

## **ECONOMIC HEATING SYSTEMS FOR LOW ENERGY BUILDINGS IN SWEDEN**

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**Abstract:** Sweden has a tradition both in building rather energy efficient houses and installing heat pumps in buildings. However heat pumps have seldom been used in very low energy houses. The purpose of the study has been to investigate which system solutions for single family houses that for Swedish circumstances gives the lowest energy use verses the lowest costs. Calculations of energy use and costs have been made for different climates and for different building envelopes combined with different systems for heating and ventilation. One result is that even if a ground source heat pump results in the lowest yearly energy cost, the investment costs are still so high that other alternatives have a lower life cycle cost. The results have also been compared with the requirements in the new Swedish building regulations. With ground source heat pumps the requirements can be met almost regardless of the building envelope. On the other hand, with a very good building envelope the requirements can also be met regardless of the type of heating and ventilation system.

**Key Words:** heating systems, low energy buildings, life cycle cost, heat pumps

### **1 INTRODUCTION**

Sweden is the country with the highest number of installed heat pumps per capita. It also has a tradition of building rather energy efficient buildings. During the last decade we have also started to build so called "passive houses". However, there have been very few cases where heat pumps have been combined with extremely low energy building envelopes.

The results presented in this paper are based on the final report of project P10 (Ruud 2010) that was part of the EFFSYS2-program run by the Swedish Energy Agency. This project was also a part of the International IEA Heat Pump Program, Annex 32 - Economical heating and cooling systems for low energy houses. The main purpose of the project was to calculate and compare the energy use and costs related to the energy use when different building envelopes were combined with different types of heating and ventilation systems. The economic calculations resulting in life cycle costs (LCC) are based on initial investment costs, reinvestment costs, life time of systems and components, operational costs and yearly energy costs. One purpose has also been to investigate how these different combinations complies the new Swedish building regulations, BBR16 (Boverket 2009), which came fully into force on the 1<sup>st</sup> of January 2010.

The results presented in this paper have been limited to a single family house with a floor area of 130 m<sup>2</sup> and two different climates covering the climatic variations for the majority of all new built single family houses in Sweden. The study has also been limited to Swedish conditions and heating only as cost calculations involving different countries would require a separate project and active cooling is not considered necessary in Swedish residential buildings (Nordman et al, 2010). The study has therefore also been limited to district heating

and electricity for the main external supply of energy as more than 90 % of all newly built single family houses in Sweden use either or both of these.

## 2 Calculation method

The calculations have been divided into two parts, energy calculations and life cycle cost calculations. The second part is based on the first but involves also economic parameters.

### 2.1 Energy calculations

The energy calculations were made with an energy calculation program originally developed for a Swedish association of producers of timber framed single family houses (TMF, Swedish Federation of Wood and Furniture Industry), "TMF-Energi, version 2.2". It is used to make a preliminary energy declaration of specific energy use in newly built single family houses according to the new Swedish building code of 2009. Due to the implementation of the European Energy Performance of Building Directive (EPBD), the Swedish National board of Housing and planning has, in the new building regulations, set maximum values on specific energy use for space heating and domestic hot water in new buildings. The calculation method is based on the European standard EN ISO 13790:2004, but with national parameters for usage (Levin 2007). It uses a stationary heat balance model and an approximate duration graph based on the mean average outdoor temperature as an input (Hallén 1981). The maximum electric power demand is for "electrically heated houses" calculated at the dimensioning winter outdoor temperature corresponding to the time constant of the house. In the present report the calculation method has been slightly modified to suit the purpose of the study.

#### 2.1.1 Building physics

The calculations have been made for three different building envelopes with very low, normal and high thermal transmission loss through the building envelope. The general properties of the three building envelopes are shown in table 1.

**Table 1: General properties of the three building envelopes**

<b>Properties</b>	<b>Env. 1</b>	<b>Env. 2</b>	<b>Env. 3</b>
Floor area in temperature-controlled spaces $A_{temp}$ (m <sup>2</sup> )	130	130	130
Total surface area of building envelope $A_{om}$ (m <sup>2</sup> )	300	360	400
Average heat transfer coefficient $U_m$ (W/m <sup>2</sup> K)	0.17	0.25	0.33
Total surface area of windows $A_w$ (m <sup>2</sup> )	26.0	32.0	39.0
Heat transfer coefficient of windows $U_w$ (W/m <sup>2</sup> K)	0.8	1.1	1.1
<b>Transmission heat loss through building envelope (W/K)</b>	<b>51</b>	<b>90</b>	<b>132</b>

These three envelopes cover the range of thermal transmission loss that almost all new built Swedish single family houses of this size are within. Envelope 1 is a very well insulated and compact building with small thermal bridges and a limited surface area of super insulated windows. In the south part of Sweden it means a building envelope suitable for a passive house. Envelope 2 corresponds to a well built Swedish standard single family house. It is a rather well insulated and moderately compact building with a normal amount of well insulated windows. Envelope 3 is a not so well insulated and less compact building with rather large thermal bridges and rather large window areas. Due to the large window area, the windows are still considered to be well insulated. One could argue that envelope 3 is not a low energy building, but (as will be shown later) combined with some types of heating and ventilation system it may achieve just as low energy use as envelope 1 combined with some other types of heating and ventilation system.

Depending on the ventilation system two different levels of air tightness of the building envelopes are used according to table 2. The reason is that a high system efficiency of a mechanical exhaust and supply ventilation heat recovery system requires a high air tightness of the building envelope.

**Table 2: Air tightness of the building envelopes**

Ventilation system	Air tightness (l/s m <sup>2</sup> Pa)
Mechanical exhaust air ventilation	0.8
Mechanical exhaust and supply air ventilation with heat recovery	0.3

### 2.1.2 Building services systems

The different building envelopes have been combined with eight different systems for heating and ventilation, see table 3. The “short description” is used when presenting the results.

**Table 3: The different systems for heating and ventilation**

Full description	Short description
District heating and mechanical exhaust air ventilation	DistrHeat + ExAirVent
Exhaust air condensing heat pump and mechanical exhaust air ventilation	ExAirVentHP
Outdoor air heat pump and mechanical exhaust air ventilation	OutAirHP + ExAirVent
Ground source heat pump and mechanical exhaust air ventilation	GrSourceHP + ExAirVent
District heating and mechanical exhaust and supply air ventilation with heat recovery	DistrHeat + Ex/SuAirVHR
Direct electricity, thermal solar for domestic hot water, mechanical exhaust and supply air ventilation with heat recovery	DirEl + ThSol + Ex/SuAirVHR
Outdoor air heat pump and mechanical exhaust and supply air ventilation with heat recovery	OutAirHP + Ex/SuAirVHR
Ground source heat pump and mechanical exhaust and supply air ventilation with heat recovery	GrSourceHP + Ex/SuAirVHR

The district heating unit (DistrHeat) is assumed to be installed inside the house and, except for having a heat loss of 50 W to its surrounding, it is assumed to have 100% heat transfer efficiency. During the heating season the heat loss contributes to the heating of the house.

The calculations for an exhaust air condensing heat pump (ExAirVentHP) are based on coefficients of performance and power outputs presented by a Swedish manufacturer. It has an inverter controlled compressor. The outlet air temperature and consequently the power output can thereby be adjusted to the demand. At the highest power output the outlet air temperature can be as low as approximately -15°C and the coefficient of performance (COP) is around 2.4. However higher COP values, up to around 3.7, are achieved when the outlet air temperatures are higher and the power output is lower. The unit can be used in the range of air flow rates from 30 liter/s to 70 liter/s. As it uses the exhaust air as a heat source the maximum power output increases with increased air flow rate from 2,5 kW to 5,5 kW. It is also equipped with an energy efficient fan and energy efficient circulation pumps. It is assumed to be installed inside the house and having a stand-by electricity consumption of 50 W. The resulting heat loss, approximately 150 W, to its surrounding contributes during the heating season to the heating of the house.

The calculations for an outdoor air heat pump (OutAirHP) are based on coefficients of performance and power outputs derived from curves presented by a Swedish manufacturer. Values for a rather small unit with nominal power output of 5,2 kW and a COP of 3.3 at an outdoor temperature of +7°C and a heating system supply temperature of +45°C are used. At lower outdoor temperatures both the power output and the COP are lower. Coefficients for larger units were tested but gave higher life cycle costs without improving the possibility to achieve the energy and/or electric power limits set by the new Swedish building regulations BBR16. To minimize the life cycle costs it was therefore decided to use the values for the small unit in all calculations involving an outdoor air heat pump. However, using a larger unit, would sometimes have led to slightly lower energy consumption. The main heat emitting parts of the unit is assumed to be installed inside the house and having a stand-by electricity consumption of 100 W. The resulting heat loss to its surrounding, approximately 200 W, contributes during the heating season to the heating of the house. The unit has a single speed compressor. Using a variable speed compressor may have led to a somewhat better performance, but also a higher investment cost.

Calculations for ground source heat pumps (GrSourceHP) are based on coefficients of performance and power outputs presented by a Swedish manufacturer. It was always possible to choose the size of the ground source heat pump so that the house would comply with the energy and/or electric power limits set by the new Swedish building regulations BBR16. It was therefore decided to choose the smallest of the units that made it possible to comply with the regulations. However, a smaller unit would sometimes have led to a slightly lower life cycle cost. The nominal power output of the chosen units ranged from 5.1 kW to 8.2 kW at a cold side inlet temperature of +/- 0°C and a heating system supply temperature of +45°C. The units are assumed to be installed inside the house and having a stand-by electricity consumption of 150 W. The resulting heat loss to its surrounding, approximately 300 W, contributes during the heating season to the heating of the house. The units have a single speed compressor. Using a variable speed compressor may have led to a somewhat better performance, but also a higher investment cost.

Direct electric space heating and thermal solar for domestic hot water (DirEl+ThSol) has been the most common heating system for the first passive houses built in Sweden, and probably also in the rest of the world (mostly in Germany). In the calculations the electric heating is assumed to have 100% distribution efficiency, regardless if it is one central heater in the supply air or if there are small electric panels in each room. The thermal solar is assumed to cover 40% of the domestic hot water demand as well as 40% of the heat losses from the hot water storage tank. The storage tank is assumed to be installed inside the house and having a heat loss to its surroundings of 150 W. During the heating season the heat loss contributes to the heating of the house. The circulation pump for the thermal solar system is assumed to have an electricity consumption of 200 kWh/year.

In the calculations the two most common ventilation systems in new built single family houses have been used; mechanical exhaust air ventilation (ExAirVent) and mechanical exhaust and supply air ventilation with heat recovery (Ex/SuAirVHR). The ventilation performance values used in the calculations are given in table 4. It is assumed that the best available technology (BAT) for energy efficient ventilation is used. The heat recovery unit values represents the overall best results from tests made by SP for the Swedish Energy Agency during 2009. Many of the tested heat recovery units even had somewhat higher temperature ratios (up to 83 %), but then they also had a higher electricity consumption. In this study values for the unit with the lowest measured specific fan power (SFP) value are used as in most cases it also gives the lowest total energy use. The exhaust air ventilation system has in all calculations, except when combined with a condensing exhaust air heat pump, been assumed to have reduced ventilation rate during periods of non occupancy. The air flow rate is then reduced from the nominal air flow rate 45.5 l/s down to 13 l/s.

**Table 4: Ventilation system performance at nominal air flow rate (45.5 l/s)**

Ventilation system	P (W)	SFP (W/(l/s))	$\eta_{t+2^{\circ}\text{C}}$ (%) *	$\eta_{t+15^{\circ}\text{C}}$ (%) *
ExAirVent	18	0.4	-	-
Ex/SuAirVHR	52	1.1	76	74 **

\*) Temperature ratio measured at equal mass flow rates according to EN 13141-7

\*\*\*) Lowered 4 %-units compared to laboratory measurements, as on an average exhaust air humidity is assumed to be lower than during the measurements.

Depending on the heat production system and the maximum power demand for space heating different heat distribution systems can be used. For the different combinations of building envelope, climate, heating and ventilation system, the possible heat distribution system that gives the lowest life cycle cost has been chosen according to table 5. Even with the best building envelope and efficient ventilation heat recovery, only in the very south part of Sweden it is possible to use supply air heating. For all other cases the heating demand at the dimensioning outdoor temperature will be too high. The COP as well as the power output of outdoor air heat pumps is in the wintertime quite much lower if the supply temperature of the heat distribution system is high. It is therefore a clear advantage if an outdoor air heat pump is combined with a low temperature floor heating system.

**Table 5: Chosen heat distribution system for the different calculation cases**

Heating and ventilation system	$T_{\text{out, mean}} = 9^{\circ}\text{C}$	$T_{\text{out, mean}} = 6^{\circ}\text{C}$
DistrHeat + ExAirVent	Water radiators in each room	
ExAirVentHP	Water radiators in each room	
OutAirHP + ExAirVent	Water floor heating in each room	
GrSourceHP + ExAirVent	Water radiators in each room	
DistrHeat + Ex/SuAirVHR	Supply air heating (water)	Water radiators in each room
DirEI + ThSol + Ex/SuAirVHR	Supply air heating (electric)	Water radiators in each room
OutAirHP + Ex/SuAirVHR	Supply air heating (water)	Water floor heating in each room
GrSourceHP + Ex/SuAirVHR	Supply air heating (water)	Water radiators in each room

### 2.1.3 Parameters of usage

The influence of the occupants has of course a large impact on the total energy consumption in any individual case. However, when comparing different system solutions it is more important that all studied cases are studied with the same and somewhat normal influence of occupancy. In this study the parameters and values of occupancy given in table 6 have been used. The value for household electricity is about 15% lower than the normal value for a single family house of this size and with three persons living in the house. The reason is that we have assumed that the implementation of the European energy using products (EuP) directive will significantly reduce the use of household electricity.

**Table 6: The different systems for heating and ventilation**

Parameter	Value
Indoor air temperature, heating season	21°C
Number of persons	3
Emitted heat during occupancy	80 W/person
Time of occupancy	14 h/day (and night)
Extract air cooker hood (60 l/s)	1 h/day *
Hot water consumption (60°C)	14 m <sup>3</sup> /year, person
Household electricity consumption	4500 kWh/year
Parameter	Value

\*) 0.5 h/day during the coldest 3 months of the year.

## 2.1.4 Climatic variations

The Calculations presented have been made for two different climatic conditions with a mean outdoor air temperature of +9°C and +6°C. This represents approximately the very south part of climate zone III and the very north part of climate zone III (or the very south part of climate zone II). In the calculation model it is also possible to state the amount of passive solar gain in three different levels. In the present study a high level of passive solar has been assumed for the +9°C-climate, a normal level for the +6°C-climate and a low level for the +3°C-climate. One could argue that the amount of passive solar should be higher for the house with large window areas and low for the house with the small window area. However, houses with large window areas can in practice seldom fully utilize the potential for passive solar.

## 2.2 Life cycle cost calculations

The life cycle cost (LCC) calculations have been made using the standard formulas for calculation of present value. In the calculations a real discount rate of 5% has been used and the energy price is assumed to increase 1% per year excluding inflation. Estimations have been made for initial investment costs, reinvestment costs and operational costs for a total lifetime of 75 years for the houses. Only different costs related to building services systems and building physics that influence the energy use are presented, i.e. the presented investment and life cycle costs are not the total costs of the houses. A calculation spreadsheet has been developed that links the life cycle cost calculations to the energy calculations. The initial investment costs, reinvestment costs, life times and operational costs used in this study for different subsystem are shown in table 7-9. The resulting LCC values are given as a present value in SEK.

Initial investment costs tend to vary over time and are also depending on region. The used values are therefore estimated based on experience and prices found on the internet, etc. Reinvestment costs are of course even more difficult to estimate than the initial investment costs. However, due to the reason that the present value method discounts future costs, they are not as important as the initial investment costs. Sometimes the “best guess” is that the reinvestment cost is the same as the initial investment cost. The life time of different components and systems is of course also a “best guess” based on experience and “internal communication”. However, also in this case the discount of future costs makes it not so crucial if the “best guess” is a little bit wrong. The life cycle calculations are simplified by only using 15, 25 and 75 years of life time, where 75 years is the same as the assumed life time of the whole house. Yearly operational costs are costs that are not directly linked to the amount of energy used. It may involve maintenance costs, but also other costs indirectly linked to chosen energy system. A set value per year is used in the calculations. However, some of these costs may come discontinuous during the years and they also tend to increase as the systems and their components are getting older.

**Table 7: Life cycle cost inputs for heating systems**

Subsystem	ThermSolar	DistrHeating	ExAirHP	OutAirHP	GrSourceHP
Initial investm. cost, SEK	30000	45000 *	80000 ***	90000	ca 120000 ****
Reinvestment cost, SEK	30000	15000	80000 ***	90000	ca 70000 ****
Life time, Years	25	25	15	15	15
Operational cost, SEK/Y	300	2000 **	1000	1000	500

\*) Including connection fee (for a house rather close to an existing district heating system).

\*\*\*) Including yearly fees for capacity etc.

\*\*\*\*) The initial investment cost of the new condensing exhaust air heat pump is much higher than for the older more simple exhaust air heat pumps.

\*\*\*\*\*) Depends on both size and in which climate it is installed.

**Table 8: Life cycle cost inputs for heat distribution systems**

Subsystem	Water radiators	Water floor heating	Electric radiators	Electric air heating	Water air heating
Initial investm. cost, SEK	60000	80000 *	30000	3000	15000
Reinvestment cost, SEK	40000	10000 *	20000	3000	10000
Life time, Years	25	25	25	25	25
Operational cost, SEK/Y	300	200	100	100	200

\*) The initial investment cost is somewhat higher for the water floor heating system compared to the water radiator system, but the reinvestment cost is much lower as most of the system is assumed to have the same life time as the whole house.

**Table 9: Life cycle cost inputs for ventilation systems and building envelope**

Subsystem	ExAirVent	EX/SuAirHR *	RedVent	Windows **	Insulation ***
Initial investm. cost, SEK	15000	45000	3000	ca 130000	ca 70000
Reinvestment cost, SEK	6000	25000	3000	ca 130000	0
Life time, Years	25	25	25	25	75
Operational cost, SEK/Y	200	600	100	0	0

\*) Also includes costs for improved air tightness.

\*\*\*) Depends on both total window area and insulation standard.

\*\*\*\*) Depends on both total envelope area and insulation standard.

The energy price for electricity is quite the same all over Sweden, even if there are some deviations regarding the price for the local distribution of electricity. The present average price for electricity, including distribution, has been estimated to 1.25 SEK/kWh. Additional indirect costs for electricity are not included in the above price, nor in the life cycle costs as all houses are assumed to have these costs regardless of the heating system.

The price for district heating varies quite much between different parts of Sweden, at least if one only looks at the direct price per bought kWh. But when also taking into account the differences in other indirect costs the total price per bought kWh tend to decrease. Some district heating utilities also offer different price plans, i.e. either you pay a low initial cost and have a high cost per used kWh, or you pay a high initial cost and have a low cost per used kWh. Only looking at the yearly energy cost the latter price plan may seem to be the best, especially for houses with a high use of energy. However, in a life cycle cost analysis that price plan may not be the best choice, especially not for a low energy house. In the present study a "normal price plan" with a rather low initial cost (covering the real investment costs) and a rather high cost per bought kWh is therefore used. The present average price for district heating has been estimated to 0.75 SEK/kWh. Additional indirect costs for district heating are not included in the above price. However in the life cycle costs additional indirect costs related to the use of district heating is included as these costs are only related to the use of district heating, i.e. connection fee, capacity fee, etc. are included in the initial investment costs and in the yearly costs.

The yearly energy costs are calculated by multiplying the used energy in the form of electricity and district heating with the estimated prices above. A rather large uncertainty is of course future changes in direct and indirect energy costs. In the present study the direct energy prices, both for electricity and district heating, are assumed to rise by one percent per year more than other prices. Except for the discount rate the indirect costs are assumed to be unchanged.

### 3 RESULTS

The results of the calculations are summarized in table 10-21 as total yearly amount of delivered/bought energy, direct yearly costs for delivered/bought energy, specific energy use, maximum electric power for the heating system, initial investment costs and life cycle costs.

**Table 10: Total amount of delivered/bought energy in south part of climatic zone III (kWh/year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	12085	16031	20492
ExAirVentHP	7925	9453	11798
OutAirHP + ExAirVent	7890	9152	10713
GrSourceHP + ExAirVent	7475	8445	9536
DistrHeat + Ex/SuAirVHR	10389	13923	18134
DirEI + ThSol + Ex/SuAirVHR	9364	12432	16151
OutAirHP + Ex/SuAirVHR	7710	8692	10085
GrSourceHP + Ex/SuAirVHR	7308	8176	9208

**Table 11: Total amount of delivered/bought energy in north part of climatic zone III (kWh/year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	14762	20090	25931
ExAirVentHP	8968	11414	15336
OutAirHP + ExAirVent	9092	11075	13772
GrSourceHP + ExAirVent	8255	9565	10878
DistrHeat + Ex/SuAirVHR	12250	17174	22775
DirEI + ThSol + Ex/SuAirVHR	10881	15200	20181
OutAirHP + Ex/SuAirVHR	8591	10170	12432
GrSourceHP + Ex/SuAirVHR	7899	9095	10520

**Table 12: Direct costs for delivered/bought energy in south part of climatic zone III (SEK/year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	11400	14372	17733
ExAirVentHP	9906	11817	14748
OutAirHP + ExAirVent	9862	11440	13391
GrSourceHP + ExAirVent	9344	10556	11920
DistrHeat + Ex/SuAirVHR	10284	12947	16119
DirEI + ThSol + Ex/SuAirVHR	11705	15540	20188
OutAirHP + Ex/SuAirVHR	9638	10865	12607
GrSourceHP + Ex/SuAirVHR	9134	10220	11511

**Table 13: Direct costs for delivered/bought energy in north part of climatic zone III (SEK/year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	13414	17427	21827
ExAirVentHP	11210	14267	19170
OutAirHP + ExAirVent	11365	13844	17215
GrSourceHP + ExAirVent	10319	11956	13598
DistrHeat + Ex/SuAirVHR	11685	15394	19613
DirEI + ThSol + Ex/SuAirVHR	13601	19000	25227
OutAirHP + Ex/SuAirVHR	10738	12712	15540
GrSourceHP + Ex/SuAirVHR	9874	11369	13150

The specific energy use has been calculated for all combinations. It is defined by Boverket (the Swedish Board of Housing, Building and Planning) as the total energy use excluding

household electricity and divided by the floor area. Used energy is defined as externally delivered/bought energy. In the new Swedish Building regulations BBR16 there are maximum values for specific energy use that new built houses should not exceed. In BBR16 there are also maximum values for the electric power that new built electrically heated houses should not exceed. A house is defined as electrically heated if the needed/installed electric power supply for heating and domestic hot water exceeds 10 W/m<sup>2</sup> heated floor area. Values not complying with the requirements in BBR 16 are marked red, otherwise green.

**Table 14: Calculated specific energy use in south part of climatic zone III (kWh/m<sup>2</sup> year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3	Max. value/BBR16
DistrHeat +ExAirVent	58	89	123	110
ExAirVentHP	26	38	56	55
OutAirHP + ExAirVent	26	36	48	55
GrSourceHP + ExAirVent	23	30	39	55
DistrHeat + Ex/SuAirVHR	45	72	105	110
DirEI + ThSol + Ex/SuAirVHR	37	61	90	55
OutAirHP + Ex/SuAirVHR	25	32	43	55
GrSourceHP + Ex/SuAirVHR	22	28	36	55

**Table 15: Calculated specific energy use in north part of climatic zone III (kWh/m<sup>2</sup> year)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3	Max. value/BBR16
DistrHeat +ExAirVent	79	120	165	110
ExAirVentHP	34	53	83	55
OutAirHP + ExAirVent	35	51	71	55
GrSourceHP + ExAirVent	29	39	49	55
DistrHeat + Ex/SuAirVHR	60	97	141	110
DirEI + ThSol + Ex/SuAirVHR	49	82	121	55
OutAirHP + Ex/SuAirVHR	31	44	61	55
GrSourceHP + Ex/SuAirVHR	26	35	46	55

**Table 16: Calculated maximum electric power in south part of climatic zone III (kW)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3	Max. value/BBR16
DistrHeat +ExAirVent	-	-	-	-
ExAirVentHP	1.23	2.09	3.72	4.5
OutAirHP + ExAirVent	1.66	2.86	4.32	4.5
GrSourceHP + ExAirVent	1.02	1.51	2.04	4.5
DistrHeat + Ex/SuAirVHR	-	-	-	-
DirEI + ThSol + Ex/SuAirVHR	2.00	3.32	4.75	4.5
OutAirHP + Ex/SuAirVHR	1.55	2.06	3.46	4.5
GrSourceHP + Ex/SuAirVHR	0.74	1.22	1.73	4.5

**Table 17: Calculated maximum electric power in north part of climatic zone III (kW)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3	Max. value/BBR16
DistrHeat +ExAirVent	-	-	-	-
ExAirVentHP	1.98	4.01	5.87	4.5
OutAirHP + ExAirVent	3.18	5.05	7.03	4.5
GrSourceHP + ExAirVent	1.57	2.61	3.54	4.5
DistrHeat + Ex/SuAirVHR	-	-	-	-
DirEI + ThSol + Ex/SuAirVHR	2.82	4.65	6.59	4.5
OutAirHP + Ex/SuAirVHR	2.72	3.95	5.89	4.5
GrSourceHP + Ex/SuAirVHR	1.16	1.88	3.42	4.5

The initial investment costs are presented as the sum of all estimated single initial investments (see table 7, 8 and 9). The calculated life cycle costs (LCC) includes the investment costs and the yearly energy costs, as well as operational costs. It therefore gives a more balanced value for deciding the most economic energy system. The best value for each building envelope is in table 18-21 marked green and the worst value red. The overall best value in each table is marked bold green and the overall worst value marked bold red.

**Table 18: Estimated initial investment costs in south part of climatic zone III (SEK)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	341235	313182	325424
ExAirVentHP	373235	345182	357424
OutAirHP + ExAirVent	406235	378182	390424
GrSourceHP + ExAirVent	406235	378182	390424
DistrHeat + Ex/SuAirVHR	323235	340182	352424
DirEI + ThSol + Ex/SuAirVHR	296235	295182	307424
OutAirHP + Ex/SuAirVHR	368235	405182	417424
GrSourceHP + Ex/SuAirVHR	388235	405182	417424

**Table 19: Estimated initial investment costs in north part of climatic zone III (SEK)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	341235	313182	325424
ExAirVentHP	373235	345182	357424
OutAirHP + ExAirVent	406235	378182	390424
GrSourceHP + ExAirVent	416235	388182	410424
DistrHeat + Ex/SuAirVHR	368235	340182	352424
DirEI + ThSol + Ex/SuAirVHR	323235	295182	307424
OutAirHP + Ex/SuAirVHR	433235	405182	417424
GrSourceHP + Ex/SuAirVHR	443235	415182	427424

**Table 20: Calculated life cycle costs in south part of climatic zone III (SEK)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	736048	773872	874735
ExAirVentHP	774547	787224	877896
OutAirHP + ExAirVent	804842	810135	877153
GrSourceHP + ExAirVent	778809	774940	828518
DistrHeat + Ex/SuAirVHR	690180	779089	875486
DirEI + ThSol + Ex/SuAirVHR	664769	756512	887870
OutAirHP + Ex/SuAirVHR	773596	835509	897548
GrSourceHP + Ex/SuAirVHR	754392	805941	857784

**Table 21: Calculated life cycle costs in north part of climatic zone III (SEK)**

Heating and ventilation system	Env. 1	Env. 2	Env. 3
DistrHeat +ExAirVent	783763	846213	971681
ExAirVentHP	805422	845228	982647
OutAirHP + ExAirVent	840884	867119	968192
GrSourceHP + ExAirVent	811904	818088	892650
DistrHeat + Ex/SuAirVHR	781779	837029	958224
DirEI + ThSol + Ex/SuAirVHR	733563	838455	1007179
OutAirHP + Ex/SuAirVHR	864654	879340	966716
GrSourceHP + Ex/SuAirVHR	840328	843149	906592

#### 4 DISCUSSION AND CONCLUSIONS

The ground source heat pump combined with ventilation heat recovery has for each building envelope and climate both the lowest amount of delivered/bought energy and the lowest yearly cost for delivered/bought energy. For each building envelope and climate district heating and no ventilation heat recovery has the highest amount of delivered/bought energy. But, as price per kWh is much lower for district heating than for electricity, it is the heating and ventilation system with ventilation heat recovery, direct electric heating and thermal solar that for each building envelope has the highest yearly cost for delivered/bought energy.

For each heating and ventilation system the building envelope with the lowest transmission heat loss of course gives the lowest amount of delivered/bought energy as well as the lowest yearly cost for delivered/bought energy. However it is of interest to notice that when the building envelope with the highest transmission heat loss is combined with a ground source heat pump, even without any ventilation heat recovery, the delivered/bought energy and the cost for this energy is almost as low as for the "standard passive house" with ventilation heat recovery, direct electric heating and thermal solar.

For the best building envelope there are rather small differences in the amount of direct costs for delivered/bought energy between the different heating and ventilation systems, especially between the different heat pump systems.

In the very south part of climatic zone III the requirement in BBR 16 can for district heating be met either by a rather well built building envelope and exhaust ventilation or by a less well built building envelope and an efficient air-to-air ventilation heat recovery system. In the north part of climatic zone III the requirement can for district heating be met either by a very well built building envelope or by the use of a rather well built building envelope and an efficient ventilation heat recovery system.

Meeting the energy requirement with an exhaust air condensing heat pump requires a rather well built building envelope, especially in the north part of climatic zone III.

An outdoor air heat pump can meet the energy requirements for all building envelopes in the south part of climatic zone III without the need for ventilation heat recovery. In the north part of climatic zone III the requirement can be met either by a very well built building envelope or by the use of a rather well built building envelope and an efficient ventilation heat recovery system.

With ground source heat pumps the energy requirements in the new Swedish building regulations BBR 16 can be met almost regardless of the building envelope. On the other hand, with a very good building envelope the requirements can also be met regardless of the type of heating and ventilation system.

The heating and ventilation system with a ground source heat pump and a ventilation heat recovery system has in most cases the highest investment cost, whereas the system with ventilation heat recovery, direct electric heating and thermal solar has the lowest. The combination with the lowest investment costs does not meet the energy requirements.

The heating and ventilation system with ventilation heat recovery, direct electric heating and thermal solar can only meet the energy requirements when combined with a very well built building envelope, i.e. a passive house. This combination also gives the lowest LCC. When combined with the least well built building envelope, this heating and ventilation system instead gives the highest LCC.

Compared to the less compact and less well insulated building envelopes the compactness and restricted window area of the building envelope with the lowest total transmission heat loss compensates for the cost for increased insulation thickness and more expensive windows.

The outdoor air heat pump gives in many cases the highest LCC. The reason is a combination of rather high investment and reinvestment costs, as well as poor performance at low outdoor temperatures.

The heating and ventilation system with a ground source heat pump and exhaust air ventilation gives the lowest LCC for a less well built building envelope.

The existing ground source heat pumps on the Swedish market are too big and/or expensive to be a cost effective system solution for a very low energy single family house. To reach a life cycle cost (LCC) comparable to a "standard passive house" a ground source heat pump should have almost half the price and half the size compared to what is available today. In most cases around 3 kW would be enough and the total initial investment cost should be around 70 000 SEK.

There are rather small savings in the amount of and direct costs for delivered/bought energy by using an air-to-air ventilation heat recovery system in combination heat pumps. In combination with district heating the savings are more significant. But when it comes to LCC the savings in combination with district heating are small, if any, and in combination with heat pumps the LCC is higher when also using ventilation heat recovery. However, there are other advantages of a ventilation heat recovery system that also should be taken into account, i.e. improved thermal comfort and lower peak power demand. The latter allowing a smaller heating system, potentially lowering the initial investment costs, reinvestment costs and LCC.

## 5 REFERENCES

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