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Monovalent and Hybrid Air-source Heat Pump Concepts for Existing Multifamily Buildings – Energy Performance and CO_2 Savings

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Abstract

Heat pump suppliers only propose hydronic concepts for buildings up to 15 kW_{th}, and very few suggest diagrams for large air-source heat pumps (> 50 kW_{th}) in existing multifamily building. This paper analyses the energy and environmental performance of hybrid diagrams adapted to existing and large multifamily buildings via a validated numerical simulation model. The concepts correspond to different fuel-switch scenarios with the possibility of using existing boilers as a back-up. For each concept, sensitivity analysis assesses the impact of different levels of heat demand and heat pump capacity. As a result, over the different scenarios, the seasonal performance of the heat pump varies between 2.8 and 3.3, and the overall performance (heat pump and boiler) between 1.5 and 2.9. Considering the hourly CO_{2eq} content of the Swiss electricity mix, emissions of hybrid systems are 1.4 to 2.2 times higher than with a monovalent system. However, they remain 2.3 to 3.5 times lower than a gas boiler, which points out their adequacy as a transitional solution to proceed to a fuel-switch before retrofitting the building envelope.

Keywords: air-souce heat pump; multifamily building; monovalent and hybrid systems; energy performance and CO_2 savings

Nomenclature

ASHP	Air-Source Heat Pump
DHW	Domestic hot water
HP	Heat pump
MFB	Multifamily building
SH	Space heating
SPF_{HP}	SPF_{HP} Seasonal performance of the heat pump
SPF_{global}	Overall seasonal performance of the heat pump and boiler

In Switzerland, buildings account for nearly 50% of the final energy demand (100 TWh/yr) and 24% of the CO_{2eq} emissions (11.2 Mio. t/yr), representing one of the most important sectors for massive decarbonization [1,2]. About 70% of the building stock is still heated with individual fossil fuel boilers, and around 80% of them were constructed before the 21st century [3]. A specific issue concerns multifamily buildings (MFB), which in urban cantons represent 60-70% of the heated area. In parallel to retrofitting of the envelope, large existing MFBs could drastically reduce CO_{2eq} emissions by switching massively from fossil to renewable energy sources, in particular via heat pumps (HP).

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In dense urban areas, air-source heat pumps (ASHP) often turns out to be the only available option for replacing fossil fuel boilers, since other renewable energy sources are often limited: too long distance to a lake or river, no groundwater or prohibition of its use (water protection), no district heating network due to crowded soil, lack of space for borehole fields, wood boilers prohibited in areas of excessive emissions, or limited solar energy due to roof size. In such a context, outside air often is the only renewable energy source for HP [4].

However, while ASHP systems represent the dominant renewable heating system for single-family houses and new buildings, they are rarely installed in large and existing MFBs. This is mainly explained by: i) lack of well-documented case studies proving the feasibility of such systems; ii) noise emissions, which can become a barrier; iii) HP weight and related structural constraints of the roof; iv) HP integration in the existing distribution system, designed originally for boilers; vii) high investment cost; viii) multiple households with diluted decision power and related problems of governance. Nowadays, those constraints make large ASHP (> 50 kW_{th}) an exception rather than a standard solution, especially in non-retrofitted MFB [5–7].

One of the most significant technical challenges for installing ASHP in existing MFBs is the lack of standardized hydronic concepts adapted to existing MFBs (> 50 kW_{th}), which usually concern power ratings up to about 15 kW_{th} [8]. The reason is an obvious lack of market demand, which has yet to lead to the development of such diagrams. On the other hand, most of the literature on the design and operation of ASHP focuses on new or existing single-family houses (< 450 m2 of heated floor area), with capacities below 30 kWth [9–12], for which HPs are mostly standardized, storage capacity within the building usually isn't a technical constraint, and optimal control strategies have already been developed.

1.1. Objective

In order to fill this gap, the objective of this paper concerns the development of monovalent and hybrid ASHP concepts (> 50 kW_{th}), adapted to the specific context of existing MFB, without (or with delayed) renovation of the building envelope. The concepts correspond to different fuel-switch scenarios, with and without the possibility of using the existing modulating or non-modulating boiler. They are analyzed via numerical simulation and calibrated on in-situ measurements. For each concept, sensitivity analysis assesses the impact on energy and environmental performance of different levels of heat demand for space heating (SH) and domestic hot water (DHW), as well as HP capacity (under or oversizing).

The results of this study are part of the AirBiVal project [8] and also contribute to the IEA Annex 50 "Heat Pumps in Multi-Family Buildings for Space Heating and DHW" [13].

2. Hydronic concepts

Figure 1 shows the four hydronic concepts used in this study, which have been developed based on an extant literature review, discussions with experts in the field, and long-term in-situ monitoring of two pilot projects with large ASHP:

- **Monovalent heat pump operation**: corresponds to the case where it is possible (technically and financially) to install a HP to cover 100% of the demand. For this variant, it is essential to consider rooftop static, soundproofing, mechanical vibration, electricity capacity, and extra height construction limits. This concept is based on a monovalent pilot project installed in Geneva, for which a detailed monitoring campaign and related energy analysis were conducted [5].
- **Hybrid parallel operation with modulating boiler**: corresponds to the case where an existing or new modulating boiler is used in parallel operation with the HP. The boiler is positioned after the SH tank to protect the HP from high return temperatures. This is especially important when using existing oil boilers with low modulation. This concept is based on recommendations for HP systems with a thermal output of more than 15 kW_{th}, elaborated on current knowledge from industry and research [14].
- **Hybrid parallel operation with a non-modulating boiler**: corresponds to the case where an existing non-modulating boiler is used in parallel operation with the HP. Ideally, the HP and non-modulating boiler should have their own SH tank, connected in series, to protect the HP from high return temperatures. However, in existing MFB space constraints usually lead to the installation of one tank only, in accordance with the proposed diagram. This concept is based on the hybrid pilot project installed in Geneva, for which an energy analysis and monitoring campaign were conducted [5].
- **Hybrid alternative operation with a non-modulating boiler**: corresponds to the case where an existing non-modulating boiler is used in alternative operation with the HP. It allows temporary

operation in hybrid mode, while waiting for a future retrofit of the building envelope. When the boiler is removed, the existing hydronic connections will not require any major modification. The concept is based on the diagrams developed within the RAVEL program [15].

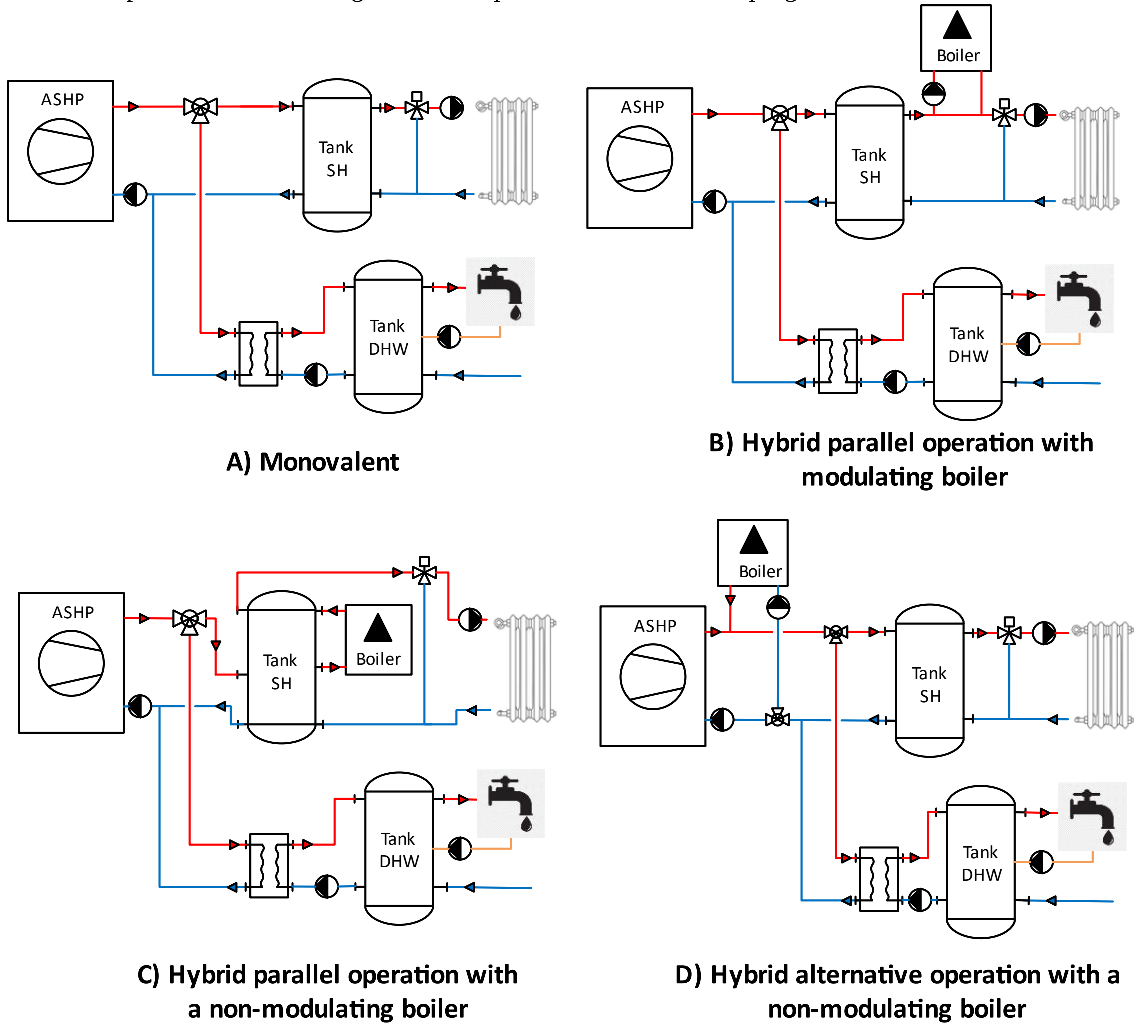

Figure 1. Hydronic concepts

2.1. Diagrams control description

For each of the four concepts, following regulation and design aspects are considered:

- The HP switches between SH and DHW production to maintain the tanks at their respective setpoint temperatures. In the case of a simultaneous demand, priority is given to DHW.
- The HP is the only heat provider for DHW (no boiler backup), so as to force the HP to cover the DHW demand in summer, when outdoor temperatures are most favorable for performance, as well as to simplify the installations diagram.
- The HP reaches 60 °C for DHW to prevent legionella proliferation. An external, rather than internal, heat exchanger is used for DHW to provide enough heat transfer area between the HP loop and the DHW tank.
- For hybrid concepts, the gas boiler only provides heat for SH, in parallel or alternative operation with the HP. The boiler is switched on if the outside temperature is below the bivalence temperature (T_{biv}) and if the HP does not reach the SH setpoint temperatures.
- The operation below the bivalence temperature is as follows (Figure 2, left): a) in the case of a parallel configuration, the HP covers the heat load up to its capacity, and the boiler provides the complement; b) in the case of the alternative configuration, the boiler operates alone. The procedure for identification of the bivalence temperature is given in section 3.3.

Detailed information on functional analysis explaining the switching on/off of the equipment is given in [8].

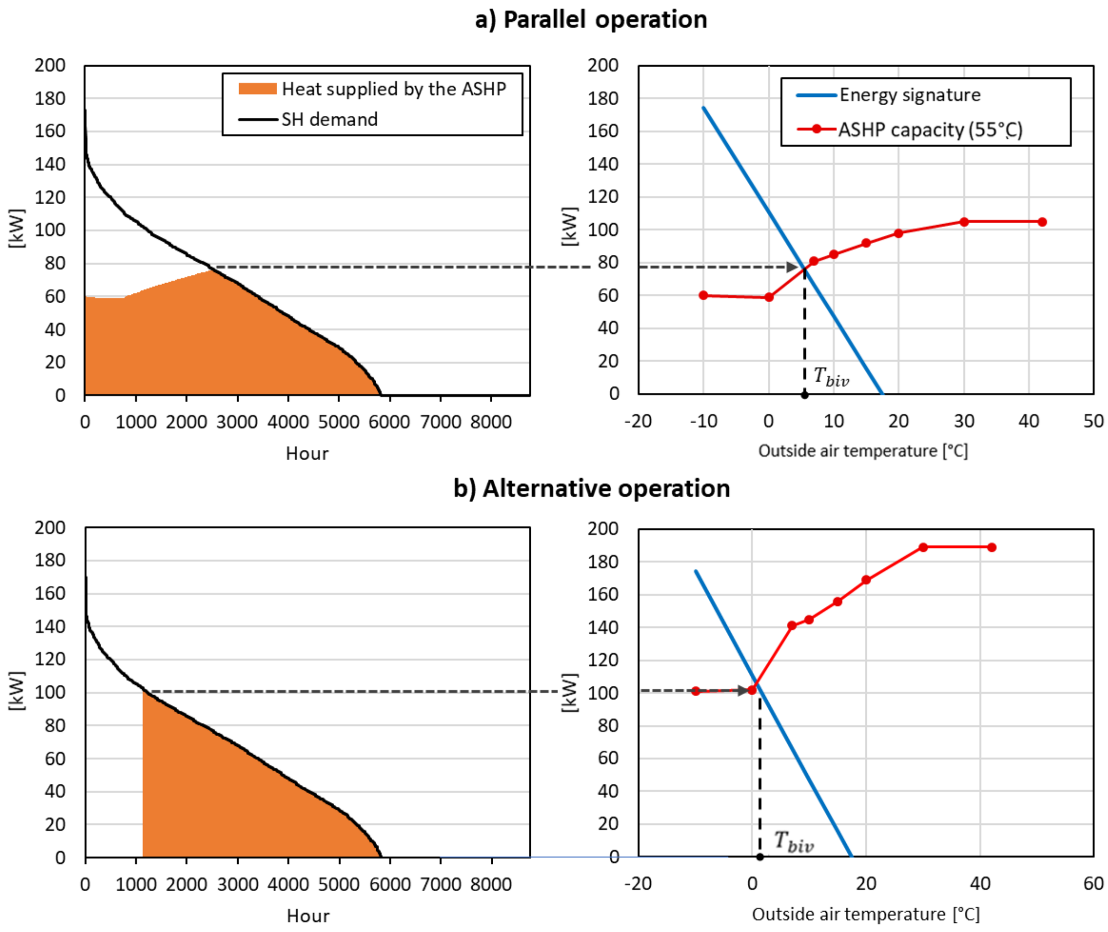

Figure 2. Identification of the ASHP bivalence temperature for a) parallel operation and b) alternative operation.

3. System modeling

In order to evaluate the performance of the proposed concepts and compare them with each other, energy models are set up using TRNSYS [16], with a time step of 1 minute. First, the model is validated based on a monovalent pilot project to ensure that the model can fairly and accurately represent reality. Then, the model is normalized to reference conditions of use, which are also applied to the three-hybrid systems model.

3.1. Validation of the monovalent system model

The model validation is based on the in-situ monitoring of a non-retrofitted MFB (4’047 m^2 of heated floor area), whose original fossil heat supply was replaced by a monovalent ASHP (312 kW_{th} @ 7°/45°C) for DHW and SH production. Monitored daily SH and DHW production, minimum/maximum outdoor temperature, as well as HP and backup boiler production (during HP failure in spring 2019) are presented in Figure 3, over two years of operation.

The model validation is carried out for one year (July 2019 to June 2020). The HP model uses the performance curves provided by the manufacturer. The tanks volume (SH: 1 m^3 and DHW: 2 m^3) and control parameters correspond to the ones of pilot project. The measured heat demand (SH and DHW), setpoint temperatures, and heating curves are provided to the simulation in hourly values. Detailed information on the controller settings used in the simulation is given in [8].

Figure 4 compares the simulated and monitored HP production as well as related electricity consumption on a daily basis. The simulated HP production faithfully reproduces the monitored values (with an annual error of 1%). On the other hand, the HP electricity consumption (without auxiliaries) is underestimated by around 20%, due to: i) the difficulty of considering all manual changes made to the real system; ii) the discrepancy between the HP performance of the manufacturer (used for the simulation) and of the monitoring (namely partial load conditions, as well as defrost cycles outside the standard testing conditions). Despite this, the simulation/measurement correlations remain very satisfactory to serve as a basis for modeling the four proposed hydronic concepts.

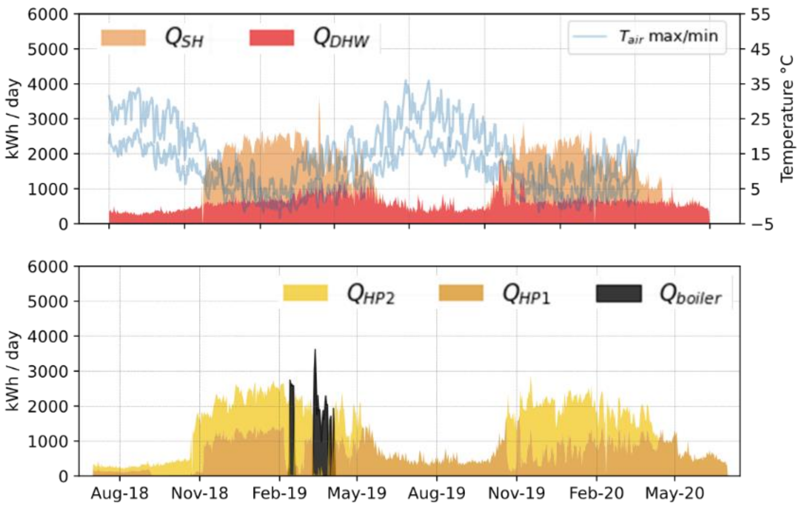

Figure 3. Monitored monovalent ASHP system (July 2018–June 2020): Daily SH and DHW production, as well as minimum/maximum outdoor temperature (top); Daily HP and boiler production, over two years of operation (bottom).

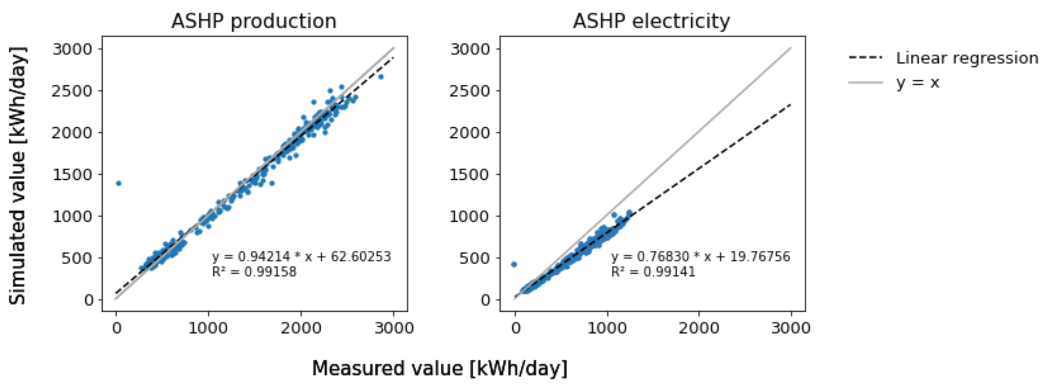

Figure 4. Comparison of simulation results with the pilot project measurements (July 2019 to June 2020, daily values). The electricity consumption of the HP does not include the consumption of the auxiliaries.

3.2. Normalization to reference conditions of use

The model is then normalized to reference conditions of use, which consists in the following modifications:

- Reference climate year for Geneva, according to the SIA 2028 standard [17];
- SH demand derived from the energy signature of the monovalent pilot project (in hourly values), but adjusted to the SIA reference climate to reach an annual demand of 101 kWh_{th}/m^2.year. This value corresponds to the median value of the existing "post-war" building stock (1948-1980) [18];
- DHW demand (35 L/day.person) given by an hourly schedule according to SIA 385/2 standard (SIA 2015) [19], but constant over the year.

The dynamic profile of the reference SH demand is presented in Figure 5, along with two alternatives (high and low demand) which will be used for sensitivity analysis (see section 6).

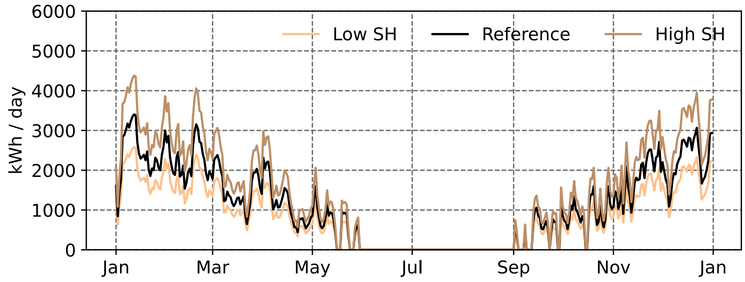

Figure 5. Daily space heating demand used for simulation: reference case as well as high/low alternatives.

3.3. Systems sizing

The three hybrid systems models are derived from the monovalent model, which are adapted according to the hydronic concepts defined above in Figure 1. For each of the four systems, we use the above-defined reference condition of use. The components are sized according to the following procedure, for which the results are shown in Table 1.

Table 1. Design parameters of the four reference systems

	Monovalent	Parallel modulating boiler	Parallel non-modulating boiler	Alternative non-modulating boiler
HP capacity required for SH*	250	78	78	137
HP capacity required for DHW*	84	84	84	84
Mode with the highest capacity requirements	SH	DHW	DHW	SH
HP capacity retained [kW_{th}]*	274	88	88	137
Boiler capacity [kW_{th}]	-	95	95	189
Bivalence temperature [°C]	-	4.5	4.5	0.5
Volume of SH tank [m^3]	2.2	2.9	2.9	2.2
Volume of DHW tank [m^3]	1.9	1.9	1.9	1.9

* HP capacities for 7 °C at the evaporator inlet and 45 °C at the condenser outlet

HP capacity

For DHW, the HP capacity is sized according to the SIA 385/2 [19], assuming a typical demand of 45 L/day.person (as used by engineering companies when the DHW demand is unknown), storage and distribution losses of 30%, as well as 6 daily charging cycles with a duration of 1 hour each. The HP has to ensure the total DHW demand, it must therefore be able to produce at 60°C in the most critical conditions (outside temperature of -7°C for the Swiss plateau).

For SH, the method for sizing the HP capacity is different for monovalent and hybrid systems:

- Monovalent system: The HP supplies 100% of the building demand (DHW and SH). Its SH capacity is defined to be able to provide the maximum daily SH demand within 18 hours (the 6 remaining hours being reserved for 6 DHW cycles of 1 hour each), with a distribution temperature of 55°C and an outdoor temperature of -7°C.
- Hybrid systems: The HP capacity is sized according to a bivalence temperature, which is determined at the intersection between the energy signature of the building and the heating capacity of the HP manufacturer, with the objective of covering 80% of the SH and DHW demand with the HP (see Figure 2). This method results in a HP capacity of 40 – 60% of the maximum hourly heat demand (189 kW_{th}), depending on the configuration (parallel or alternative operation).

Once the above sizing procedure has been applied separately for SH and DHW, the higher of the two HP capacity is selected, and adjusted to existing HP models on the market.

Tank volume

For DHW, the tank volume is sized according to the SIA 385/2, assuming the same conditions used for HP capacity sizing, explained above.

For SH, the tank is sized in relation with the HP capacity, to ensure that the HP runs for at least 20 minutes each time it is switched on. The aim is to prevent short cycling for ensuring the HP lifespan.

Boiler capacity

For the hybrid systems, we assume that an existing gas boiler is reused (installed before the implementation of the HP system), with a total capacity corresponding to the maximum hourly SH demand (189 kW_{th} at -7°C outdoor), subdivided in two capacity levels (95 kW_{th} each).

In the case of the parallel systems, the boiler completes the heat production of the HP below the bivalence point. It is assumed that only the first stage of the boiler is necessary. In the case of the alternative system, the boiler ensures the entire production below the bivalence point, whereby the two stages are therefore necessary.

4. Performance indicators

In order to evaluate and compare the performance of the different hydronic concepts, following energy and environmental performance indicators are used.

4.1. Energy performance

The annual energy performance of the system is evaluated by the seasonal performance factor (SPF_{HP}) according to Equation (1). It is defined as the ratio between annual heat production (Q_{HP}) and annual HP electricity consumption (E_{HP}).

$$SPF_{HP} = \frac{\sum Q_{HP}}{\sum E_{HP}} \quad (1)$$

In the case of the hybrid system, the overall system performance is evaluated by Equation (2), where Q_{boiler} is the annual heat production of the boiler and E_{gas} is the related annual gas consumption. The efficiency of the boilers is assumed to be equal to 90% (relative to the higher heating value).

$$SPF_{global} = \frac{\sum(Q_{HP} + Q_{boiler})}{\sum(E_{HP}+E_{gas})} \quad (2)$$

For all hybrid systems, HP capacity is sized to cover 80% of the annual heat production. In order to check if this objective is respected, the share of the HP production is calculated as follows:

$$HP\ share = \frac{Q_{HP}}{Q_{HP}+Q_{boiler}} \quad (3)$$

4.2. Environmental performance

The emissions related to the HP electricity consumption are calculated using Equation (4), where $E_{HP.h}$ is the hourly electricity consumption of the HP (in kWh_{elec}) and $f_{elec.h}$ is the hourly CO_{2eq} content of Swiss electricity, averaged over the years 2016 to 2019 (in gCO_{2eq}/kWh_{elec}). The latter is taken from Romano et al. [20], which considers domestic generation and imports from neighboring countries. The CO_{2eq} electricity content has an overall average of 99 gCO_{2eq}/kWh_{elec}, but daily peak values in the winter reaching 300 gCO_{2eq}/kWh_{elec}.

$$C_{elec} = \sum_h E_{HP.h} \cdot f_{elec.h} \quad (4)$$

The gas boiler emissions (C_{gas}) are evaluated by a constant emission factor of 203 gCO_{2eq}/kWh_{th} [1].

The total CO_{2eq} emissions of the system (in gCO_{2eq}) are evaluated by Equation (5) and are finally related to the total heat demand (gCO_{2eq}/kWh_{th}) by Equation (6), where Q_{SH} and Q_{DHW} are the annual SH and DHW demand (in kWh_{th}), respectively:

$$C_{global} = C_{elec} + C_{gas} \quad (5)$$

$$C_{th} = \frac{C_{global}}{Q_{SH}+Q_{DHW}} \quad (6)$$

5. Results for reference systems

The energy balances, performances, and CO_{2eq} emissions of the 4 reference systems are shown in Figure 6. Given the boiler backup, in particular during the coldest days, the hybrid systems have a better SPF_{HP} (between 3.13 and 3.20) than the monovalent system (2.85). As planned during sizing (with an objective of 80%), the HP share of the hybrids systems amounts to 79%, except for the parallel non-modulating gas boiler (c), which drops to 71%. In this case, since the boiler cannot modulate its capacity, it overproduces at each start-up, so the storage tank temperature exceeds its set point. As a result, despite a sufficient capacity, the HP is less solicited than it could be. As a result, the latter system consumes 35% more gas than the other two hybrid systems.

The CO_{2eq} emissions of the hybrid systems are 1.7 to 2 times higher than with the monovalent system. Two-thirds of their emissions are related to gas consumption, even though gas covers only 21% to 29% of the total heat demand. Thus, even with a high carbon content of the electricity mix in winter, the use of a HP remains more advantageous in terms of emissions, due to its high efficiency (> 2.8) compared to the boiler efficiency (90 %). For comparison, a system with only a boiler emits nearly 3 times more CO_{2eq} (119 tCO2eq/an) than the hybrid systems, and 5 times more than the monovalent system.

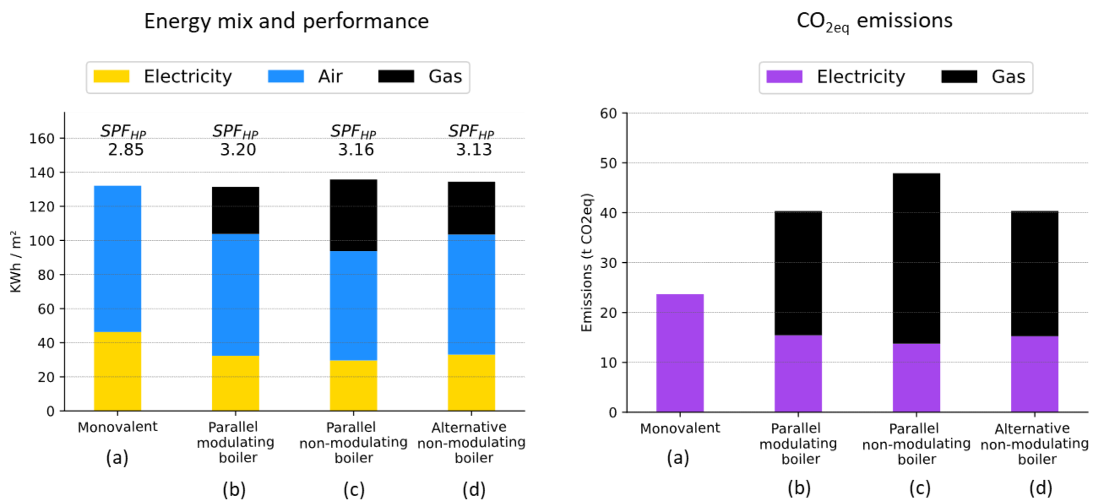

Figure 6. Energy mix and CO_{2eq} emissions of the four reference systems (SPF_{HP} does not include auxiliary consumption).

6. Sensitivity analysis

As a complement to the four reference cases, the impact of different levels of heat demand (SH and DHW) and HP capacity are assessed by following sensitivity analysis (see Table 2):

- Three levels of SH demand, representative of Geneva's post-war MFB stock (1948-1980) [18]: i) 78 kWh_{th}/m^2.year (1st decile of MFB stock); ii) 101 kWh_{th}/m^2.year (median), corresponding to our reference case; and iii) 130 kWh_{th}/m^2.year (9th decile).
- Three levels of DHW consumption: 25, 35 and 50 L/day.person, which correspond approximately to the minimum, median and 9th decile of a benchmark of DHW demand of nearly one million m^2 of heated floor area of MFB in Geneva [21].
- For the hybrid systems, three levels of HP capacity for SH: 30%, 40-60% and 80% of the maximum hourly demand, with their respective bivalence temperature. Note that the intermediate case of 40-60% (reference case) results from the above defined sizing procedure (with the objective to cover 80% of the annual heat demand).

In each case, the HP capacity as well as the SH and DHW tanks are sized according to the method described in section 3.3. This concerns in particular separate HP sizing for SH and DHW, with selection of the higher of the two values. In this regard, for hybrid systems, the "low capacity" for SH (30%) turns out to be unfit for the DHW constraint, so that these cases actually resume to the respective reference cases (see Table 2).

Table 2. Summary of the cases studied for the sensitivity study

Système	Variant*	#	HP capacity* for SH (@7°C/45°C) [kW_{th}]	HP capacity* for DHW (@7°C/45°C) [kW_{th}]	HP capacity** retained (@7°C/45°C) [kW_{th}]	Boiler capacity [kW_{th}]	T_{biv} [°C]	Volume tank SH [m^3]	Volume tank DHW [m^3]
Monovalent	**Reference**	**A0**	250	(84)	274	-	-	2.2	1.9
	Low DHW	**A1**	250	(84)	274	-	-	2.2	1.9
	High DHW	**A2**	250	(84)	274	-	-	2.2	1.9
	Low SH	**A3**	189	(84)	208	-	-	2.2	1.9
	High SH	**A4**	322	(84)	350	-	-	2.8	1.9
Parallel / modulating boiler	**Reference**	**B0**	(78)	84	88	95	4.5	2.9	1.9
	Low DHW	**B1**	(78)	84	88	95	4.5	2.9	1.9
	High DHW	**B2**	(78)	84	88	95	4.5	2.9	1.9
	Low SH	**B3**	(60)	84	88	72	2	2.9	1.9
	High SH	**B4**	104	(84)	104	122	5	2.2	1.9
	Low capacity	**B5**	(53)	84	88	95	4.5	2.9	1.9
	High capacity	**B6**	201	(84)	208	95	-8	2.2	1.9
Parallel / non-modulating boiler	**Reference**	**C0**	(78)	84	88	95	4.5	2.9	1.9
	Low DHW	**C1**	(78)	84	88	95	4.5	2.9	1.9
	High DHW	**C2**	(78)	84	88	95	4.5	2.9	1.9
	Low SH	**C3**	(60)	84	88	72	2	2.9	1.9
	High SH	**C4**	104	(84)	104	122	5	2.2	1.9
	Low capacity	**C5**	(53)	84	88	95	4.5	2.9	1.9
	High capacity	**C6**	201	(84)	208	95	-8	2.2	1.9
Alternative / non-modulating boiler	**Reference**	**D0**	137	(84)	137	189	0.5	2.2	1.9
	Low DHW	**D1**	137	(84)	137	189	0.5	2.2	1.9
	High DHW	**D2**	137	(84)	137	189	0.5	2.2	1.9
	Low SH	**D3**	104	(84)	104	143	0.5	2.2	1.9
	High SH	**D4**	175	(84)	175	243	0.5	2.8	1.9
	Low capacity	**D5**	(53)	84	88	189	4.5	2.9	1.9
	High capacity	**D6**	201	(84)	208	189	-8	2.2	1.9

DHW: Low DHW = 25 L/hab.day, Reference = 35 L/hab.day, High DHW = 50 L/hab.day;

SH: Low SH = 78 kWh_{th}/m^2.an, Reference = 101 kWh_{th}/m^2.an, High SH = 130 kWh_{th}/m^2.an;

HP capacity (only hybrid sys.): Low capacity: 30%, Reference: 50%, High capacity: 80%

**Values that are not in parenthesis correspond to the highest HP capacity requirements between the two modes.*

*** HP capacity corresponding to an existing HP model, meeting the highest HP capacity required for the system.*

7. Results of sensitivity analysis

The results of the sensitivity analysis are presented in Figure 7. In total, 26 variants are simulated (4 reference cases + 22 variants). For comparison, the CO_{2eq} emissions are also estimated for a "100% gas" system, where a boiler produces all the heat.

In the case of the monovalent system, the SPF_{HP} turns out very stable, at 2.85 ± 0.01. For the hybrid cases, it raises to values between 3.06 and 3.31 (due to boiler backup during the coldest days), except for the HP with *"High capacity"* (B6, C6, D6), for which it drops to around 2.90. For these cases, it turns out that the HP does in fact ensure almost 100% of the heat production, despite a significant reduction of the HP capacity as compared to the monovalent system (208 kW_{th} instead of 274 kW_{th} @7°C/45°C). Such result raises questions regarding the best method for sizing the HP, in particular for monovalent systems, to avoid oversizing and reduce investment costs.

For the hybrid systems (except for the *"High capacity"* cases, for the reason explained above), the SPF_{global}, which considers the gas consumption and related heat production, drops to values between 1.52 and 2.40, with HP shares between 56% and 88%. Furthermore, the higher the overall performance (SPF_{global}) and HP share, the lower the HP performance (SPF_{HP}), due to lesser boiler backup during the colder days.

Emissions of the monovalent systems and hybrid cases with *"High capacity"* are around 49 gCO_{2eq}/kWh_{th}. The hybrid systems reach values between 68 and 127 gCO_{2eq}/kWh_{th} (to be compared with the 247 gCO_{2eq}/kWh_{th} of the "100% gas" system).

At more specific levels:

- For all four system types, the variation of the DHW demand (*"Low DHW"* and *"High DHW"*) has no significant impact, as compared to the respective reference case.
- The same is true for cases with *"High SH"* demand. In parallel systems, the cases with "*Low SH"* demand (B3 and C3) lead to a minor increase of the HP share, with related decrease of SPF_{HP}, increase of SPF_{global} and reduction in CO_{2eq} emissions. Latter is due to an "oversized" HP capacity in SH mode (due to sizing done for the DHW mode, see Table 2), which brings about a colder bivalence temperature (2°C) than for the reference case (4.5°C). As a result, the HP operates over an increased period of time, but in more severe conditions for its performance.
- As explained before, hybrid systems with "*Low capacity"* turn out to be unfit for the DHW constraint, so that these cases actually resume to the respective reference cases. Similarly, for the "*High capacity"* cases where the HP covers almost 100% of the heat production, de facto operating like the monovalent system.

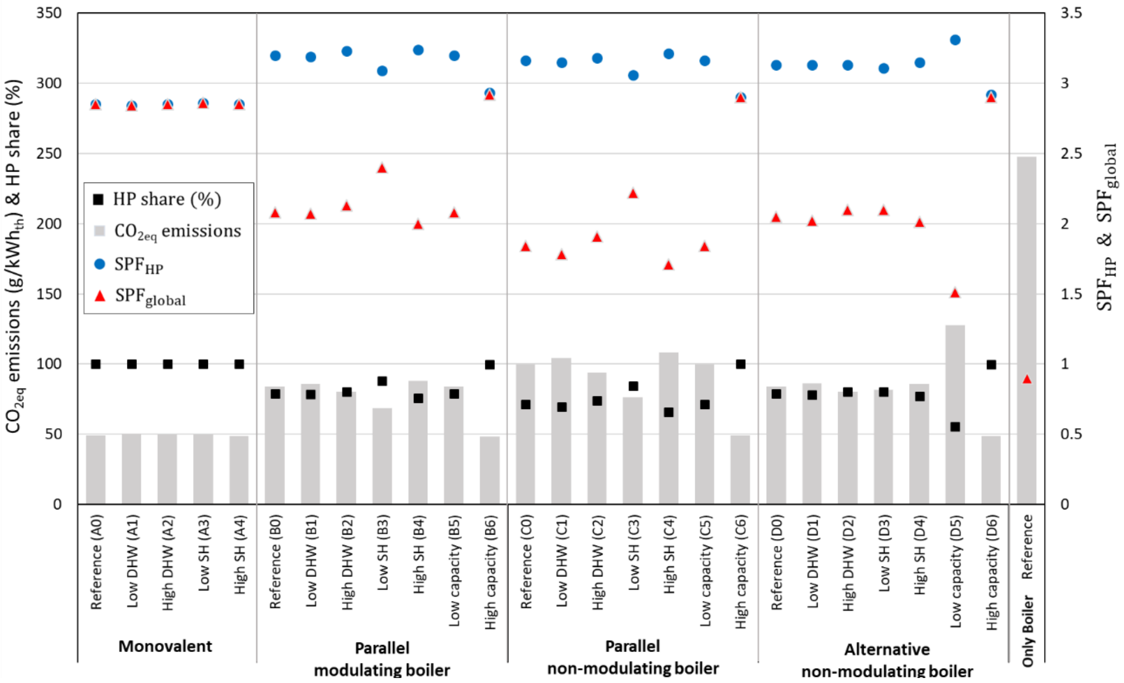

Figure 7. Results of the sensitivity analysis. Left axis: CO_{2eq} emissions per kWh_{th} of demand (bars) and HP share production (square points). Right axis: SPF_{HP} and SPF_{global} (triangles and circles points)

8. Limitations and future work

With the hydronic concepts chosen in this study, the HP provides the entire DHW production, even for hybrid systems. At least for the parallel configurations, linking the boiler to the DHW production system would allow to reduce the HP capacity (see Table 2). While latter would most probably be interesting from an economic point of view, the environmental impact needs to be assessed.

Similarly, the proposed systems consist of a unique HP for SH and DHW, due to space availability and economic constraints. However, the installation of separate HPs for each mode (DHW and SH) could have the advantage of: i) adapting the HP capacity to the respective demands; ii) using refrigerants adapted to the temperature level of each operating mode; iii) simplifying the system hydronic and control.

Further work should also include: i) impact of sizing of storage tanks, in relation with actual constraints in existing MFB buildings; ii) sensitivity analysis regarding SH distribution temperature; iii) diverse climate conditions / locations; iv) sensitivity to / future evolution of the electricity mix and the related CO_2 content.

9. Conclusions

This paper aims to develop hybrid concepts with air-source heat pumps adapted to the specific context of existing multifamily buildings, without renovation of the building envelope. The concepts correspond to different fuel-switch scenarios, with and without the possibility of using pre-existing modulating or non-modulating boilers. They are analyzed via numerical simulations, validated on detailed in-situ monitoring. For each concept, a sensitivity analysis assesses the impact of different levels of heat demand and heat pump capacity (under or oversizing in hybrid mode), in terms of energy and environmental performance.

The sensitivity analysis shows that for optimizing the energy mix and reducing CO_{2eq} emissions, not only the heat pump performance should be considered, but also the overall system performance (heat pump and boiler). Over the different scenarios, the seasonal performance of the heat pump varies between 2.8 and 3.3, while the overall performance (heat pump and boiler) is between 1.5 and 2.9.

Despite reduced HP efficiency and high CO_{2eq} content of the hourly electricity mix in winter, monovalent systems lead to lower emissions than hybrid systems. However, emissions of hybrid systems remain 2.3 to 3.5 times lower than with a fossil boiler, which points out their adequacy as a transitional solution to proceed to a fuel-switch before retrofitting the building envelope (hence avoiding sizing the heat pump to meet the entire demand before the renovation, when only a fraction of the heat pump capacity will be needed in the long term).

Among the hybrid systems, none of the analyzed systems stands out significantly in terms of performance. In addition to performance, the economic aspects also come into play when deciding which system to install. While these were not directly considered, several elements relating to the heat pump sizing were raised. In this regard, monovalent systems require the installation of a heat pump that is 2 to 3 times more powerful than hybrid systems, sized to ensure 80% of the production with the heat pump.

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