Comparison of two HVAC renovation solutions: A case study

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Abstract

Within the aging building stock of Europe, there is great potential of saving energy through renovation and upgrading to modern standards, and to thereby approach the internationally set goals of lower energy use. This paper concerns the planned renovation of the building envelope and HVAC systems in a multi-family house in Ludwigsburg, Germany. Five systemic HVAC solutions were compared, with special focus on two systems: A) Balanced ventilation with HRC + Micro heat pump, and B) Forced exhaust ventilation + Heat pump with exhaust air HRC + Ventilation radiators. Given the predicted heating demand and ventilation rate of the house after renovation, the performance of the two systems was compared, alongside three common systems for reference. Calculations were made using TMF Energi, a tool developed by SP Technical Research Institute of Sweden.

Both systems A and B were found to have the lowest electrical energy use together with the ground source heat pump system for the assumed conditions. For other assumptions, including different climate and degree of insulation, some differences between these three systems were noted. Most significant is the increased electrical use of system B for higher heating loads due to limitations in the power available from the heat source, exhaust air, which is dependent on the ventilation rate.

Keywords - energy renovation; HVAC; system comparison; low-energy house; ventilation radiator; micro heat pump

1. Introduction

The European Union energy policy implies a 20 % increase of energy efficiency from 2005 to 2020. As the building sector accounts for 40 % of the total energy use [1], it is clearly one of the most important sectors to improve on in order to reach the set goals. The predominant type of household energy use is space heating, accounting for as much as 2/3 of the total energy use in households in the EU-15 [2].

Over the last few decades, great progress has been made in the field of construction and building practice. New buildings, in general, use less energy than older buildings, which is of course good from an energy saving perspective. However, improved energy performance of new buildings alone will most likely not be enough to reach the internationally set goals of lower energy use. The life span of a building is relatively long, i.e. a majority of the existing building stock is more than 20 years old. Thus, old buildings present a much greater potential of saving energy than new ones, by means of renovation and upgrading to modern standards [3].

This paper treats a case study of a multi-family house in Ludwigsburg, Germany. The house was built in the early 1970's and is scheduled for renovation within the near future. The current heating and ventilation system, featuring traditional radiators, will be replaced with a modern, energy efficient system. Renovation will also include fitting of prefabricated façade elements, possibly with integrated solar panels. Other than being a renovation case in itself, the house is also intended as an example for other similar renovations to come.

The aim of this paper is to compare and analyze how different combined space heating and ventilation systems perform under certain conditions, specifically for the house in Ludwigsburg. This comparison is intended to be a useful support in the choice of energy systems for this and other, similar, buildings, although it does not consider all possible aspects of such a decision. The emphasis is on technical performance and energy use of the systems, while aspects of thermal comfort, installation costs and system compatibility are treated in the discussion part. For comparison and discussion, the systems were also tested under the climatic conditions of Falun, Sweden.

2. Theory

2.1. Micro heat pump and air heat recovery

One of the solutions suggested for the house in Ludwigsburg is a balanced ventilation system with heat recovery in combination with a micro heat pump. The micro heat pump works by the same principles as a regular sized air-to-water heat pump, but is smaller and designed to work at low temperatures. It is meant to be placed in series with the ventilation HRC unit. Exhaust air from the house will first pass through the HRC unit and then enter the micro heat pump at a temperature close to that of the incoming ventilation air, which is the same as the outdoor temperature. To raise the flow rate of the micro heat pump, outdoor air may be used directly as a complementary heat source. The micro heat pump will serve both space heating and DHW. [4]

2.2. Ventilation radiators

A ventilation radiator is a combined system for ventilation and space heating. Air from outdoors is let in through a duct in the wall and heated by the radiator panels, before entering the room. While a traditional radiator may need an inlet water temperature of 55-60 °C, the ventilation radiator produces the same heat output at an inlet temperature of 40-45 °C, due to the lower inlet air temperature, according to

$$P = k \cdot A \cdot \Delta\theta_m, \quad (1)$$

where $\Delta\theta_m$ is the mean temperature difference between the radiator surface and the air in contact with the heated radiator surfaces. More explicitly, rather than using the greater temperature difference to give a larger heat supply, which is not desired for reasons of thermal comfort, the inlet water temperature is adapted to give the same heat output as a traditional radiator would. This makes the ventilation radiator a low temperature heating system.

Ventilation radiators have been proven to provide better thermal comfort than both floor heating and traditional radiators, giving a more stable and uniform indoor climate. The thermal response of ventilation radiators is also faster than that of a floor heating system. A change in temperature of the incoming air to the radiator immediately gives a higher heat output, following the relation in (1).

In order to function as intended, ventilation radiators are best combined with a forced exhaust ventilation system, which creates a pressure slightly below ambient in the building and helps driving the flow of inlet air through the radiator. [5]

3. Method

3.1. Investigated energy systems

Five different systems for combined heating and ventilation of the building were compared. The composition of each system is described in Table 1. Two of the systems, A and B, were of special interest in this comparison, as they were expected to be more energy efficient and to better meet future energy standards than the other systems. Systems C, D and E are well-known and proven systems and were included for reference.

Table 1. Investigated heating and ventilation systems

System	Heating	Ventilation
A	Micro heat pump (exhaust air-to-water)	Forced ventilation with exhaust-to-inlet HRC
B	Ventilation radiators Heat pump (exhaust air-to-water)	Forced exhaust ventilation
C	Ground source heat pump	Forced exhaust ventilation
D	Air-to-water heat pump	Forced exhaust ventilation
E	District heating	Forced exhaust ventilation

3.2. System data

Table 2. Given/predicted system data

Parameter	Denotation	Value	Unit
Tempered area	A_{temp}	285	m^2
Enclosing area	A_{en}	550	m^2
Volume of tempered area	V	712.5	m^3
Air change rate	V_{rate}	0.3	h^{-1}
Number of residents	n_{res}	8	p
Leakage q50 per m^2 enclosing area	V_{leak}	0.6	$l/s{\cdot}m^2$
Mean U-value	U_m	0.28	$W/m^2{\cdot}K$
Household energy use	E_h	11,000	kWh/a
Domestic hot water use	V_{DHW}	25	l/p·d
Solar gain	Q_{sol}	1.4	W/m^2
Residents gain	Q_{res}	80	W/p
Indoor temperature	T_{in}	21	℃
Average outdoor temperature	$T_{av,L}$ ($T_{av,F}$)	9.0 (4.2)	℃
Design winter outdoor temperature (48 h)	$DVUT_L$ ($DVUT_F$)	-8.1 (-21.9)	℃
Heat recovery of FTX system	HRC at +2 ℃ (-15)	90 (85)	%
Seasonal performance factor of micro heat pump	SPF_L (SPF_F)	2.25 (2.10)	-
Water temperatures of ventilation radiators	T_{in} (T_{return})	40 (30)	℃
Coefficient of performance of exhaust ventilation heat pump	COP_{nom} at 20/35 ℃ (20/45)	3.67 (3.25)	-
	COP_{max} at 20/35 ℃ (20/45)	2.69 (2.31)	-
Coefficient of performance of air-to-water heat pump	COP at 7/35 ℃ (7/45)	4.00 (3.00)	-
	COP at -15/35 ℃ (-15/45)	2.00 (1.50)	-
Coefficient of performance of ground source heat pump	COP at 0/35 ℃ (0/45)	4.00 (3.00)	-

As the building in question had not yet been renovated, some assumptions were made about the building envelope and its energy performance after renovation.

Unknown data for the energy systems was estimated based on experience. The data used is presented in Table 2.

For a broader understanding of the strengths and weaknesses of the systems, studies were made for the following parameters: the mean U-value; the SPF of the micro heat pump; the HRC efficiency for system A; the ventilation rate. When varying one parameter, the other parameters were held to their default value, according to Table 2. All parameter variations were done for two different climatic conditions: the actual climate of Ludwigsburg and the colder climate of Falun, Sweden. In Table 2, index L is used for climatic data specific for Ludwigsburg, while F indicates climatic data for Falun.

3.3. Simulation tool

TMF Energi is a commercial energy calculation tool for buildings, based on Microsoft Excel. It was developed by SP, the Technical Research Institute of Sweden, on behalf of TMF, the association for Swedish wood- and furniture industries [6]. The main use is to calculate the specific energy use for heating in new houses, to ensure that they meet the regulating maximum values, but it can also be used to make energy calculations for renovated low-energy houses.

Based on user input data about the house, the number of residents, the local climate and the installed energy systems, TMF Energi calculates the energy use of the building, both the total and the energy use of subsystems such as DHW use, heat pumps and ventilation fans. The program uses the average ambient temperature to derive a duration curve for a complete year, which is then used in 4 hour blocks to calculate the heating required, using an energy balance of the building. The COP of the heat pump is interpolated from the input data for standard conditions to that for the boundary conditions of ambient temperature and flow temperature for heat distribution for the 4 hour block. The program has been validated against the results of annual simulations with programs from commercial manufacturers of heat pumps.[7]

The heat pumps used in TMF Energi for systems B, C and D were based on specific products. For C and D, the heat pumps were scaled up to give a higher heat output, using the same COP values. They were sized to cover 100 % of the heating demand, without need for auxiliary electric heating, for the case with U_m-value of 0.4 W/m^2 and the climate of Falun, which means they were oversized for all other cases.

As there is no predefined system in TMF Energi including both ventilation with HRC and a heat pump (system A), this was obtained by dividing the annual heating required after the HRC by the estimated SPF of the micro heat pump. The SPF of the micro heat pump was the same as that for the air-to-water heat pump in system D. In practice, this method also meant oversizing of the micro heat pump and no need for auxiliary heating in system A.

4. Results

The comparison of the five systems concerns the calculated annual specific purchased energy (kWh/m^2·a). For the default case, comparison is also made between the types of final energy use for each system. In the figures, the systems are denoted A, B, C, D and E, while (L) and (F) are used to indicate data for Ludwigsburg and Falun, respectively. System descriptions are found in Table 1. If nothing else is specified in the figure, the values used are the default values found in Table 2.

Fig. 1 displays the specific purchased energy for each system divided into types of use. The DHW demand is equally large for all systems, but for the systems featuring heat pumps (A, B, C and D) this number is reduced, as well as the space heating and the DHW losses, i.e. heat losses from hot water tank and pipes. Looking at the types of purchased energy, systems A, B, C and D use 100 % electricity, while system E uses about 2-6 % electricity and 94-98 % heat.

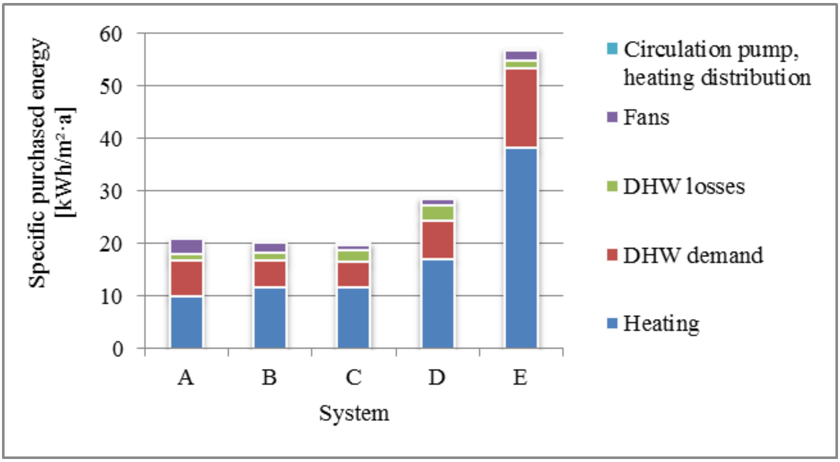

Fig. 1 Specific purchased energy divided into types of use (L)

Fig. 2 and 3 show how specific purchased energy for the systems varies with the U_m-value of the building, given the climatic conditions of Ludwigsburg and Falun, respectively. In both cases, system A is more energy efficient than system B for high U_m-values, with a greater margin for the Falun case. For higher heating loads, system C is significantly better than both system A and B.

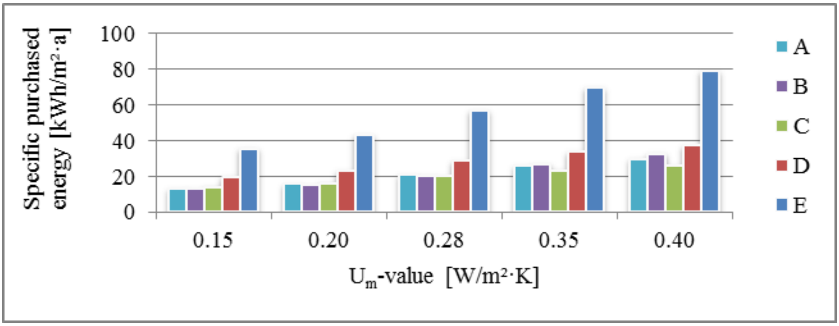

Fig. 2 Specific purchased energy varying with U_m-value (L)

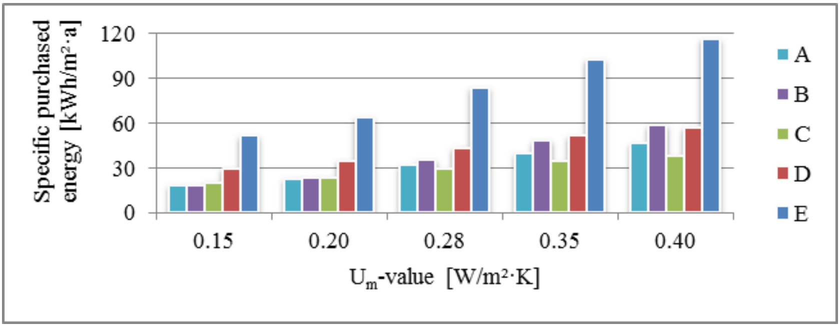

Fig. 3 Specific purchased energy varying with U_m-value (F)

Fig. 4 and 5 show the impact of SPF and HRC efficiency for system A for both Ludwigsburg and Falun. The SPF has a significant impact, as does the efficiency of the HRC, although not as big.

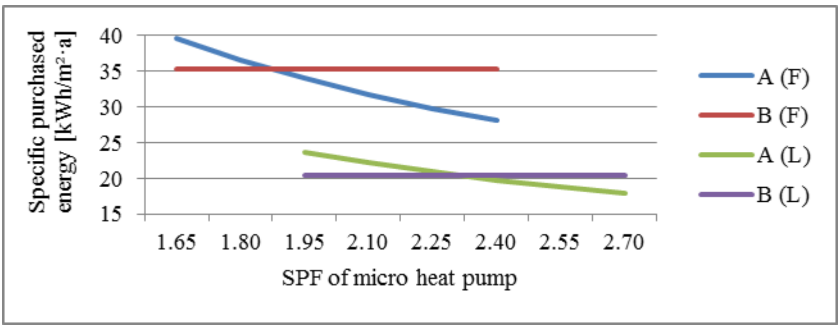

Fig. 4 Specific purchased energy for system A with varying SPF of micro heat pump, compared to system B

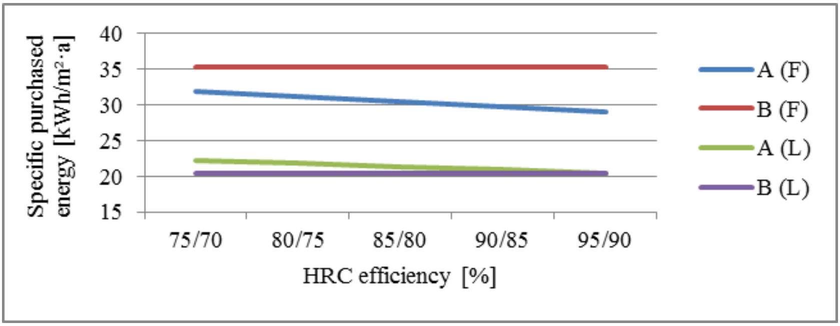

Fig. 5 Specific purchased energy for system A varying with the HRC efficiency, compared to system B

Fig. 6 illustrates the influence of ventilation rate on the specific purchased energy of systems A and B for the climatic conditions of Ludwigsburg.

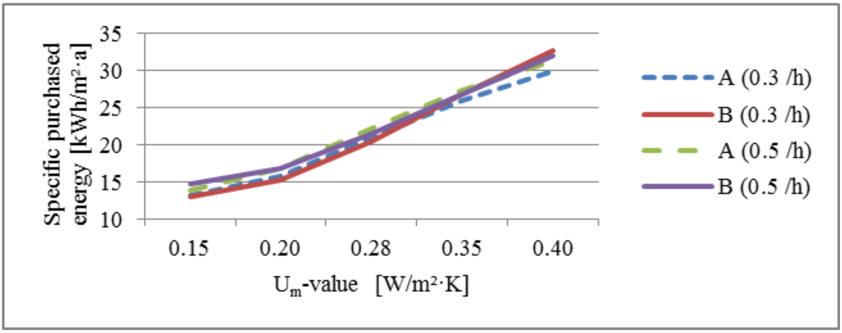

Fig.6 Specific purchased energy for system A and B varying with U_m-value and air change rate (L)

5. Discussion

Results indicate that systems A and B are almost equal in performance to system C (ground source heat pump) for low heating loads. For high U_m-values and the colder climate of Falun, system A has lower energy use of the two, with system C being even better. For higher ventilation rate, as shown in Fig. 6, the difference between systems A and B is smaller.

The differences between systems A and D are mainly because of the HRC of system A, which brings down the specific purchased energy. From Fig. 4 and 5, it is clear that the SPF of the micro heat pump has a bigger influence on the specific energy use than the HRC efficiency. This is due to the fact that the micro heat pump affects the whole energy use for heating, including DHW, while the HRC only affects the space heating part.

The heat pumps of systems C and D were sized to eliminate the need for auxiliary heating, in order to make a fair comparison to system A. Oversizing of these heat pumps did not affect the results, as the details of extra losses for high rate of cycling (on/off control) are not considered in the program. In practice, due to economic constraints, the sizing criteria might be such that the heat pump only provides 60-80 % of the peak load, and thus less than 100 % of the total heat. A reduced size of the heat pump in these systems would significantly increase the purchased energy. For system B, the sizing of the heat pump depends on the ventilation rate of the building. The heat pump must be big enough to cope with the air flow rate, but it is not economically viable to oversize it.

Another aspect to consider in the decision-making is thermal comfort. For the studied house in Ludwigsburg, which is assumed to be well-insulated and with relatively high internal heating gain, the balance temperature is expected to be somewhere around 10-12 °C. At outdoor temperatures close to but greater than the balance temperature, the heating system will not be operating, while the ventilation system will run regardless of the outdoor temperature. The inlet air to a well-insulated house may then cause draught and thermal discomfort if the inlets are not carefully designed and placed. To avoid this type of problem for system B, it is recommended to choose ventilation radiators that allow mixing of indoor air to the inlet.

Looking at conditions for installation, the systems differ in adaptability to the current state of the building. The simplest installation would probably be that of the ventilation radiators, considering that there is already a piping system for radiators in the house. Choosing a system that does not use the existing pipes would mean that these would have to be either sealed or removed. The micro heat pump, on the other hand, is meant to be small enough to be integrated into the new prefabricated façade, which means it would not have to be fitted on site.

System E, exhaust ventilation and district heating, is clearly the most energy intensive solution of the five. However, the use of electric energy is only a fraction of those of the other systems, as the heat in this case is produced by other means. From an environmental point of view, district heating may often be preferable to a heat pump, if the availability is good and the production is free from fossil fuels.

As for economics, for systems A, B, C and D it is clear that the cheapest system in use is the one which requires the least energy. To compare these with system E, the tariffs of electricity and district heating will also need to be compared. When it comes to installation costs, it is likely that the systems which include the fewest and simplest new components and require the least change of the existing system will be the least expensive. The order between the systems with respect to installation costs may differ from that with respect to operating costs, leading to a trade-off situation: either raising the rents to pay off the installation costs or letting tenants pay more for heating and ventilation. In the end, the cost to be considered should be the total life cycle cost.

6. Conclusions

From a technical point of view, system A and B both present competitive solutions for heating and ventilation of the house in Ludwigsburg. They were almost equal in performance, but in the colder climate (Falun) and for high U_m-values, system A proved to be the most energy efficient of the two. Even though some parameters may vary, they are both comparable to other systems featuring heat pumps in terms of energy use. A deeper study, including more detailed models of the house and the heating and ventilation systems, could be of interest to obtain more accurate and robust results. It could also be interesting to explore the combination with solar thermal systems, to find solutions with even lower levels of primary energy use.

Nomenclature

A	Heat transfer area of radiator (m^2)
k	Heat transfer coefficient ($W/m^2 \cdot K$)
P	Heat emission from radiator (W)
$\Delta\theta_m$	Mean temperature gradient between heated radiator surfaces and surrounding air (K)

Acronyms

COP	Coefficient of performance
DHW	Domestic hot water
HRC	Heat recovery
HVAC	Heating, ventilation and air conditioning
SPF	Seasonal performance factor

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