Residential demand controlled extract ventilation combined with heat recovery via a heat pump

Ivan Pollet[*1,2], Clint Coulier[1], Anneleen Vens[1], Filip Grillet[3]

1 Renson Ventilation
Maalbeekstraat 10
Waregem, Belgium

2 Ghent University
Department of Biosystems Engineering
Coupure Links 653
Gent, Belgium
**Corresponding author:*
ivan.pollet@ugent.be

3 3E nv
Kalkkaai 6
Brussel, Belgium

ABSTRACT

In this study the performance of a residential demand controlled (DC) extract ventilation system with an air-to-water heat pump was analysed via dynamic simulations. A real life test case was setup to validate results. The ventilation system controls automatically the extract air in functional as well as habitable rooms, ensuring indoor air quality (IAQ). The total extract rate is mixed with outdoor air as heat source of the air-to-water heat pump (2.5 kW at standard reference conditions). Domestic hot water (DHW) as well as space heating (SH) can be alternatively supplied. A gas boiler as back-up guarantees comfort temperature (SH and DHW) at all time. The ventilation heat losses and fan consumption are reduced by the demand control. The heat recuperation on the extract air by means of the heat pump provides a further reduction of the energy consumption.

Dynamic simulations were performed in Virtual Environment (VE) on an apartment geometry (total heating demand of ±3 kW (at -8°C)) for a 2 and 4 persons family. Results of ventilation performance, heat pump performance (off or DHW or SH and (S)COP), back-up (on/off) and heating demand were analysed. Besides a comparison was made with common mechanical extract ventilation and double flux heat recovery systems.

In the apartment case 6% of the year the back-up is activated, 53% of the year, the heat pump is active. Using mixed air instead of outdoor air as heat pump source has led to an augmentation of the SCOP by 0.4 to 3.64 for SH and by 0.3 to 3.37 for DHW. Compared to a demand controlled mechanical extract ventilation system (MEV) an average reduction of the yearly primary energy demand by 31% is achieved due to the use of a heat pump. Compared to a mechanical ventilation system with heat recovery (MVHR) on half ventilation rate, a reduction of 16 to 23% in primary energy use is achieved mainly because of the demand control and the strongly reduced fan energy consumption.

For the simulated apartment and the test dwelling 18% of the ventilation heat losses are recovered towards SH and DHW. In case of dwellings with a higher heating demand, more of the ventilation heat losses can be recovered, since the operating period of the heat pump for SH increases.

KEYWORDS

Demand controlled ventilation, air-to-water heat pump, heat recovery, hybrid system

1 INTRODUCTION

Energy efficiency is at the heart of the European Union’s 2020 strategy for smart, sustainable and inclusive growth and of the transition to a resource efficient economy. Improved energy efficiency is one of the most cost effective ways to enhance the security of energy supply and to reduce emissions from greenhouse gases. In many ways, energy efficiency can be seen as Europe’s biggest energy resource. This is why the Union has set itself a target for 2020 to save 20% of its primary energy consumption (Hogeling, 2015). In order to achieve these savings, especially after the adoption of the Directive 2002/91/EC, local authorities have introduced new and more stringent requirements in building regulations. Particularly, the focus consists in reducing the thermal energy need working on the building envelope and using passive techniques and, at the same time, in improving the efficiency of systems such as heating, cooling, ventilation and lighting (Madonna & Bazzocchi, 2013). Regarding systems, heat pumps are one of the most interesting solutions as they represent a valid alternative to conventional systems, due to the reduced primary energy use (Madonna & Bazzocchi, 2013).

Mechanical ventilation is commonly provided by natural air inlets and one extract fan (MEV) or a supply and extract fan with heat recovery (MVHR). MVHR reduces the heat amount needed to condition the supply airflow, however they also require more power to operate than an extract fan (Logue, et al., 2013). Ventilation devices can be made more energy efficient in different ways: use of less fans or more efficient fan(s), modulation of the air flow rate (demand controlled ventilation, DCV) and application of heat recovery (an air-to-air heat exchanger or an exhaust air heat pump) (Laverge, 2013). Exhaust air heat pumps (EAHP) make it possible to recover heat from exhaust air and are often defined as active regenerators (in that the energy consumption takes place and a heat transfer occurs between the two fluid streams, a transfer that is absent in the case of heat exchangers, which is in fact defined as passive recovery) or thermodynamic regenerators (since they operate according to a thermodynamic cycle) (Fracastoro & Serraino, 2010).

As stated by (Hogeling, 2015) products cannot longer be considered as just parts from the shelf. Products are more and more considered as sub-systems, as they are including control-devices, electronics, other auxiliary functions, … Following this philosophy Renson, a Belgian manufacturer of ventilation, ventilative cooling and sun protection solutions, has integrated a demand controlled mechanical extract ventilation device (DCMEV) with an air-to-water heat pump. Renson refers to this system as the E^+ system. As suggested by (Fracastoro & Serraino, 2010) EAHPs are able to cover a relevant fraction of the thermal energy requirements for air-conditioning and allow a remarkable reduction in the primary energy consumption even though they often require an auxiliary plant.

The aim of the present study was to compare the performance of the E^+ system with traditional ventilation systems namely demand controlled mechanical extract ventilation (DCMEV) and mechanical ventilation with heat recovery (MVHR) in combination with a gas boiler. To this end dynamic simulations were carried out in Virtual Environment. The ventilation performance, heat pump performance (off, active for DHW or SH and (S)COP), back-up performance (on/off) and primary energy use were analysed. Besides, first measurements on a test case were analysed.

2 SYSTEM DESCRIPTION

The E^+ system can be described as a demand controlled mechanical extract ventilation system (DCMEV) of which the total extract air flow is mixed with an outdoor air flow as heat source for an air-to-water heat pump (2.5 kW at standard reference conditions). A gas boiler (no electrical resistance) is used as back-up to guarantee comfort temperatures for space heating (SH) and domestic hot water (DHW) at all times. Domestic hot water (DHW) as well as space heating (SH) can be alternatively supplied. For reasons of legionella prevention, the hot water storage is warmed up to 60°C once a week by the gas boiler.

In contrast to other EAHP, the ventilation rate does not augment when the heat pump is activated for space heating (SH) or domestic hot water (DHW), in order not to increase the ventilation losses. The ventilation system controls automatically the extract air in functional as well as habitable rooms, ensuring indoor air quality (IAQ). The total extract flow is mixed with outdoor air in order to reach a constant air flow rate of 350 m³/h as heat source of the air-to-water heat pump.

The ventilation heat losses and fan consumption are reduced by the demand control. The heat recuperation on the extract air by means of the heat pump provides a further reduction of the energy consumption. In order to avoid summer overheating free cooling is integrated in the system. Free cooling means that the ventilation rate is set to its maximal capacity in order to achieve a cooling effect. Conditions to be met in order to activate free cooling were:

T_in > 21°C (to avoid interference with the heating setpoint)
T_out > 14°C
T_in > T_out

3 METHODS

By means of dynamic simulations in Virtual Environment (VE 2014.2.1.0) the performance of three system variants was calculated for an apartment located in Belgium. Simulation time step was 6 minutes. The three considered variants were:

1) Demand controlled mechanical extract ventilation with gas boiler for space heating and domestic hot water (**DCMEV**)
2) Demand controlled mechanical extract ventilation of which the total extract air flow is mixed with outdoor air as heat source of an air-to-water heat pump. A gas boiler as back-up guarantees comfort temperature at all time (E^+ further referred to as **DCMEV hybrid HP**)
3) Mechanical ventilation with heat recovery with gas boiler for space heating and domestic hot water (**MVHR**).

Besides, monitoring data of an installed DCMEV hybrid HP system were available from mid-2014 till mid-2015 for analysis of the real life performance.

3.1 Simulations

The simulated apartment is illustrated on Figure 1, having 90 m² floor area, a volume of 260 m³ and 76 m² exposed surface area. The floor plan is sketched on Figure 2, the large window in the living room with balcony is oriented to the southeast.

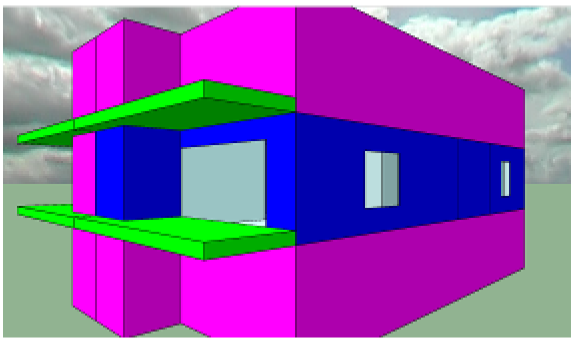

Figure 1: Geometry of the simulated apartment.

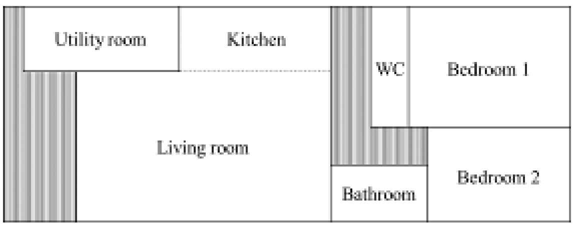

Figure 2: Floor plan of the simulated apartment.

Two occupancy schemes were considered:

- the first one consisting of two working adults and two children, while the heating setpoint was 20°C (referred to as **occ. 2+2**).
- the second considered occupancy scheme consisted of two retired persons which were more at home and had a higher heating setpoint namely 21°C (referred to as **occ. 2**).

The tapping pattern for both occupancy schemes was medium according to EN 16147. Other parameters are listed in Table 1. The apartment had a total heating demand of ±3 kW (at T_{out} = -8°C).

When demand controlled extract ventilation was applied, CO_2 values in the kitchen and bedrooms and relative humidity (RH) in the other wet rooms determined the ventilation rate. The total extract rate of the DCMEV variants varied between 80 and 260 m³/h. When MVHR was applied the total ventilation rate was permanently 230 m³/h which is lower than the maximal DCMEV ventilation rate, since there is no extract in the functional rooms (bedrooms). Weekly thermal disinfection of the water storage tank was simulated by an arbitrary value of 6 kW.

Table 1: Boundary conditions.

	DCMEV	**DCMEV hybrid HP**	**MVHR**
U-value			
wall	0.24 W/m².K	0.24 W/m².K	0.24 W/m².K
glazing	1.1 W/m².K	1.1 W/m².K	1.1 W/m².K
window frame	1.6 W/m².K	1.6 W/m².K	1.6 W/m².K
Solar factor glazing	0.62	0.62	0.62
Solar factor sunshading + glazing	0.101	0.101	0.101
Ventilation			
SFP	1 x 0.15 W/(m³/h)	1 x 0.11 W/(m³/h)	2 x 0.31 W/(m³/h)
Demand controlled	✓	✓	---
Extract in functional rooms	✓	✓	---
Free cooling	✓	✓	---
Heat recovery	---	Via heat pump	Via heat exchanger (η = 75%)
Cooker hood	150 m³/h	150 m³/h	150 m³/h
Floor heating temp. regime	35/30°C	35/30°C	35/30°C
DHW setpoint	45°C ± 5°C	45°C ± 5°C	45°C ± 5°C
Heat source for SH and DHW	Condensing boiler (η = 90%)	Air-to-water heat pump (2.5 kW) + condensing boiler (10 kW) (back-up)	Condensing boiler (η = 90%)

3.2 In-situ measurements

In a test case -situated in Zulte, Belgium- the DCMEV hybrid HP variant was installed and energy consumption (gas and electricity) was recorded. The detached dwelling had 172 m² floor area, a volume of 543 m³ and 414 m² exposed surface area. Weekly output was available for electricity use of the heat pump and gas consumption of the gas boiler (back-up) for a whole year (12 May 2014 till 10 May 2015). Due to a system fault no data was available from 10 till 23 November 2014. The data of the Renson weather station (< 10 km) was used to calculate the weekly mean outdoor temperature.

4 RESULTS – DYNAMIC SIMULATIONS

For the occupancy scheme referred to as 2+2, the ventilation system, the heat pump and the back-up performance were analysed. For both occupancy schemes the primary energy use was calculated and compared for the three considered systems.

4.1 Ventilation performance

The resulting hourly extract ventilation rate due to demand control and free cooling of the DCMEV system is plotted next to the constant extract ventilation rate of the MVHR system as a function of the outdoor temperature on Figure 3. Different ventilation levels due to demand control are visible as horizontal lines (minimum of 80 m³/h). The free cooling zone can clearly be distinguished in the range of 14-25°C, with varying mean ventilation rates between 80 and 260 m³/h. This has an impact on the indoor temperature as shown on Figure 4. When the outdoor temperature is high, indoor temperatures are clearly lower than when MVHR (without bypass) was applied. On colder days, this also occured due to the absence of a heat exchanger in a DCMEV system.

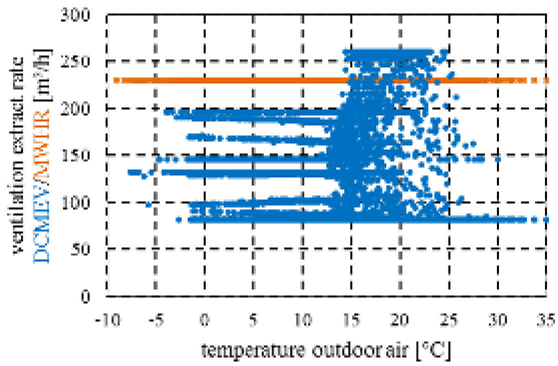

Figure 3: Difference on hourly ventilation extract rate using DCMEV with free cooling vs. MVHR (occ. 2+2).

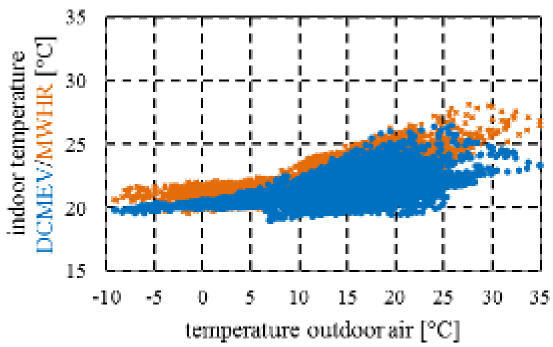

Figure 4: Difference on hourly indoor temperature using DCMEV with free cooling vs. MVHR without free cooling (occ. 2+2).

4.2 Heat pump performance

On Figure 5 the resulting hourly source temperature (temperature of the mixed air) is plotted as a function of the outdoor temperature. Using mixed air instead of outdoor air as heat source led to a mean increase of the supply temperature of the heat pump of 5°C (dotted line). When the outdoor temperature is low the source temperature has increased the most. This source temperature increase gives rise to an increased heat pump COP as illustrated on Figure 6. The mean SCOP for SH has increased by 0.4 to 3.64. The mean SCOP for DHW has increased by 0.3 to 3.37. This augmentation can be used to calculate the equivalent heat recovery effectiveness of the system (ε) according to formula (1) with Φ_{HP} the electricity demand of the heat pump during the heating season (1 October - 30 April; 1097 kWh for SH and 309 kWh for DHW) and Φ_{vent} the ventilation losses (3000 kWh). For the apartment 18% of the ventilation heat losses were recovered towards SH and DHW.

$$\varepsilon = \Phi_{HP} \,.\, \Delta COP \,/\, \Phi_{vent} \qquad (1)$$

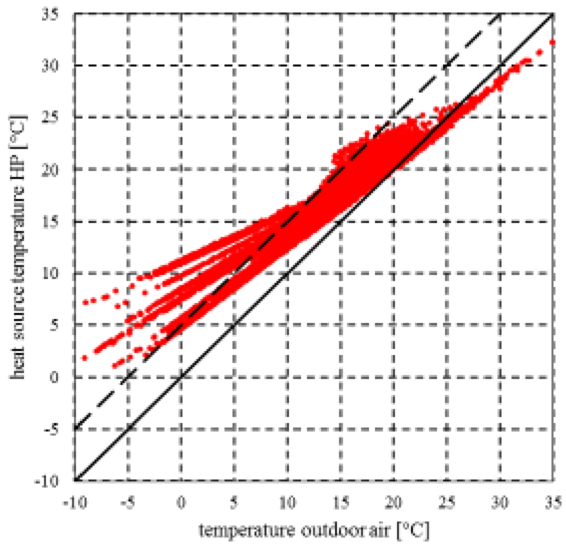

Figure 5: Effect of using mixed air instead of outdoor air as heat pump source.

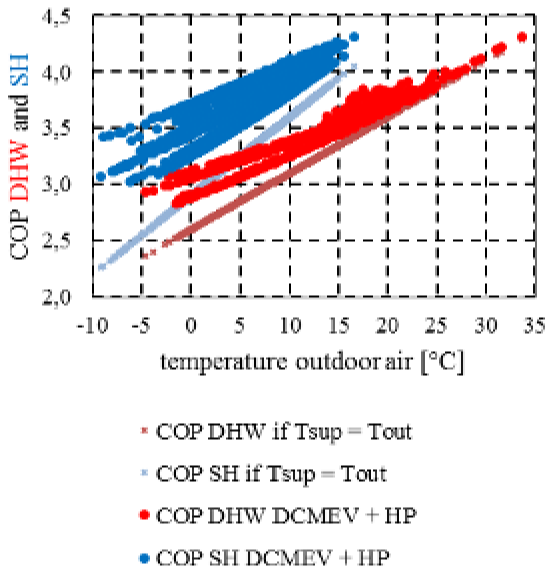

Figure 6: Effect of using mixed air instead of outdoor air as heat pump source on COP.

4.3 Back-up performance (gas boiler)

On Figure 7 the net heating demand of the heat pump and back-up is plotted on a weekly basis. The heating season is marked in green. The whole year the back-up is weekly used for thermal disinfection of the DHW at a temperature of 60°C. During the heating season the back-up was also active for SH when the heat pump was heating the storage tank (priority) and there was a demand for space heating at the same time. Overall the back-up was active for 6% of the whole year, mainly for disinfection. The heat pump was active 53% of the year meaning the rest of the year the heat pump fan was only used for ventilation purposes. On Figure 8 the cumulative net heating demand is plotted as a function of the hourly outdoor temperature. Since Belgium has a temperate maritime climate with moderate winters cumulative net heating demand is largest when the outdoor temperature is between 0 and 10°C what is the typical range of the Belgian heating season (Figure 12). Outdoor temperatures under -2°C are rarely and only few DHW demand occurred during that simulation period. The total final energy consumption and heating demand are summarized in Table 2 (system efficiency for SH of 90% and 77% for DHW). The simulation results indicated the back-up was used to cover 11% of the net heating demand (10% of total space heating demand and 16% of total domestic hot water demand).

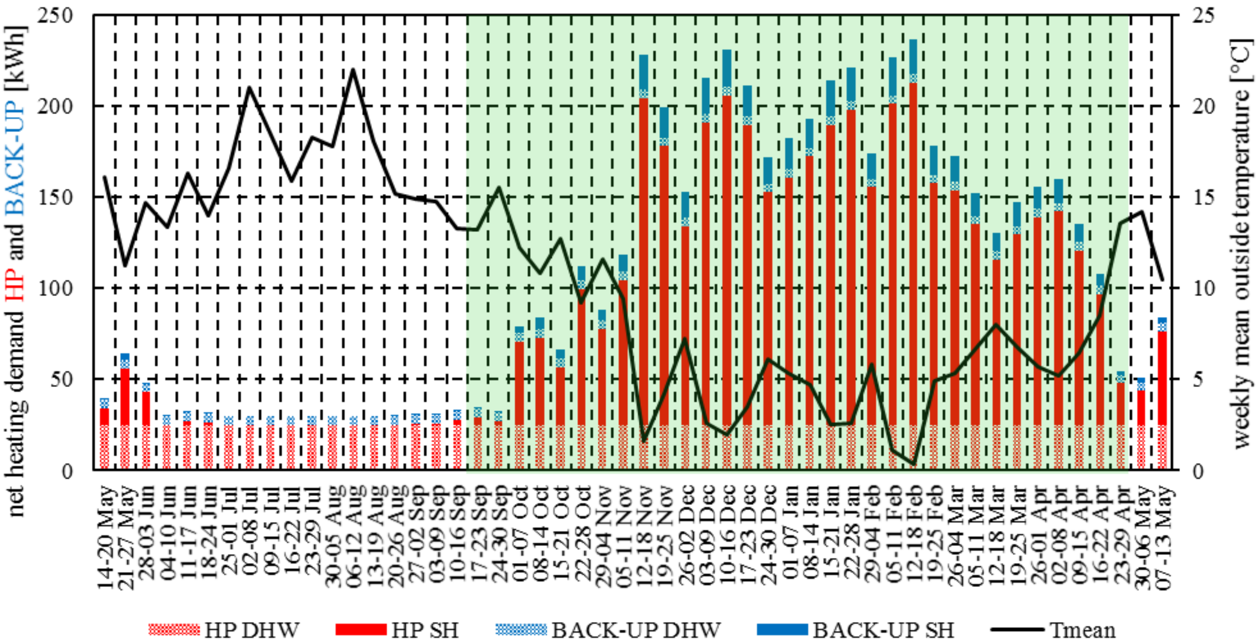

Figure 7: Simulated weekly net heating demand of the heat pump (red) and the gas-boiler (back-up, bleu). Typical Belgian heating season marked in green.

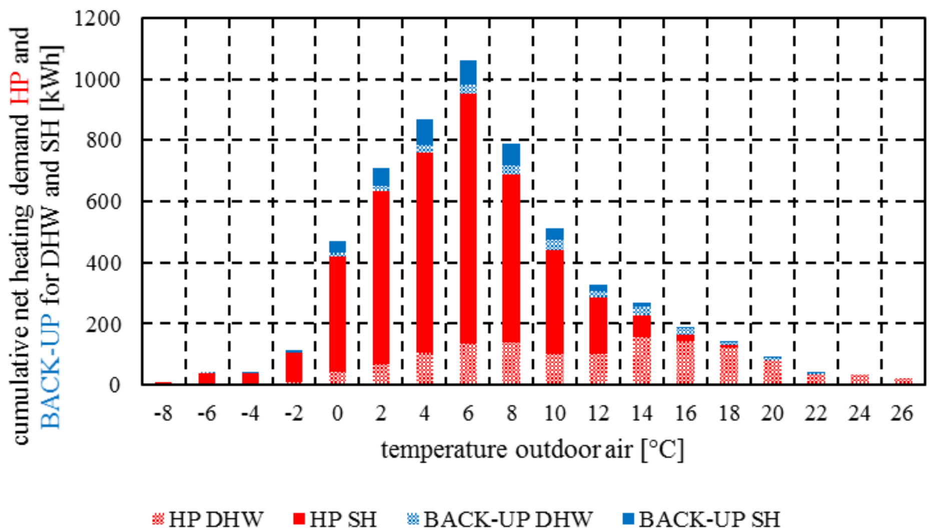

Figure 8: Cumulative net heating demand heat pump (HP) and gas back-up for DHW and SH as a function of hourly outdoor temperature.

4.4 Primary energy use

The performance on primary energy use for the different system variants and both occupancy schemes is presented on Figure 9. Since MVHR systems are frequently set at a lower rate by the occupants, a fourth variant with only 50% of the maximal ventilation rate is added (MVHR(50%)). Calculations were performed with a primary energy factor (PEF) for electricity of 2.5 and for natural gas of 1. The DCMEV hybrid HP variant has the lowest primary energy use: 31% lower than the DCMEV with gas boiler variant (for both occupancy schemes), respectively for occ. 2+2 and occ. 2 41% and 36% lower than the MVHR variant and 23% and 16% for the MVHR(50%) variant. The high primary energy use of the MVHR with gas boiler variant is mainly caused by the MVHR without demand control and the rather energy inefficient fans (high SFP cf. Table 1, even though the input data was based on a frequently used ventilation system) whereas the DCMEV hybrid HP variant uses only one fan for both ventilation and heat pump performance.

The impact of the occupancy scheme (from occ. 2+2 to occ. 2) was a reduction of 6% to 7% for respectively the DCMEV with gas boiler and the DCMEV hybrid HP variant. For the MVHR and MVHR(50%) with gas boiler the impact was higher namely 16%. The hot water consumption of the two people occupancy scheme was lower than for the two adults with two children but the comfort temperature was higher (21°C instead of 20°C). The increased comfort temperature for space heating had a larger impact on the system variants with natural air supply resulting in an overall smaller impact on the difference in primary energy consumption.

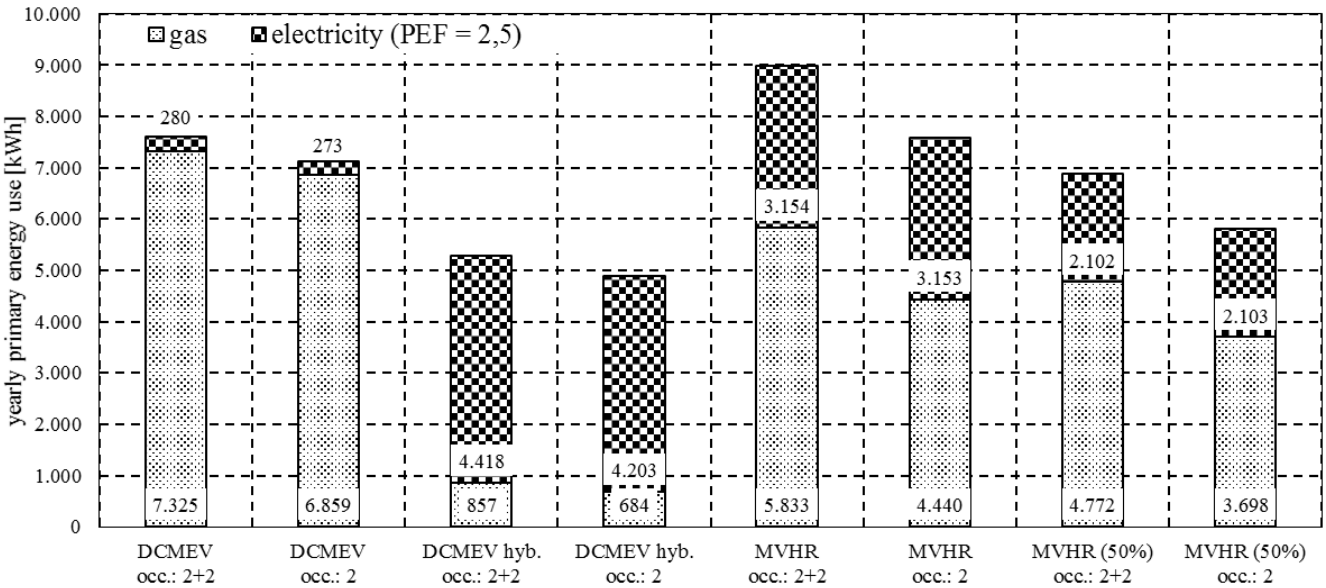

Figure 9: Primary energy use for different systems and for different occupancy schemes.

5 RESULTS - IN-SITU MEASUREMENTS

Since the actual COP of the heat pump was not logged, an average COP of 3.5 and system efficiency of 85% was assumed in order to analyse the results. The weekly net heating demand is plotted in Figure 10. Clearly during the heating season the back-up was more active as was also seen in the simulations (Figure 7). But in this test case the back-up share was larger than in the simulated case. In week 16-22 March the back-up was even used to cover more than 50% of the heating demand. Also in the following weeks the back-up share is close to 50%.

Same as in the simulated case the back-up is still necessary in summer for thermal disinfection purposes. In this summer period weekly heating demand (for DHW purposes) is quite constant as was assumed in the simulations. In the test dwelling an increase in DHW demand occurred from week 21-27 July on. Probably because of a higher setpoint for DHW.

On Figure 11 the net heating demand is plotted as a function of the outdoor temperature. In contrast to Figure 8 the back-up has a larger share in the total energy use in the zone from 0 to 10°C. This was also visible when comparing Figure 10 with Figure 7. From the data collected in Table 2 the back-up share was calculated. The back-up was used to cover 33% of the total heating demand where in the simulated apartment this was only 11%.

Assuming that the application of mixed air leads to an increase of the COP with 0.4 the equivalent heat recovery effectiveness of this installation could be calculated according to formula (1). Based on the measurements results Φ_{HP} = 1100 kWh during the heating season (29 September - 3 May). The mean outdoor temperature during the heating season was 7,4°C. Assuming the average extract air rate is 100 m³/h, the ventilation losses heat losses are 2400 kWh resulting in ε = 18% which is the same as in the simulated case.

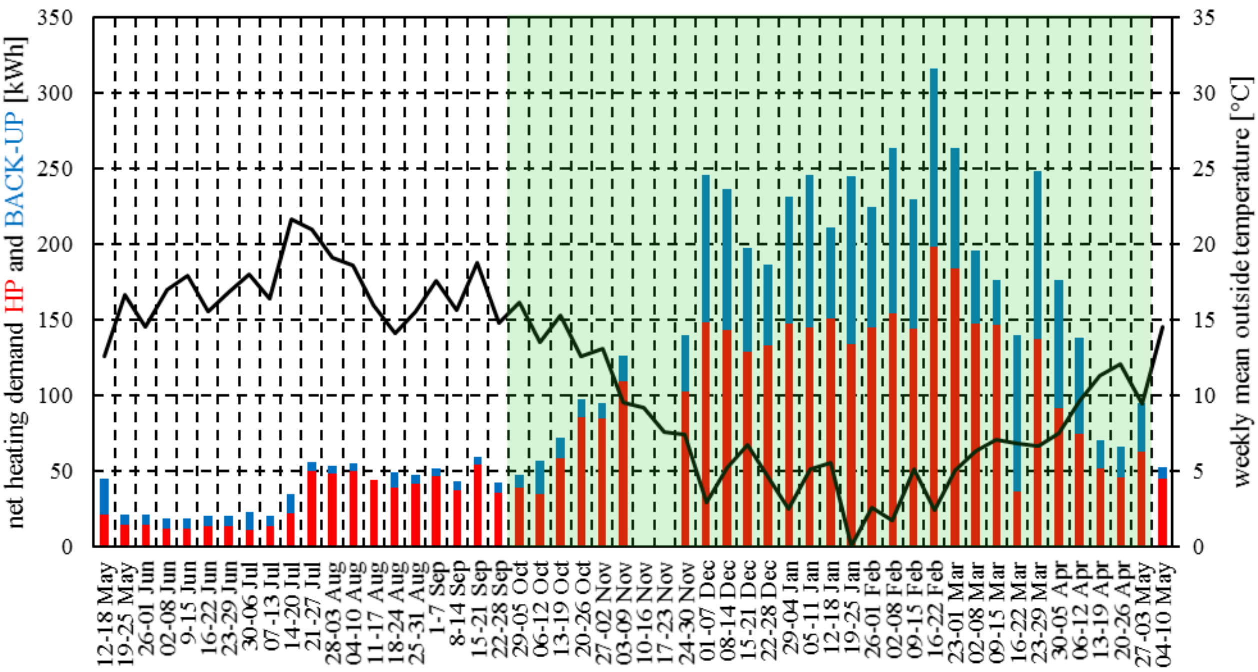

Figure 10: Measured weekly net heating demand of the heat pump (red) and the gas-boiler (back-up, bleu). Typical Belgian heating season marked in green.

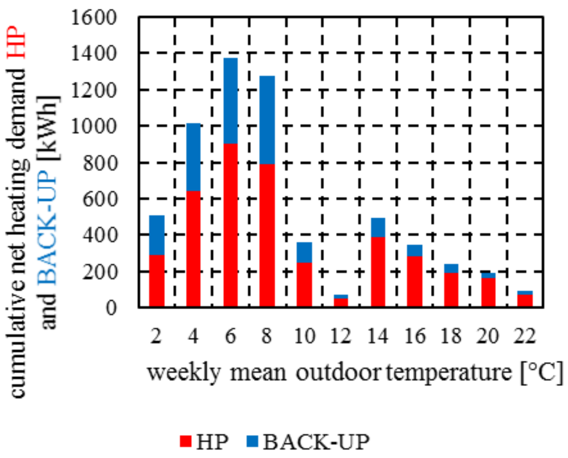

Figure 11: Cumulative net heating demand heat pump (HP) and gas back-up for DHW and SH from 12 May 2014 till 10 May 2015.

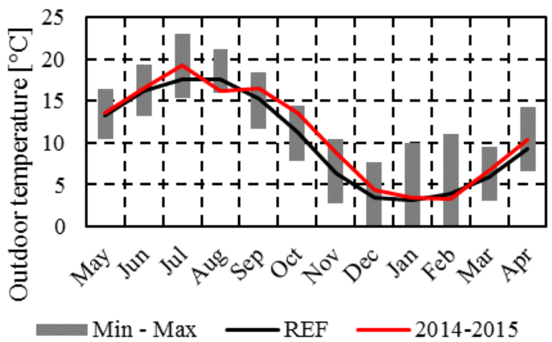

Figure 12: Belgian climate. Reference mean outdoor temperature (black) vs. period 2014-2015 (red) vs. spread in mean temperature (grey).

Table 2: Results of the dynamic simulations for the apartment case and the measurements in the test dwelling for DCMEV hybrid HP variant.

	Case 1: Apartment Dyn. Sim.	Case 2: Test dwelling Meas. 2014-2015
Final energy consumption [kWh]		
SH - HP	1150	---
SH - back-up	508	---
DHW - HP	507	---
DHW - back-up	349	---
Total HP	1657	1309
Total back-up	857	2528
Net heating demand [kWh]		
SH - HP	3771	---
SH - back-up	411	---
DHW - HP	1314	---
DHW - back-up	242	---
Total HP	5086	3894
Total back-up	653	1934
TOTAL	5739	5828

6 CONCLUSIONS

Using mixed air instead of outdoor air as heat pump source leads to an augmentation of the SCOP by 0.4 for SH and 0.3 for DHW. Calculated equivalent heat recovery effectiveness for the DCMEV hybrid HP variant was 18% in both the simulated case and the test dwelling which is lower than traditional efficiencies of MVHR systems. But in contrast to these systems heat recovery occurs during the whole year and not only during the heating season. Moreover the coupling of ventilation extract air and heat pumps makes sure the dwelling is partly heated by means of renewable energy. In case of dwellings with a higher heating demand, more of the ventilation heat losses can be recovered, since the operating period of the heat pump for SH increases.

The back-up is used to cover 11% of the total heating demand in the dynamic simulations whereas in the test dwelling this is 36%. To be able to understand the cause of these differences further research will focus on more real life performances of the DCMEV hybrid HP variant. Detailed logging (ventilation rate, temperatures, energy, COP, …) will be available for further investigation.

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