Combining solar collectors with an air heat pump for domestic hot water and space heating

A case study for electric heated single family houses in Sweden

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Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

Keywords

Abstract

Today there are still single family houses with direct electric heating systems, even though this is an expensive and inefficient way of heating a house. It is common to install an air-to-air heat pump that requires less electricity to produce the same amount of heat as a direct electricity heating system. These heat pumps do not produce any energy for domestic hot water since the water is heated via separate hot water storage. To cut the cost of water heating a solar collector system could be installed that covers the heating need during the summer. If it was possible to change the construction of the heat pump so it could heat the water as well, this would eliminate all need for direct electric heating.

A simulation model of a heat pump used for both domestic hot water and space heating was built using TRNSYS software. The heat pump was modelled in such a way that heat is directed either for indoor space heating, or to a heat exchanger in the hot water tank. In this thesis, a single family house using approximately 17 300 kWh during a year for heating was modelled, which is close to the Swedish average.

The simulation results indicates that if the heating system is changed from direct electricity to an air heat pump that produces both indoor space heating and domestic hot water, without using a hydronic heat delivery system and combined with solar collectors, it is possible to save 76.6-79.5% of the electricity used for heating. Such a system would have a seasonal coefficient of performance between 4.28 and 4.89. This investment in a heating system would have a simple pay-back time of 2.3 to 8.8 years.

Contents

1. Introduction

1.1 Background

Out of the existing 1 928 000 single-family houses in Sweden there are 106 000 houses that only use direct electrical heating systems. In addition there are 8 000 single-family houses that use direct electrical heating in combination with a fireplace and another 24 000 that use air-to-air heat pumps in combination with a fireplace and direct electricity. In total there are 343 000 air- to-air heat pumps in Sweden today.[1]

Direct heating systems are a very inefficient way of heating a home since electricity is a high value energy source. It was during the 1970s that most of these houses were built.[2] The 70s were the time when Sweden's electrical future seemed to be nuclear. It was commonly believed that there would be an excess of electricity in the future and therefore this was the preferred heating system in new buildings. Sweden only built half of the nuclear reactors planned, hence the electricity did not get as inexpensive as expected and to use direct electric heating is today very costly. This makes it common to upgrade the space heating system to an air-to-air heat pump that uses less electricity to produce the same amount of heat. This will still leave the domestic hot water to be produced by direct electricity since a separate hot water tank is commonly used. Depending on how the electricity is produced, the production could have a serious impact on the environment, and it is an expensive way of heating a house. If it was possible to combine the air-to-air heat pump to produce both space and water heating, this would eliminate the need for direct electricity in the heating system, without installing a water distribution system. If this heat pump is combined with solar collector systems, this would reduce the time the heat pump has to be used, especially during the summer period, and it would reduce the need for externally produced electricity as well as creating a more environmentally friendly heating system.

1.2 Problem formulation

Is it possible to use an air-to-air heat pump to provide heat for both space heating and for domestic hot water? How can such a system be designed and how would it be controlled?

How could solar collectors be combined in such a system?

Is this type of system cost-effective?

1.3 Purpose

The purpose of this thesis is to conclude regarding the functional and economic feasibility of a combination of an air-to-air heat pump and solar thermal collectors for both space heating and domestic hot water production in a single family house without a hydronic heat delivery system.

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[1] (Energimyndigheten, 2014)
[2] (Heier, 2013)

1.4   Focus and limitations

This report is limited to air heat pumps in combination with solar collectors for an average Swedish single family house and will focus on Swedish weather conditions. No parameter study was performed for different hot water load profiles, different energy consumptions or different heat pump characteristics. This thesis is limited to a theoretical investigation, and no measurements were performed.

1.5   Outline

This report is divided into two parts. In the first part the introduction of the thesis and the theory are presented. In the second part the simulations and calculations are described. These constitute the main part of the report where specific results regarding how the simulations and calculations have been produced and what variables have been chosen are presented. The second part ends with simple economic calculations. The report ends with a discussion about the results and conclusions.

1.6   Theory

1.6.1 Energy use in a Swedish single family house

According to the Swedish nergy agency, single family houses in Sweden use an average of 22 700 kWh of energy each year. This energy is used in three ways: 6 000 kWh for household electricity, 4 500 kWh for hot water and 12 200 kWh for indoor space heating.[3]

In single family houses in Sweden one person uses between 35 and 80 cubic meters of water each year, of this water 40 percent is used as hot water. This result in a hot water consumption of 14 to 32 cubic metres per person a year or 38.5 to 87.7 litres each day, which gives an average of 63 litres per person a day. In a house with four people this results in a total of 252 litres of hot water each day. It takes 55 kWh to heat one cubic metres of water. With our calculated average hot water use this gives a heating demand of 5059 kWh during a year. This is slightly over the 4 500 kWh that is used on average, which can be explained by the fact that an average single family house in Sweden consists of less than four people.[4]

1.6.2 Heat pumps

A heat pump is a device that moves heat from one space to another by a medium called refrigerant. This refrigerant is commonly R410a or R407c but there are many different refrigerants that can be selected by the manufacturers. A heat pump moves heat from a cold space to a hot one, from the outside to the inside of a house for example, by using the natural laws of physics. First it lowers the pressure of the refrigerant which decreases the temperature of the refrigerant. When the temperature is lower than the source temperature, it is sent through an evaporator and heated until it has turned to gas. When it is in gas phase, it is compressed to a pressure that correlates to a

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[3] (Energimyndigheten, 2015)
[4] (Energimyndigheten, 2011)

temperature higher than the load and then releases its energy in a condenser. When this is done energy has been moved from the outside by the evaporator to the inside by the condenser and the process restarts. In this way it is possible to get more kWh of heat than used electricity, while a direct electricity system would produce the same amount of heat as the electricity that has been used. It is important to notice that a heat pump does not create energy (which is impossible according to the first law of thermodynamics), it only moves energy from one reservoir to another. It is easier to move heat than create it and therefore a heat pump can deliver ("produce") more kWh of heat than it uses kWh of electricity. This also puts a limit to heat pumps. Heat pumps usually cannot work in temperatures below -25 degrees Celsius (depending on manufacturer) [5] since there is too little energy in the reservoir at such low temperatures.

The relationship between electricity demand and heat production is called coefficient of performance, or in short COP.

$$COP = \frac{Produced\ heat}{Requierd\ electrical\ input}$$ (Equation 1)

The Carnot COP equation can be written as follows.

$$COP_{Carnot} = \frac{T_{high}}{T_{high} - T_{low}}$$ (Equation 2)

In this Carnot equation it is possible to see what is true for all heat pumps, that COP will decrease when delta T increases.

The European Union's sustainable design demands that the SCOP (seasonal coefficient of performance, average COP over a year) for all air-to-air heat pumps with a power up to 12 kW should, since 1st of January 2014, be at least 3.8[6]. This limit is set according to a standardized way of measuring SCOP for heat pumps so they can be compared in the European Union. In SCOP eventual flow pumps are not considered.

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[5] (Thermia, u.d.), (Nibe, u.d.)
[6] (Energimyndheten, 2015)

2. Simulation

2.1   Method

This thesis uses the simulation programme TRNSYS.[7] TRNSYS has been chosen since it is a flexible simulation tool appropriate for the task that is being investigated in this report and has a big library of components. Some handmade calculations and graphic solutions were also used.

All simulations use a weather data file from Arlanda, Sweden. The outdoor temperature and the mains water temperature for one year can be seen in figure 1 and figure 2 below. The load profile used is the same one that is given in the Trnsys SDHM example file (solar domestic hot water file). This load profile distributed with 25 % use at 07:00, 25 % use at 09:00, 12.5 % at 11:00, 12.5 % at 13:00, 12.5 % at 18:00 and 12.5 % at 12:00. All simulations will be over one year (8760 hours) with time steps of 0.25 hours (15 minutes). The integrations and the convergence tolerance have been put to 0.001. The number of iterations that is allowed before a warning is set to 30, and the number of warnings before an error is also set to 30.

In the models full lines represent physical flow of water or air, blue lines for cold flow and red for hot flow and dotted lines represent information flow.
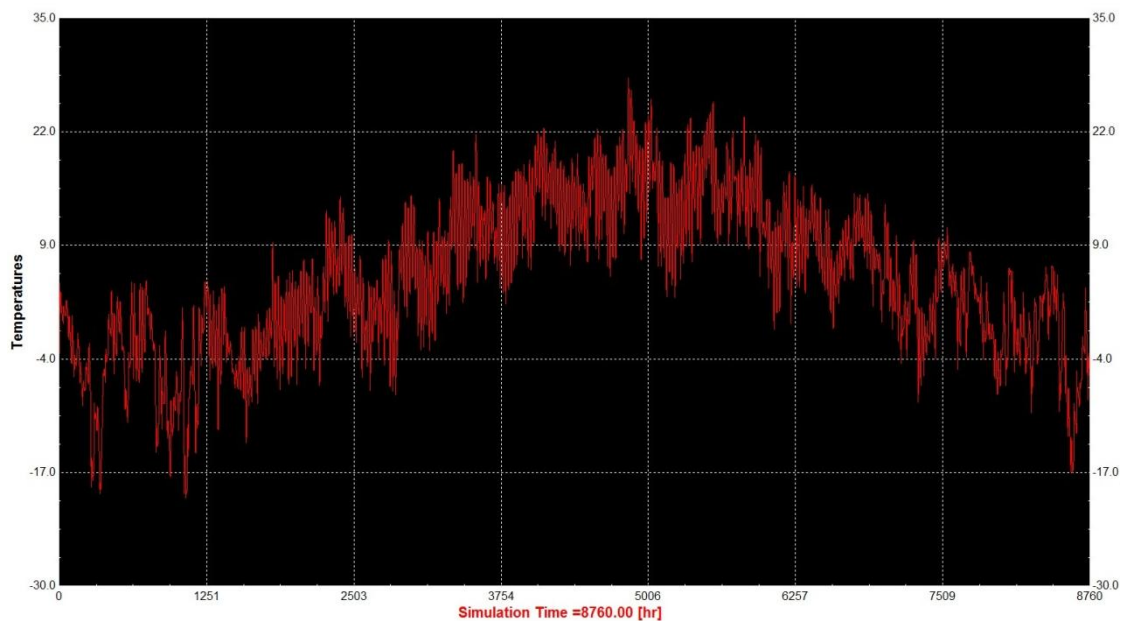

Figure 1: Outdoor temperature at Arlanda during one year

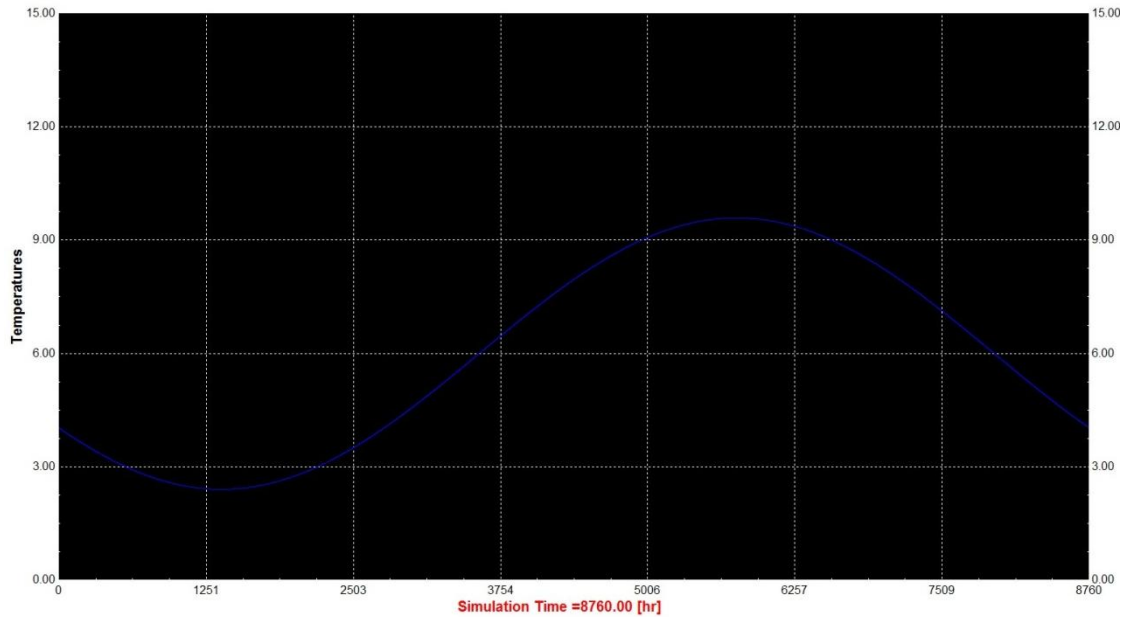---

[7] (TRNSYS, u.d.)

Figure 2: Mains water temperature at Arlanda during one year

2.2 Design of the combined heating system

A suggestion for a system layout where an air heat pump is used both for airborne space heating and domestic hot water heating can be seen in figure 3 below. This layout is derived from an air-to-air heat pump where the indoor space is heated from a condenser only. In this system one diverter and a T-piece have been added so the refrigerant can be sent to a hot water accumulator. To heat the hot water the refrigerant has to be at a higher temperature than that of the indoor air. This heat is achieved by letting the compressor create a higher pressure in the refrigerant system. The change in compressor output will have to be internally combined with the diverter so the system delivers right pressure and temperature to the right place. The heat in this system is sent either to the hot water or to the space heating. Both the house and the tank can keep their temperatures for a while and are used as heat batteries when no heat is delivered. If the system was designed in a way so that it always sent heat to both places, it would always have to be at a temperature level that the domestic hot water requires. By alternating the temperatures this system requires less energy input since it does not always have the high temperature difference. This also results in a higher SCOP. To create a control system with deadbands and set temperatures was a central challenge of this thesis. As shown in figure 3, it is assumed that there are extra connections into the tank that can be used for the solar collector. In reality, common existing storage tanks do not have any available connections, these connections have been added to make the simulation easier. This problem can be solved without a decrease in efficiency.[8]
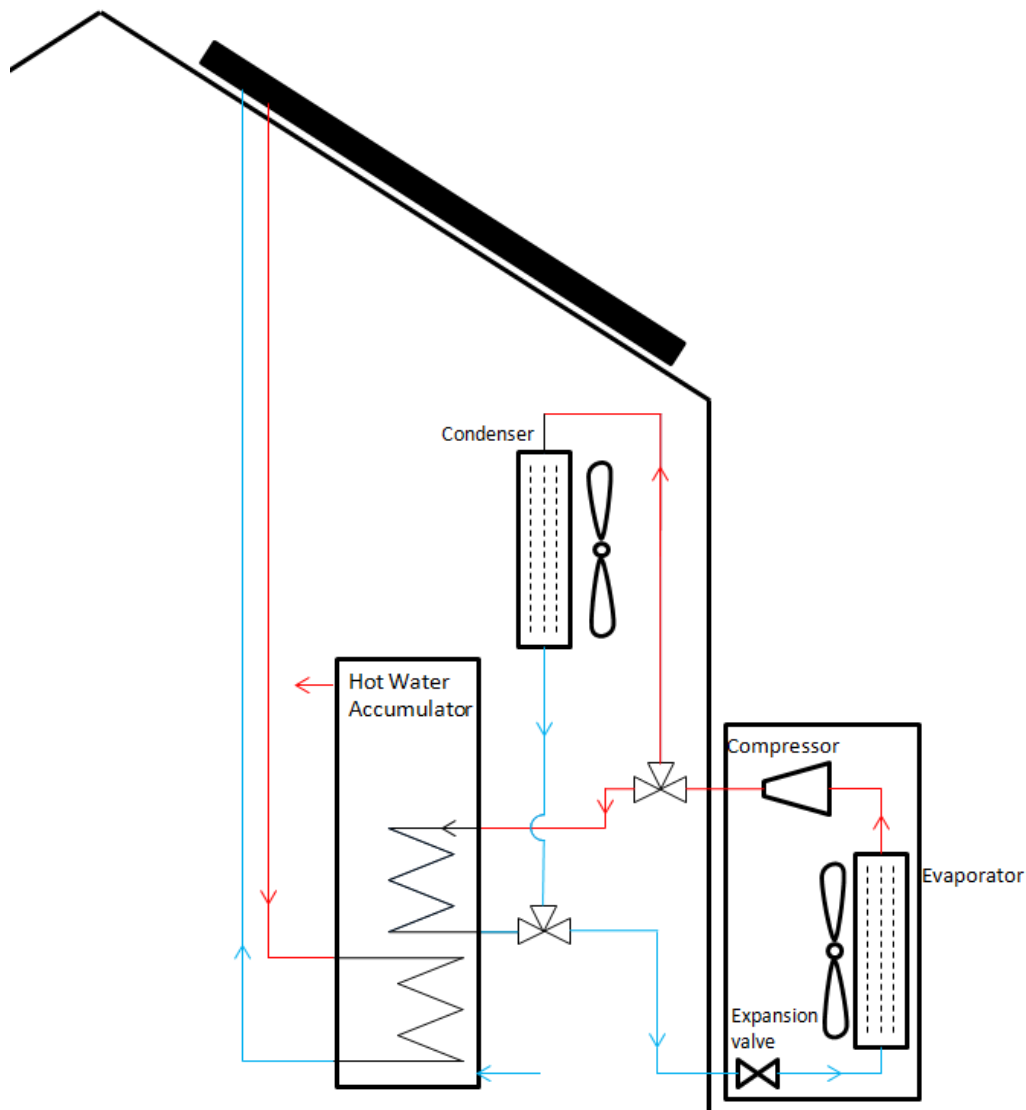
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[8] (Bernado, 2013)

Figure 3: Air heat pump in combination with solar collectors for indoor space and domestic hot water heating

Today there is not a commercially widespread heat pump that works in this way, so this model and its control were modelled for theoretical investigations.

2.3   Simulation of basic features

2.3.1 Simulation of domestic hot water load

In chapter 1.6.1 the energy consumption of a house with only electricity heating is presented. It is necessary to create a house and a hot water load in Trnsys that has this desired consumption. This was done by creating small separated simulations where the heat comes from auxiliary heaters (direct electricity), and the loads are configured to create the wanted load characteristics.

To create the wanted hot water load a model with a hot water accumulator, together with the load profile, was designed. This model can be seen in figure 4. As described in chapter 1.6.1 the hot water consumption was set to 252 litres per day. This consumption should demand an energy input of somewhere above 4500 kWh per year. The tank that is used in the model is Type 4 with fixed inlets and uniform losses, and can be seen in figure 5, with the inputs that can be seen in table 1.
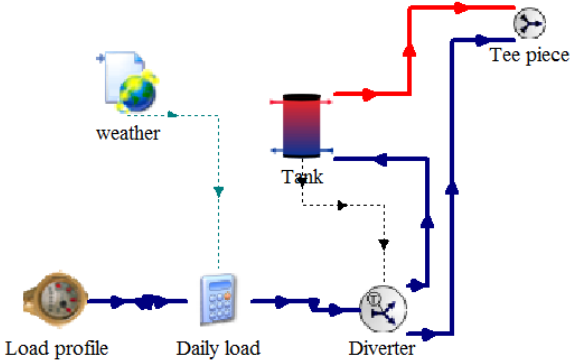

Figure 4: Simulation of domestic hot water load model

Table 1: Variables in tank model for domestic hot water heating load

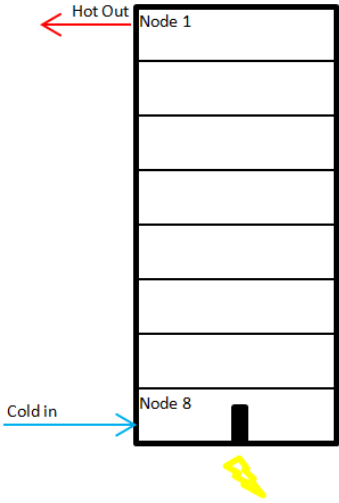|	
Tank volume	0.3 [m^3]
Number of nodes	8
Height of nodes	0.2
Node containing heating element	8
Set point temperature for element	65 °C
Deadband for heating element	5°C
Maximum heating rate of element	3 kW

Figure 5: Domestic hot water tank, Type 4

The variable that was changed to adjust the consumption was the tank loss coefficient [W/m^{2}K].

2.3.2 Simulation of indoor space load

The indoor space load was created using a Type 12c as a load that will be configured to fit the energy demand described in chapter 1.6.1. The model can be seen in figure 6 below. The load is controlled by an external controller regulating an electrical heater. The input variables can be seen in table 2.
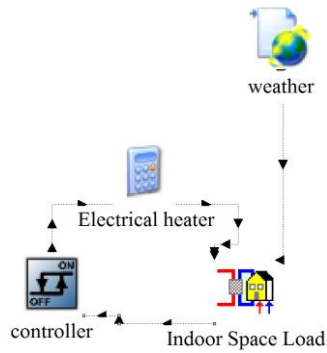
Figure 6: Model of indoor space load

One person produces 100 W of heat to their surroundings, and 70 percent of the household electricity use is transformed to heat.[9] In our simulated house there are 4 people living and 6000 kWh of electricity is used per year. This gives us an internal heat generation of

$$4 * 100 + \frac{6000 * 10^3}{8760} * 0.7 = 879.45\ W \qquad \text{(Equation 3)}$$

Table 2: Input variables to the model of indoor space heating

Effectiveness-Cmin product (Minimum fluid capacitance rate of heat inlet = $\dot{m} * C_p$)	197.85 [W/K]
Internal gains	879.45 W
Set temperature	21°C
Maximum heating rate of element	13 kW

The variables that can be changed to create a wanted load are the overall loss coefficient of the house [W/K].

[9] (Sveby, 2012)

2.4   Simulation of an air heat pump combined with solar collectors

A Trnsys model of the system suggested in 1.6.3 can be seen in figure 7 below. The two pumps in the model are only there for simulation purposes to create a flow in the separate streams and give no other effect on the simulation. No energy input will be measured from these two pumps. The two heat pump models in the simulation should be seen as one air heat pump with two functions. The two functions are indoor space heating and domestic hot water heating and are so named. The hot water delivery is prioritized by the heat pump since the old electric heating system can be used as a back up to maintain the indoor temperature. Domestic hot water is also being heated with solar collectors.
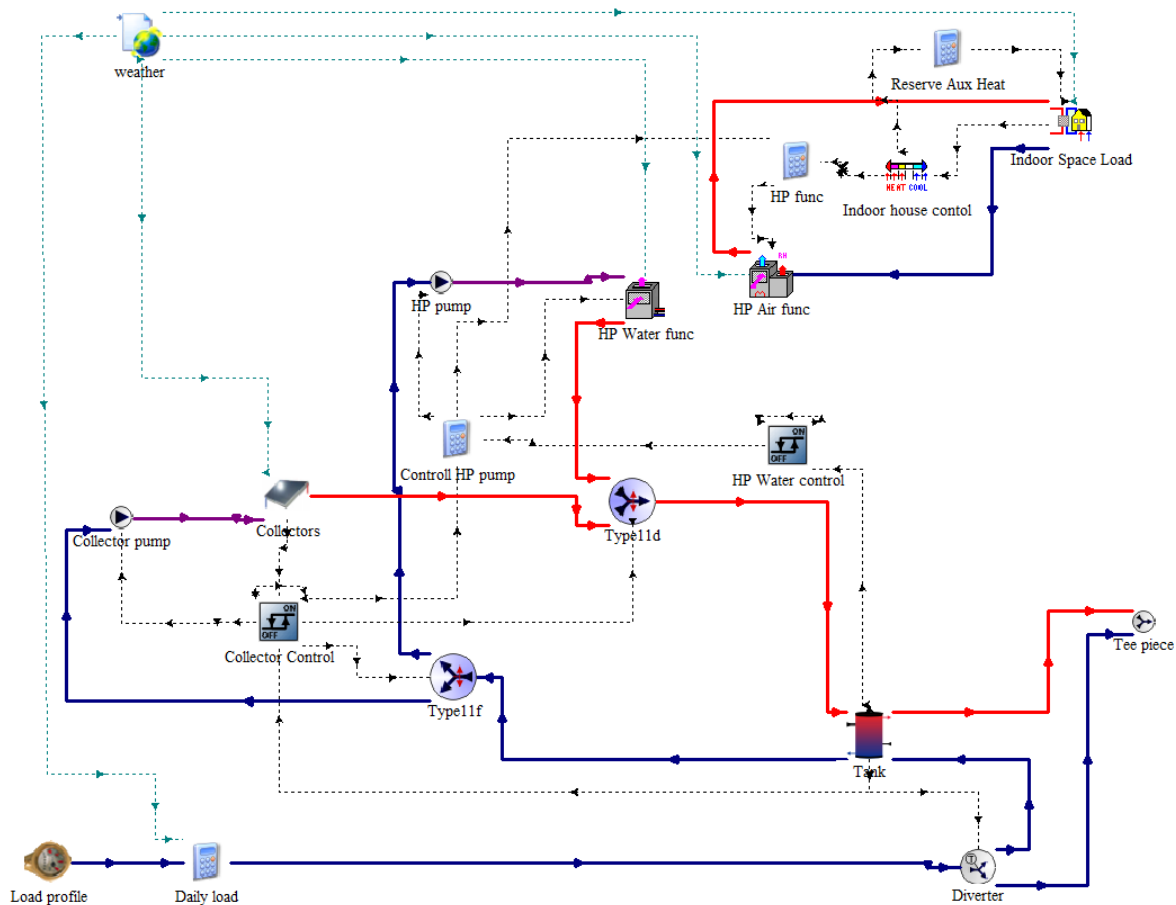

Figure 7: Simulation model of the whole heating system

The domestic hot water load profile is the same as before, but the tank has been changed from the simulation in chapter 2.3.1 to a Type 4 -with user designated inlets and uniform losses. This is the equivalent to the tank that has to be installed with a solar collector system. The settings are the same as in 2.2.1, except that the tank now has additional connections to the heat source and there is no heating element. This tank can be seen in figure 8.
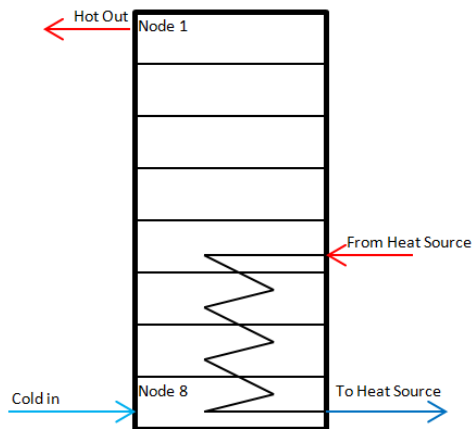
Figure 8: New tank with connections to heat pump and solar collectors

On the source side of the tank there are two diverters of Type 11f and Type 11d that redirect the flow to either the collector or the heat pump, depending on which of them should deliver energy. Since the solar energy is free when the collector system is installed, the controls are created in such a way that the collectors are always prioritised to deliver hot water to the tank. The choice of this control setup will be discussed in the discussion part, chapter 5. This is regulated by "Collector Control" that measures the outlet temperature from the collector and the temperature to the heating source from the tank and decides if there is any solar energy to collect.

The collectors are flat plate collectors with intercept efficiency of 0.8, efficiency slope of 13 kJ/hr*m^{2*}K and efficiency curvature of 0.05 kJ/hr*m^{2*}K. The size is varied to investigate how different sizes affect the whole system. The different inputs to the solar collector are given in the Arlanda weather file.

The heat pump water function is a Type 941 and its inputs are based on Nibe F2030[10], the input variables can be seen in table 3. Type 941's performance data were inconsistent and made the pump work in an undesirable way. This led to a new performance data file being created according to Nibe F2030. Regulation of the water function is done by the "control HP water" control that measures the temperature out from the tank to the load. This outlet temperature is set to not fall below 50 degrees Celsius to avoid microbial growth (for example Legionella).[11] The set temperature and deadband depend on how big the solar collectors are (how much they produce) and were determined by parametrical testing and measuring of different settings for different collector sizes. The outlet signal is sent to the "Control HP pump" that consists of equation 4.

$$Signal\ out = control\ HP\ water * ((collector\ control - 1) * -1) \qquad \text{(Equation 4)}$$

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[10] (Nibe, u.d.)
[11] (Boverket, 2015)

In this way the heat pump water function and the solar collector will not be ON at the same time since the signal from "control HP water" will be multiplied by zero if the collector produces energy, and multiplied by one if the collector does not produce any useful energy.

Table 3: Input values to the heat pump water function

Total air flow rate	2500 m^3/hr
Rated heating capacity	7000 W
Rated heating power	1818 W
Inlet liquid flow rate	540 kg/hr

The indoor space heating loop consists of the house load created in chapter 2.3.2. Thermia Aura[12] has been the base for the heat pump air function that consists of the two-stage heat pump Type 922 (one low power/speed and one high power/speed stage). The inlet parameters can be seen in table 4. Unlike the previous Type 941, Type 922 has an extensive performance data file that makes the model work as expected, and in combination with the problem to find extensive necessary data for air-to-air heat pumps, we will use the original performance data file. To be able to have an acceptable indoor climate even on the coldest days, a reserve electrical heater (reserve aux heat) of 7 kW was added. This may be seen as the existing direct electric heating system. The indoor space heating is controlled with a three-stage thermostat (Type 108) that controls the indoor temperature. The thermostat has a set temperature of 21 degrees Celsius for the heat pump's low stage power, 20 degrees Celsius for the high stage power and 18 degrees Celsius for the reserve electric heater, the thermostat has a deadband of 3 degrees Celsius. It is not possible to set an average temperature since this temperature depends on user preferences. The temperature in this model has been set to match a temperature that, by experience, people would be comfortable with.

There is only supposed to be one heat pump and this creates a need for a control that does not allow both heat pump functions in this simulation to be turned ON at the same time. The output signal from the "Indoor house control" is sent to "HP func" that also includes equation 4, but this time it is the output from control HP pump that governs what comes out of "HP func". With this equation both heat pump functions cannot be on at the same time and can then be considered as the single unit presented in chapter 2.2.

Table 4: Inputs to the heat pump air heating function

Total air flow rate – low speed (indoor)	390 m^3/hr
Rated heating capacity – low speed	1400 W
Rated heating power – low speed	290 W
Total air flow rate – high speed (indoor)	588 m^3/hr
Rated heating capacity – high speed	6000 W
Rated heating power – high speed	1700 W

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[12] (Thermia, u.d.)

3. Results

The simulation of the domestic hot water load gives a tank loss coefficient of 1.13[W/m^{2}K]. This heat loss coefficient correlates to real measurements.[13] The electricity consumption over one year can be seen in figure 9. The annual sum is 5062.9 kWh.

The simulation of the indoor heating load gives an overall loss coefficient in the house of 114.1 [W/K] and the electricity consumption over one year can be seen in figure 9. The annual sum is 12198.8 kWh.

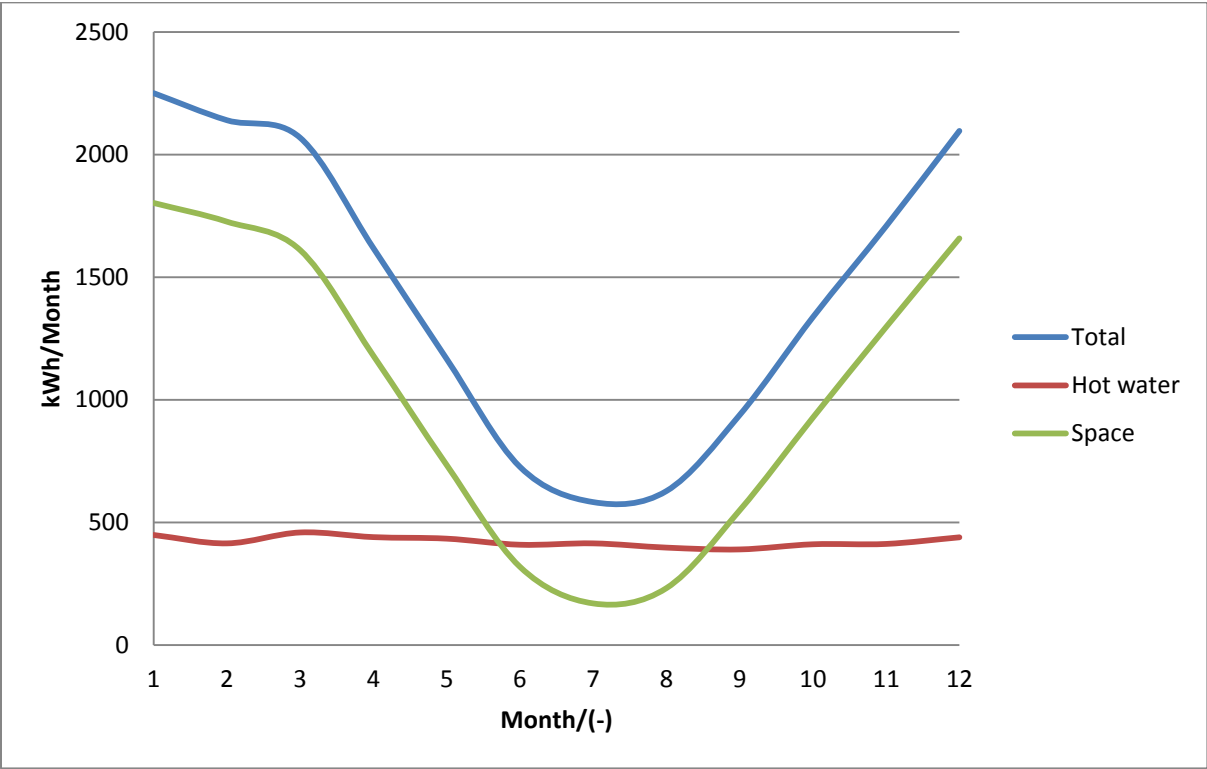This leads to a total consumption of 17 261.66 kWh per year, the monthly consumption can be seen in figure 9.

Figure 9: Electricity consumption over one year with direct electricity heating

For a heating system with solar collectors and heat pump in combination the need for electricity to the heat pump will depend on how large the solar collector area is since the collector contribution depends on the area. The total heat pump electricity consumption for both indoor space and domestic hot water can be seen in figure 10. These results can also be expressed as fraction of original load (new load/original load) to show how much electricity is saved for the different collector area sizes. This fraction can also be seen in figure 10.
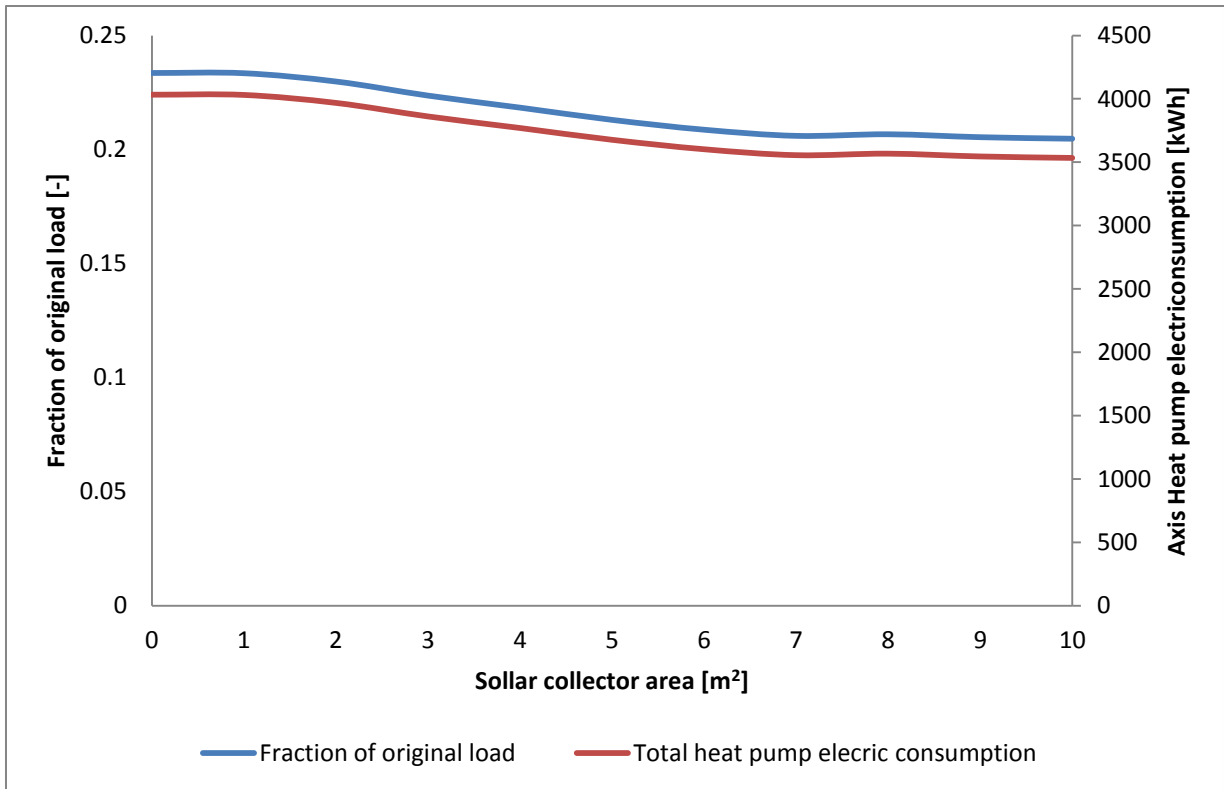
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[13] (Bernado, 2013)

Figure 10: The electricity consumption by the heat pump for different areas of the collector and the fraction of original load

As could be expected there is a change in the slope of the curves in figure 10, this is further addressed in the discussion. This change in slope makes 6 m^2 most desirable to examine closer, since it is the last measurement before the gradient changes.

The yearly electrical consumption by the heat pump for domestic hot water with 6 m^2 can be seen in figure 11. The sum is 752.9 kWh. Figure 11 also demonstrates the electrical consumption for indoor space heating with a heat pump, this is not dependent on the area of the collector. The yearly sum is 2848.7 kWh.
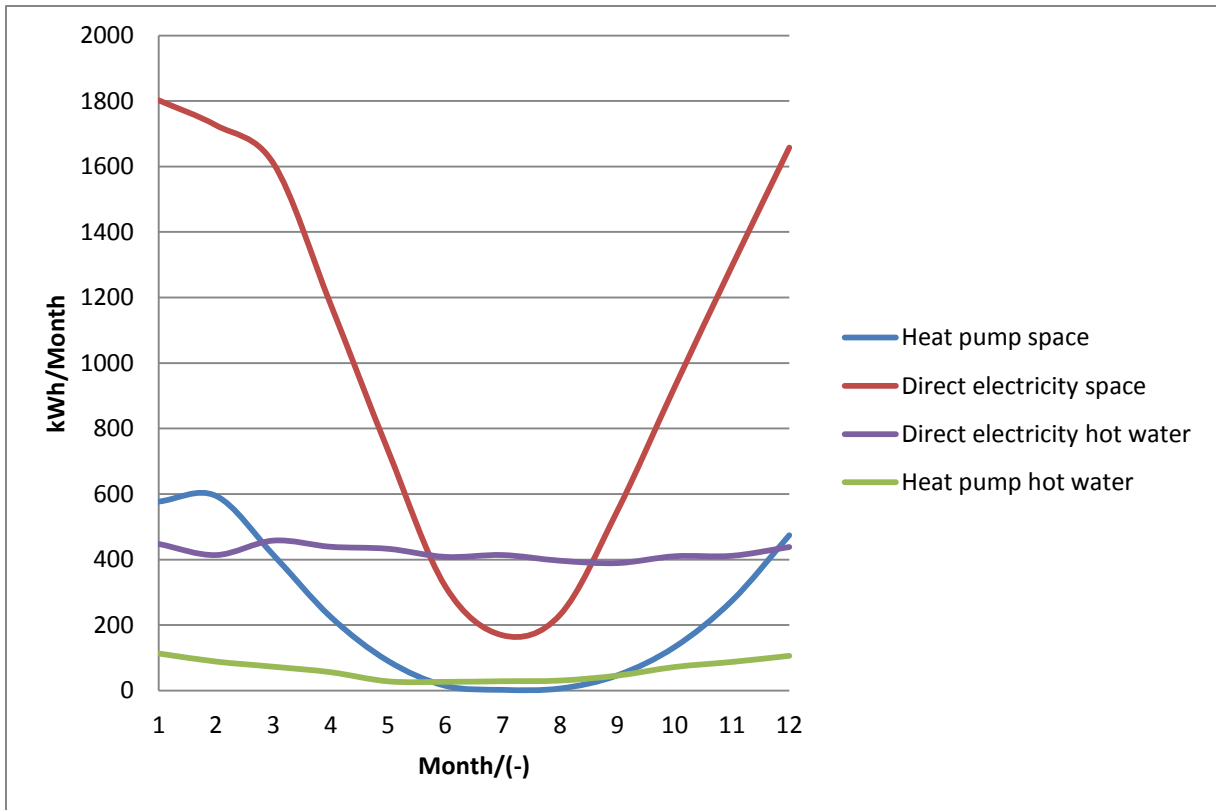
Figure 11: Electrical consumption for domestic hot water heating with direct electric heating and heat pump in combination with 6 m^2 solar collector and electrical consumption for space heating with direct electric heating and heat pump

The total electrical consumption of the heat pump over one year, both for domestic hot water and indoor space heating, with a collector area of 6 m^2 can be seen in figure 12. The yearly sum is 3601.6 kWh.
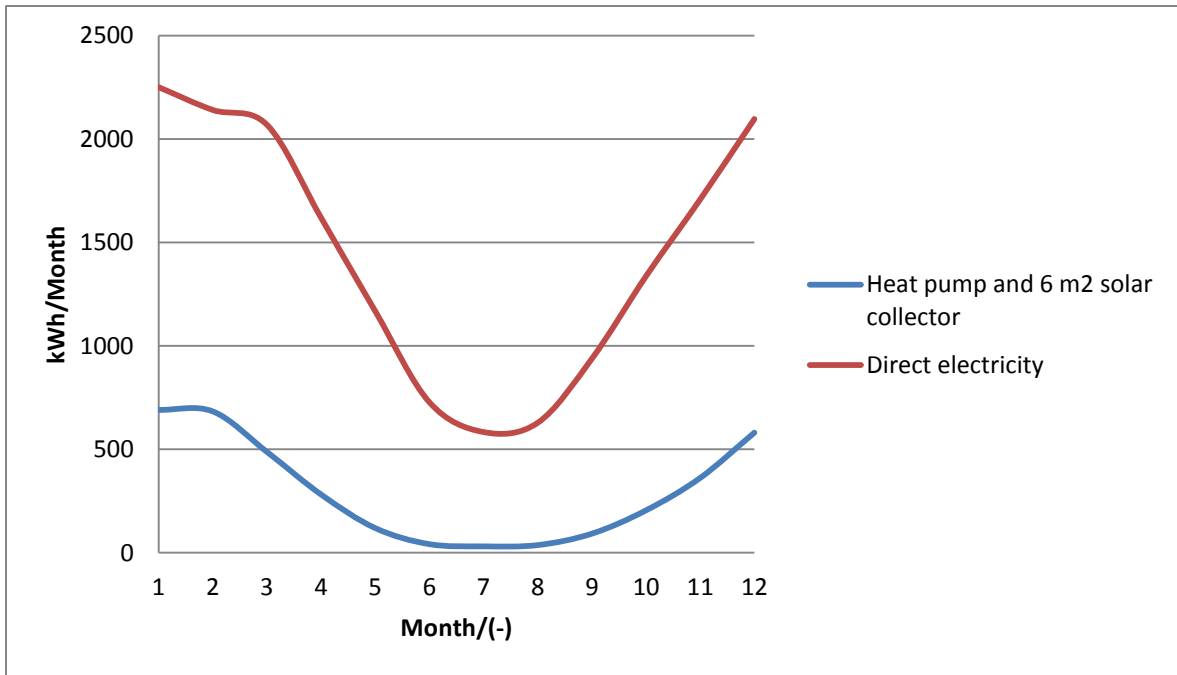
Figure 12: Total electric consumption over one year for a direct electric system and for a heat pump in combination with 6 m² solar collector

The COP of the heat pump water function and for the heat pump air function in combination with a 6 m² solar collector can be seen in figures 13 and 14 below. The SCOP for every different solar collector area can be seen in figure 15.
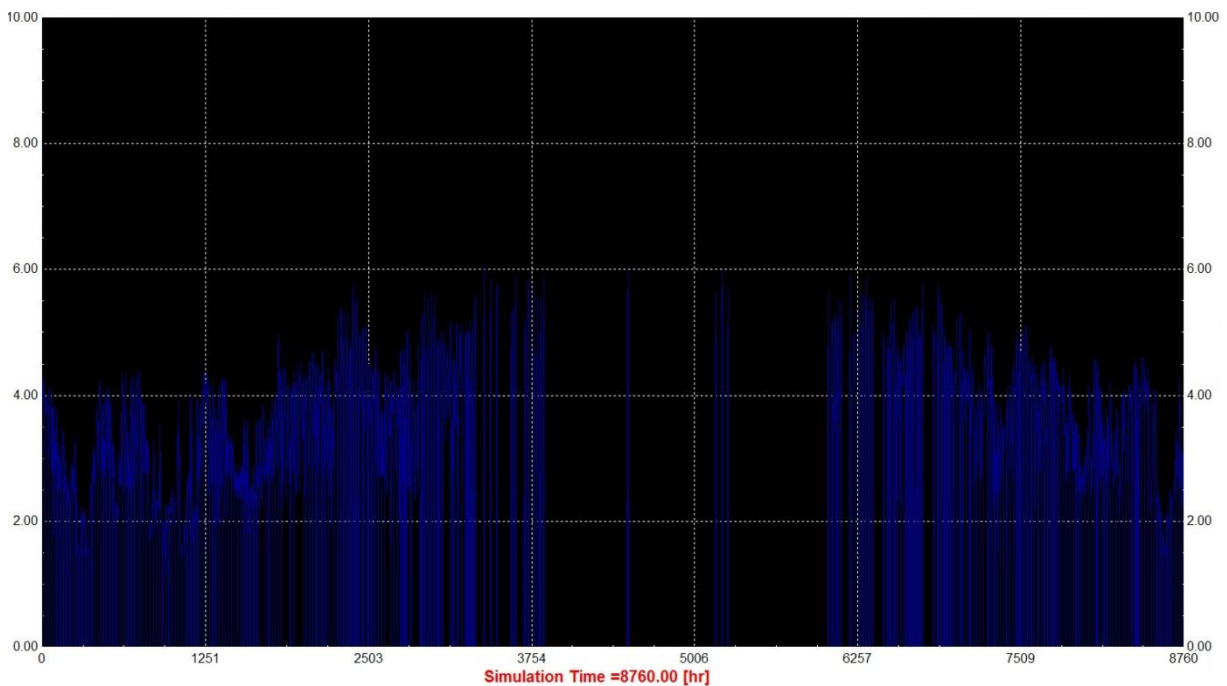

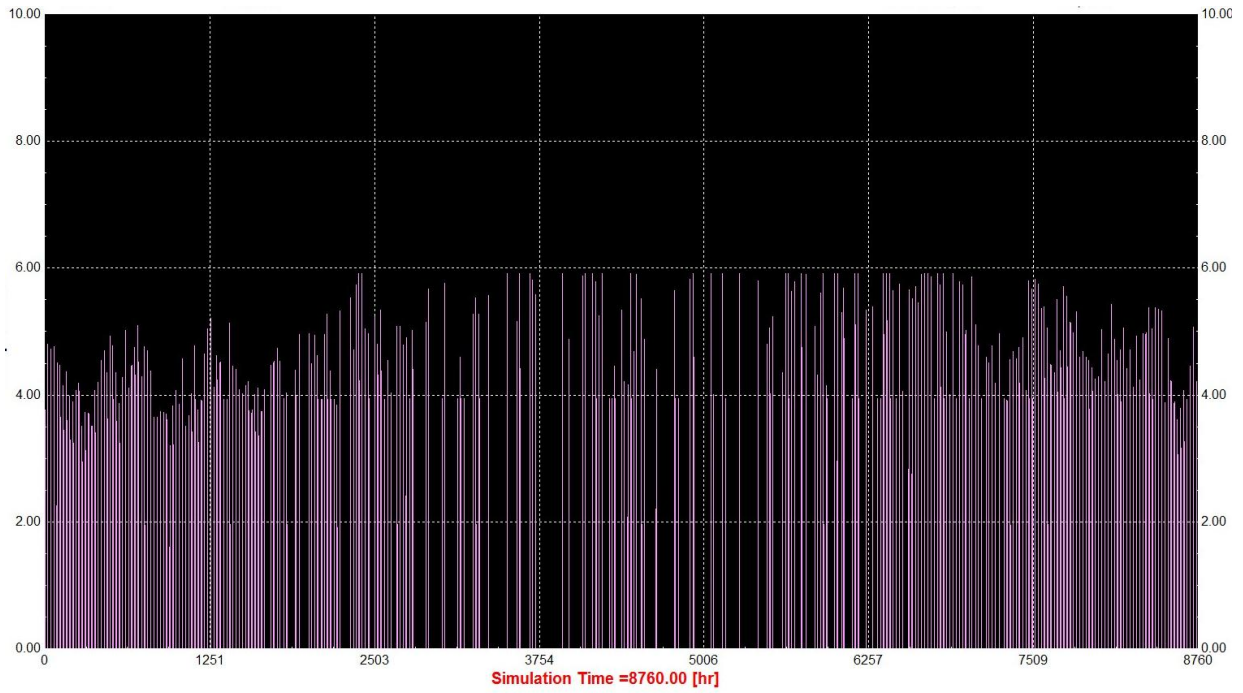**Figure 13: COP of the air-to-air part of the heat pump**

Figure 14: COP of the air-to-water part of the heat pump
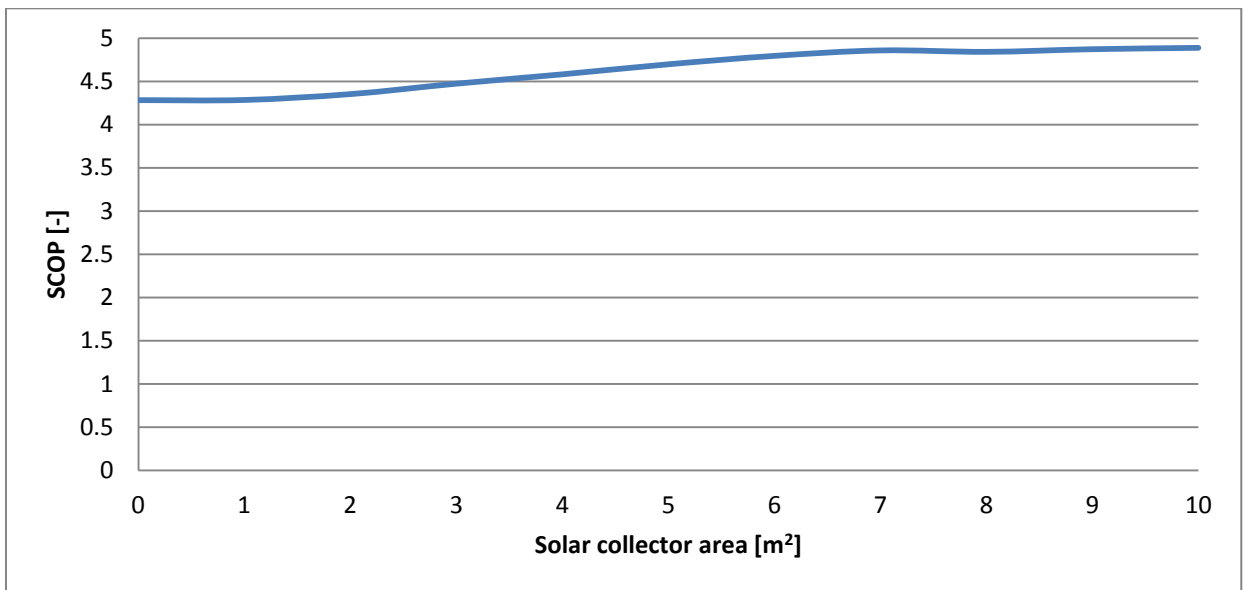

Figure 15: SCOP of the system with different collector areas

The outlet temperature from the tank to the load over one year can be seen in figure 16 and the indoor temperature over one year can be seen in figure 17.

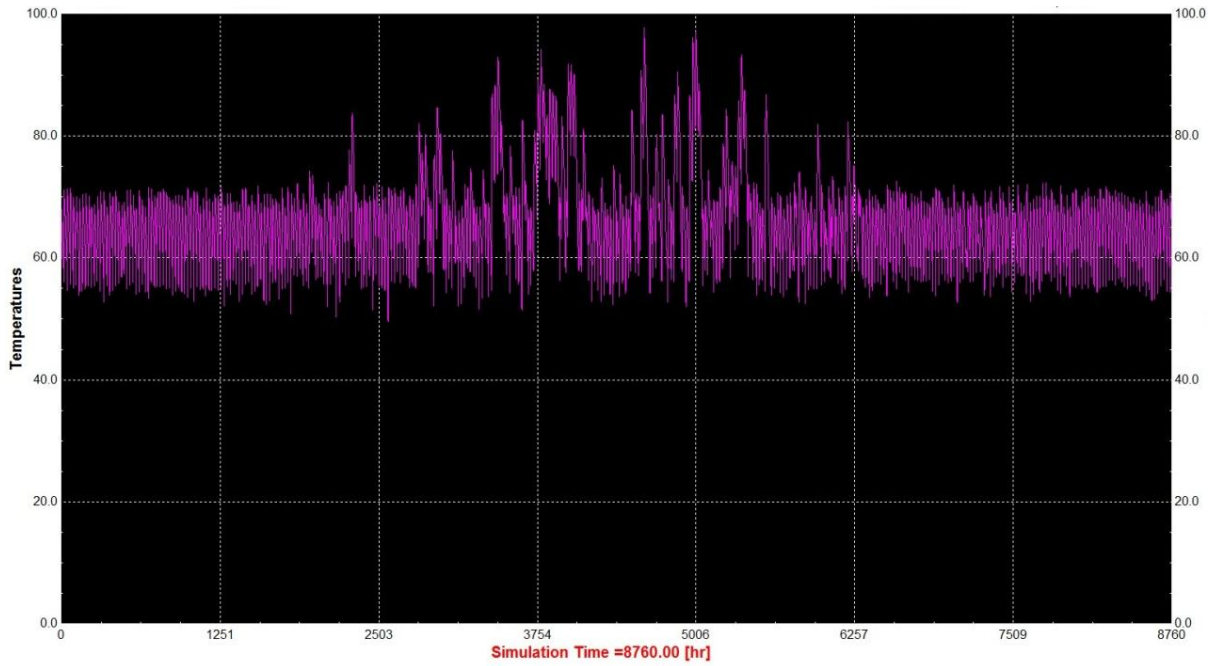**Figure 16: : Temperature out from tank to load over one year**
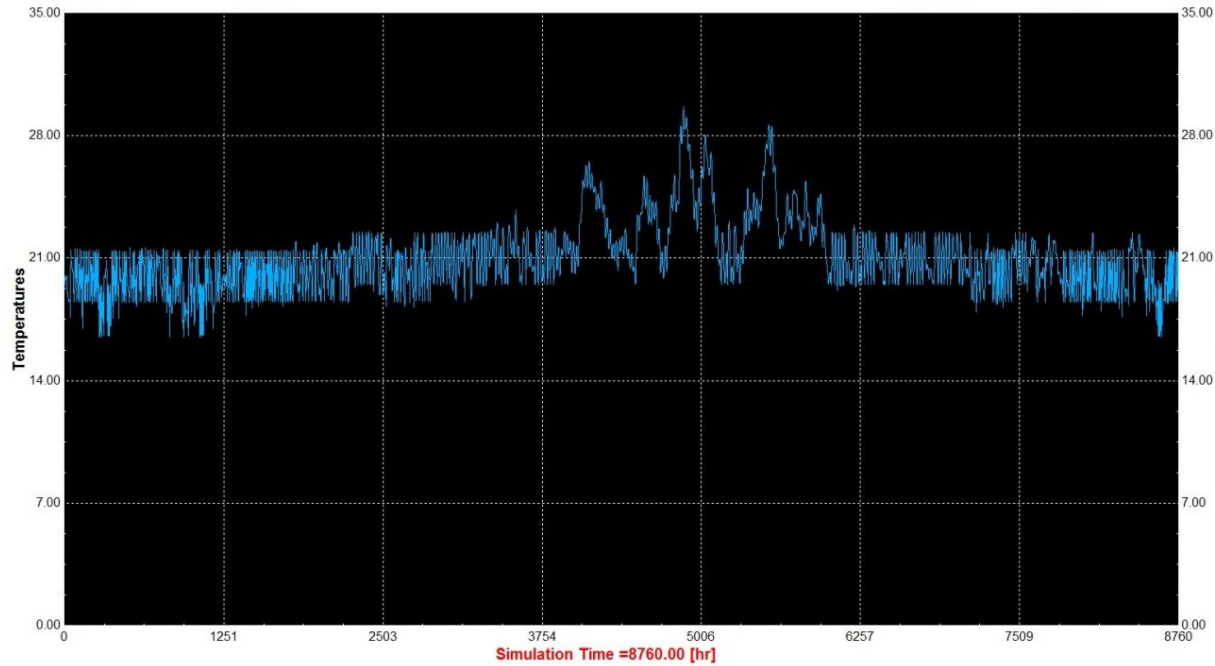

Figure 17: Indoor temperature over one year

In figure 17 it can be seen a few temperature drops to around 17℃, these temperature drops correlates to the time when the outdoor temperature falls below -15℃ which makes it hard for the heat pump to produce enough heat and the reserve electric radiators have to step in. The indoor

temperature drops to this low temperatures less than 100 hours in one year, or around 1% of the year and can therefore be considered acceptable.

The simulation has shown that it is possible to alternate the heat pump functions as proposed in chapter 2.2. The tank as well as the house are sufficiently insulated to retain the heat within them during the time the other one is heated.

4. Cost analysis

The price of a Nibe F2030 7kW is 61 500 sek[14] and a Thermia Aura would cost about 20 000 sek[15]. In this cost analysis the prices will not be added since an installation of the system used in the report would not require two units. The price of the Nibe F2030 will be used. The price used for the solar collectors can be seen in table 5. A new water tank that can be connected to the solar heating system is also required. Such a tank costs 14 600 sek.[16]

Table 5: Price for solar collectors in different sizes[17]

Size [m^2]	Cost [sek]
4	23 841
6	30 544
8	37 736
10	44 436

To calculate the economical aspects of the system, a simple payback is used. The equation can be seen in equation 5.

$$Simple\ Pay\ Back = \frac{Costs}{Savings} = \frac{Heat\ pump + tank + collector}{Electricty\ savnings * electricty\ price} \qquad \text{(Equation 5)}$$

The price of electricity is a big uncertainty and therefore prices from 1 sek to 2 sek are used. This gives a payback time of between 2.3 and 8.8 years, the results can be seen in figure 18.

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[14] (Nibe, u.d.)
[15] (Värmepumpservice, u.d.)
[16] (Nibe, u.d.)
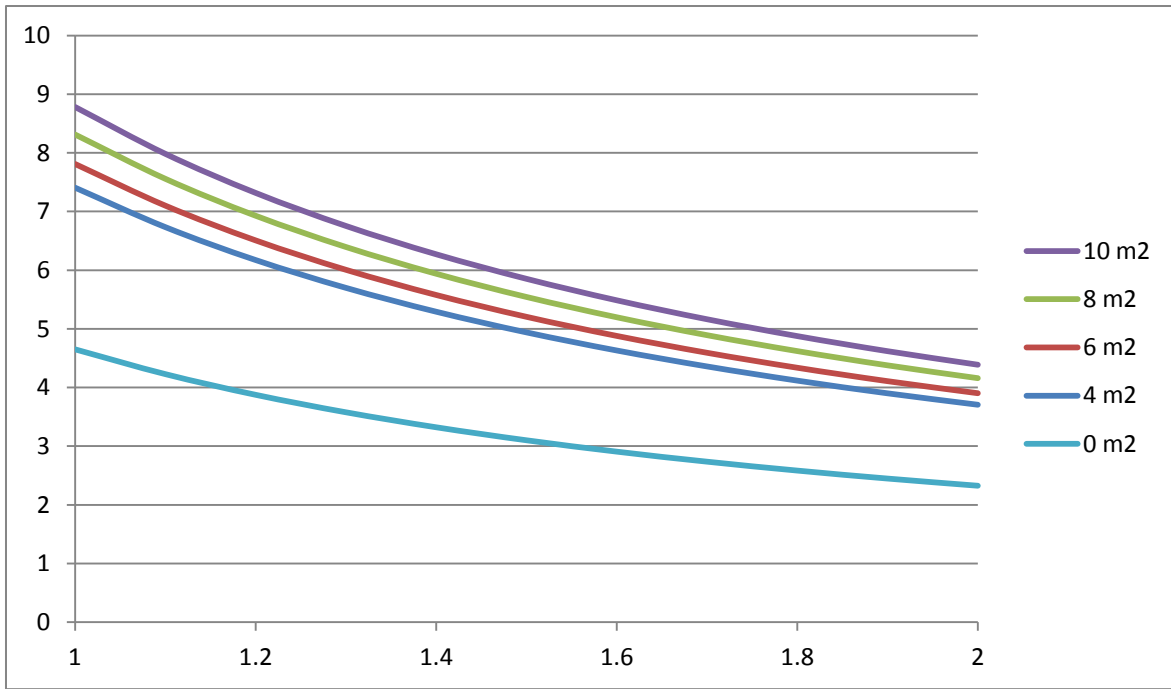[17] (Solenergiteknik, u.d.)

Figure 18: Simple payback time for different solar collector areas and electricity prices

5. Discussion

It has to be noted that this simulation takes its weather conditions from Arlanda, Sweden, and the results could be rather different for places where the sun is stronger during summer and the temperatures are milder during the winter. In this report different preferences about indoor temperature have not been accounted for. If a higher indoor temperature was required, the heat pump would need more electricity to deliver the extra energy, and the opposite would happen if the temperature was set lower.

In the simulation two different heat pumps have been used as models for the heat pump. This has been done since the heat pump used is a combination of two separate heat pumps. These different heat pumps can be expected to have various characteristics as they are designed for different purposes, for example an air-to-air heat pump does not have a water stream through it. They are also designed for different temperature spans since the desired indoor temperature is not the same as the domestic hot water temperature.

Space heating is not produced constantly, but commonly set to produce a temperature of around 20 degrees Celsius. Hot water does not have to be produced constantly either but has to be around 60 degrees Celsius. This raises the question if it is possible to build an air heat pump as the one suggested in reality with the same effectiveness, or if the different pressures make it impossible. When only producing a short range of pressures and temperatures the components in a heat pump can be optimized for that small range. Will components that have a broader range be as effective?

The simple payback that was used to calculate the economics of the system is a very simplified calculation and only an indication of how cost effective the system will be. A more detailed economic calculation method (for example life cycle cost, LCC) would give a more reliable result. What would this heat pump cost? It is possible that it would cost more than the Nibe F2030 since the parts have to withstand different temperatures and pressures and the piping would be more extensive.

In figure 10 a change in slope can be seen. This slope change comes when the solar collector has reached its maximum production during the summer and can only produce more during early spring and late autumn. During this time the available solar energy is less, hence a larger area is required to produce the same amount of energy as during the summer months. It can also be seen that it is better to have 7 m^2 than 8m^2, this goes against all logic and we can assume a measurement fault at either 7 or 8 m^2.

In figure 10 (fraction of original load) we can see that a system without solar collectors is not less effective and it can therefore be argued that it is not feasible to take the extra installation cost that comes with solar collectors. It is possible that a different control setting would make them more effective. The controls in this simulation have been designed in this way for the sake of simplicity. A design that perhaps would make more use of the collectors is if they are used to preheat the water before the heat pump. This would require less electricity for the heat pump since the temperature increase it would have to create would not be as high as it is now. This also correlates to what can be seen in figure 18 (payback time) that indicates that it would be cheaper to not use any collectors.

The SCOP of the heat pump air function can be considered high but still reasonable. The SCOP of the water function is very high but this SCOP also includes the energy gained by the solar collectors. In

figure 13 the COP for the air-to-air heat pump can be seen for every time step over the year and here we can see that the COP varies between 2 and 6 with the higher COP during summer, which is reasonable and expected.

An installation of this system could be useful for the whole Swedish power system since it would not only require less energy but would also demand less power. This would be beneficial with increased effect demand probably being a future problem as more and more renewable and intermittent energy sources are installed in the grid.

6. Conclusions

This study investigated a possible way of modifying the construction of an air heat pump to deliver both domestic hot water and indoor space heating by air. It has been shown that it is possible to combine this system with solar collectors of different sizes. It has also been demonstrated that a system combining air heat pumps for domestic hot water heating and indoor space with solar collectors, using the parameters used in this simulation, have the possibility to save 76.6-79.5% of the electricity needed to heat the same house with direct electricity. The SCOP of the system would be between 4.28 and 4.89.

It was also concluded that the economic feasibility of the whole system, with the prices used, results in a payback time between 2.3 and 8.8 years depending on the electricity price. The reason for the short payback time is because the original system with only electrical heating is very expensive to use. The shortest payback time did the system without any solar collectors have. This shows that it is not cost effective to use solar collectors. This might change if the control system was designed in another way or if the solar collectors were used to preheat the water before the heat pump.

Further work is needed on a more detailed cost analysis. Further work should also be done on the control and setup of the system to find a more suitable combination.

7. Bibliography

Bernado, R., 2013. *Retrofitted solar domestic hot water system for single-family-electrically-heated houses,* Lund: Lund University. ISSN 1651-8136.

Boverket, 2015. *Boverkets byggregler - föreskrifter och allmänna råd, BBR,* s.l.: Boverket.

Energimyndheten, 2015. *Energimyndigheten.* [Online]
Available at:
http://www.energimyndigheten.se/Foretag/Ekodesign/Produktgrupper1/Luftkonditionering
[Accessed 15 February 2015].

Energimyndigheten, 2011. *Energimyndigheten.* [Online]
Available at: https://www.energimyndigheten.se/Hushall/Varmvatten-och-ventilation/Vatten-och-varmvattenberedare/
[Accessed 12 April 2015].

Energimyndigheten, 2014. *Energistatistik för Småhus,* s.l.: Energimyndigheten. ISSN 1654-7543.

Energimyndigheten, 2015. *Energimyndigheten.* [Online]
Available at: http://www.energimyndigheten.se/Hushall/Din-uppvarmning/
[Accessed 12 April 2015].

Heier, J., 2013. *Energieffektivisering i småhus i Dalarna,* s.l.: Högskolan Dalarna.

Nibe, n.d. *Nibe.* [Online]
Available at: http://www.nibe.se/nibedocuments/14915/639524-3.pdf
[Accessed 2015].

Nibe, n.d. *Nibe.* [Online]
Available at: http://www.nibe.se/Produkter/Luftvattenvarmepumpar/NIBE-F2030/
[Accessed 27 May 2015].

Nibe, n.d. *Nibe.* [Online]
Available at: http://www.nibe.se/Produkter/Varmvattenberedare/NIBE-COMPACT-300-SOL/
[Accessed 27 May 2015].

Solenergiteknik, n.d. *Solenergiteknik.* [Online]
Available at: http://www.solenergiteknik.se/rwdx/files/Intelli-heat-solpaket.PDF
[Accessed 27 May 2015].

Sveby, 2012. *Brukarindata bostäder,* s.l.: Sveby.

Thermia, n.d. *Thermia.* [Online]
Available at: http://www.thermia.se/docroot/dokumentbank/Thermia-Varmepumpar-Aura.pdf
[Accessed 2015].

TRNSYS, n.d. *trnsys.* [Online]
Available at: http://www.trnsys.com/
[Accessed 1 June 2015].

Värmepumpservice, K. &., n.d. *kylvarmepumpservice.* [Online]
Available at: http://www.kylvarmepumpservice.se/erbjudanden.html
[Accessed 27 May 2015].

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