Gustafsson, M., Bales, C., Myhren, J A., Holmberg, S. (2014)
Techno-economic analysis of three HVAC retrofitting options.
In:

Roomvent 2014

TECHNO-ECONOMIC ANALYSIS OF THREE HVAC RETROFITTING OPTIONS

Marcus Gustafsson[1,2], Chris Bales[1], Jonn Are Myhren[1], Sture Holmberg[2]
[1]Dalarna University, Borlänge, Sweden.
[2]KTH Royal Institute of Technology, Stockholm, Sweden.

Abstract

Accounting for around 40% of the total final energy consumption, the building stock is an important area of focus on the way to reaching the energy goals set for the European Union. The relatively small share of new buildings makes renovation of existing buildings possibly the most feasible way of improving the overall energy performance of the building stock. This of course involves improvements on the climate shell, for example by additional insulation or change of window glazing, but also installation of new heating systems, to increase the energy efficiency and to fit the new heat load after renovation. In the choice of systems for heating, ventilation and air conditioning (HVAC), it is important to consider their performance for space heating as well as for domestic hot water (DHW), especially for a renovated house where the DHW share of the total heating consumption is larger.

The present study treats the retrofitting of a generic single family house, which was defined as a reference building in a European energy renovation project. Three HVAC retrofitting options were compared from a techno-economic point of view: A) Air-to-water heat pump (AWHP) and mechanical ventilation with heat recovery (MVHR), B) Exhaust air heat pump (EAHP) with low-temperature ventilation radiators, and C) Gas boiler and ventilation with MVHR. The systems were simulated for houses with two levels of heating demand and four different locations: Stockholm, Gdansk, Stuttgart and London. They were then evaluated by means of life cycle cost (LCC) and primary energy consumption. Dynamic simulations were done in TRNSYS 17.

In most cases, system C with gas boiler and MVHR was found to be the cheapest retrofitting option from a life cycle perspective. The advantage over the heat pump systems was particularly clear for a house in Germany, due to the large discrepancy between national prices of natural gas and electricity. In Sweden, where the price difference is much smaller, the heat pump systems had almost as low or even lower life cycle costs than the gas boiler system. Considering the limited availability of natural gas in Sweden, systems A and B would be the better options. From a primary energy point of view system A was the best option throughout, while system B often had the highest primary energy consumption. The limited capacity of the EAHP forced it to use more auxiliary heating than the other systems did, which lowered its COP. The AWHP managed the DHW load better due to a higher capacity, but had a lower COP than the EAHP in space heating mode. Systems A and C were notably favoured by the air heat recovery, which significantly reduced the heating demand.

It was also seen that the DHW share of the total heating consumption was, as expected, larger for the house with the lower space heating demand. This confirms the supposition that it is important to include DHW in the study of HVAC systems for retrofitting.

Keywords: HVAC, retrofit, techno-economic, heat pump, ventilation radiator, gas boiler, LCC, primary energy, dynamic simulation

1 Introduction

In Europe, the building sector accounts for around 40% of the total final energy consumption (European Commission, 2008). The building sector, and particularly the large stock of existing buildings, is therefore an important area of focus in the work towards the '20-20-20' goals stipulated in current directives from the European Commission: a reduction of primary energy consumption in the union by 20%, 20% increased share of renewable energy and 20% reduced greenhouse gas emissions by year 2020 (European Commission, 2008).

As the building standards are getting better, the space heating demand decreases and the hot water use constitutes a larger share of the total energy consumption. This makes it more important to consider not only space heating and ventilation, but complete systemic solutions, in order to maximize the energy efficiency of a house.

More than 20% of the final energy consumption in the EU is accounted for by natural gas (Eurostat, 2014a), a fossil fuel which for many European countries is related with a great import dependency. In a British study (Kelly and Cockroft, 2011), air source heat pumps are found to be a good alternative to gas boilers for heating houses in the UK, reducing the annual energy use by nearly 70% and CO_2 emissions by 12%. A study by Gustafsson et al. (2014) showed that a system with exhaust air heat pump (EAHP) and low-temperature ventilation radiators can be a competitive retrofitting solution for space heating in northern and central Europe, as the advantage of using exhaust air for the heat pump evaporator becomes larger in cold climates.

Although many heat pumps are designed to provide both space heating and domestic hot water (DHW), there are separate European testing standards for the two services: EN 14511 (CEN, 2011a) for space heating and EN 16147 (CEN, 2011b) for DHW. This makes it difficult to get an idea about the actual performance of heat pumps in combined space and water heating mode from the listed performance data. In most studies where heat pumps are used for both space and DHW heating, the heat pumps are combined with another heat source, which also affects the heat pump performance.

The present study treats three HVAC retrofitting options for a northern European single family house: A) Air-to-water heat pump (AWHP) and mechanical ventilation with heat recovery (MVHR), B) Exhaust air heat pump (EAHP) with low-temperature ventilation radiators, and C) Gas boiler and MVHR. All systems were designed to provide space heating, DHW and ventilation, while cooling was left out of the scope. The aim of the study was to evaluate the life cycle cost (LCC) and primary energy consumption of the three HVAC systems under different conditions regarding climate, heating demand, gas and electricity prices. Simulations were run in TRNSYS17 (Klein et al., 2011), taking into account the dynamic effects of simultaneous space heating and hot water tapping.

2 Method

2.1 Building model

The building modelled in this study was defined within the FP7 project iNSPiRe (2012-2016) as a typical European single family house construction. It is a 2-storey semi-detached house, with a heated floor area of 88 m² and a volume of 249 m³, including the heated attic. The western wall, adjacent to the neighbouring house, was taken to be adiabatic. The model was divided into two zones: one for the ground floor, and one for the first floor and the attic. The house was assumed to have no mechanical ventilation system installed before the HVAC retrofitting, while improvements to the building envelope were assumed to already have taken place and was therefore not included in the analysis.

Boundary conditions regarding internal gains from occupants and electrical equipment, shading, open window ventilation and hot water use were the same as in iNSPiRe, most of them originating in IEA SHC Task 44 (2012). The house was assumed to be inhabited by four people, each contributing 120 W of internal heat gains. Heat gains from cooking and electrical appliances were considered in accordance with IEA SHC Task 44. The ventilation systems were set to supply 0.4 air changes per hour of fresh air. For the systems with HRC, an additional 0.1 /h of infiltration was added. For the exhaust ventilation used in system B, an infiltration rate of 0.2 /h was assumed, as this type of ventilation creates a larger pressure difference between indoor and ambient.

The DHW profile, taken from Task 44, stipulated an average DHW use of 5.85 kWh/day for the whole household. The tapping temperature was 45 °C, except for dishwashing which required 55 °C. A cold water temperature of 10 °C was assumed. The DHW storage tank was heated to 45 °C, and an external electric auxiliary heater was used to raise the tapping temperature to 55 °C when needed.

Data for four different European locations were used: Stockholm, Sweden; Gdansk, Poland; Stuttgart, Germany; and London, UK. The locations were chosen as representative for northern and central European climate zones. They also represent varying conditions in terms of energy prices and investment costs. For each climate, two renovation levels were defined, corresponding to annual heating demands of 55 kWh/(m²·a) and 85 kWh/(m²·a). These ideal heating demands were defined for the case without HRC and were derived through simulations in TRNSYS 17. Climatic conditions were simulated using weather data from Meteonorm (2014), while the disturbed ground temperature was approximated as a sine, calculated according to ISO 13370 (ISO, 2007).

2.2 HVAC system models

System A

System A had an air-to-water heat pump (AWHP) providing space heating via traditional panel radiators. Data for an existing AWHP with constant speed compressor (NIBE, 2013a) was used to create a performance map for the model; data on heating capacity and COP for a number of operating points was used to interpolate instantaneous values in the simulation. The heat pump was scaled down by 50% to better suit the heat load of the studied building, assuming the COP to be independent of the size. The performance values used are listed in Table 1.

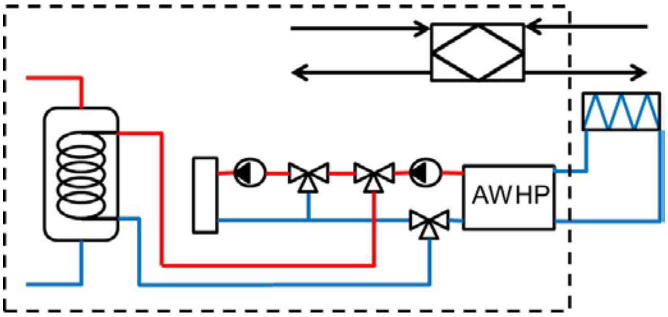

***Figure 1:** Layout of the AWHP system*

The heat pump comprised a 270 l storage tank for DHW with an internal heat exchanger coil for the heating medium and direct connection for DHW. This retrofitting option also included installation of mechanical ventilation with heat recovery (MVHR) and the ducts needed to realize supply and exhaust ventilation. A thermal efficiency of 85% was assumed for the heat recovery unit.

***Table 1:** Rated performance of AWHP*

	Water temperature [°C]	Air temperature [°C]			
		-15	-7	2	7
Heating capacity [kW]	35	2.09	2.42	2.94	3.18
	45	2.18	2.48	3.05	3.73
COP [-]	35	3.01	3.36	4.11	4.81
	45	2.53	2.80	3.37	4.05

***Table 2:** Rated performance of EAHP*

	Water temperature [°C]	Air flow [l/s]			
		30	40	50	60
Heating capacity [kW]	35	1.14	1.30	1.42	1.46
	45	1.15	1.21	1.30	1.35
COP [-]	35	4.46	4.76	5.12	5.24
	45	3.34	3.49	3.72	3.86

System B

System B had exhaust ventilation and an exhaust air-to-water heat pump (EAHP), and the radiators, the same as in the other systems, were converted into ventilation radiators by installing supply air ducts behind them. The EAHP model was based on performance data for an existing EAHP with variable compressor speed (NIBE, 2013b), as listed in Table 2. The exhaust ventilation provided the heat pump with an air flow of 41.6 l/s. A multi-dimensional performance map was used to allow the compressor speed to vary with the load. In a recent study on ground source heat pumps (Madani and Lundqvist, 2011), variable speed was found to be better than on/off control if the heat pump does not cover close to 100% of the heating demand at nominal conditions, as it reduces the need for auxiliary heating. The EAHP had a 180 l storage tank for DHW with an internal heat exchanger coil for the heating medium and direct connection for DHW.

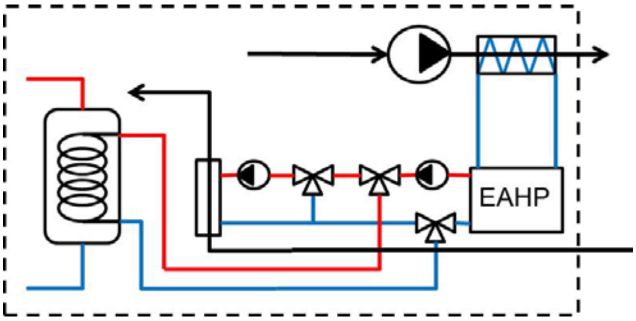

Figure 2: *Layout of the EAHP system*

Ventilation radiators are basically panel radiators through which supply air is preheated and distributed to the room. Outdoor air flows in through a duct in the wall behind the radiators, driven by the pressure difference between outdoor and indoor created by the exhaust ventilation. The heat output of a radiator is proportional to the mean temperature difference between the radiator surface and surrounding air. Because of the lower temperature of supply air compared to indoor air, a ventilation radiator can work with a lower water supply temperature than a traditional radiator, typically around 35 °C, which makes it a very low temperature heat emitter (Eijdems and Boerstra, 2000). Ventilation radiators have also been proven to give a stable and uniform indoor climate (Myhren and Holmberg, 2009), and the low water temperature favors the performance of the heat pump.

System C

In system C a gas boiler provided space heating via panel radiators, the same as in the system A, and DHW via a 270 l storage tank. The boiler was fueled by natural gas and had an efficiency of 90%. This retrofitting option also included installation of mechanical ventilation with heat recovery, the same as in system A, with an assumed thermal efficiency of 85%.

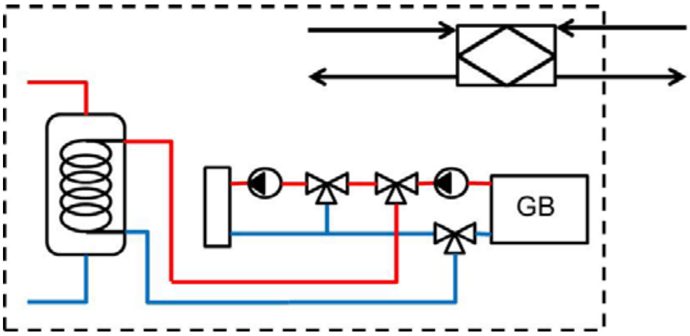

Figure 3: *Layout of the gas boiler system*

2.3 Simulation tool

The building and its related systems were modelled in TRNSYS 17, a computer software for transient simulation of buildings and building energy systems. For the radiators, an Excel model provided by a radiator manufacturer was used, with formulas based on measurements on the manufacturer’s own products (Ivonen, 2007). The Excel model was connected to the rest of the system via a link embedded in TRNSYS.

The operation of the heating systems was controlled using the air temperature in the house and the water temperature in the storage tank as input variables. A set point of 20 °C was used for space heating, while the set point for the DHW storage tanks was 45 °C. An external electric heater was used to heat the tap water to 55 °C when needed. On/off differential controllers were used for the constant-speed AWHP and the gas boiler, whereas the variable capacity of the EAHP was realized using PI-controllers. Ventilation fans were run at all times, but the heat recovery unit of the MVHR was deactivated when the outdoor temperature was above 14 °C.

2.4 LCC and primary energy assessment

In the LCC calculations, an interest rate of 5% was used. The time frame for the LCC was set from installation of the systems to the end of their technical lifetime, which was assumed to be 15 years. Renovation of the building envelope was assumed to be the same for all HVAC options and was not included in the calculations. National gas and electricity prices for domestic users, listed in Table 3, were used to calculate the energy costs (Eurostat, 2014b; 2014c). The annual price development for both gas and electricity was estimated to 5% from the overall trends in Europe of the last seven years. Investment costs for one country were taken from manufacturers' or retailers' websites (Idealo.de; Nibe.se) or from other reports (Ruud, 2010). Estimates for other countries were made taking into account the relative difference in consumer prices. The down-scaled AWHP was assumed to have a slightly lower cost than the full-sized original. Installation costs were based on estimated installation time and statistics on national labour costs (Eurostat, 2013). National primary energy factors were taken from official reports or websites (Enercity.de; Gode et al., 2011; UK Department of Energy and Climate Change, 2008; Woce.pl).

Table 3: *Energy prices, primary energy factors (PEF), investment and maintenance costs*

		Sweden	Poland	Germany	UK
Energy price (incl. VAT)	Natural gas	0.12	0.05	0.07	0.06
[€/kWh]	Electricity	0.21	0.14	0.29	0.18
PEF [kWh/kWh]	Natural gas	1.09	1.10	1.10	1.00
	Electricity	1.90	3.00	2.60	2.60
Investment and	AWHP (A)	10 400	6 300	7 600	8 400
installation costs [€]	EAHP (B)	10 100	6 200	7 400	8 200
	Gas boiler (C)	3 300	1 900	2 400	2 600
	DHW storage tank (C)	1 500	800	1 100	1 200
	MVHR (A, C)	4 200	2 300	3 100	3 200
	Exhaust ventilation (B)	1 500	800	1 200	1 100
	Supply air ducts (B)	300	100	200	200
Maintenance [€/year]	(All systems)	100	20	80	50

3 Results

The life cycle costs for the three studied options are presented in Figure 4: HD55 stands for the house with a space heating demand of 55 kWh/(m²·a) and HD85 represents the house with a heating demand of 85 kWh/(m²·a). System C had the lowest cost in most cases, except for the HD85 house in Stockholm where it had a higher cost than A and almost as high as system B. The largest difference between this and the systems with heat pumps was seen for Stuttgart. Due to the MVHR of

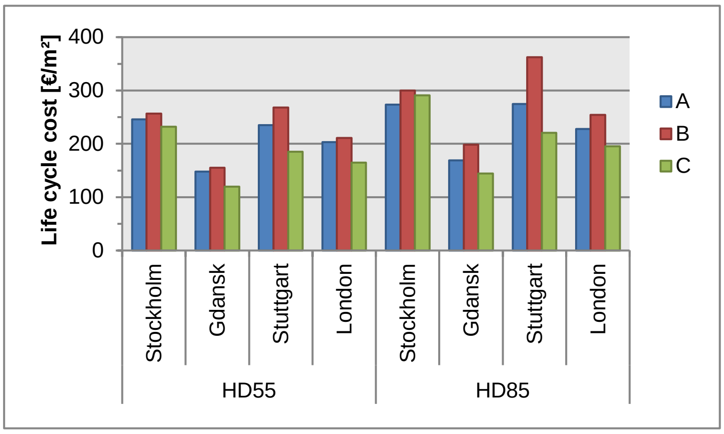

Figure 4: *LCC for different retrofitting options and locations*

systems A and C, the AWHP and the gas boiler had to manage space heating demands of 22-29 kWh/(m²·a) for the HD55 house and 47-57 kWh/(m²·a) for the HD85 house; the lower figures for the climate of Stockholm and the higher for the climate of London.

1-5% of the total life cycle costs were accounted for by maintenance, while investment and installation stood for 30-70%, with variations depending on system, climate and national prices. DHW accounted for 20-30% of the total heating consumption for the HD85 renovation level, while for the HD55 level that share was around 33-45%.

Figure 5 shows the primary energy consumption for the three retrofitting options on different locations. Systems A and B used 100% electricity, while system C used some electricity for fans and pumps, apart from gas. Despite the higher primary energy factor of electricity, system A had much lower primary energy consumption than system C, as it greatly reduced the amount of purchased energy. System B had the highest consumption of primary energy in most cases, the EAHP having a lower COP and using more auxiliary heat in DHW mode than the AWHP of system A. However, in space heating mode the EAHP had a higher COP than the AWHP.

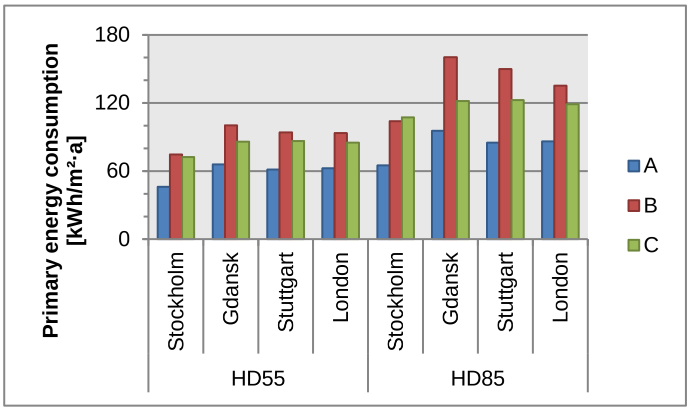

Figure 5: *Primary energy consumption for different retrofitting options and locations*

4 Discussion

It is worth noting that the most energy efficient system does not always have the lowest life cycle cost. In Germany, the primary energy factor of electricity is 2.4 times higher than that of gas, while the prices differ by a factor 4.2. This makes system C with the gas boiler the most economical choice, even though it consumes more primary energy than system A. In order to promote lower primary energy consumption, it would be better if the price difference reflected the difference in primary energy factors, which is more the case in Sweden.

One of the greatest uncertainties in the LCC is the future development of energy prices, especially as two different energy carriers were compared. If the price of one or the other were to increase more than expected, this would affect the results accordingly. Such scenarios could for example be induced by shifting to cleaner, but also more expensive, energy sources for electricity production, or by reduced availability of natural gas.

The outcome of the LCC is also decided by the system boundary and the assumed starting point. Many houses may for example already be fitted with air ducts for exhaust ventilation, which would facilitate the installation of new ventilation systems. A complete LCC for the retrofitting of a house would include the improvements to the building envelope, to find the optimum combination of insulation thickness, windows and HVAC system.

In Sweden, gas boilers are not very common, due to lack of distribution network, while the choice between exhaust ventilation and ventilation with heat recovery is a recurrent dilemma. Exhaust air heat pumps are relatively favoured from a high ventilation rate, as a higher flow on the source side increases their capacity and improves their performance.

The set temperature for DHW heating may in practice need to be higher than the desired tapping temperature, in order to avoid bacterial growth in the storage tank. For example, the Swedish building regulations recommend a minimum temperature of 60 °C in DHW storages (Boverket, 2011). This would of course require a higher heating capacity, and possibly more auxiliary heating.

The approach to scale down an existing heat pump keeping the COP constant was applied and discussed in the previously mentioned study by Gustafsson et al. (2014). As they conclude, it may not be entirely correct to assume that the COP remains the same independently of the capacity of the heat pump. This would add plausible error margin to the results for system A in this study of some percent.

The EAHP had a higher COP in space heating mode, but its capacity was smaller than that of the AWHP and could not cover the entire DHW load without auxiliary heating. For the HD85 renovation level, it even used some auxiliary heating in space heating mode. This made the average COP end up a bit lower for the EAHP, and raised the energy costs and primary energy consumption of system B compared to system A.

The deciding factor between system B and the other options seems to have been the HRC. Both the AWHP and the gas boiler had significantly lower heating demands to cover than the 55 kWh/(m²·a) and 85 kWh/(m²·a) that the system B worked with, since the MVHR eliminated most of the ventilation losses – in some cases more than 50% of the total space heating demand.

5 Conclusions

From an LCC point of view, the choice between heat pump and gas boiler is dependent on the prices of electricity and gas, more than on the climate or the heating demand. In Sweden, where the price difference is small, heat pumps can have equally low or even lower costs. In Germany, where price discrepancy between electricity and gas is the largest in Europe, it is more economical to install a gas boiler.

Looking at primary energy consumption, a good heat pump is a better choice than a gas boiler, despite the higher primary energy factor of electricity. It is also evident that the higher the heating demand, the greater the saving potential of the heat pump. The EAHP did not perform as well as the AWHP in this study, due to a lower capacity forcing it to use more auxiliary heating to cover the DHW load. Both system A and system C were also greatly favoured by the air heat recovery, which reduced the heating demand significantly.

With DHW accounting for up to 33-45% of the total heating consumption, it was clear from the results of this study that it is important to include DHW in the study of HVAC systems, especially in retrofitting cases where the space heating demand is decreased.

6 Acknowledgement

The research leading to these results has received funding from the European Union’s Seventh Programme for research, technological development and demonstration under grant agreement No 314461. The European Union is not liable for any use that may be made of the information contained in this document which is merely representing the authors’ view.

7 References

Boverket, 2011, *Swedish Building Regulations, BBR 19, BFS 2011:26* (in Swedish)

CEN, 2011a, *European Standard EN 14511-2 - Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling - Part 2: Test conditions*

CEN, 2011b, *European Standard EN 16147 - Heat pumps with electrically driven compressors. Testing and requirements for marking of domestic hot water units*

European Commission, 2008, *Energy efficiency: delivering the 20% target*

Enercity.de (in German). Accessed 2014-06-10. Available: http://www.enercity.de/privatkunden/produkte/fernwaerme/primaerenergiefaktor/index.html

Eurostat, 2013, *European social statistics*.

Eurostat, 2014a, *Energy supply, transformation, consumption - all products - annual data*

Eurostat, 2014b, *Electricity prices for domestic consumers, from 2007 onwards - bi-annual data*

Eurostat, 2014c, *Gas prices for domestic consumers, from 2007 onwards - bi-annual data*

H. H. E. W. Eijdems, A.C. Boerstra, 2000, *Low Temperature Heating Systems: Impact on IAQ, Thermal Comfort and Energy Consumption*, Annex 37, Newsletter 1

J. Gode, F. Martinsson, L. Hagberg, A. Öman, J. Höglund, D. Palm, 2011, *Miljöfaktaboken 2011 - Uppskattade emissionsfaktorer för bränslen, el, värme och transporter* (in Swedish), Värmeforsk

M. Gustafsson, G. Dermentzis, J.A. Myhren, C. Bales, F. Ochs, S. Holmberg, W. Feist, 2014, *Energy performance comparison of three innovative HVAC systems for renovation through dynamic simulation*, Energy and Buildings 82, pp 512-519

Idealo.de – Vaillant ecoTEC price comparison (in German). Accessed 2014-06-10. Available: http://www.idealo.de/preisvergleich/OffersOfProduct/2498912_-ecotec-exclusiv-vc-206-4-7-vaillant.html

IEA, 2012, *The Reference Framework for System Simulation of the IEA SHC Task 44 / HPP Annex 38 - Part B: Buildings and Space Heat Load*

iNSPiRe, 2012-2016, *iNSPiRe: Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems,* European Commission 7th Framework Programme project

ISO, 2007, *Thermal performance of buildings - Heat transfer via the ground - Calculation methods*

M. Ivonen, 2007, *Purmo Air Simulator Vers. 05.11.2007*

N. J.Kelly, J. Cockroft, 2011, *Analysis of retrofit air source heat pump performance: Results from simulations and comparison to field trial data,* Energy and Buildings 43, pp 239-245.

S. A. Klein, A. Beckman, W. Mitchell, A. Duffie, 2011, *TRNSYS 17 - A TRansient SYstems Simulation program,* Solar Energy Laboratory, University of Wisconsin, Madison

B. Kurkowiak, 2012, *Eurostat: Major dispersion in consumer prices across Europe*.

H. Madani, P. Lundqvist, 2011, *Evaluation of the annual performance of Ground Source Heat Pump systems: A comparison between single speed and variable speed systems,* 23rd IIR International Congress of Refrigeration. Prague, Czech Republic

Meteonorm, 2014. Accessed 2014-06-10. Available: http://meteonorm.com/.

J. A. Myhren, S. Holmberg, 2009, *Design consideration with ventilation-radiators: Comparisons to two-panel radiators,* Energy and Buildings 41, pp 92-100.

Nibe.se – NIBE F750. Accessed 2014-06-10. Available: http://www.nibe.se/Produkter/Franluftsvarmepumpar/Produktsortiment/NIBE-F750/

Nibe.se – NIBE F2030 and VVM310. Accessed 2014-06-10. Available: http://www.nibe.se/Produkter/Luftvatten-varmepump/Produktsortiment1/System-med-NIBE-F2030/NIBE-F2030--VVM-3101/

Nibe, 2013a, *Indata till TMF:s program ver 2.1 för NIBE F2030* (in Swedish)

Nibe, 2013b, *Indata till TMF:s program ver 2.1 för NIBE F750* (in Swedish)

S. Ruud, 2010, *Economic heating systems for low energy buildings – Calculation, comparison and evaluation of different system solutions,* SP Report 2010:43

UK Department of Energy and Climate Change, 2008, *Climate Change Agreements: Conversion factors and procedures*

Woce.pl (in Polish). Accessed 2014-06-10. Available: http://www.woce.pl/metodologia/energia-pierwotna-i-koncowa/159-wspolczynnik-nakladu-nieodnawialnej-energii-pierwotnej