3 2017	HTank on/off	55 °C / 4 K	35 °C / 4 K	c)

- High set point temperature level in SH and DHW volume in storage tank
- Lower solar energy supply to storage tank in Sup modul mode than in HTank on/off mode
- Similar SH and DHW consumption
- The points from the two measurement periods lay in two curves, one curve with c) points in Sup module mode and one curve with c) points in HTank on/off mode. The tilt of the curve with c) points in Sup modul mode is lower than the tilt of the curve with c) points in HTank on/off mode. The higher tilt in HTank on/off mode is related to the fact that the heat pump power is now too low to supply the needed heat to a storage tank. There is mixing between the domestic

hot water volume and the space heating volume and the heat pump operates constantly on the minimum frequency of 30 Hz. Consequently, the heat pump runs in domestic hot water preparation mode most of the time and the efficiency of the heat pump compressor decreases, see Figure 62

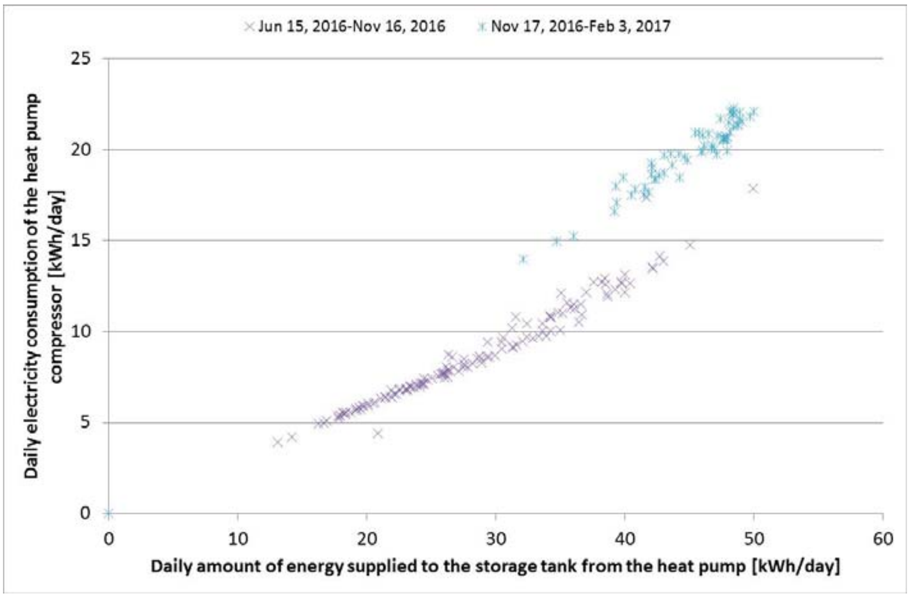


Figure 62. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration c) in Sup modul heat pump mode to c) in HTank on/off heat pump mode.

Going from system configuration c) in HTank on/off heat pump mode to e) in HTank on/off heat pump mode, se control and operation conditions in Table 18:

Table 18. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Feb 4 2017 – Mar 8 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	c)
Mar 9 2017 – Mar 22 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	d)
Mar 23 2017 – August 28 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	e)

- High set point temperature level in SH and DHW volume in storage tank
- Similar solar energy supply before new solar collectors (June 2 2017). More solar energy supply to e) than c) with new solar collectors
- Similar SH and DHW consumption before valve in shunt in SH loop is closed (June 2 2017). More consumption in e) than in c) after valve in shunt in SH loop is closed
- The points from the measurement periods lay in three curves, one curve with c) points and two curves with d) points. The tilt of the curve with c) points is higher than the tilt of the two curves with e) points. The decrease of the tilt is a result of better thermal stratification in the e) tank

and thereby better operation conditions of the heat pump operated in HTank on/off mode (the heat pump operates constantly on the minimum frequency of 30 Hz)

- Further the tilt of the curve with e) points is higher before the new solar collectors and the closed valve in the shunt in the space heating loop than after. The decrease in tilt is related to more solar energy being transferred to the storage tank with the new solar collectors. The change in consumption alone does not change the tilt of the curve, see Figure 63

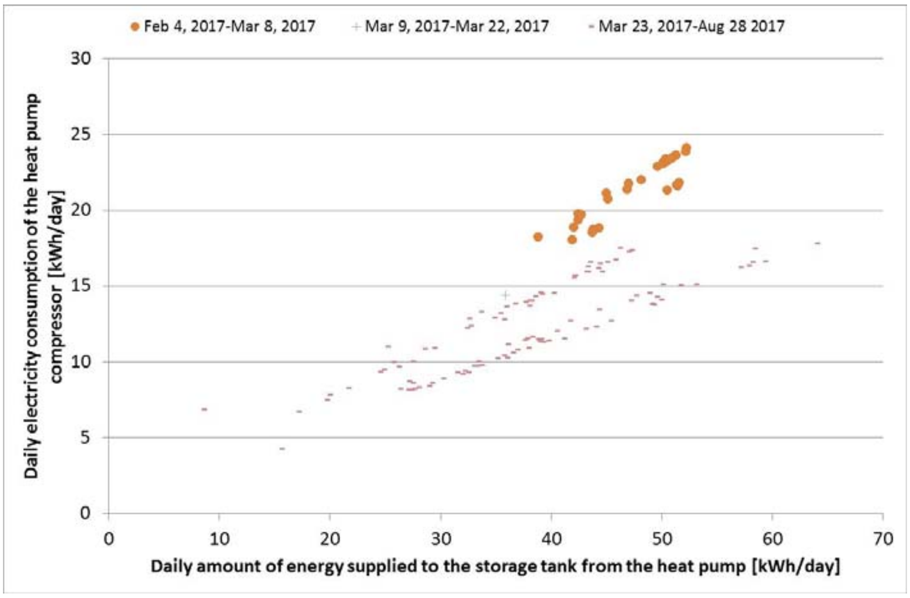


Figure 63. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, Going from system configuration c) in HTank on/off heat pump mode to e) in HTank on/off heat pump mode.

Going from system configuration e) in HTank on/off heat pump mode (after new solar collector and valve in shunt in SH loop is closed) to e) in HTank mod heat pump mode, se control and operation conditions in Table 20:

Table 19. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Jun 2 2017 – August 28 2017	HTank on/off	55 °C / 4 K	45 °C / 15 K	e)
Aug 29 2017 – Sep 7 2017	HTank mod	55 °C / 4 K	45 °C / 15 K	e)

- High set point temperature level in SH and DHW volume in storage tank
- Similar solar energy supply
- Similar SH and DHW consumption
- The points from the two measurement periods lay in two curves, one curve with e) points in HTank on/off heat pump mode and one curve with e) points in HTank mod mode. The tilt of the curve with e) points HTank on/off heat pump mode is slightly higher than the tilt of the curve

with e) points in HTank mod mode. The heat pump is slightly more efficient in HTank mod mode than in HTank on/off mode, see Figure 64

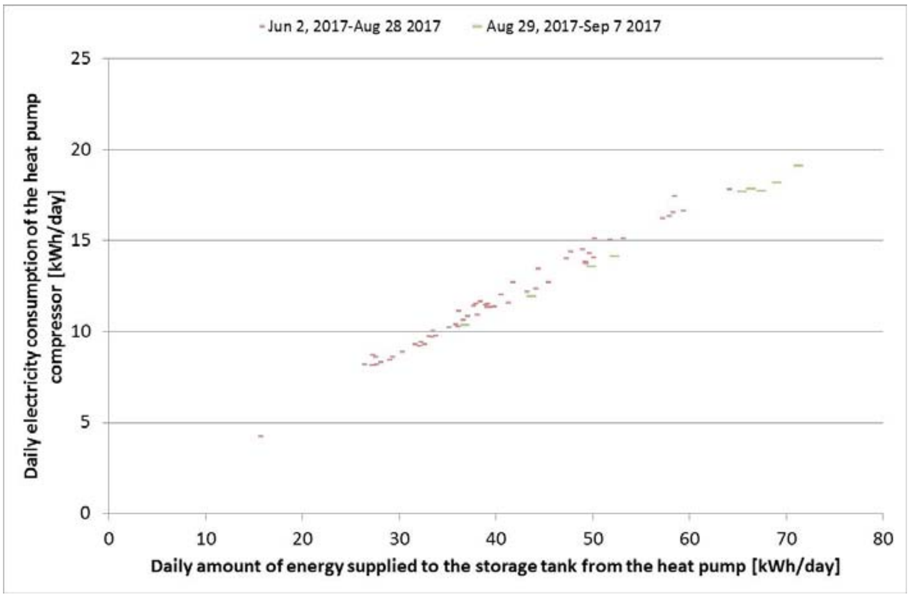


Figure 64. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration e) in HTank on/off heat pump mode (after new solar collector and valve in shunt in SH loop is closed) to e) in HTank mod heat pump mode.

Going from system configuration e) with high SH temperature level to e) with low SH temperature level, se control and operation conditions in Table 20:

Table 20. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Aug 29 2017 – Sep 7 2017	HTank mod	55 °C / 4 K	45 °C / 15 K	e)
Sep 8 2017 – Sep 18 2017	HTank mod	55 °C / 4 K	35 °C / 5 K	e)

- High set point temperature level in DHW volume in storage tank
- Similar solar energy supply
- Higher SH consumption with higher SH temperature level
- The points from the two measurement periods lay in two curves, one curve with e) points with high SH temperature level and one curve with e) points with low SH temperature level. The tilt of the curve with e) points with high SH temperature level is slightly higher than the tilt of the curve with e) points with low SH temperature level. This shows that a low temperature level in space heating loop influences the heat pump efficiency in a positive way, see Figure 65

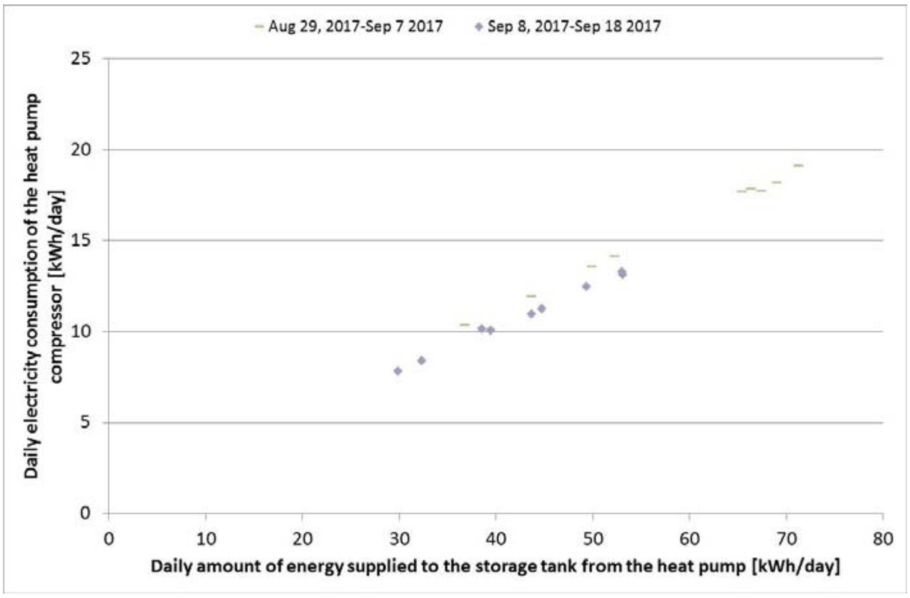


Figure 65. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration e) with high SH temperature level to e) with low SH temperature level.

Going from system configuration e) with high DHW temperature level to e) with low DHW temperature level, se control and operation conditions in Table 21:

Table 21. Control and operation conditions for the solar heating/heat pump system.

Period	HP control strategy	Operation conditions		Storage tank design
		DHW Set point temp. / Neutral zone	SH Set point temp. / Neutral zone	
Sep 8 2017 – Sep 18 2017	HTank mod	55 °C / 4 K	35 °C / 5 K	e)
Sep 19 2017 – Sep 30 2017	HTank mod	52 °C / 4 K	35 °C / 5 K	e)

- Low set point temperature level in SH volume in storage tank
- Similar solar energy supply
- The points from the two measurement periods lay in one curve indicating that the heat pump is equally efficient with the two slightly different temperature levels in the DHW volume, see Figure 66

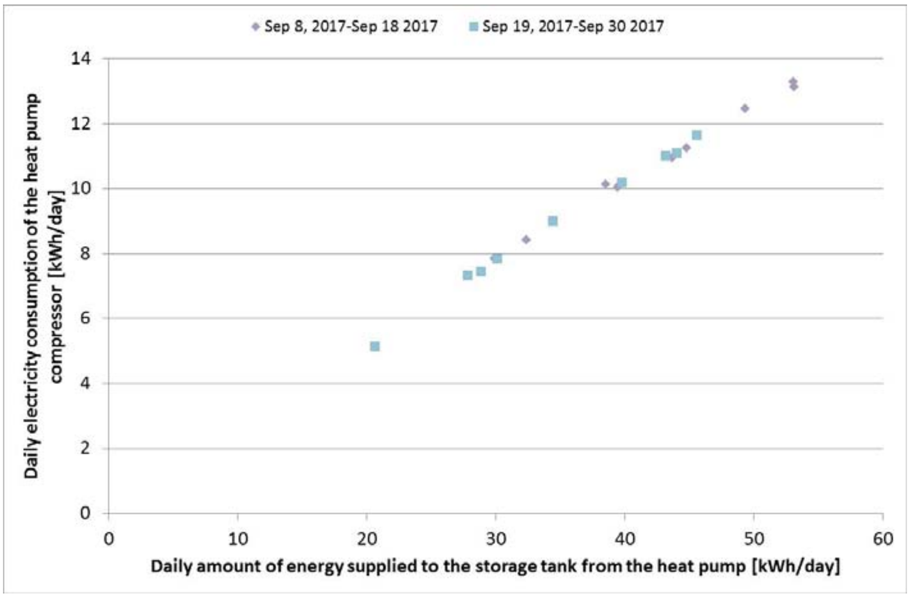


Figure 66. Daily values of electricity consumption of heat pump compressor as function of energy supplied to the storage tank from the heat pump, going from system configuration e) with high DHW temperature level to e) with low DHW temperature level.

Measurements from the ground

Figure 67 - Figure 69 show monthly values of the temperatures from the boreholes in the ground. On the x-axis, the temperature is shown and on the y-axis, the depth below the soil surface is shown. Each curve represent one day in the middle of the month. Measurements from borehole B1 10 meter away from the ground source heat exchanger are shown with dotted curves while the measurements from borehole B2 in the middle of the ground source heat exchanger are shown with full curves.

Until November 26 2014, no energy is drawn from the ground. Until September 2015 energy is drawn from the ground for domestic hot water only. Hereafter, energy is also drawn from the ground for space heating. The left graph in Figure 67 shows the monthly energy amounts drawn from the ground source from November 2015 to September 2017, see also Table 13. It can be seen that the monthly amount of energy drawn from the ground increases gradually from November 2015 to September 2017.

As previously mentioned, a new data acquisition system is installed in the beginning of 2014. The data acquisition system used to obtain the measurements in 2013 is based on a cDAQ system and temperature measurement cards type NI 9213 from the company National Instruments. In 2014, the new data acquisition system is based on a cRIO and temperature measurement cards type NI 9214 also from the company National Instruments. The new data acquisition system and the new measurement cards have a better accuracy than the old data acquisition system and the old measurement cards. This results in a shift in the temperature measurements of about 1 K. It can be observed at the temperature measurements in 10 meters depth which are around 10 °C in 2013 and around 11 °C at the same time in 2014. Therefore, the measurements from 2013 are only used to show the temperature distribution in the undisturbed ground source in borehole B1 and B2.

It can be seen that the undisturbed ground temperatures change during the year, even in the depth of 10 meter. It can also be seen that the temperature variations during the year are larger in B2 than in B1 during summer where the ground is heated by the sun.

After the solar heating/heat pump system is put in operation and heat is extracted from the ground, the temperature variations in B2 becomes larger in the whole ground volume and the temperature level in the ground volume decreases.

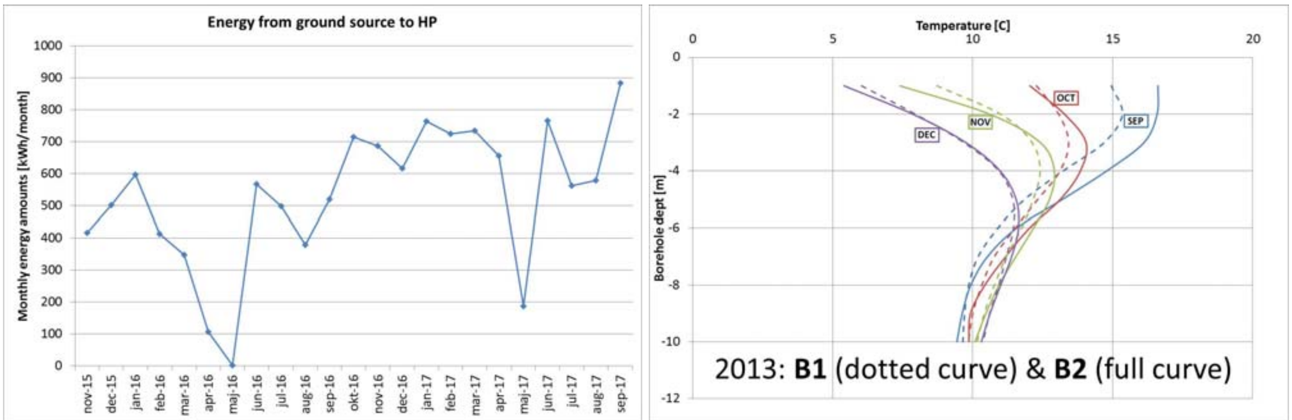


Figure 67. Left: Monthly amount of energy drawn from the ground source, November 2015 – September 2017. Right: Ground temperatures from the middle of each month in 2013.

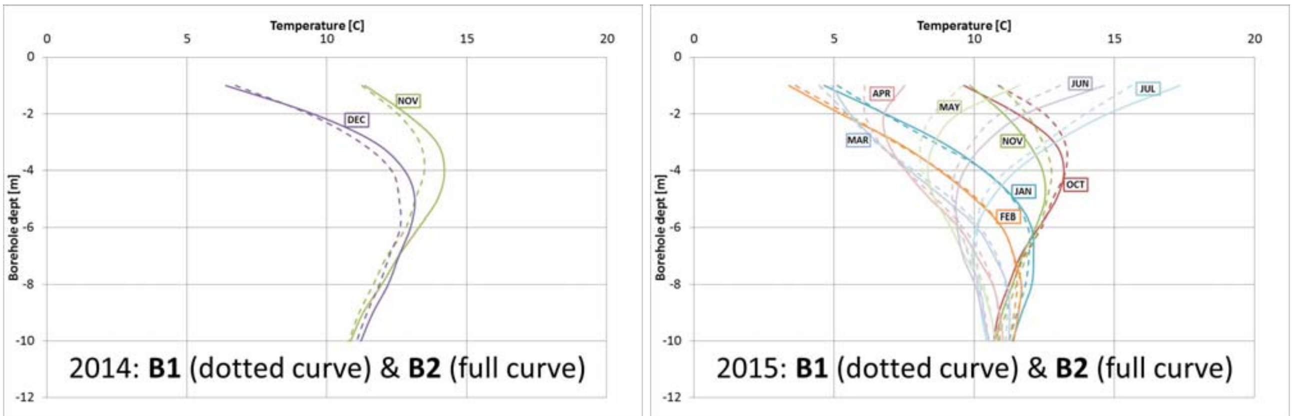


Figure 68. Ground temperatures from the middle of each month in 2014 and 2015.

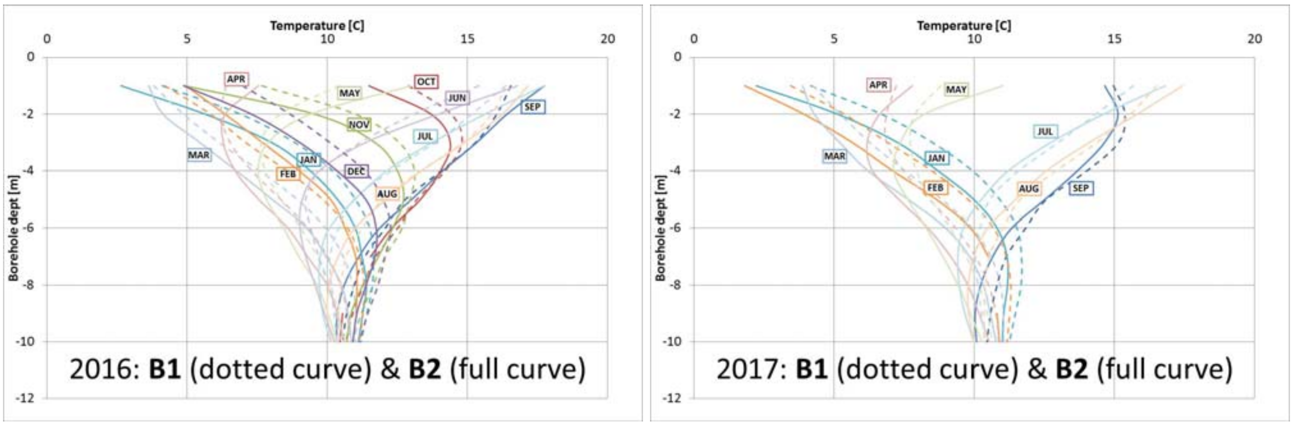


Figure 69. Ground temperatures from the middle of each month in 2016 and 2017.

Figure 70 shows daily temperatures in the ground in the boreholes B1 and B2 from November 2014 to September 2017. The figure also shows daily solar radiation on the 45° South and daily ambient temperatures. Measurements from borehole B1 10 meter away from the ground source heat exchanger are shown with dotted curves while the measurements from borehole B2 in the middle of the ground source heat exchanger are shown with full curves.

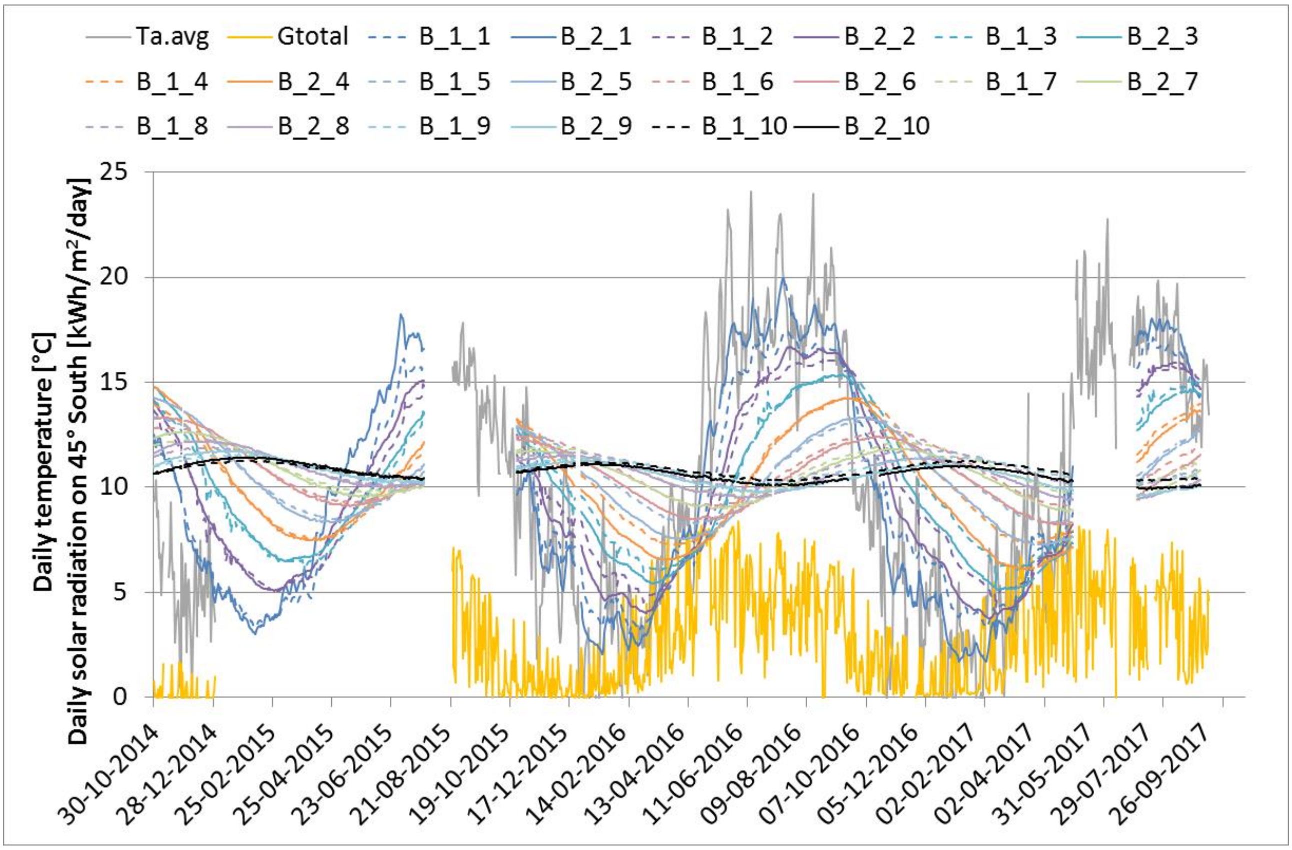


Figure 70. Daily values of ground temperatures in borehole B1 and B2, ambient temperature and solar radiation.

During the winter 2014 – 2015 where only small amounts of energy are drawn from the ground, the temperatures in the two boreholes are very similar. Between spring and autumn 2015, the periods where the days are longer and the sun more powerful, there is difference between the temperatures in the two boreholes. The temperatures in B2 in the middle of the ground source heat exchanger are higher than the same temperatures in B1.

After September 2015 where larger amounts of energy are drawn from the ground for both domestic hot water and space heating, the temperatures in borehole B2 are lower than the temperatures in borehole B1 during winter in the whole borehole depth. During summer, the temperatures in boreholes B1 and B2 increase again, but it can also be seen that the temperature level in the whole borehole B2 is slowly decreasing. The decrease of the temperature level in borehole B2 in 10 meters depth is 0.4 K in the period November 2014 – September 2017 compared to the temperature level in borehole B1.

The gradual temperature decrease may be avoided by heating the ground with solar energy during the summer period.

Conclusions

A solar heating/heat pump system with a horizontal ground source heat exchanger is investigated experimentally. The electrical energy consumption, the energy flows in the whole system and in the ground source heat exchanger are measured. Also the temperatures in the ground are measured every meter until the depth of 10 meters below the soil surface both in the middle of the ground source heat exchanger (B2) and 10 meters away from the edge of the ground source heat exchanger (B1). B1 is located in a shaded area while B2 is located in the sunny area in the middle of the ground source heat exchanger.

The measurements of the ground temperatures are performed in the period from August 2013 until September 2017 while the measurements of the solar heating/heat pump system are performed from November 2014 where the system was put in operation until September 2017.

The system has been operated with daily draw offs for domestic hot water from November 2014 and from October 2015 also daily draw offs for space heating are performed.

The solar heating/heat pump system consists of 9 m^2 flat plate solar collectors, a 3-12 kW modulating heat pump that is connected to a horizontal ground source heat exchanger with 480 meter ground pipes laid in 4 slings 1 meter below the soil surface. A 725 liter tank-in-tank storage is used as a combined storage tank for domestic hot water and space heating with domestic hot water in the inner tank and still water for space heating in the outer tank. The inner tank has a mushroom shape and a volume of 175 liter.

The solar heating/heat pump system is tested with different set point temperatures of the domestic hot water and the space heating water in the storage tank. Further different control strategies of the heat pump have been applied in the test period. The heat pump can operate in modulating mode where it can modulate the power used to heat the water that flows through the condenser. The heat pump can either modulate the power in order to meet the required flow temperature (Sup modul) or the heat pump can modulate to meet the required storage tank temperatures (HTank mod). The heat pump can also operate in on/off mode with a constant power to heat the water that flows through the condenser and meet the required storage tank temperatures (HTank on/off).

Five different system configurations (a – e) of the solar heating/heat pump system are investigated in a step by step improvement of the design of the storage tank.

The measurement results from the solar heating/heat pump system shows that:

- The efficiency of the heat pump is constant for a specific system configuration and specific operation conditions of the heat pump. The efficiency is defined as the ratio between the heat produced by the heat pump and the electricity used by the heat pump compressor.
- The efficiency of the heat pump is higher when the system is combined with solar heating than without, because: solar energy can be used directly for domestic hot water and space heating, the heat pump is less activated, the heat extraction from the ground is reduced, the ground temperatures stay at a higher temperature level and the inlet temperatures from the ground to the heat pump are higher.
- Good thermal stratification in the tank is very important. The efficiency of the heat pump improves when mixing in the tank between the domestic hot water volume and the space heating volume is reduced.
- Low set point temperatures in domestic hot water volume and space heating volume are important. The efficiency of the heat pump improves when the set point temperature levels in the domestic hot water volume and in the space heating volume are reduced.
- The efficiency of the heat pump is not influenced by the total consumption of space heating and domestic hot water.
- The efficiency of the heat pump is not influenced by the heat pump operation mode if the design of the storage tank prevents mixing between the domestic hot water volume and the space heating volume.
- The efficiency of the heat pump can be further improved by improving the design of the draw off from the storage tank for the space heating loop.
- The monthly seasonal performance factor for the heat pump system without solar collectors, SPF_{HP+HS} is lower than the seasonal performance factor for the solar heating/heat pump system, SPF_{bst}.
- For the period June 2017 – September 2017 where the solar heating/heat pump system design has been improved to system configuration e) and the new solar collector is put in operation, the average monthly seasonal performance factor for the heat pump system, SPF_{HP+HS} is 3.35 compared to the average monthly seasonal performance factor for the heat pump system with solar assistance, SPF_{bst} which is 4.44.

The measurement results from the ground source heat exchanger and the ground show that:

- The ground source heat exchanger is long enough in order for the fluid to heat up to the temperature level in the ground in level of the ground source heat exchanger both summer and winter.
- There are temperature gradients both vertically and horizontally in the ground where the heat exchanger is located.

- The ground temperatures are lower around the inner sling than around the outer sling of the heat exchanger.
- During summer, the ground temperature in level of the outer sling of the ground source heat exchanger is warmer than the temperature that flows out of the ground source heat exchanger while the ground temperature in level of the inner sling equals the temperature that flows out of the ground source heat exchanger. The reason is that heat from the surrounding ground flows towards the ground source heat exchanger and raises the ground temperature level from the edge of the heat exchanger.
- In winter, the ground temperature in level of the outer and inner slings of the ground source heat exchanger equals the temperature that flows out of the ground source heat exchanger.
- The temperatures in the ground follow a natural seasonal variation even in the depth 10 meter below the soil surface. In summer the ground temperatures increase and in winter the ground temperatures decrease.
- Due to heat extraction from the ground, the ground temperature below the ground source heat exchanger 10 meter below the soil surface has decreased by 0.4 K in the period 2014 – 2017.

The investigations show that it is very good to combine the ground source heat pump system with a solar heating system because the operation conditions of the heat pump are improved.

Nomenclature

Q	Thermal energy [kWh]
E	Electrical energy [kWh]

Subscripts

ctr	Control system
c	Heat pump condenser
x	Hose number in ground source heat exchanger
y	Measurement line number across ground source heat exchanger
Z, z	Depth below soil surface

Abbrevations

ST	Solar thermal
CP	Circulation pump
HS	Heat source
F	Flow sensor
P	Pump
H	Hose
B	Borehole
SH	Space heating
DHW	Domestic hot water
AUX	Auxiliary
HP	Heat pump
PP	Polypropylene

POM	Polyoxymethylene
PEX	Crosslinked polyethylene
IPA	Isopropyl alcohol
Sup modul	Control mode of compressor. Modulating compressor power to meet the required supply temperature
HTank on/off	Control mode of compressor. Fixed compressor power to meet the required temperature in the storage tank
HTank mod	Control mode of compressor. Modulating compressor power to meet the required temperature in the storage tank

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