Heat pumps on exhaust air for space heating and domestic hot water, in very high energy performance multifamily building (Geneva, Switzerland): feedback in actual condition of use

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Heat pumps on exhaust air for space heating and domestic hot water, in very high energy performance multifamily building (Geneva, Switzerland): feedback in actual condition of use

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Abstract. This paper, which is based on a monitored case study, analyses the issues and potential of heat recovery on exhaust air in new multi-family buildings, for combined DHW and SH production by way of heat pumps, in combination with a gas boiler for peak loads. Analysis of the hydraulic diagram, as well as readings of heat and energy meters, allows to point out the causes of an actual HP share (38%) much lower than the projected value (61%), while bringing up the necessity to elaborate standard schemes and sizing rules for such systems.

1. Introduction

In the canton of Geneva, CO_2 emissions from the energy system represent about 4.2 t/capita, of which 2.2 t/capita for space heating (SH) and domestic hot water (DH), 1.1 t/capita for the transport sector (excluding the airport) and 0.8 t/capita for the electricity sector [1]. The sector of heat supply to buildings is still mainly based on fossil fuels and represents almost half of the final energy consumption, offering the highest potential for reducing CO_2 emissions.

A set of recent prospective scenarios shows that the development of heat pumps (HPs), in combination with other modes of production such as medium depth geothermal energy, development of district heating networks, as well as demand reduction of the building stock, would allow to reduce the CO_2 emissions of the heating sector to about 1 t/capita by 2035, respectively 0.2 t/capita by 2050 [1; 2].

One of the ways to reduce CO_2 emissions of buildings concerns waste heat recovery, currently mainly on exhaust air from ventilation (a legal obligation for new buildings [3]), in some cases also from waste water [4]. Heat recovery on exhaust air is mainly done by double-flow ventilation, but growingly also by HPs.

Double-flow ventilation, which allows to reduce the SH demand, is a well-known system whose efficiencies are now excellent, ranging from 70 to 90% and whose coefficients of performance (COP) are in the range of 7 to 15, but whose integration can be complex and/or costly, particularly in the case of renovations [5; 6].

Exhaust air HPs are mainly used for preheating of (DHW), which can be done all year round, a situation in which the sizing and design rules are well identified to ensure a good performance of the heat pumps [6], with measured COP in real use in the order of 3.2 to 3.3 and up to 4.85 in the best case [6]. However, they are still rarely used for combined supply of DHW and SH. In Geneva, the only known analysis of such a system concerns a high energy performance multi-family building (MFB), with a COP of about 4.4 [7].

It is hence crucial to have further feedback, in actual condition of integration and use, regarding exhaust air HP for combined DHW preheating and SH production.

2. Case study

Located in Geneva and built in 2017 by two housing cooperatives, the building under consideration has a 4607 m^2 heating reference area, which includes business premises on the ground floor and collective housing on the 5 upper floors. Its planned SH demand (18.6 kWh/m^2/year) meets the cantonal "very high energy performance" standard. The heat production system consists of two exhaust-air HPs (2 x 22 kW), which supply the underfloor SH system as well as DHW preheating, via common buffers. A condensing gas boiler (125 kW) ensures the complementary SH and DHW production. The simplified hydraulic diagram is shown in figure 1.

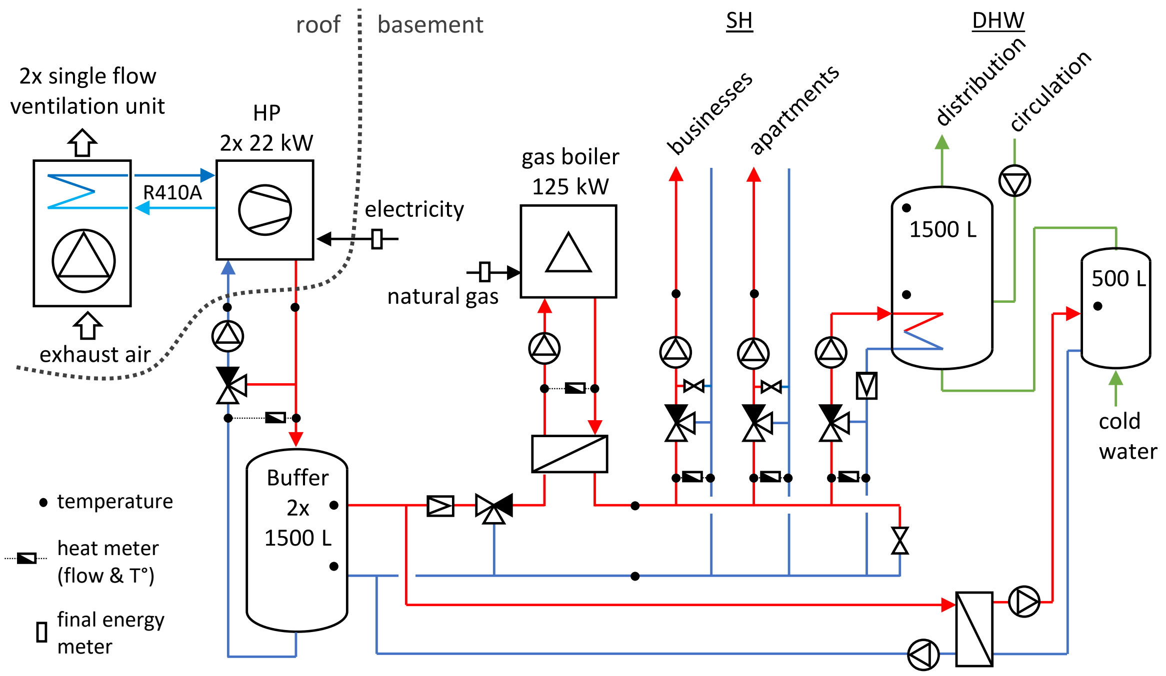

Figure 1: Simplified hydraulic diagram of heat production and distribution.

While the project planned a 61% heat share by the HPs, during the first years of operation it turned out that the vast majority of heat was actually produced by the gas boiler. A close follow-up by the owners (housing cooperatives), technicians (architect, heating engineer) and inhabitants, led to various optimizations and modifications: i) addition of a 3-way valve to separate the boiler production from the HP buffers; ii) cleaning of the boiler heat exchanger; iii) addition of a DHW preheating tank for DHW, connected directly to the HP buffers; iv) hydraulic balancing of SH distribution; v) modifications in the control system. Despite these modifications, the HP share still only amounts to 38% (see next section).

Analysis of the hydraulic diagram and operation modes of the system, allows to identify several elements that seem to limit the achievement of optimal system performance, in particular with regard to the HP performance and share:

- When only one HP is in operation (namely when the ventilation runs at low speed), its water flow is mixed with the one going through the standstill HP, which reduces the effectively available downstream temperature.
- A three-way valve at HP exit voluntarily maintains the HP return flow of 35°C, which degrades its COP, but is possibly needed for reaching the desired production at 45°C.

- All HP production passes through the buffer tanks, whose lack of stratification causes a temperature mix between return on demand side and production by the HPs, which further degrades the actually available temperature.
- Heat transfer for DHW production in the main DHW tank occurs via an internal exchanger, whose characteristics and operating parameters (exchange surface: 3.0 m^2; nominal primary flow: 3.3 m^3/h at 80°C) are not compatible with HP operating temperatures.

Note that the HP buffer temperature (which doesn't exceed 40°C) is sufficient for SH and DHW preheating, but not for total DHW production (at 60°C).

3. Energy and CO_2 balance

Manual readings of heat and energy meters by the housing cooperatives, as well as specific complementary measurements, allow to establish an ex-post energy balance of heat production (HP and boiler) and heat demand (DHW and SH).

On average over three years (2019-2021, see figure 2), only 37.6% of the total 50.5 kWh/m^2/year heat production is covered by the HPs. The corresponding heat demand splits between 18.2 kWh/m^2/year for DHW production (including storage and distribution losses) and 31.6 kWh/m^2/year for SH (34.7 kWh/m^2/year with climate correction). Over this period, the average annual SPF of the HPs is 3.28, and the efficiency of the gas boiler is 87.3% (on the higher calorific value).

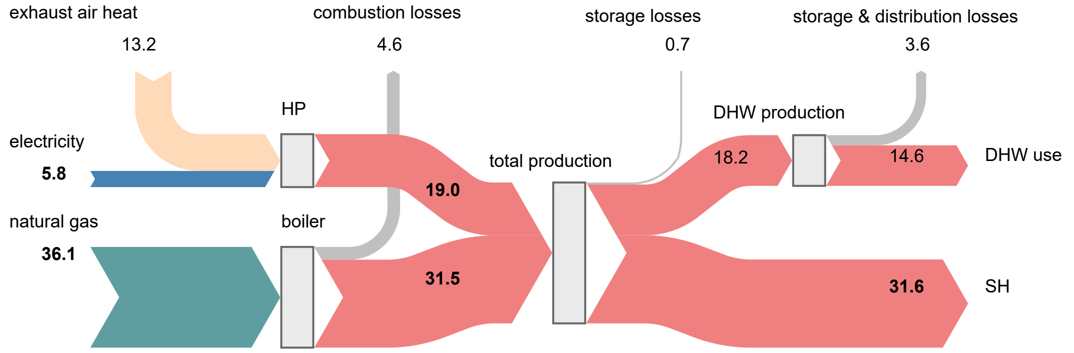

Figure 2: Sankey diagram of the system (kWh/m^2/year). Average values over 3 years (2019 - 2021), without climate correction. In bold: measured values.

Based on a CO_2 content of natural gas at 230 gCO_2-eq/kWh (on the higher calorific value) and a CO_2 content of electricity of 125 gCO_2-eq/kWh [8], the CO_2 emissions of the heat production amounts to 41.6 tCO_2-eq/year (9.0 kgCO_2-eq/m^2/year) on average, of which 8% from HP electricity, and 92% from gas. This underlines the importance of improving the HP share, for reducing of the CO_2 emissions.

4. Energy signatures

Manual readings of heat and energy meters (at irregular intervals, from a few days to several weeks) allow to generate energy signatures (figure 3) of heat production (HP and boiler) and demand (DHW and SH), as a function of outdoor temperature. While during winter HP production reaches up to 20 kW (as averaged over the reading periods), it drops to less than 5 kW during summer, which allows only for DHW preheating, with a necessary complement from the gas boiler. As pointed out above, such is due to the HP production being limited to 45°C, along with the subsequent temperature degradations due to non-optimized system integration.

As a complementary information, the energy signatures indicate a peak load of 77 kW (at -5°C outdoor), much lower than the total installed capacity of 169 kW (HPs + boiler), pointing out a consequent over-dimensioning.

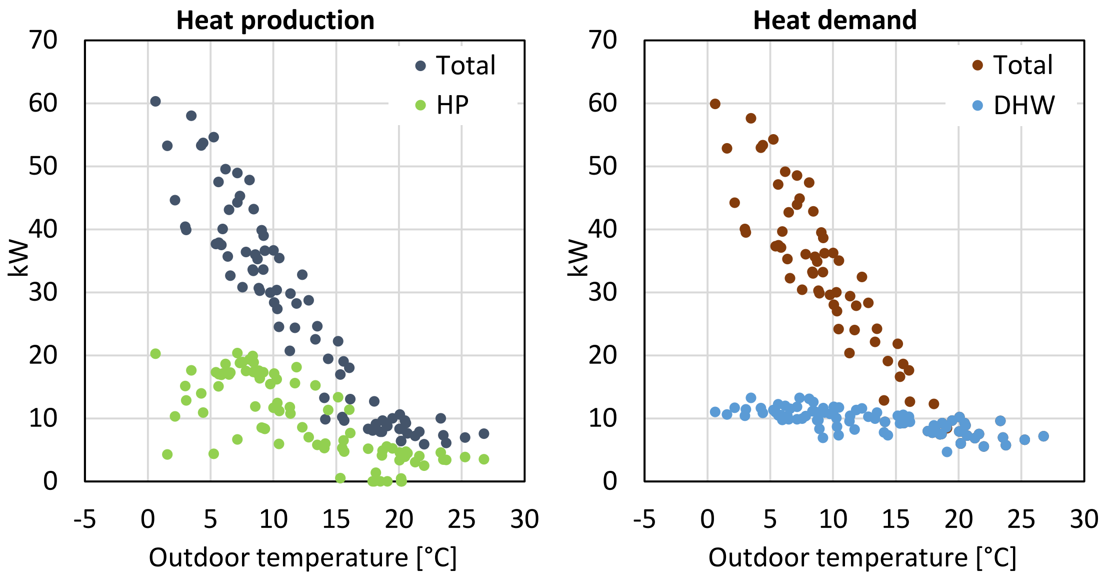

Figure 3: Energy signatures for heat production and demand (January 2019 - May 2022). Total heat production includes production of HP and boiler. Total heat demand includes heat demand for DHW production and space heating demand.

5. Focus on heat demand and production

5.1. Heat demand

The climate corrected SH demand (34.7 kWh/m^2/year) is 87% higher than the project value (18.6 kWh/m^2/year), probably due to actual conditions of use (indoor temperature, ventilation rates, ...) which differ from normalized values. However, in spite of this relative difference, the SH demand of this building is close to the median of Geneva's MFBs constructed between 2011 and 2020, which is 35.7 kWh/m^2/year [9].

In contrast, the DHW production (18.2 kWh/m^2/year) turns out to be at the lower end of a benchmark on existing MFBs in Geneva [10], which includes values ranging from 20 to more than 50 kWh/m^2/year, with a median at 34 kWh/m^2/year.

5.2. Heat production

In absence of continuous monitoring data, it is not possible to perform a detailed analysis of the system dynamic and related issues. However, the quantification of the actual thermal potential of the exhaust air and the related HP capacity gives some insight into the issues at stake.

The thermal potential of the exhaust air can be estimated to an average of 19.9 kW, based on the average ventilation rate (5700 m^3/h) and a temperature differential of 10 K (extracted air at 20°C, rejected after heat recovery at 10°C). With a COP of 4.1 (related to a production at 45°C and a technical efficiency of 45%), this resource represents a potential HP production of 26.3 kW, in continuous mode. Taking into account an HP shut down of 6 h at night (SH completely off and no DHW demand), this potential reduces to 21.6 kW, which is close to the maximum measured HP production according to the energy signature. Latter corresponds to half of the 2 x 22 kW nominal HP capacity, which is due to: i) a production temperature (45°C) higher than the nominal value (40°C); ii) unquantified heat losses between HP evaporator (heat exchanger on exhaust air) and HP, as well as between HP (on the roof) and heat meter (in boiler room); iii) possible underperformance of the machines.

This analysis also confirms that the amount of heat from exhaust air is significantly higher than the heat requirement for DHW production, which makes the use of this resource for combined DHW preheating and SH supply relevant. Such would in principle also be the case for a higher DHW demand, at least up to twice higher than the one observed (i.e. corresponding to the median observation in MFBs). With higher DHW demands, the concept could still make sense with an increased heat recovery potential, i.e. with a higher ventilation rate and/or a larger temperature differential on exhaust air.

6. Limitations and outlook

While ex-post analysis of manually read heat meters allowed to establish the actual energy and CO_2 system balance, as well as to identify critical issues regarding HP valorization of exhaust air for combined DHW and SH production, quantification of the potential improvement (namely in terms of HP share) would require more in-depth analysis, namely by way of numerical simulation. Such would allow to disentangle the effects of i) possibly differentiated HP temperature levels, in SH and DHW modes; ii) system integration; iii) level of SH and DHW demand, as well as of effective ventilation rates.

7. Conclusions

Heat recovery in new MFB buildings, especially from ventilation, has the potential to cover a large part of their heat demand. While the use of HPs on exhaust air for the preheating of DHW is widespread, their use for combined DHW and SH production is much less known.

In this case study, a HP system on exhaust air covers 38% of the heat production for SH and DHW of a new MFB, against a 61% projected value. Such seems to be due to: i) a miss evaluation of the actual HP production / performance, as well as of the intrinsic HP temperature limitations in regard to DHW production; ii) a non-optimized hydraulic system, inducing unnecessary HP temperature degradation along the distribution chain.

While such solutions seem of interest for high energy performance buildings, and a fortiori when the DHW demand is lower than the potential heat recovery on exhaust air, it results in a more complex heat production and distribution system, for which standard solutions and hydraulic schemes need to be developed, and further monitoring in real condition of use needs to be done.

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