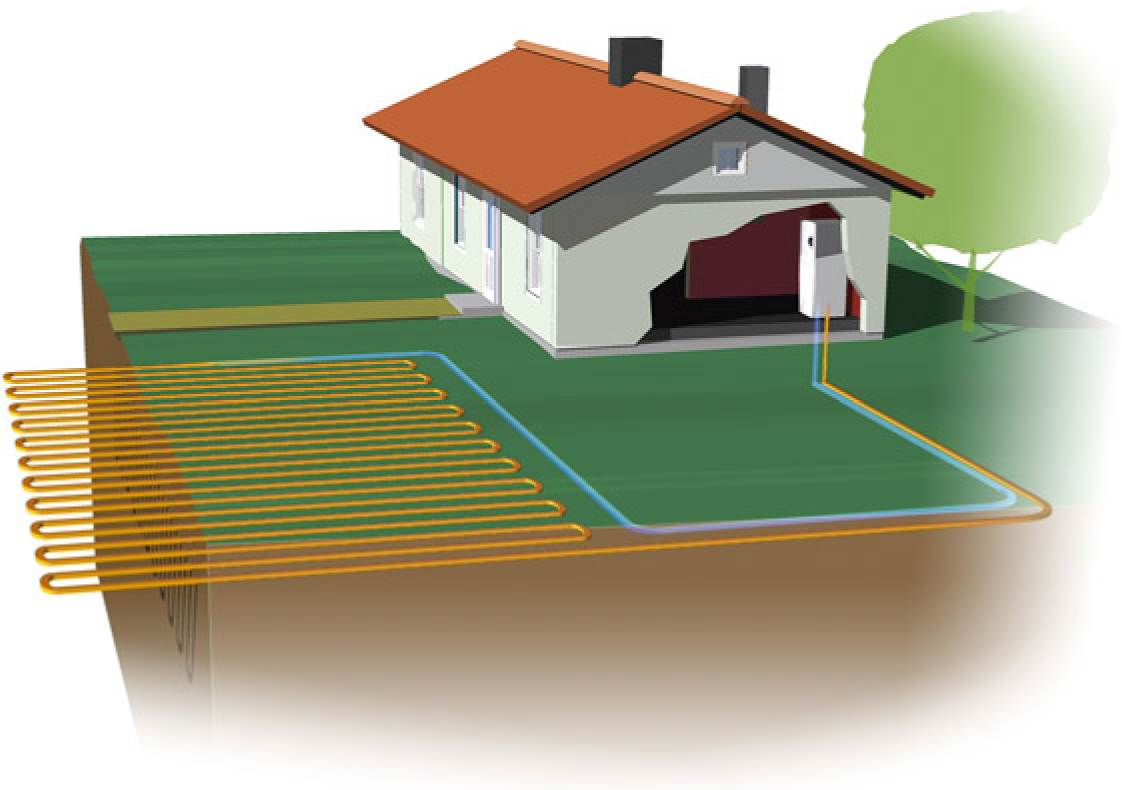
Economic heating systems for low energy buildings
- Calculation, comparison and evaluation of different system solutions

Svein Ruud



Energy Technology

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Economical heating systems for low energy houses
- Calculation, comparison and evaluation of different system solutions

Svein Ruud

Abstract

Sweden has a tradition both in building rather energy efficient houses and installing heat pumps in buildings. Heat pumps, however, have very seldom been used together with very low energy houses. In this study energy and economic calculations have been made for three different building envelopes combined with eight different systems for heating and ventilation. The calculations have also been made for three different climates. The results have also been compared with 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 be met regardless of the type of heating and ventilation system. The economic calculations result in a life cycle cost (LCC) that is based on initial investment costs, reinvestment costs, life time of systems and components, operational costs and yearly energy costs. The 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 comes out with a lower life cycle cost. Heat pumps on the Swedish market are still too large and/or expensive to be installed in very low energy houses with a low life cycle cost.

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

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Preface

This is the final report of project P10 that is part of the EFFSYS2-program run by the Swedish Energy Agency. It is also a part of the International IEA Heat Pump Program, Annex 32 - Economical heating and cooling systems for low energy houses.

During the project Swedish manufacturers of heat pumps as well as manufacturers of detached single family houses has been involved;

Nibe AB
http://www.nibe.se

Thermia Värme AB
http://www.thermia.se

IVT AB
http://www.ivt.se

NCC Teknik
http://www.ncc.se

LB-Hus AB

VästkustStugan

Sätila Bygg AB

I would like to thank all of them for their participation.

Svein Ruud, June 2010

Summary

This is the final report of project P10 that is part of the EFFSYS2-program run by the Swedish Energy Agency. It is also the Swedish contribution to the IEA Heat Pump Program, Annex 32 - Economical heating and cooling systems for low energy houses. In this study energy and economic calculations have been made for three different single family building envelopes combined with eight different systems for heating and ventilation. The calculations have been made for three different climates. The results regarding energy have also been compared with the new Swedish building regulations. Finally life cycle cost (LCC) calculation has been made for all combinations.

- Compared to the less compact and less well insulated building envelopes the compactness and restricted window area of the building envelope with the lowest transmission heat loss compensates for the cost for increased insulation thickness and more expensive windows. Hence, for any given combination of heating and ventilation system the building envelope with the lowest transmission loss always has a lower LCC than the less compact and less well insulated building envelopes.
- The building envelope with the lowest transmission loss fulfills the energy requirements in BBR16 regardless of which heating and ventilation system that is chosen. On the other hand, when using a ground source heat pump the energy requirements can be fulfilled regardless of which building envelope that is chosen. As expected, the lowest energy use is achieved when the building envelope with the lowest transmission loss is combined with ground source heat pump and ventilation heat recovery.
- The “standard passive house” (a very airtight building envelope with very low total transmission heat losses, air-to-air ventilation heat recovery, direct acting electric supply air heating and thermal solar for the domestic hot water) has the lowest LCC of all the studied heating and ventilation systems. However, the yearly energy use (bought energy) and the yearly energy costs are not the lowest.
- It is notable 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 energy use (bought energy) is almost as low as for the “standard passive house”.
- Notable is also that combined with a heat pump the use of a ventilation heat recovery system gives a rather small energy saving. The impact of combining ventilation heat recovery with district heating is much more significant.
- The condensing exhaust air heat pump can fulfill the building requirements if the building envelope does not have too high total thermal transmission heat losses. For a building envelope with a very low total transmission loss it is, except for the “standard passive house”, the heating and ventilation system on the Swedish market that has the lowest LCC. However, for more standard building envelopes with higher total transmission losses the ground source heat pumps has the lowest LCC of the heating and ventilation systems on the Swedish market.
- In the south part of Sweden the energy requirements can sometimes also be met by using an outdoor air heat pump, preferably in combination with an air-to-air heat recovery system and especially for a building envelope with a very low total transmission loss. However, in most cases other types of heat pumps have a lower yearly energy use/LCC.
- District heating need to be combined with a building envelope with a rather low total transmission loss and in most cases also with an air-to-air ventilation heat recovery system to meet the building requirements. For any give building envelope district heating without ventilation heat recovery has the highest energy use (bought energy), the highest yearly energy costs and the highest LCC of all heating and ventilation systems studied.
- To reach an 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.
- Also other types of heat pumps would lower the LCC by radically decreasing the initial and reinvestment costs, but the higher yearly energy use would still remain the same.
- Most of the single family houses built in Sweden today seem to minimize the initial investment cost rather than the LCC.

Sammanfattning (summary in Swedish)

Detta är slutrapporten till projekt P10 som är en del av EFFSYS2-programmet som har drivits av Energimyndigheten. Det är också det svenska bidraget till IEA:s program för värmepumpar (HPP), Annex 32 – Ekonomiska värme- och kylsystem för lågenergihus.
I den här studien har energianvändning och kostnader beräknats för tre olika byggnadsskal för ett småhus när de har kombinerats med åtta olika system för uppvärmning och ventilation. Beräkningarna har gjorts för tre olika klimat. Resultaten med avseende på energi har också jämförts med de nya svenska byggreglerna (BBR16). Slutligen har livscykelkostnader (LCC) beräknats för samtliga kombinationer.
- Jämfört med de ej så kompakta och välisolerade byggnadsskalen så kompenserar kompaktheten och den begränsade fönsterytan hos byggnadsskalet med den lägsta totala värmetransmissionsförlusten för kostnaderna för tjockare isolering och bättre fönster. För ett givet värme- och ventilationssystem får därför byggnadsskalet med den lägsta totala transmissionsförlusten alltid en lägre LCC än byggnadsskalen som inte är så kompakta och välisolerade.
- Byggnadsskalet med de lägsta transmissionsförlusterna uppfyller energikraven i Boverkets Byggregler BBR16 oberoende av vilket uppvärmnings- och ventilationssystem som väljs. Å andra sida, med en bergvärmepump kan man uppfylla energikraven i BBR16 oberoende av vilket byggnadsskal som väljs. Den lägsta energianvändningen uppnås som förväntat när byggnadsskalet med de lägsta transmissionsförlusterna kombineras med en bergvärmepump och ventilationsvärmeåtervinning (FTX).
- Ett ”standard passivhus” (ett mycket lufttätt byggnadsskal med låga totala transmissionsförluster, ventilationsvärmeväxlare med luftvärmesystem och termiska solfångare för tappvarmvatten) har lägst LCC av de studerade värme- och ventilationssystemen. Men, den årliga energianvändningen (köpt energi) och de årliga energikostnaderna är inte lägst.
- Det kan uppmärksammas att när byggnadsskalet med den högsta transmissionsförlusten, även utan ventilationsvärmeåtervinning (FTX), kombineras med en bergvärmepump så blir energianvändningen (köpt energi) likvärdig med den för ett ”standard passivhus” med direktverkande elvärme.
- Noterbart är också att kombinerat med en värmepump så ger FTX-ventilation en relativt begränsad energibesparing. Kombinerat med fjärrvärme ger FTX-ventilation en desto större energibesparing.
- Med en kondenserande frånluftsvärmepump kan man klara byggreglernas energikrav om byggnadsskalet inte har för höga transmissionsförluster. För ett byggnadsskal med mycket låga transmissionsförluster är den kondenserande frånluftvärmepumpen, förutom ett ”standard passivhus”, det värme- och ventilationssystemet som har lägst LCC. Men för ett vanligt byggnadsskal med högre transmissionsförluster ger bergvärmepumpar en lägre LCC.
- I den södra delen av Sverige kan byggreglernas energikrav ibland klaras även med en luft-vattenvärmepump, företrädesvis i kombination med FTX-ventilation och speciellt om man har ett byggnadsskal med mycket låga transmissionsförluster. Men i de flesta fall har andra typer av värmepumpar en lägre LCC.
- Fjärrvärme behöver kombinera med ett byggnadsskal med låga transmissionsförluster och i de flesta fall också FTX-ventilation för att klara byggreglernas energikrav. Med ett givet byggnadsskal, välisolerat eller inte, så är fjärrvärme utan ventilationsåtervinning det av de studerade värme- och ventilationssystemen som har högst energianvändning (köpt energi), högst årlig energikostnad och högst LCC.
- För att komma lika låg LCC som ett ”standard passivhus” behöver en bergvärmepump ha **halva priset och halva storleken** jämfört med vad som finns på marknaden idag.
- Även andra typer av värmepumpar skulle kunna minska sin LCC genom att radikalt minska sitt pris, men den högre årliga energianvändningen skulle ändå bestå.
- De flesta småhus som byggs i Sverige idag tycks snarare minimera den initiala kostnaden för ett värme- och ventilationssystem än LCC-kostnaden.

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.

2 Purpose

The main purpose of this project has been to calculate and compare the energy use and costs related to the energy use when different building envelopes are combined with different types of heating and ventilation systems. One purpose has also been to investigate how these different combinations comply the new Swedish building regulations, BBR16, that came fully into force on the1th of January 2010.

The study has been limited to a single family house with a floor area of 130 m^2 and three different climates covering the climatic variations for more than 90 % 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.

3 Calculation method

3.1 Energy calculations

3.1.1 General

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 2.1”. 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 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 et al, 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. A new, not yet released, version for outdoor air heat pumps has also been used.

3.1.2 Building physics

3.1.2.1 Thermal transmission losses

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

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

These three envelopes cover the range of thermal transmission loss that almost all new built Swedish single family houses of this size is 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. I 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.

3.1.2.2 Air tightness of building envelope

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 ($l/s\ m^2\ Pa$)
Mechanical exhaust air ventilation	0.8
Mechanical exhaust and supply air ventilation with heat recovery	0.3

3.1.3 Building services systems

The three different building envelopes has been combined with eight different systems for heating and ventilation, see table 3. The “short description” is used when presenting the results in chapter 4 and 5.

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

3.1.3.1 Heating system parameters

3.1.3.1.1 District heating

The district heating unit 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.

3.1.3.1.2 Exhaust air condensing heat pump

Calculations involving an exhaust air condensing heat pump are based in coefficients of performance and power outputs presented by NIBE for its F750 unit, see table 4. 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 demand the outlet air temperature can be as low as approximately -15°C. However higher COP values are achieved when the outlet air temperatures are higher and the power output is lower. As it uses the exhaust air as a heat source the power output increases with increased air flow rate. It is also equipped with an energy efficient fan and energy efficient circulation pumps. There is also another exhaust air condensing heat pump with similar performance on the Swedish market, the Comfort Zone (CE50 Eco).

Table 4. Coefficients of performance and power outputs presented for NIBE F750

Air flow rate (l/s)	30	40	**50**	60	70
P heat 20/35, nom (W)	1417	1685	**1779**	1872	1919
COP heat 20/35, nom (-)	3.37	3.56	**3.62**	3.67	3.65
P heat 20/45, nom (W)	1396	1657	**1746**	1791	1880
COP heat 20/45, nom (-)	3.03	3.21	**3.26**	3.25	3.30
P heat 20/35, max (W)	2288	3051	**3874**	4709	5397
COP heat 20/35, max (-)	2.79	2.80	**2.77**	2.69	2.66
P heat 20/45, max (W)	2505	3348	**4215**	5047	5503
COP heat 20/45, max (-)	2.47	2.45	**2.39**	2.31	2.44

The F750 unit can be used range of air flows as shown in table 4. Values in the column for 50 l/s have been used in the calculations as it is closest to the nominal air flow of a house of the actual size. The energy calculation program automatically makes corrections for the air flow rate in the model house being slightly lower. The F750 unit is assumed to be installed inside the house and having a stand-by electricity consumption of 50 W. The resulting heat loss to its surrounding contributes during the heating season to the heating of the house.

3.1.3.1.3 Outdoor air heat pump

Calculations involving an outdoor air heat pump are based on coefficients of performance and power outputs derived from curves presented for an IVT OPTIMA 600, see table 5. Coefficient for larger OPTIMA-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.

Table 5. Coefficients of performance and power outputs derived for an IVT OPTIMA 600

P vp värme 7/35°C (W)	5700
COP värme 7/35°C (-)	4.03
P värme, 7/45°C (W)	5200
COP heat 7/45°C (-)	3.26
P heat -15/35°C (W)	2650
COP heat -15/35°C (-)	1.93
P heat -15/45°C (W)	2500
COP heat -15/45°C (-)	1.61

To minimize the life cycle costs it was therefore decided to use the values for the OPTIMA 600 in all calculations involving an outdoor air heat pump. However, using a larger unit, would sometimes have led to a slightly lower energy consumption. The main heat emitting parts of the Optima 600 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 contributes during the heating season to the heating of the house. The OPTIMA 600 has a single speed compressor. Using a variable speed compressor may have led to a somewhat better performance, but also a higher investment cost.

3.1.3.1.4 Ground source heat pumps

Calculations involving ground source heat pumps are based in coefficients of performance and power outputs presented by IVT for its Greenline HE-units, see table 6. It was always possible to chose a ground source heat pump among these HE-units so that the house would with the energy and/or electric power limits set by the new Swedish building regulations BBR16. It was therefore decided to chose the smallest of the HE-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.

Table 6. Coefficients of performance and power outputs presented for IVT HE-units

Model	Greenline HE 6	Greenline HE 7	Greenline HE 9
P heat 0/35°C (W)	5500	7170	8700
COP heat 0/35°C (-)	4.02	4.11	4.09
P heat 0/45°C (W)	5100	6660	8220
COP heat 0/45°C (-)	3.12	3.19	3.21

The HE-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 contributes during the heating season to the heating of the house. The HE-units have a single speed compressor. Using a variable speed compressor may have led to a somewhat better performance, but probably also a higher investment cost. There are also exhaust air units available on the market that can be combined with a ground source heat pump. They can potentially increase the system efficiency, but have not been included in the study as they need to be further improved before they in practice can improve the efficiency.

3.1.3.1.5 Direct electric space heating and thermal solar for DHW

This 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).

The electric heating is assumed to have 100% distribution efficiency, regardless if it is one central heater in the supply air or if there is 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 hot water storage tank is assumed to be installed inside the house and having a heat loss to its surrounding of 150 W. During the heating season to 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.

3.1.3.2 Heat distribution systems

Depending on the heating 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 heating system that gives the lowest life cycle cost has been chosen according to table 7.

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.

Table 7. Chosen heat distribution system for the different calculation cases

Heating and ventilation system	Env. 1 + $T_{out, mean}$ = 9 °C	All other combinations
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
DirEl + 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

The coefficient of performance as well as power output of outdoor air heat pumps is in the wintertime is quite much lower if the supply temperature of the heat distribution system is high. It is a clear advantage if an outdoor air heat pump is combined with a low temperature floor heating system. An alternative solution, not an option in the calculation program used, would have been to use fan coil units. It has therefore not been studied, but would from an energy point of view perform close to or better than a floor heating system but have lower investment costs than a radiator system.

For other types of heat pumps the total energy use is almost the same for water radiators and water floor heating. The increase in COP is in that case compensated by the increase of other heat losses (through the ground floor and by less efficient temperature control). In the present study water radiator are assumed to have a slightly lower investment cost than water floor heating. If the energy use is almost equal, the water radiator heating system is chosen to minimize the life cycle cost.

Combined with district heating, water radiators will always give a lower energy use than water floor heating. Also considering the investment cost, water radiators will in this case clearly have the lowest life cycle cost.

3.1.3.3 Ventilation systems

In the calculations the two most common ventilation systems in new built single family houses has been used:

1. Mechanical exhaust air ventilation (ExAirVent)
2. Mechanical exhaust and supply air ventilation with heat recovery (Ex/SuAirVHR)

The ventilation performance values used in the calculations are given in table 8. It is assumed that the best available technology (BAT) for energy efficient ventilation is used.

Table 8. Ventilation system performance at nominal air flow rate (45,5 l/s)

Ventilation system	P (W)	SFP (W/(l/s))	$\eta_{t\ +2°C}$ (%) *	$\eta_{t\ +15°C}$ (%) *
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.

The values in table 8 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 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.

3.1.4 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 9 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 EuP-directive will significantly reduce the use of household electricity.

Table 9. Parameters and values of occupancy influence

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^3/year, person
Household electricity consumption	4500 kWh/year

*) 0.5 h/day during the coldest 3 months of the year. In the calculation model this also simulates the influence window airing during the heating season.

3.1.5 Climatic variations

Calculations have been made for three different climatic conditions with a mean outdoor air temperature of +9°C, +6°C and +3°C. This represents approximately the very south part of climate zone III, the very north part of climate zone III (or the very south part of climate zone II) and the very north 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.

3.2 Life cycle cost calculations

3.2.1 General

The life cycle cost (LCC) calculations has 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 10-12. The resulting LCC values are given as a present value in SEK.

3.2.2 Initial investment costs

Initial investment costs tend to vary over time and are also depending on region. The used values are therefore estimates based on experience and prices found on the internet, etc.

3.2.3 Reinvestment costs

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.

3.2.4 Life times

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.

3.2.5 Yearly operational costs

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 uses 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 10. Life cycle cost inputs for heating systems

Subsystem	ThermSolar	DistrHeating	ExAirHP	OutAirHP	GrSourceHP
Initial investm. cost, SEK	30000	45000 [1]	80000 [3]	90000	ca 120000 [4]
Reinvestment cost, SEK	30000	15000	80000 [3]	90000	ca 70000 [4]
Life time, Years	25	25	15	15	15
Operational cost, SEK/Y	300	2000 [2]	1000	1000	500

1) Including connection fee (for a house rather close to an existing district heating system).
2) Including yearly fees for capacity etc.
3) The initial investment cost of the new condensing exhaust air heat pump is much higher than for older more simple exhaust air heat pumps.
4) Depends on both size and in which climate it is installed. Initial investment costs ranges from 110 000 SEK to 155 000 SEK. Reinvestment costs ranges from 70 000 SEK to 80 000 SEK.

Table 11. 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 [5]	30000	3000	15000
Reinvestment cost, SEK	40000	10000 [5]	20000	3000	10000
Life time, Years	25	25	25	25	25
Operational cost, SEK/Y	300	200	100	100	200

5) 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 12. Life cycle cost inputs for ventilation systems and building envelope

Subsystem	ExAirVent	EX/SuAirHR [6]	RedVent	Windows [7]	Insulation [8]
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

6) Also includes costs for improved air tightness.
7) Depends on both total window area and insulation standard.
8) Depends on both total envelope area and insulation standard.

3.2.6 Energy prices

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 include 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.

4 Results

4.1 Energy use

4.1.1 Total energy use

The calculated total energy use for the different combinations of building envelope, climate, heating and ventilation system are shown in table 13-15 below. Used energy is equal to externally delivered/bought energy.

Table 13. Calculated **total energy use** in south part of climatic zone III (**kWh/year**)

Outdoor temp $_{Year, mean}$ (9 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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
DirEl + ThSol + Ex/SuAirVHR	9364	12432	16151
OutAirHP + Ex/SuAirVHR	7710	8692	10085
GrSourceHP + Ex/SuAirVHR	**7308**	8176	9208

Table 14. Calculated **total energy use** in north part of climatic zone III (**kWh/year**)

Outdoor temp $_{Year, mean}$ (6 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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
DirEl + ThSol + Ex/SuAirVHR	10881	15200	20181
OutAirHP + Ex/SuAirVHR	8591	10170	12432
GrSourceHP + Ex/SuAirVHR	**7899**	9095	10520

Table 15. Calculated **total energy use** in north part of climatic zone II (**kWh/year**)

Outdoor temp $_{Year, mean}$ (3 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
DistrHeat +ExAirVent	18099	24851	**32087**
ExAirVentHP	10329	14106	19638
OutAirHP + ExAirVent	10840	13969	18237
GrSourceHP + ExAirVent	9306	10917	12700
DistrHeat + Ex/SuAirVHR	14713	21115	28136
DirEl + ThSol + Ex/SuAirVHR	12916	18586	24862
OutAirHP + Ex/SuAirVHR	9739	12337	15954
GrSourceHP + Ex/SuAirVHR	**8694**	10335	12021

The highest energy use has the building envelope with the highest transmission loss, district heating and no ventilation heat recovery. The lowest energy use has the building envelope with the lowest transmission loss, ground source heat pump and ventilation heat recovery. Notable, is 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 energy use is almost as low as for the "standard passive house" (DirEl + ThSol + Ex/SuAirVHR + UA_{tot} = 51 W/K). Notable is also that when using a heat pump there are no big decrease in energy use when also using a ventilation heat recovery system. The impact of combining ventilation heat recovery with district heating is much more significant.

4.1.2 Specific energy use

The specific energy use has been calculated for all combinations and presented in table 16-18. 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. In the new Swedish building regulations BBR16 there are also maximum values for specific energy use that new built houses should not exceed, neither as calculated in the project phase nor when taken into normal operation. Calculated values that do not comply with the new Swedish building regulations BBR 16 are marked red, otherwise green. Values for combinations that do not comply with the requirements in 4.1.3 regarding maximum electric power for electrically heated houses are given in brackets.

Table 16. Calc. **specific energy use** in south part of climatic zone III (**kWh/m^2 year**)

Outdoor temp $_{Year, mean}$ (9 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
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
DirEl + ThSol + Ex/SuAirVHR	37	61	(90)	55
OutAirHP + Ex/SuAirVHR	25	32	43	55
GrSourceHP + Ex/SuAirVHR	22	28	36	55

Table 17. Calc. **specific energy use** in north part of climatic zone III (**kWh/m^2 year**)

Outdoor temp $_{Year, mean}$ (6 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
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
DirEl + ThSol + Ex/SuAirVHR	49	(82)	(121)	55
OutAirHP + Ex/SuAirVHR	31	44	(61)	55
GrSourceHP + Ex/SuAirVHR	26	35	46	55

Table 18. Calc. **specific energy use** in north part of climatic zone II (**kWh/m^2 year**)

Outdoor temp $_{Year, mean}$ (3 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
DistrHeat +ExAirVent	105	157	212	130
ExAirVentHP	45	(74)	(116)	75
OutAirHP + ExAirVent	49	(73)	(106)	75
GrSourceHP + ExAirVent	37	49	63	75
DistrHeat + Ex/SuAirVHR	79	128	182	130
DirEl + ThSol + Ex/SuAirVHR	65	(108)	(157)	75
OutAirHP + Ex/SuAirVHR	40	(60)	(88)	75
GrSourceHP + Ex/SuAirVHR	32	45	58	75

The first thing one can notice is that the building envelope with the lowest transmission loss fulfills the energy requirements in BBR16 regardless of which heating and ventilation system that is chosen. The second thing one can notice is that when using a ground source heat pump the energy requirements in BBR16 can be fulfilled regardless of which building envelope that is chosen. It is easier to meet the energy requirement in the south part of a climate zone. In the south part of climate zone III a standard building envelope with district heating meets the requirement without the need of any ventilation heat recovery, whereas in most parts of Sweden ventilation heat recovery is needed. The condensing exhaust air heat pump can fulfill the requirements if the building envelope does not have too high thermal transmission heat loss.

Maximum electric power

In the new Swedish building regulations BBR16 there are also maximum values for the electric power that new built electrically heated houses should not exceed, neither as calculated in the project phase nor when taken into normal operation. The definition of an electrically heated house is if the need electric power supply for heating and domestic hot water exceeds 10 W/m^2 heated floor area. Calculated values that do not comply with the new Swedish building regulations BBR 16 are marked red, otherwise green. Values for combinations that do not comply with the requirements in 4.1.2 regarding specific energy use are given in brackets.

Table 19. Calculated **maximum electric power** in south part of climatic zone III (**kW**)

Outdoor temp $_{Year, mean}$ (9 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
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	-	-	-	-
DirEl + 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 20. Calculated **maximum electric power** in north part of climatic zone III (**kW**)

Outdoor temp $_{Year, mean}$ (6 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
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	-	-	-	-
DirEl + 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

Table 21. Calculated **maximum electric power** in north part of climatic zone II (**kW**)

Outdoor temp $_{Year, mean}$ (3 °C)	UA_{tot} (W/K)			Max. value in BBR16
Heating and ventilation system	51	90	133	
DistrHeat +ExAirVent	-	-	-	-
ExAirVentHP	**3.13**	**5.21**	**(7.43)**	5.0
OutAirHP + ExAirVent	**4.68**	**6.91**	**(9.27)**	5.0
GrSourceHP + ExAirVent	**2.08**	**3.36**	**4.68**	5.0
DistrHeat + Ex/SuAirVHR	-	-	-	-
DirEl + ThSol + Ex/SuAirVHR	**3.43**	**(5.60)**	**(7.91)**	5.0
OutAirHP + Ex/SuAirVHR	**3.34**	**5.60**	**(7.91)**	5.0
GrSourceHP + Ex/SuAirVHR	**1.53**	**2.94**	**4.32**	5.0

The pattern is similar to the tables for the specific energy use. The building envelope with the lowest transmission loss fulfills the power requirements in BBR16 regardless of which heating and ventilation system that is chosen and when using a ground source heat pump the power requirements in BBR16 can be fulfilled regardless of which building envelope that is chosen. In climate zone III the outdoor air heat pump is possible to use in a standard building envelope with exhaust air ventilation, but in the north part of the climate zone it has to be combined with ventilation heat recovery.

4.2 Cost calculations

4.2.1 Initial investment costs

The initial investment costs are in table 22-24 presented as the sum of all estimated single initial investments (see table 10, 11 and 12). Combinations that according to 4.1.2 and/or 4.1.3 do not comply with the new building regulations BBR 16 are given in brackets. For each building envelope the highest and the lowest value are marked in red and green respectively. The most extreme values are also marked with bold letters. If the lowest or the highest value is in brackets, the lowest or the highest value not in brackets are also marked green.

Table 22. Estimated **initial investment costs** in south part of climatic zone III (**SEK**)

Outdoor temp $_{Year,\ mean}$ (9 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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
DirEl + ThSol + Ex/SuAirVHR	296235	**(295182)**	(307424)
OutAirHP + Ex/SuAirVHR	368235	405182	**417424**
GrSourceHP + Ex/SuAirVHR	388235	405182	**417424**

Table 23. Estimated **initial investment costs** in north part of climatic zone III (**SEK**)

Outdoor temp $_{Year,\ mean}$ (6 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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)
DirEl + ThSol + Ex/SuAirVHR	323235	**(295182)**	(307424)
OutAirHP + Ex/SuAirVHR	433235	405182	(417424)
GrSourceHP + Ex/SuAirVHR	**443235**	415182	427424

Table 24. Estimated **initial investment costs** in north part of climatic zone II (**SEK**)

Outdoor temp $_{Year,\ mean}$ (3 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
DistrHeat +ExAirVent	341235	(313182)	(325424)
ExAirVentHP	373235	(345182)	(357424)
OutAirHP + ExAirVent	406235	(378182)	(390424)
GrSourceHP + ExAirVent	426235	408182	435424
DistrHeat + Ex/SuAirVHR	368235	340182	(352424)
DirEl + ThSol + Ex/SuAirVHR	323235	**(295182)**	(307424)
OutAirHP + Ex/SuAirVHR	433235	(405182)	(417424)
GrSourceHP + Ex/SuAirVHR	**453235**	425182	447424

The lowest initial investment cost occurs for the direct electrically heated house with ventilation heat recovery. In the south part of climate zone III for the building envelope with the lowest transmission loss and in the other climatic conditions for the house with standard insulation. The reason is that in the south part air heating, that is a very cost effective solution, can be used in the building envelope with the lowest transmission loss.

4.2.2 Yearly energy costs

The yearly energy costs are calculated by multiplying the used energy in the form of electricity and district heating with the estimated energy prices. Combinations that according to 4.1.2 and/or 4.1.3 do not comply with the new building regulations BBR 16 are given in brackets. For each building envelope the highest and the lowest value are marked in red and green respectively. The most extreme values are also marked with bold letters. If the lowest or the highest value is in brackets, the lowest or the highest value not in brackets are also marked green.

Table 25. Calculated **yearly energy costs** in south part of climatic zone III (**SEK/year**)

Outdoor temp $_{Year, mean}$ (9 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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
DirEl + ThSol + Ex/SuAirVHR	11705	(15540)	**(20188)**
OutAirHP + Ex/SuAirVHR	9638	10865	12607
GrSourceHP + Ex/SuAirVHR	**9134**	10220	11511

Table 26. Calculated **yearly energy costs** in north part of climatic zone III (**SEK/year**)

Outdoor temp $_{Year, mean}$ (6 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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)
DirEl + ThSol + Ex/SuAirVHR	13601	(19000)	**(25227)**
OutAirHP + Ex/SuAirVHR	10738	12712	(15540)
GrSourceHP + Ex/SuAirVHR	**9874**	11369	13150

Table 27. Calculated **yearly energy costs** in north part of climatic zone II (**SEK/year**)

Outdoor temp $_{Year, mean}$ (3 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
DistrHeat +ExAirVent	15927	(21012)	(26460)
ExAirVentHP	12911	(17633)	(24548)
OutAirHP + ExAirVent	13550	(17462)	(22796)
GrSourceHP + ExAirVent	11633	13647	15875
DistrHeat + Ex/SuAirVHR	13539	18361	(23648)
DirEl + ThSol + Ex/SuAirVHR	16144	(23233)	**(31078)**
OutAirHP + Ex/SuAirVHR	12173	(15421)	(19942)
GrSourceHP + Ex/SuAirVHR	**10868**	12919	15027

The tables are similar to the earlier tables 13-15 for total energy use. Due to different energy prices for district heating and electricity the highest values do now not occur for a house with district heating but for the house with direct electric heating. It can also be noted that combinations that had the highest initial investment costs now have the lowest yearly energy costs. The "standard passive house solution" has a rather high energy cost.

4.2.3 Life cycle costs

The calculated life cycle costs (LCC) are presented in table 28-30. The LCC includes both 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. Combinations that according to 4.1.2 and/or 4.1.3 do not comply with the new building regulations BBR 16 are given in brackets. For each building envelope the highest and the lowest value are marked in red and green respectively. The most extreme values are also marked with bold letters. If the lowest and the highest value is in brackets, the lowest and the highest values not in brackets are also marked green.

Table 28. Calculated **life cycle costs** in south part of climatic zone III (**SEK**)

Outdoor temp $_{Year, mean}$ (9 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
DistrHeat +ExAirVent	736048	773872	(874735)
ExAirVentHP	774547	787224	(877896)
OutAirHP + ExAirVent	804842	810135	877153
GrSourceHP + ExAirHVent	778809	774940	828518
DistrHeat + Ex/SuAirVHR	690180	779089	875486
DirEl + ThSol + Ex/SuAirVHR	**664769**	(756512)	(887870)
OutAirHP + Ex/SuAirVHR	773596	835509	**897548**
GrSourceHP + Ex/SuAirVHR	754392	805941	857784

Table 29. Calculated **life cycle costs** in north part of climatic zone III (**SEK**)

Outdoor temp $_{Year, mean}$ (6 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
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)
DirEl + ThSol + Ex/SuAirVHR	**733563**	(838455)	**(1007179)**
OutAirHP + Ex/SuAirVHR	864654	879340	(966716)
GrSourceHP + Ex/SuAirVHR	840328	843149	906592

Table 30. Calculated **life cycle costs** in north part of climatic zone II (**SEK**)

Outdoor temp $_{Year, mean}$ (3 °C)	Transmission loss through building envelope, UA_{tot} (W/K)		
Heating and ventilation system	51	90	133
DistrHeat +ExAirVent	843251	(931094)	(1081391)
ExAirVentHP	845681	(924940)	(1109954)
OutAirHP + ExAirVent	892185	(952829)	(1100348)
GrSourceHP + ExAirVent	853007	882491	975951
DistrHeat + Ex/SuAirVHR	825678	907280	(1053766)
DirEl + ThSol + Ex/SuAirVHR	**803400**	(938676)	**(1145741)**
OutAirHP + Ex/SuAirVHR	898075	(942890)	(1071801)
GrSourceHP + Ex/SuAirVHR	873871	889878	975433

The calculations indicate that the “standard passive house” has the lowest LCC regardless of climate. However, except for the south part of climate zone III supply air heating is not an option. But even with panels for direct electric heating in each room this combination still has the lowest LCC. However, for the building envelopes with normal transmission loss direct electricity, thermal solar and heat recovery is a less good solution, and for a poorly insulated building envelope it has the highest LCC. District heating with ventilation heat recovery has the second lowest LCC for a building envelope with low thermal transmission heat losses. Combining district heating with a less well insulated building envelope is a less good solution. For the building envelopes with normal and high transmission loss the ground source heat pumps are the best solution.

The initial costs and the reinvestment costs are very important inputs to the LCC-calculation. In the LCC-calculations above the ground source heat pump has the lowest yearly energy costs but the highest initial investment costs. The latter resulting in a rather high LCC for the building envelope with the lowest transmission loss. One reason for this is that even if one of the smallest ground source heat pumps on the Swedish market is used in the calculations, this heat pump is in most cases still too large for a house with a very low energy demand. It is therefore of interest to see the influence on the LCC-calculation if the price and size is radically reduced. In tables 31-33 below it has been assumed that a heat pump with half the capacity could be installed at half the cost. The COP-values are the same as in the earlier calculations, but the stand-by electricity consumption is assumed to have been reduced from 150 W to 50 W. The latter means mainly that the heat loss from the domestic hot water tank is radically decreased by optimizing size and insulation.

Table 31. Energy use, yearly/initial costs and LCC in the south part of climatic zone III

Outdoor temp $_{Year, mean}$ (9 °C) **Heating and ventilation system**	Total bought energy (kWh/a)	Yearly energy cost (SEK/a)	Initial investment (SEK)	Life Cycle Cost (SEK)
DirEl + ThSol + Ex/SuAirVHR	9364	11708	**296235**	664769
GrSourceHPstd +ExAirVent	7475	9344	406235	778809
GrSourceHPstd + Ex/SuAirVHR	7308	9134	388235	754392
GrSourceHPnew +ExAirVent	7048	8810	351235	680470
GrSourceHPnew + Ex/SuAirVHR	**6841**	**8551**	333235	**654874**

Table 32. Energy use, yearly/initial costs and LCC in the north part of climatic zone III

Outdoor temp $_{Year, mean}$ (6 °C) **Heating and ventilation system**	Total bought energy (kWh/a)	Yearly energy cost (SEK/a)	Initial investment (SEK)	Life Cycle Cost (SEK)
DirEl + ThSol + Ex/SuAirVHR	10881	13601	**323235**	733563
GrSourceHPstd +ExAirVent	8255	10319	416235	811904
GrSourceHPstd + Ex/SuAirVHR	7899	9874	443235	840328
GrSourceHPnew +ExAirVent	7945	9931	356235	**712000**
GrSourceHPnew + Ex/SuAirVHR	**7443**	**9304**	383235	736120

Table 33. Energy use, yearly/initial costs and LCC in the north part of climatic zone II

Outdoor temp $_{Year, mean}$ (3 °C) **Heating and ventilation system**	Total bought energy (kWh/a)	Yearly energy cost (SEK/a)	Initial investment (SEK)	Life Cycle Cost (SEK)
DirEl + ThSol + Ex/SuAirVHR	12916	16144	**323235**	803400
GrSourceHPstd +ExAirVent	9306	11633	426235	853007
GrSourceHPstd + Ex/SuAirVHR	8694	10868	453235	873871
GrSourceHPnew +ExAirVent	9325	11656	361235	**757853**
GrSourceHPnew + Ex/SuAirVHR	**8325**	**10406**	388235	767205

The result is that the ground source heat pump now comes out with the lowest LCC. In the very south part in combination with an air-to-air ventilation heat recovery system and an air heating system. In the colder parts in combination with an exhaust air ventilation system (without heat recovery) and a water radiator heating system. However, due to the possibility for improved thermal comfort it might still be a good idea to consider a rather small additional cost for an air-to-air ventilation heat recovery system. Further, as in the colder parts the heating capacity of the smaller heat pump do not cover the maximum power demand in the wintertime, the use of an air-to-air ventilation heat recovery system reduces the need for an additional electric heater.

5 Conclusions

The conclusions from the project and the calculations performed are the following:

- 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.
- Hence, for any given combination of heating and ventilation system the building envelope with the lowest total transmission loss always has a lower LCC than the less compact and less well insulated building envelopes.
- On the other hand, 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 energy use (bought energy) is almost as low as for the "standard passive house" with direct electric heating.
- Combined with a heat pump the use of a ventilation heat recovery system gives rather small energy saving. The impact of combining ventilation heat recovery with district heating is much more significant. However, there are other advantages of an air-to-air ventilation heat recovery system that should be taken into account, especially in the north part of Sweden;
  - improved thermal comfort
  - lower peak power demand

  The latter allowing a smaller heating system, potentially lowering the initial investment costs, reinvestment costs and LCC.
- Air heating only, using the supply air part of the an air-to-air ventilation heat recovery system, is only possible in the very south part of Sweden and in combination with the very well insulated and air tight building envelope, i.e. a "passive house". In other parts of Sweden other types of heat distribution systems must be used, at least partly, also for the very well insulated building envelope.
- A building envelope with very low total thermal transmission heat losses will have a rather low energy use and comply with the new Swedish building regulations, BBR 16, regardless of the heating and ventilation system chosen.
- Sometimes a combination meets the energy requirement in the new Swedish building regulations but not the maximum electric power requirement, and vice versa sometimes a combination meets the maximum electric power requirement but not the energy requirement.
- District heating need to be combined with a rather well insulated building envelope and/or an air-to-air ventilation heat recovery system to meet the building requirements.
- A condensing exhaust air heat pump combined with a rather well insulated building envelope will also meet the building requirements.
- In the southern part of climate zone III all building envelopes can meet the building requirements using an outdoor air heat pump and exhaust air ventilation without any ventilation heat recovery. In other parts of climatic zone III and in the south part of climatic zone II a rather well insulated building envelope and/or ventilation heat recovery is required. In the more northern parts of Sweden an outdoor air heat pump can only be used in combination with a very well insulated building envelope and sometimes even ventilation heat recovery is needed.
- When using a ground source heat pump the energy requirements in BBR16 can be fulfilled almost regardless of which ventilation system and building envelope that is chosen.

- The lowest amount of bought energy is achieved when the building envelope with very low thermal transmission heat losses is combined with ventilation heat recovery and a ground source heat pump.
- The lowest initial investment cost occurs for the direct-acting electric heating system combined with the envelope with standard insulation. However, this combination do not meet the requirements in the new Swedish building regulations BBR 16 regardless of the climate it is built in.
- Neither the yearly energy costs nor the initial investment costs gives as a single value not enough information for choosing the most economic heating system. A life cycle cost (LCC) analysis will weight these two values into one value.
- The results and conclusions of the LCC calculations are valid for the input values used, especially those used for initial investment costs, energy costs and other yearly costs. As the price levels for district heating varies very much between different parts of Sweden the conclusion for district heating may not be fully general. Also regarding other costs used in the LCC-calculations there are of course uncertainties, but they are still assumed to be less uncertain than for the district heating.
- Most of the single family houses built in Sweden today seem to minimize the initial investment cost rather than the LCC.
- District heating combined with exhaust air ventilation has a rather low investment cost. The yearly direct energy costs and other yearly indirect costs are however rather high. Combined with a very well insulated building it then also has a rather low LCC.
- The best solution (lowest LCC) when using district heating is the very well insulated building envelope combined with an air-to-air ventilation system.
- A condensing exhaust air heat pump has an appropriate size for a very low energy house and has for such a house the lowest LCC of the heat pumps available on the Swedish market today. However to compete with the very low LCC of a “standard passive house” the initial cost should be almost half of what it is today. And even so, a smaller and cheaper ground source heat pump would reach the same low LCC and would have a lower yearly energy cost.
- When the outdoor air heat pump can be used according to the building regulations it always has a higher LCC than other heat pump solutions. This is partly due to a less good performance in the wintertime and partly due to higher reinvestment costs.
- The “standard passive house” (air-to-air ventilation heat recovery, direct acting electric supply air heating and thermal solar for the domestic hot water) has the lowest LCC. However, according to the new Swedish building regulations BBR 16, that heating and ventilation system is only possible when combined with a very well insulated and air tight building envelope.
- For a less well insulated building envelope a standard ground source heat pump is the best solution giving the lowest yearly energy cost as well as the lowest LCC.
- 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 also other improvements that should be implemented in future small heat pumps for low energy houses. These are for instance capacity controlled compressors and low stand-by consumption. The latter involves the size and insulation of the domestic hot water storage tank.

- Future studies should also look into the possibility to use the exhaust air in combination with the ground as a source. Another interesting thing to incorporate in future studies is the use of fan coil units for heat distribution.
- To reach the lowest energy use possible, the heat pumps should not only be placed in a building envelope with low transmission losses. Further improvements on system level can be made by using the heat pumps in combinations with low cost low temperature heat distribution systems that has a fast response and no increase of transmission loss. These systems could probably also more easily be run in both heating and cooling mode as well as in simultaneous heating (of domestic hot water) and cooling (of space).
- Calculation of active cooling demand in Swedish single family houses is very difficult as it in most cases is very small, if any, and dependent on the amount of free cooling available/used by window airing as well as how the sun is shaded of. Another aspect is which temperatures that should be used, if the temperature may be allowed to change during the day and in that case how much. The latter also involves the thermal capacity of the building as well as how this thermal mass is exposed to the indoor air. Active cooling should also not be necessary when no one is in the house for a longer period of time. This occurs in most Swedish single family houses for several weeks during the period July to August, i.e. during the warmest period of the year.
- Other climatic conditions than for Sweden would for the life cycle cost calculations have required information of local costs for energy, installation, maintenance, etc. As these costs are very diverse between different countries it is difficult to make a general calculation for a warmer climate that would be comparable to the Swedish circumstances. Further, district heating is very uncommon in other European countries whereas gas heating is very uncommon in Sweden. Calculating and comparing the life cycle costs for different heating and ventilation systems in different countries with their local condition would therefore require a separate project.

6 References

Nordman, R., et al, *Nästa generations klimatkyla i bostäder och lokaler*, SP Rapport 2010:50, SP Technical Research Institute of Sweden, Borås, Sweden, 2010

Boverket (2008), *Boverkets författningssamling, BBR 16, BFS 2008:20*, The National Board of Housing, Building and Planning (*Boverket*; in Swedish), www.boverket.se

Boverket (2009), *Regelsamling för byggande, BBR 2008. Supplement februari 2009, 9 Energihushållning,* The National Board of Housing, Building and Planning (*Boverket*; in Swedish), www.boverket.se

Levin, P., Blomsterberg, Å., Wahlström, Å., Gräslund, J. (2007), *Indata för energiberäkningar i kontor och småhus,* report to the National Board of Housing, Building and Planning (*Boverket*; in Swedish), www.boverket.se

EN ISO 13790:2008 (and EN ISO 13790:2004, Annex G)

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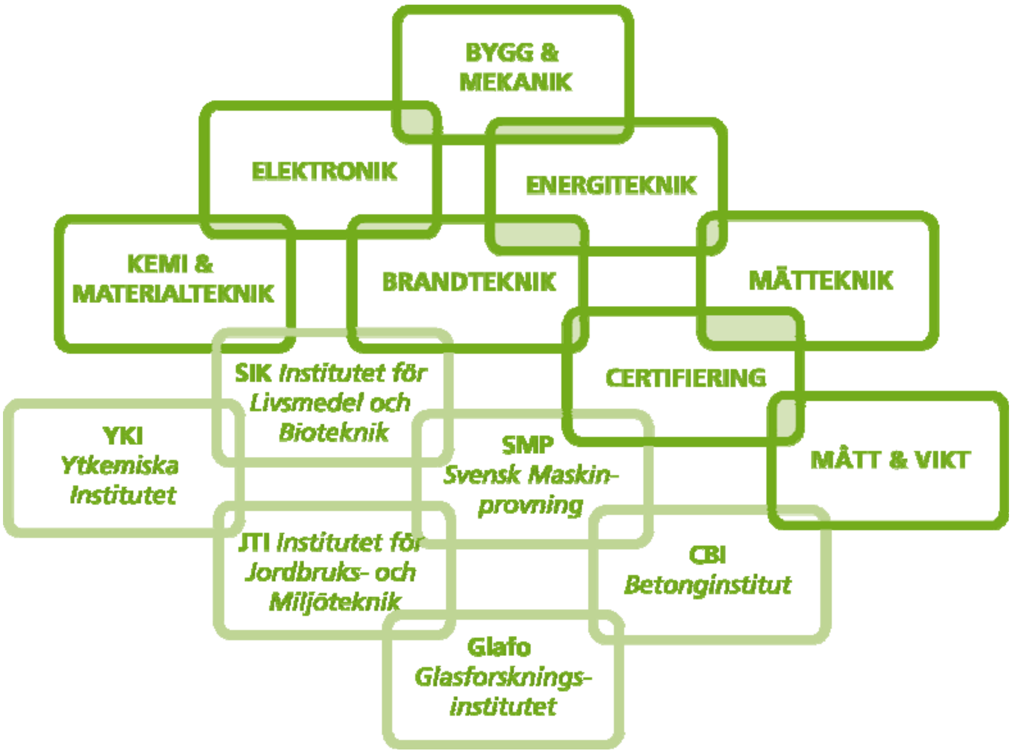

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