Retrofitting Electrically Heated Single-Family Houses to Net-Zero Energy

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Abstract

Only in Sweden, single-family houses account for approximately 30% of energy use in all buildings and a large part uses only electricity for heating. The potential for improvements on energy efficiency in these houses is large. This study theoretically investigates retrofitting of electrically heated Swedish single-family houses by using an air-source heat pump for both space heating and domestic hot water. Combination with solar collectors and solar cells were also theoretically investigated. Since this solution is an add-on to the existing heating system the investment cost can be reduced compared with a new heat pump installation for domestic hot water. The total annual energy reduction for domestic hot water and space heating in a Swedish single-family house when using the combined heat pump and solar thermal collectors was estimated to be roughly 70%. The remaining electricity demand for electric appliances can be covered by approximately 10 kWp solar cells therefore reaching net-zero energy level.

Keywords: *retrofit, net-zero energy houses, solar thermal, heat pump, single-family houses.*

1. Introduction (SWC_Heading1)

In order to meet the current energy and climate targets for 2020 and 2050 in EU countries, the existing building stock needs to be addressed. A construction boom was experienced across Europe after the Second World War and there is now a need for renovation. Since such houses have high levels of energy consumption, this is a good opportunity to also perform an energy renovation. For example in Sweden, single-family houses account for about 30% of energy use in all buildings and a large part, around 500 000, uses only electricity for heating (Swedish Energy Agency, 2013). The potential for improvements on energy efficiency in these houses is large. A typical Swedish single-family house uses in average 12200 kWh/y for space heating, 4500 kWh/y for domestic hot water (DHW) and 5000 kWh for household electricity (Swedish Energy Agency, 2015). It is common to upgrade the space heating system, for example by installing an air-to-air heat pump. Commonly, this decreases the space heating demand to levels close to the energy used for domestic hot water, shown later in Fig. 3. However, simple and cost-effective renovation solutions for reducing the energy consumption for domestic hot water production are not wide spread today.

This study investigates theoretically the retrofitting of electrically heated Swedish single-family houses by using an air-source heat pump for both space heating and domestic hot water. The heat pump not only heats the indoor air but is also connected directly to the existing hot water heater (boiler). The investigation addresses the system configuration, comfort level, control strategies and energy savings. Combination with solar collectors and solar cells were also theoretically investigated. Since this solution is an add-on to the existing heating system no large changes are needed which has the potential to significantly reduce the investment cost in comparison with a new heat pump installation for domestic hot water.

At this stage the investigation excludes some of the practical challenges and assumes that existing air heat pumps reach desirable temperatures for domestic hot water. The focus is instead on evaluating whether a conventional air heat pump can alternate on providing heat for space heating and domestic hot water and still reach comfort on both. This is the ground for any further investigation. A short discussion on possible practical problems and future work is addressed under the discussion chapter.

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2. Method

A model was built in TRNSYS in order to theoretically assess the potential for energy savings and possible challenges of using an air-source heat pump for both space heating and domestic hot water in a Swedish single-family house. The goal is to model a hybrid heat pump that alternates between providing lower temperature heat to space heating and higher temperature heat for domestic hot water. This thought to achieve high system efficiency. A sketch of the system is shown below in Fig. 1.

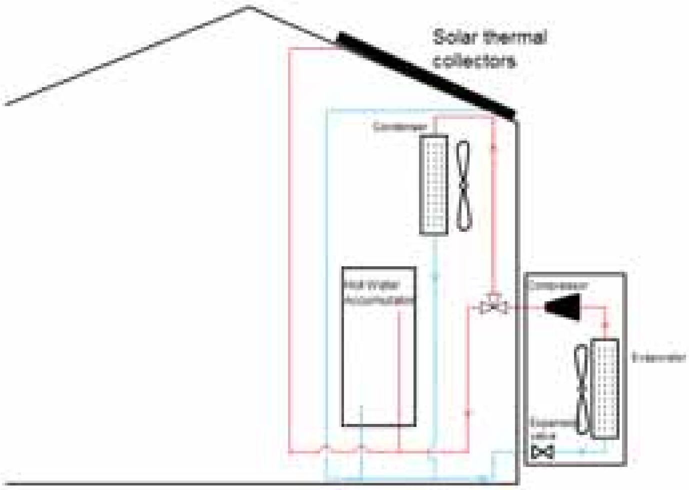

Fig. 1: Simplified sketch of the energy flow in the modelled system.

Since there is no standard TRNSYS model describing such a hybrid heat pump, the model was built by using two separate heat pump models: one air-to-air heat pump, Type922 Tess library (2015), and one air-to-water heat pump, Type941 Tess library (2015). For this purpose it was assumed that each of these heat pumps are common heat pumps in today's market and that they have conventional performance parameters such as described in the respective technical data sheets. In reality, a hybrid heat pump that delivers heat for both DHW and space heating at different temperatures may have different parameters and this is therefore a limitation of the investigation.

The operation of these two heat pumps was set in order to only allow one of them working at the time since the goal is to model one single heat pump. In this case, the air-to-water heat pump for DHW was prioritized. Hence, both the DHW storage and the house will work as heat "batteries" with only one heat source. These two heat "batteries" are charged alternately at different temperature levels and therefore at different efficiencies. In case there is deficit energy for space heating the existing direct electric heating was also modelled and is used as a backup heater. The heat pump starts at 20 °C and the direct electric heating at 18 °C. The solar collectors are used to preheat the incoming cold water to the air-to-water heat pump. When possible, during the summer period, the solar collectors alone will provide heat to DHW.

The model was used to estimate the comfort level, control strategies and energy performance. An overview of the modeled system in TRNSYS, the used components and the most relevant assumed parameters are illustrated in Fig. 2 and Tab. 1.

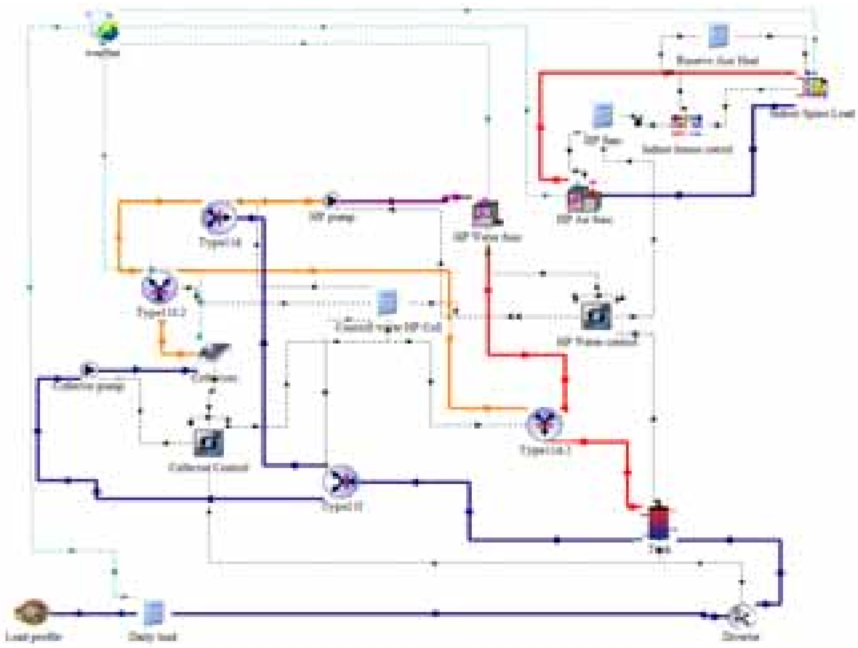

Fig. 2: Overview of the TRNSYS model.

Tab. 1: Parameters and TRNSYS types used in the simulation tool.

Type 12, house	The building has an average UA-value of 142 W/K. The internal gains were assumed to be approximately 900 W. Temperature setting 20 °C for the heat pump and 18 °C for the direct electric heating with a power of 7 kW.
Type 15, weather data	The weather data is data from Stockholm, Sweden.
Type922, air-to-air heat pump	The inputs are based in the heat pump model Thermia Aura (Thermia, 2015). This heat pump can work at two power levels: rated heating capacity 1,4-6 kW and rated heating power 0,3-1,7 kW.
Type941, air-to-water heat pump	The inputs are based in the heat pump model Nibe F2030 (NIBE, 2015) with a rated heating capacity 7 kW and rated heating power 1,8 kW
Type 1, flat-plate solar collectors	Collector area 6 m^2, zero-loss efficiency 0,8, efficiency slope 3,6 $W/m^2/K$, efficiency curvature 0,05 $W/m^2/K^2$ and first order incidence angle modifier 0,2.
Type 4, storage tank	Tank volume 0,3 m^3, 8 nodes, height of nodes 0,2m, U-value 1,15 $W/m^2/K$. No auxiliary heater is used, all the heat is provided by the air-to-water heat pump. The connections are fixed and placed at the top and bottom of the storage.

3. Results

The simulation results show that, in total, the heating energy (DHW plus space heating) was reduced from approximately 16760 kWh/y to 5170 kWh/y (69% decrease) without solar collectors and to 4790 kWh/y (71% decrease) with solar collectors (Tab. 2 and Fig. 3). The annual energy need for space heating was reduced from 12280 kWh/y to 4178 kWh/y. The heat pump in combination with solar collectors reduced the annual energy need for domestic hot water from 4480 kWh/y to 620 kWh/y.

Tab. 2: Energy use for DHW and space heating before and after the heat pump installation; with and without solar collectors.

	Before the heat pump installation (kWh/y)	After the heat pump installation without collectors (kWh/y)	After the heat pump installation with collectors (kWh/y)
Space heating	12280	4178	4178
DHW	4475	989	616
TOTAL	16755	5167	4794

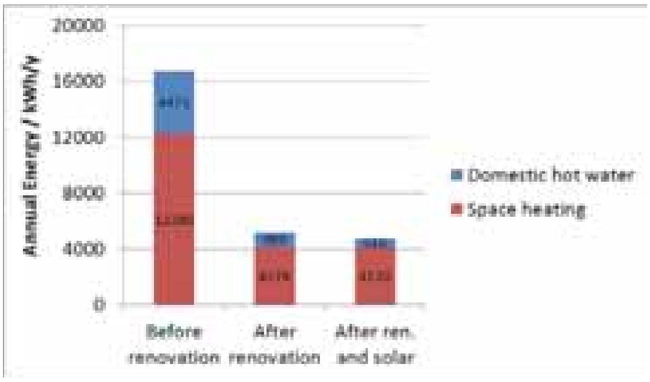

Fig. 3: Annual energy use before and after the heat pump installation, with and without solar collectors.

During the coldest winter months the heat pump was in fact not sufficient to provide all the required heat for space heating in order to keep the indoor temperature above 18 °C. To keep the indoor temperature above 18 °C during this period the existing direct electric heating system was used as an auxiliary heater. This situation corresponds to reality where standard air-to-air heat pumps also need support from a direct electric heater during the peak of the winter in Sweden. The comfort level reach for the indoor ambient and DHW is illustrated in Fig. 4.

Fig. 5 illustrates the energy load and production. In Tab. 3 the space heating energy is divided in two parts: the part covered by the heat pump (3667 kWh/y) and the remaining part covered by the existing direct electric heating system (511 kWh/y). If one excludes the direct electric heating and the use of solar collectors, the SCOP of the air-to-air heat pump is equal to 3,2 ($\frac{space\ heating\ load - direct\ electric\ heating}{heat\ pump\ energy\ for\ space\ heating - without\ direct\ electric\ heating} = \frac{12280-511}{4178-511}$). The SCOP of the air-to-water heat pump without solar collectors is equal to 4,5 ($\frac{DHW\ load}{heat\ pump\ energy\ for\ DHW}$).

It is roughly estimated that 10 kWp solar cells (67 m^2 solar photovoltaic modules at 15% efficiency) should be installed in order to cover the total annual electricity demand of roughly 5000 kWh/y for space heating and domestic hot water and additionally 5000 kWh that are estimated to be the average use of household electricity. Hence, net-zero energy level can be achieved.

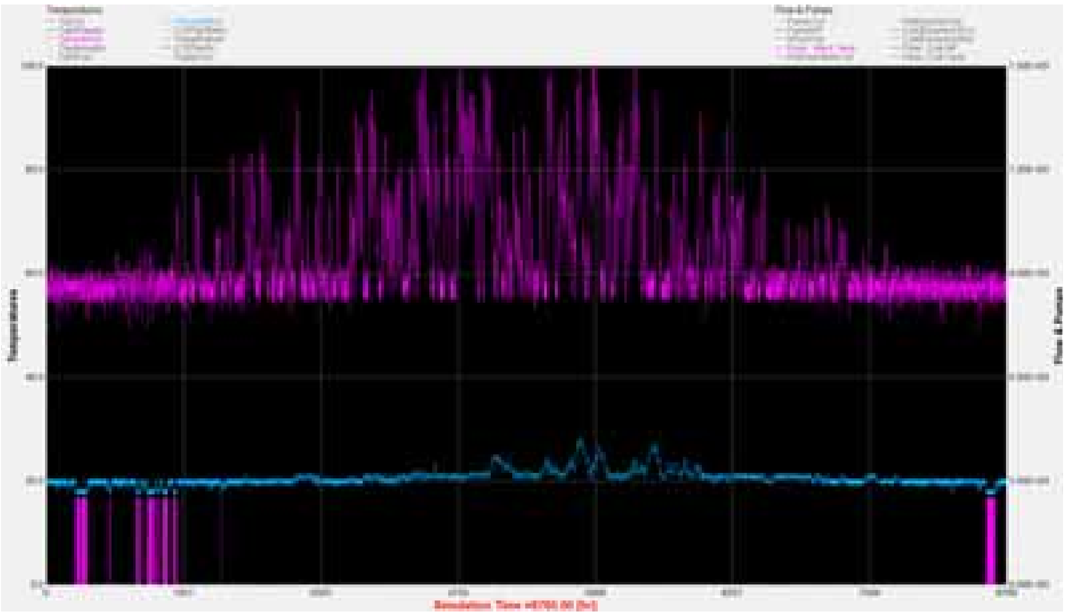

Fig. 4: Comfort analysis with heat pump and solar collectors: the upper curve shows the temperature at the top of the storage tank; the middle curve shows the indoor temperature of the house and the lower curve shows the use of the auxiliary direct electric heating system.

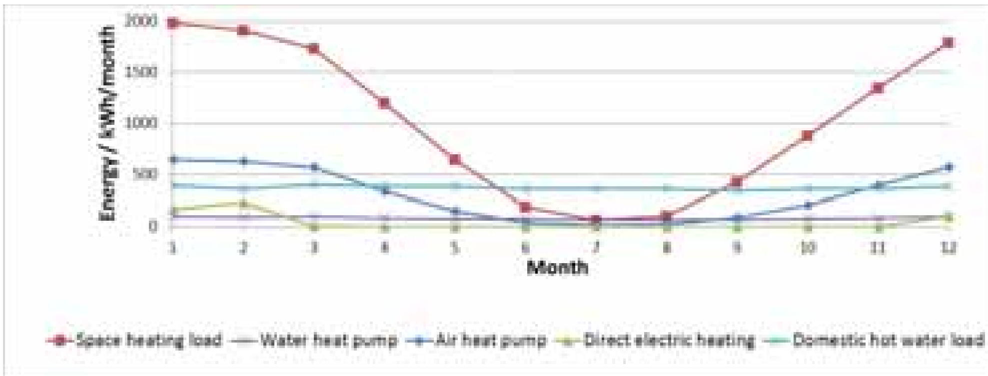

Fig. 5: Estimated monthly energy load and production.

Tab. 3: Space heating energy consumption divided in the part that is covered by the heat pump and the remaining covered by the existing direct electric heating system.

	Heat pump only used for space heating (kWh/y)	Heat pump also used for DHW (kWh/y)	Variation (kWh/y)	Relative variation (%)
Air heat pump	3740	3667	-73	-2
Direct electric heating	361	511	+150	+42
TOTAL space heating	4101	4178	+77	+2

4. Discussion

One practical challenge in retrofitting existing hot water storages is the fact that, in reality, these lack available connections to other heat sources such has heat pumps or solar collectors. This has been previously investigated and shown that the two available connections can be also used by for example solar collectors without a decrease in the system performance (Bernardo, 2013). This was kept outside of the scope of this study.

The SCOP of the air-to-water heat pump is higher than expected and probably overestimated, especially when compared with the SCOP of the air-to-air heat pump that works at a lower temperature. The reason for this is the fact that the model did not include COP data for the desired temperature intervals and this was therefore extrapolated and probably overestimated. Improvements regarding this data are needed in future studies. This overestimation is thought to influence mostly the level of energy savings for DHW while the other results are thought not to change significantly.

The fact that the air-to-air heat pump is also used to provide energy for DHW showed almost no change on the annual energy spend for space heating. However, the contribution of the heat pump for space heating was decreased by 2% (73 kWh/y) which was compensated by a 42% increase (150 kWh/y) of the direct electric heating in the peak of the winter. This decrease in performance is largely compensated by energy savings on the DHW of approximately 3500 kWh/y.

The solar collector add-on does not provide a significant energy reduction since most of the energy is already saved by the heat pump. Since the SCOP of the air-to-water heat pump is 4,5, in order to save 1 kWh electricity to the heat pump the collectors need to produce in average 4,5 kWh of heat. Also, the existing hot water storage presents low levels of temperature stratification which also contributes significantly to the low output of the solar collectors.

Existing air-to-air heat pumps may not be able to reach the desired temperature for domestic hot water heating (approximately 55-60°C). This is a crucial limitation for the retrofitting and that needs further investigation. One possible solution is to install an extra small compressor as shown on the left hand-side in Fig. 6. Nonetheless, retrofitting can be complicated due to several factors such as complicated installation, different type of heat pump configurations in the market, problems with warrantee and insurances, low profitability, etc. Therefore, it might be more realistic to consider this concept for new heat pump installations instead. In that case a heat exchanger for the DHW can be installed as one of the multi-splits units as shown in the right-hand side in Fig. 6. The main competitive advantage of this new hybrid heat pump compared with a regular air-to-air heat pump is the large energy savings for DHW production. Depending on the eventual extra costs of using a stronger compressor that reaches 55-60°C, the extra investment may be compensated by such large energy savings. This needs further investigation that also includes costs.

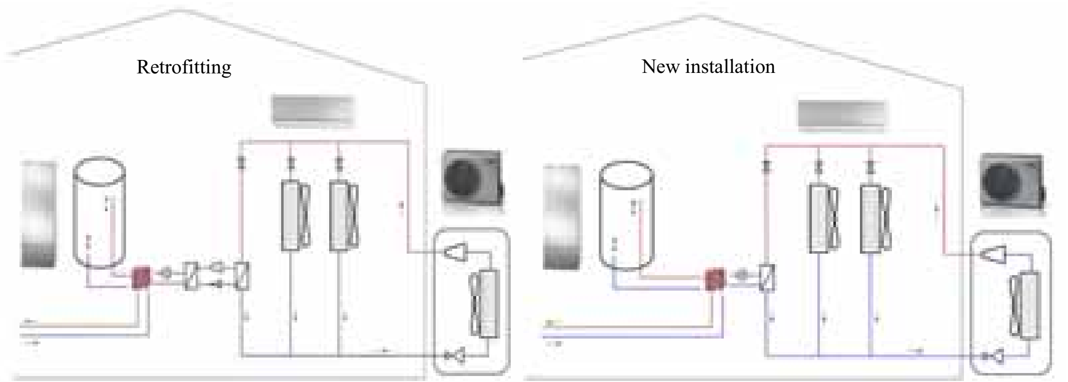

Fig. 6: Sketch of the hybrid heat pump for retrofitting (left-hand side) and new installations (right-hand side).

5. Conclusion

A model was built for assessing energy savings of retrofitting a common air-to-air heat pump for providing heat not only for space heating but also for domestic hot water (DHW). The heat pump was controlled in such a way to alternate the heat deliver between DHW and space heating at different temperatures and therefore at different efficiencies. The DHW production was prioritized. Combining solar collectors into the system was also investigated.

The simulation results show that the total annual heating demand (DHW plus space heating) was reduced from 16755 kWh/y to 5167 kWh/y (69% decrease) without solar collectors and 4794 kWh/y (71% decrease) with 6 m^2 solar collectors. The annual energy need for space heating was reduced from 12280 kWh/y to 4180 kWh/y while the annual energy need for domestic hot water was reduced from 4480 kWh/y to 620 kWh/y. The remaining electricity demand for heating and electric appliances can be covered by approximately 10 kWp solar cells and therefore reaching net-zero energy level. The energy provided by 6 m^2 solar collectors was only 370 kWh/y which confirms that this is not profitable combination. This is explained by the combination with a high efficient heat pump and due to low levels of temperature stratification in the hot water storage.

The comfort analysis showed that in order to prevent the indoor temperature to fall below 18 °C in the peak of the Swedish winter the existing direct electric heating system had to use around 510 kWh/y. The rest was provided by the heat pump. The temperature in the hot water storage did not drop below 50 °C indicating a good comfort level.

Results indicate that this concept has potential for large energy savings but the implementation in retrofitting (and upgrading) existing air-to-air heat pumps can be significantly complicated and compromise therefore the cost-efficiency. It seems more realistic to apply the same concept at new installations where the heat pump can be chosen from the beginning to reach higher temperatures. Such extra cost needs to be compensated by the energy savings for domestic hot water production.

6. References

Bernardo, 2013. Retrofitting Conventional Electric Domestic Hot Water Heaters to Solar Water Heating Systems in Single-Family Houses-Model Validation and Optimization. Energies 6(2), 953-972, 2013.

NIBE, 2015. Available online at: http://www.nibe.se/Produkter/Luftvattenvarmepumpar/NIBE-F2030/. [Accessed May 2015].

Swedish Energy Agency, 2013. Energy statistics for one- and two-dwelling buildings, ES2014:05. Stockholm: Swedish Energy Agency.

Swedish Energy Agency, 2014. Available online at: http://www.energimyndigheten.se/Hushall/Din-uppvarmning/. [Accessed June 2015]

Tess Library, 2015. Thermal Energy System Specialists Component Library Package; Transient System Simulation Tool: Madison, WI, USA. Available online at: http://www.trnsys.com/tess-libraries. [Accessed 2012].

Termia, 2015. Available online at: http://www.thermia.se/docroot/dokumentbank/Thermia-Varmepumpar-Aura.pdf. [Accessed May 2015].

TRNSYS, 2015. TESS libraries available at http://www.trnsys.com/tess-libraries/ (last visited on April 2015).