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Large Air-to-Water Heat Pumps for Fuel-Boiler Substitution in Non-Retrofitted Multi-Family Buildings—Energy Performance, CO_2 Savings, and Lessons Learned in Actual Conditions of Use

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Citation: Montero, O.; Brischoux, P.; Callegari, S.; Fraga, C.; Rüetschi, M.; Vionnet, E.; Calame, N.; Rognon, F.; Patel, M.; Hollmuller, P. Large Air-to-Water Heat Pumps for Fuel-Boiler Substitution in Non-Retrofitted Multi-Family Buildings—Energy Performance, CO_2 Savings, and Lessons Learned in Actual Conditions of Use. *Energies* **2022**, *15*, 5033. https://doi.org/10.3390/en15145033

Academic Editor: Gianpiero Colangelo

Received: 31 May 2022
Accepted: 6 July 2022
Published: 10 July 2022

Abstract: The use of air source heat pumps (ASHP) in the specific context of existing multi-family buildings (MFB) represents an important challenge, especially in terms of performance and technical constraints in real conditions of use. This study concerns the actual performance of two non-retrofitted MFB (4047 and 7563 m^2), whose original fossil heat supply was replaced by a centralized monovalent (2×156 kW) and hybrid (6×34 kW) ASHP system for space heating and domestic hot water. Based on a detailed monitoring campaign covering two years of operation, it can be concluded that both systems are able to supply the required temperature and cover the entire heat demand. By closely following up these pilot projects, constraints linked to integration and operation were identified. Optimization measures allowed us to increase the COP of the monovalent system (from 1.3 up to 3.4, with an optimized SPF of 2.3) and to raise the HP share of the hybrid system (from 50% to 67%, with an optimized SPF of 2.3). Both systems offer major progress in terms of CO_2 savings (92% and 68%) and increased renewable energy share (75% and 43%), considering the hourly CO_2 content of the Swiss electricity mix.

Keywords: air to water heat pump; multi-family building; retrofit; monovalent and hybrid system; actual performance; in-situ monitoring

1. Introduction

1.1. Context and Issues

In Switzerland, buildings account for nearly 50% (100 TWh/yr) of the final energy demand and 24% (11.2 Mio. t/yr) of the CO_2 emissions [1,2], representing one of the most important sectors for massive decarbonization. Only demand for space heating (SH) and domestic hot water (DHW) amounts to about 94 TWh/yr [3], of which residential multi-family buildings (MFB) and single-family buildings (SFB) represent about 80%. Of these, 70% are still heated with individual fossil fuel boilers and around 80% of them were constructed before the 21st century. It is estimated that 80% of all residential buildings have an area-specific heating demand which exceeds the current minimum energy performance value for new constructions, with 40% of them reaching more than double this threshold [4].

Given the long lifespan of buildings (typically > 100 years), existing buildings will continue, within the next decades, to represent the overwhelming part of the energy demand of the entire stock. It has, for example, been shown that, with an increase of new heated area by 13% over 20 years, along with effective energy retrofit at an annual rate of

2%, in 2035 existing buildings of the Canton of Geneva would still represent around 93% of the entire heat demand of the sector [5]. In reality, we are however still witnessing quite low annual retrofit rates of the building stock and a nearly ineffective way of retrofitting: overall 1.7%, of which only 0.8% have resulted in an effective gain of at least one energy class [6]. Furthermore, the performance gap between projected and actual energy savings is quite significant, related to organizational disruptions along the retrofit process, as well as user-behavioral issues [7].

Especially in urban areas, MFB represent a particular challenge. While at a Swiss level, buildings with more than 5 households represent somewhat less than 15% of the stock, they account for about 45% of the heated area, and in urban cantons they represent about 30% of all buildings, but 60–70% of the heated area.

A massive switch from fossil to renewable energy could drastically reduce CO_2 emissions of the building stock (with or without combination of envelope retrofit, which could still stretch over several decades). This is particularly the case for HP systems, which represent the dominating renewable heating system for new buildings but are yet rarely installed in non-refurbished MFBs.

In dense urban areas, the air-source heat pump (ASHP) technology 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, lack of boreholes, no groundwater or prohibition of its use (water protection), no district heating network due to crowded soil, wood boilers prohibited in areas of excessive emissions, or limited solar energy due to roof size [8]. In such a context, outside air is the only renewable energy source for heat pumps available everywhere and in large quantity.

1.2. Heat Pump Market

While the potential Swiss market HP is huge (estimated up to 34 GW, respectively 75 billion CHF investment [9]), many challenges and obstacles need to be solved, in particular for large ASHPs in MFBs. One of the most significant technical challenges for the implementation of ASHP in MFBs is the lack of commercially available machines with a heating capacity above 50 kW_{th}, specifically designed for the residential sector. As a consequence, 81% of the 2016 Swiss HP market consists of machines below 20 kW_{th}, while in the fossil fuel boiler market, machines above 50 kW_{th} are almost on par with smaller ones [10,11].

The lack of large HP models can be explained by the fact that their implementation in existing MFB is more complex than in SFBs, mainly because of: (i) noise emissions, which can become a barrier, typically > 70 dB(A) for industrial HPs as compared to 50 dB(A) for residential HPs; (ii) use of refrigerant quantities that exceed the limit values for the residential sector; (iii) HP weight and related structural constraints of the roof; (iv) HP integration in the existing distribution system, originally designed for boilers, (v) higher shares of DHW, which can affect the HP performance; (vi) high investment cost; (vii) multiple households with diluted decision power and related problems of governance; (viii) lack of well-documented case studies proving the feasibility and sound operation of such systems. Nowadays, those constraints make large ASHP (>50 kW_{th}) an exception rather than a standard solution, especially in non-retrofitted MFB [10,12–14].

To reach capacities adapted to existing MFBs, the two current options are cascading smaller HP standardized for SFBs, or choosing a larger industrial product that is not designed for residential use [14]. So far, detailed case studies demonstrating the techno-economic feasibility and the environmental assessment of these two options have, however, not been documented in the literature.

1.3. Monitoring

Most of the literature on monitoring of ASHP in existing buildings focuses on SFBs (<450 m^2 of heated floor area), with capacities below 30 kW_{th} for a combined supply of SH and DHW. For example, Erb et al. [15] monitored 105 such systems in Switzerland

(<20 kW_{th}) in existing, new, and renovated single-family buildings. They observe, on average, an annual seasonal performance factor (SPF) of 2.7. Additionally, in Switzerland, Prinzing et al. [16] measured 12 ASHPs (20–30 kW_{th}) in renovated SFBs with floor heating or radiators, and found an average SPF of 3.0 (range: 2.4–3.7), without decreasing comfort. In Germany, Huchtemann et al. [17] analyzed 21 ASHP in existing SFBs formerly heated by oil boilers, with an SPF average of 2.33 (1.77–3.05). Two large monitoring campaigns in existing German SFBs were carried out by Miara et al. [18] and Danny et al. [19], respectively. In the first study (2008), 35 ASHP (<14 kW_{th}) showed an average SPF of 2.6 (2.1–3.4) in SFBs built between 1919–1996. In the second campaign (2018), 29 ASHP achieved an average SPF of 3.0 (2.4–3.7) in SFBs built between 1850 and 2005. As pointed out in [20], the increase in performance between the two studies is due to an increase of HP efficiency in the last ten years.

In some cases, ASHPs are used in SH mode only. For example, Xu et al. [21] monitored the performance of 103 ASHP (8–14 kW_{th}) in existing and new SFBs for SH in China. On average, floor heating systems reached an SPF of 2.37 as opposed to radiator systems with a value of 2.10. Chesser et al. [22] analyzed the in situ performance of 12 ASHPs (8.5–11 kW_{th}) for SH in retrofitted Irish houses. They obtained an SPF between 2.50–3.43, while the difference to rated manufacturer COP (coefficient of performance) values amounted to 16–24%.

As a complement to preceding studies, IEA Task 50 focuses specifically on the use of HPs for SH and DHW in new and existing MFBs. Within this task, various case studies in different European countries are analyzed, but they mostly concern new buildings and/or other heat sources than air [23].

1.4. Simulations

Several studies analyze the performance of ASHP in existing buildings via numerical simulation. As is the case for monitoring, most of them focus on small ASHP (<17 kW_{th}) in existing SFBs [24–28]. The performance results depend on the climate consideration, simulation method (ASHP and building), and whether they include DHW and/or SH.

Considerable attention is also paid to hybrid systems, i.e., the implementation of ASHPs in combination with the pre-existing boiler, used for peak-load. Several numerical simulation studies analyze the advantages of such hybrid systems in existing buildings, as compared to monovalent boiler or HP systems. They demonstrate benefits such as (i) primary energy savings as compared to boilers, (ii) higher performance and economic advantages compared to monovalent HP systems, (iii) avoidance of part-load operation, and a lower number of on–off cycles. However, most of these studies base their models on existing single houses with capacities below 30 kW_{th} for SH [29–34], and only a few include DHW [35].

To the best of our knowledge, only a few simulation studies concern larger existing buildings, with HP capacity above 30 kW_{th}. Lämmle et al. [36] simulate larger ASHP (52 kW_{th}) to cover the SH demand of existing and renovated MFB built in 1995 (2112 m^2 on five floors with a total of 30 apartments), with a focus on the reduction of SH temperatures in order to increase the ASHP performance. They show that each Kelvin of reduced heat pump temperature increases the SPF by 0.10–0.13 points. On the other hand, Fraga et al. [37] performed simulations of six different HP sources (air, geothermal, deep lake, river, groundwater, and solar) for different MFB demands (new, renovated, and non-renovated buildings). The results show an SPF of 3.0 for non-renovated residential buildings with an ASHP.

1.5. Environmental Indicators

Besides the intrinsic HP performance, several researchers quantified the CO_{2eq} emissions related to the use of electricity in HPs, but this is usually done by means of an average annual CO_{2eq} emission factor for electricity from the grid [17,25,27,29,30,38]. However, this assumption could strongly underestimate the emissions, since the carbon content of electricity varies across the seasons. In winter, and in particular for ASHPs, the HP performance drops when the building's thermal demand is at its maximum load, which is usually also the period when the grid has the highest CO_{2eq} content due to the relatively high share of fossil-fuel based power plants. A recent simulation study taking into account the hourly electricity consumer mix of Switzerland showed that the CO_{2eq} content of electricity used by ASHPs is around 150 g/kWh_{elec}, as compared to 108 g/kWh_{elec} for the annual average grid mix [39].

1.6. Objectives of This Study

Overall, the extant literature review shows no reliable evidence of the technical feasibility, constraints under actual conditions of use, nor of the actual technical and environmental performance of large ASHPs, implemented in a monovalent or hybrid system, especially in non-retrofitted MFBs. Given this knowledge gap, the public utility of Geneva, together with the Cantonal authorities, the umbrella associations of the building industry and building owners, are setting up a program for massive replacement of individual fossil-fueled boilers by HPs. The objective for the next 15–20 years is to realize 25,000 fuel-switch operations (1.6 GW), with expected CO_{2eq} savings of 450,000 t/yr. In terms of installed capacity, around 35% of these operations concern large, non-retrofitted MFBs, mainly in a dense urban environment, with air as the main available heat source, hence leading to the above-mentioned challenges.

This paper concerns the monitoring and the detailed analysis of the first two pilot projects of this program, with monovalent and hybrid ASHP (>50 kW_{th}) implemented in non-retrofitted MFBs. Both projects were monitored in time steps of 5 min over the first two years of operation and they were assessed in terms of SPF, CO_{2eq} emissions, and renewable energy share, taking into account the actual Swiss electricity mix in hourly values. Issues and constraints linked to the integration and operation of the system were also identified.

The present paper addresses the following research questions:

- What actual performance can we expect from ASHP systems in large non-retrofitted MFBs?
- What are the potential constraints and issues of such systems, namely in terms of monovalent versus hybrid HPs, as well as large industrial HP units versus bundled standardized small HP units?
- What are the renewable energy fraction and the actual CO_{2eq} savings based on the actual hourly Swiss electricity mix?

2. Description

2.1. Monitorited Buildings

Located in the city center of Geneva, both pilot projects concern non-retrofitted MFBs, with a heated floor area above 4000 m^2 each. The two buildings represent the most common building types in Geneva, constructed during the two main phases of the city's development:

- Project 1 (monovalent HP system): This building was constructed in 1972, during the baby-boom period, and it is characterized by a cheap structure and a poor envelope quality. It has a heated floor area of 4047 m^2 (7 floors), and its envelope has not undergone any retrofit.
- Project 2 (hybrid HP system): This building was built in 1992 during a construction boom, using a pre-fabricated envelope. It has a total heated floor area of 7563 m^2 (5 floors), and its thermal envelope has not been renovated.

Figure 1a shows the distribution of the normalized SH demand (climate corrected to standard 2659 heating degree days, as given by the Swiss norm SIA 381/3 [40]) for the stock of MFBs in Geneva, grouped according to three major construction periods [41]. While this distribution characterizes the situation in Geneva, a study has shown that it compares well with the Swiss national building stock [3]. Red dots represent normalized space heating demand of the monovalent (277 MJ/m^2/yr) and hybrid (259 MJ/m^2/yr) systems, respectively. It can be seen that even though their thermal envelopes have not been renovated, their SH is lower than the median value of their respective construction period.

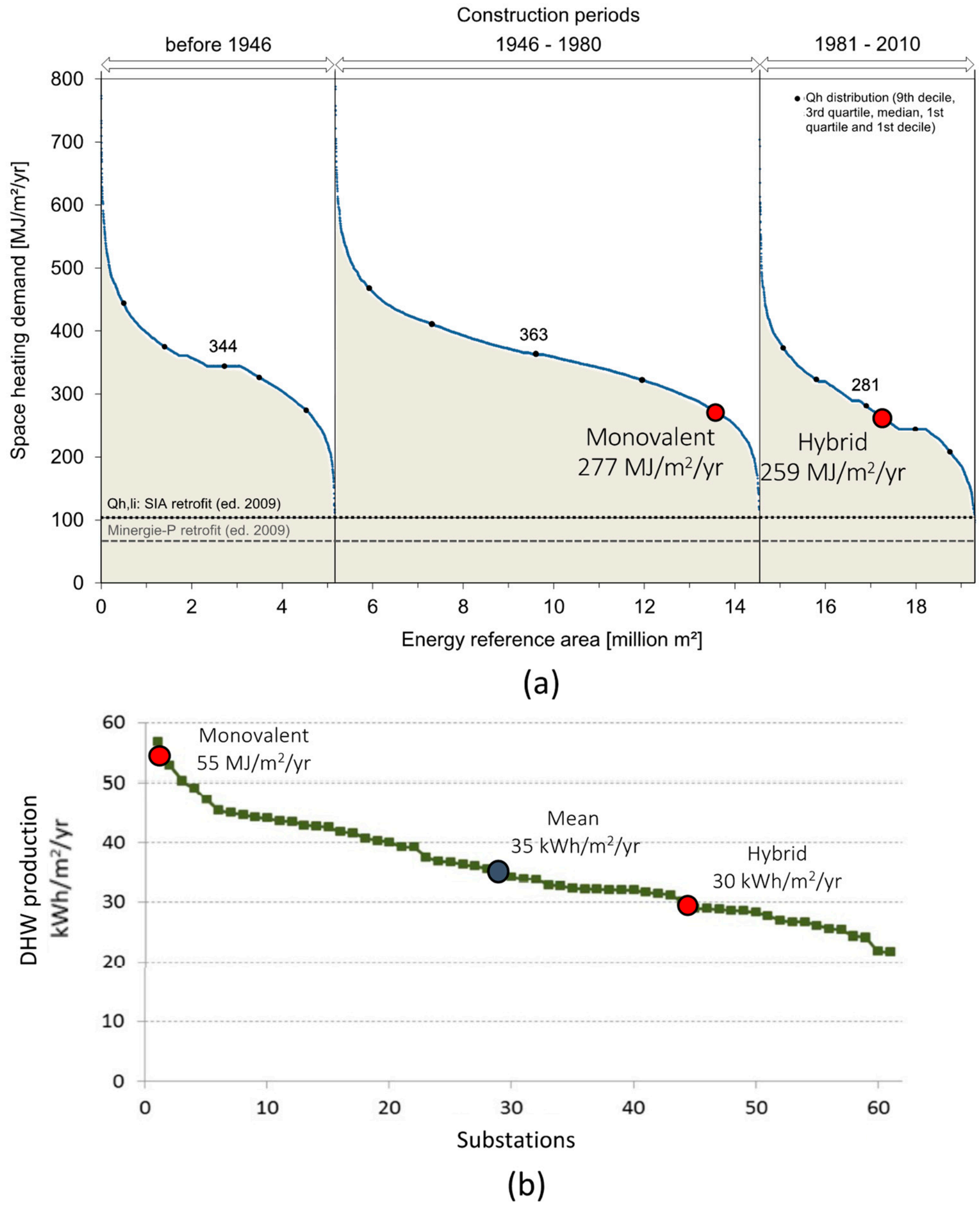

Figure 1. SH and DHW heat demand of monitored buildings (red dots) compared to Geneva's multifamily building stock. (**a**) SH demand of Geneva's multifamily building stock sorted in three construction periods [41]. (**b**) Distribution of the DHW demand of 61 substations supplying residential buildings for a total of approximately one million m^2 of heated floor area [42].

It is also possible to benchmark these projects regarding their heat demand for DHW production. Figure 1b shows the heat production for DHW (including storage and distribution heat losses) of 61 substations connected to a district heating network (DHN) in Geneva [42]. The DHN supplies 434 MFBs (with about 1 million m^2 of heated floor area). Red dots represent the DHW production of the monovalent (55 kWh$_{th}$/m^2/yr) and hybrid (30 kWh$_{th}$/m^2/yr) systems, while the black dot represents the benchmark average (35 kWh$_{th}$/m^2/yr). The monovalent system is among the highest values observed for DHW heat demand values (useful energy) found in MFBs in Geneva, whereas the hybrid building is below the benchmark average.

2.2. ASHP System

For both projects, given the location and legal constraints, implementation of ground source HP or biomass boiler was not possible. At the same time, these projects are representative of the available options to install large capacity ASHP in existing MFB, with two distinct options: (i) large industrial ASHP units, not specifically designed for residential use (monovalent system) or (ii) cascading of small modules designed for SFBs (hybrid system). Table 1 summarizes the main characteristics of the two pilot projects.

Table 1. Summary of the main characteristics of the two pilot projects.

	Monovalent	**Hybrid**
Type of building	Residential	Mixed (residential + commercial)
Construction year	1972	1992
Heated floor area	4047 m^2	7563 m^2
Old heating system	Oil boiler (319 kW_{th})	Gas boilers (2 × 200 kW_{th})
New heating system [1]	2 industrial ASHPs (2 × 156 kW_{th})	6 ASHPs (6 × 34 kW_{th}) + Existing gas boiler (200 kW_{th})
SH demand (measured)	58 $kWh_{th}/m^2/yr$	64 $kWh_{th}/m^2/yr$
SH demand (normalized) [2]	77 $kWh_{th}/m^2/yr$	72 $kWh_{th}/m^2/yr$
DHW demand [3]	55 $kWh_{th}/m^2/yr$	30 $kWh_{th}/m^2/yr$
Monitoring period	July 2018–June 2020	July 2017–June 2019

[1] Capacity reported by manufacturer for 7 °C at the evaporator inlet and 45 °C at the condenser outlet. [2] The normalized heating season in Geneva is 2659 heating degree days (HDD) 18/12 °C [40]. [3] Including storage and distribution losses.

2.2.1. Monovalent ASHP System

In this case, the existing oil boiler was replaced by two industrial ASHP (2 × 156 = 312 kW_{th}) installed on the roof and surrounded by sound-proofing wall panels (see Figure 2b). The nominal COP is 3.42 for an evaporator inlet temperature of 7 °C and a condenser outlet temperature of 45 °C. Each ASHP has a fixed flow rate (30 m^3/h each) and 4 scroll compressors, providing 4 power levels adjusted to the load. These units can reach up to 60 °C for DHW preparation, to avoid legionella risk. The internal ASHP regulation manages the cascade (including compressors of the two units), while an external regulation controls the elements located in the boiler room (valve openings, activation of circulators, etc.). The oil boiler was kept as a backup for the first year of operation, but it was eventually dismantled.

Figure 2. Monovalent ASHP system. (**a**) non-retrofitted MFB and (**b**) industrial ASHP on the roof with sound-proofing wall panels.

As can be seen in Figure 3, the distribution includes one storage tank for SH (1 m^3) and two storage tanks for DHW (1 m^3 each). For better stratification (and as represented by the orange line), the DHW tanks are connected in series: tank 1 for preheating, tank 2 for heating up to a 55 °C setpoint (respectively 60° once a week during 3 h, for anti-legionella treatment). In case of DHW production, the flowrate from the ASHPs (design value: 30 m^3/h each) is reduced by way of a three-way valve positioned before the heat exchangers for DHW (design value: 2.3 m^3/h each).

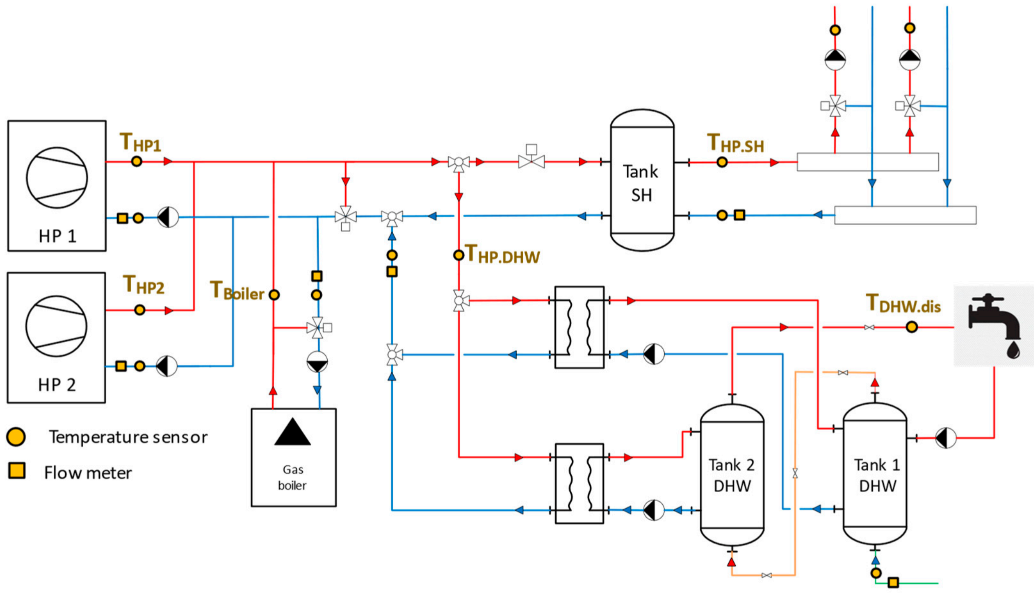

Figure 3. Hydraulic diagram of the monovalent ASHP system. The ASHP production is measured close to the HP units; for this reason, the measured heat production includes distribution losses. Red lines: hot flows, blue lines: cold flows and yellow lines: warm flows.

The ASHP 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.

2.2.2. Hybrid ASHP System

Unlike the previously described pilot project, in this case the roof could not support heavy ASHPs. Therefore, six single-family house-type ASHPs (Figure 4b) were installed on the roof (6 × 34 kW_{th} = 204 kW_{th} at 7 °C/45 °C), operating in parallel with a pre-existing gas boiler (200 kW_{th}). The installed ASHP capacity was designed to cover 80% of the total annual heat demand (SH and DHW), which is coherent with the HPs production temperatures being intrinsically limited to 55 °C.

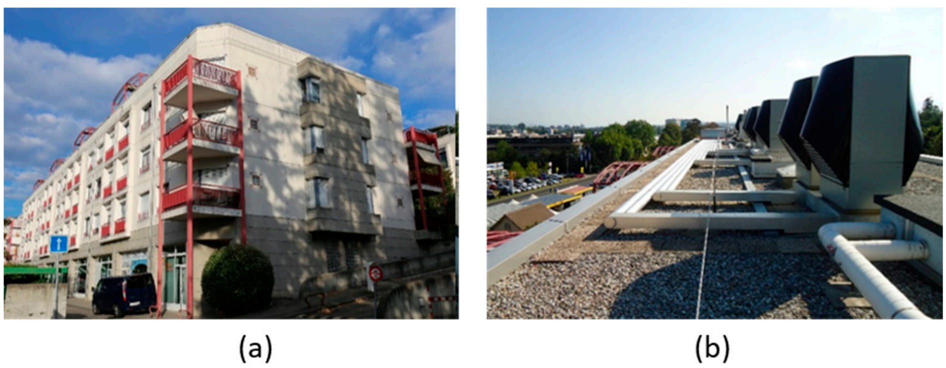

Figure 4. Hybrid ASHP system. (**a**) Non-retrofitted MFB and (**b**) six air-to-water heat pumps on the roof.

Since these ASHP are optimized for residential use, there was in principle no need to invest in a specific soundproofing structure. The COP reported by the manufacturer is 3.5 (at 7 °C/45 °C). Each ASHP has two power levels (two scroll compressors) and operates at a fixed water flow rate (5 m^3/h).

Of the 6 HP units, 3 are dedicated to SH production, while the other 3 provide DHW in priority and backup SH if necessary. The gas boiler supplies the uncovered heat for SH and DHW, either in terms of missing load or insufficient temperature levels.

The DHW and SH systems (Figure 5) each include two storage tanks of 1 m^3 each connected in series (total: 2 m^3 for DHW + 2 m^3 for SH). In both cases, the HPs provide preheating of the first tank (HP tank), while the gas boiler provides the complementary heat to the second one (boiler tank).

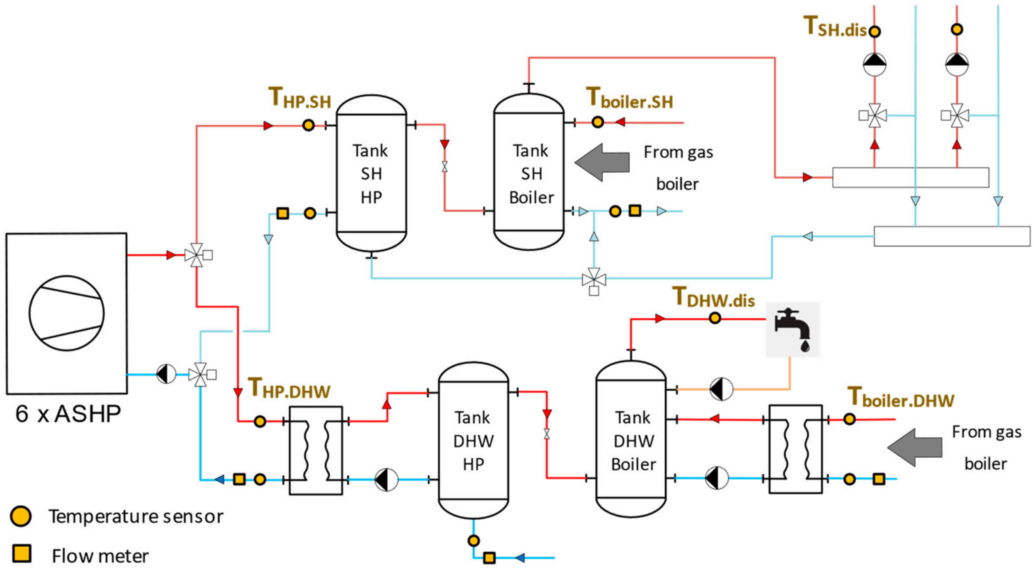

Figure 5. Simplified hydraulic diagram of the hybrid ASHP system. The six heat pumps are represented schematically by a single unit. The ASHP production is measured on the roof; for this reason, the measured heat production does not include distribution losses. Red lines: hot flows, blue lines: cold flows and yellow lines: warm flows.

Control and cascading of the diverse units is a specific and complex issue (see also Appendix A):

- In SH mode, the 6 HP units are bundled in 2 groups, each composed of a master HP controlling two slave HPs (which is the maximum number of slaves the internal regulation of these master HPs can handle). Optimal heat production in relation with SH load is provided by the internal regulation of each master HP, which controls cascading of the three related units (according to the actual SH distribution temperature, related to the SH heating curve). The master of the first HP group (dedicated to SH) also controls complementary on/off switching of the boiler, with a parametrizable time delay.
- In DHW mode, the 3 dedicated HP units operate independently from each other (no integrated master/slave operation available). A "manual" cascade is induced by way of distinct temperature setpoints for on/off switching in relation to the temperature of the HP storage tank (common upper setpoint for HP switch off, distinct lower setpoints for each HP switch on). In the absence of an integrated master/slave operation mode, complementary on/off switching of the boiler is activated by a mechanical thermostat.

3. Methodology

3.1. Monitoring

For the monovalent system, the instrumentation consists of 29 sensors (Figure 3): 14 thermocouples, 6 flowmeters, 2 electric and 6 heat meters, and 1 sensor for air outlet temperature. They allow for control of the following energy flows: HP production; DHW heat charge (at the inlet of heat exchangers) and discharge (outlet of tank storage); SH heat discharge of the tank; electricity consumption of the HPs (including electricity of the HPs circulation pump) and boiler production.

For the hybrid system, the instrumentation consists of 23 sensors (Figure 5): 12 thermocouples, 5 flowmeters, 1 electric and 4 heat meters, and 1 sensor for air outlet temperature. They allow for control of the following energy flows: HP production for DHW and SH; boiler production for DHW and SH; DHW discharge from the tanks and overall electricity HPs consumption (including electricity of the six HP circulation pumps).

In both cases, additional data is monitored by the internal ASHP software, such as compressor activation, defrost cycles, high pressure/low pressure alarms, SH or DHW mode, etc.

All the data is recorded by the building management system every 5 min (instantaneous values) and is sent on a daily basis to a server to be cleaned and analyzed in python later on.

The monitoring campaign covered two years of operation for each project: July 2018–June 2020 for the monovalent system; July 2017–June 2019 for the hybrid system.

3.2. Performance Indicators

In order to evaluate the performance of the different systems and to compare them, various energy and environmental performance indicators are used in this study.

3.2.1. Energy Performance

For short time periods (days), the energy performance of the systems is evaluated using the HP coefficient of performance (COP), with and without auxiliaries, as defined by Equations (1) and (2). Q_{HP} represents the amount of daily heat production. E_{HP} is the daily electricity consumption (without auxiliaries), while E_{HP+aux} is the daily HP electricity consumption, including auxiliaries.

$$COP_1 = \frac{Q_{HP}}{E_{HP}} \quad (1)$$

$$COP_2 = \frac{Q_{HP}}{E_{HP+aux}} \quad (2)$$

The annual energy performance of the system is evaluated by the seasonal performance factor (SPF_{sys}) according to Equation (3). It is defined as the ratio between annual heat production (Q_{HP}) and annual HP electricity consumption, including HP circulators (E_{HP+aux}).

$$SPF_{sys} = \frac{\sum Q_{HP}}{\sum E_{HP+aux}} \quad (3)$$

In the case of the hybrid system, the overall system performance is evaluated by the Equation (4), where Q_{boiler} is the annual heat production by the boiler and E_{fossil} is the annual gas consumption.

$$SPF_{global} = \frac{\sum(Q_{HP} + Q_{boiler})}{\sum(E_{HP+aux} + E_{fossil})} \quad (4)$$

3.2.2. Environmental Performance

The environmental performance of the systems was evaluated in terms of CO_{2eq} emissions related to the operation of the heat generators (ASHP and boiler).

Emissions related to the ASHP electricity consumption are calculated by means of Equation (5), where $E_{HP.aux.h}$ is the hourly electricity consumption of the ASHP (in kWh_{elec}) and $f_{elec.h}$ (in g or $kgCO_{2eq}/kWh_{elec}$) is the hourly CO_{2eq} content of Swiss electricity mix during the monitoring period, taking into account domestic generation as well as imports from neighboring countries. The latter profile is given by the work of Romano et al. [43], which is presented in Appendix B for the period 2017 to 2020, with an overall average of 96 gCO_{2eq}/kWh_{elec} (but daily peak values, mainly in the winter, reaching 500 to 800 gCO_{2eq}/kWh_{elec}).

$$C_{elec} = \sum_h E_{HP+aux.h} \cdot f_{elec.h} \quad (5)$$

For the fossil boilers, emissions are evaluated by Equation (6), with a constant emission factor (f_{fossil}) equal to 203 gCO_2/kWh_{th} for gas and 265 gCO_2/kWh_{th} for oil [44]. Finally, the total CO_2 emissions of the system (in g or $kgCO_{2eq}$) were evaluated by Equation (7).

$$C_{fossil} = \sum E_{fossil} \cdot f_{fossil} \quad (6)$$

$$C_{global} = C_{elec} + C_{fossil} \quad (7)$$

The annual renewable energy fraction from ASHP electricity consumption was assessed with Equation (8), where $E_{HP.aux.h}$ is the hourly electricity consumption of the ASHP (in kWh_{elec}) and $\phi_{Elec.h}$ is the hourly Swiss electricity share produced by primary energy originating from renewable sources, according to the work of Romano et al. [43]. The latter profile is presented in Appendix B for the period 2017 to 2020, with an overall average share of the electricity originating from renewable sources of 47% (but daily shares values in summer reaching 60% to 80%).

Finally, the annual renewable fraction of total heat production ($\beta_{Heat.REN}$), including heat extracted from the air source (Q_{air}), is estimated by Equation (9).

$$E_{REN} = \sum_h E_{HP+aux.h} \cdot \phi_{Elec.h} \quad (8)$$

$$\beta_{Heat.REN} = \frac{\sum(E_{REN} + Q_{air})}{\sum(Q_{HP} + Q_{boiler})} \quad (9)$$

4. Results—Monovalent System

4.1. Annual Energy Balance, CO_2 Emissions, and Renewable Energy Fraction

In the case of the monovalent system, the annual heat production (Second year of operation, 1st July 2019 to 30th June 2020) amounts to 113 $kWh_{th}/m^2/yr$, with a SPF_{sys} of 2.3, including auxiliaries, as shown in the Sankey diagram (Figure 6a). The production is divided into 49% for DHW (55 $kWh_{th}/m^2/yr$, including storage and distribution losses) and 51% for SH (58 $kWh_{th}/m^2/yr$). Losses related to DHW storage and the recirculation loop account for 25% (14 $kWh_{th}/m^2/yr$) of the total DHW production. For this type of building, these losses are rather low compared to 30% reported in norms [45], which could be explained by the fact that this building has an exceptionally high DHW demand, thus losses become less significant.

As shown in Figure 6b, 75% of the annual heat production (83.3 $kWh_{th}/m^2/yr$) turns out to be renewable, of which 56% is extracted from the air, with 19% of electricity originating from renewable sources (as given by the hourly electricity mix).

Figure 7 represents the evolution of the heat production over the 2010–2019 period, normalized to standard weather, and subdivided by heat generator (boiler + HP). For the 2010–2016 period, the heat production is derived from measured oil consumption, with an estimated a boiler efficiency of 70% and an uncertainty of 5% (represented by the error bars). In the first two years of HP operation (2018 and 2019), both the HP and the boiler production are measured values, which were determined with the newly installed heat-meters.

In 2018, the oil boiler had to be exceptionally turned on due to a HP breakdown. Interestingly (and without straightforward explanation), the normalized heat production (151 $kWh_{th}/m^2/yr$) was significantly above the average of the 2010–2016 period (110 $kWh_{th}/m^2/yr$). A much smaller gap is observed for 2019, the second year of HP operation (132 $kWh_{th}/m^2/yr$, of which 55 for DHW and 77 for normalized SH).

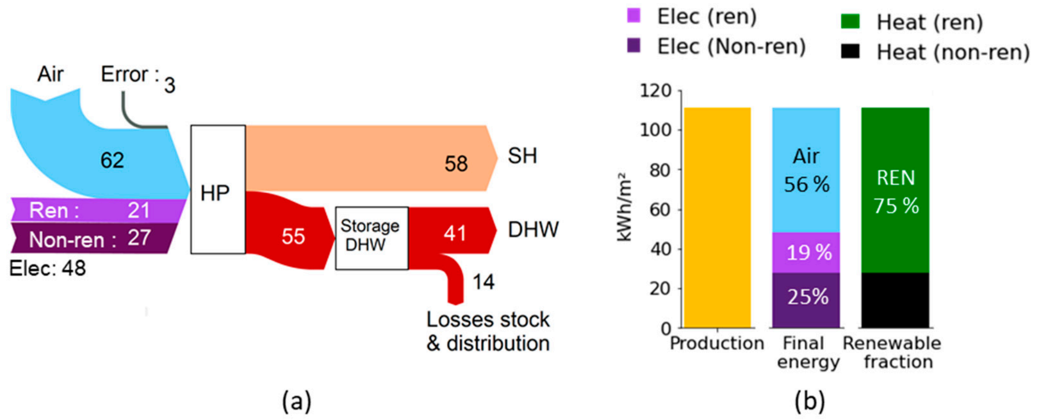

Figure 6. (**a**) Sankey diagram of the monovalent ASHP sytem in kWh/m^2/yr. (**b**) Heat production, decomposed by source and renewable/non-renewable energy fraction. Second year of operation (1 July 2019 to 30 June 2020) in kWh/m^2/yr.

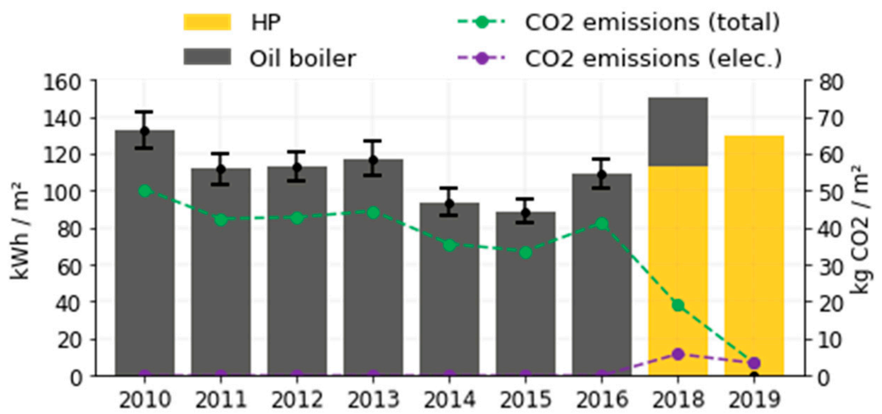

Figure 7. Monovalent ASHP system: evolution of the heat production (normalized to standard weather) in kWh$_{th}$/m^2/yr and CO_{2eq} emissions in kgCO_{2eq}/m^2/yr, over the 2010–2019 period. Each year runs from July to June of the next year (e.g., 2019 = 1st July 2019 to 30th June 2020). The error bars represents the heat production uncertainty due to the boiler efficiency estimated at 70% $\pm$ 5%.

Figure 7 also shows the evolution of the CO_{2eq} emissions, global (boiler + HP) or linked to electricity consumption of the HP only. While we observe average emissions of 42 kgCO_2/m^2/yr during the 2010–2016 period, this value drops to 3.4 kgCO_2/m^2/yr during the second year of HP operation. Due to the overall low carbon content of the Swiss electricity mix (even if considering electricity imports from neighboring countries), the replacement of the oil boiler by an ASHP system hence resulted in significant emissions savings of 92%, despite a rather low SPF_{sys} of 2.3, as well as the relatively high carbon content of the electricity during some winter months (see Appendix B). Note that the savings of CO_{2eq} (92%) are higher than the renewable energy share (75%), which is due to the share of nuclear electricity in the Swiss mix (average of 43% in 2019), which contains little CO_{2eq} emissions.

4.2. Heat Demand and Production

Figure 8 represents the daily heat demand and production over the two years of operation (July 2018–June 2020). Overall, the DHW production is higher during the first than during the second year (64.8 and 54.1 kWh$_{th}$/m^2/yr, respectively), as shown in Figure 8a. There are also notable differences with regard to the pattern: (i) at the beginning of the second heating season (around November 2019), we observe 3 short periods of unexplained high DHW loads; (ii) except for latter peaks, the seasonal pattern is somewhat more regular than during the first year. Regarding SH, due to slightly colder weather, the first year of operation (76.6 $kWh_{th}/m^2/yr$, for 2368 HDD) is characterized by higher demand than the second year (58.0 $kWh_{th}/m^2/yr$, for 2007 HDD).

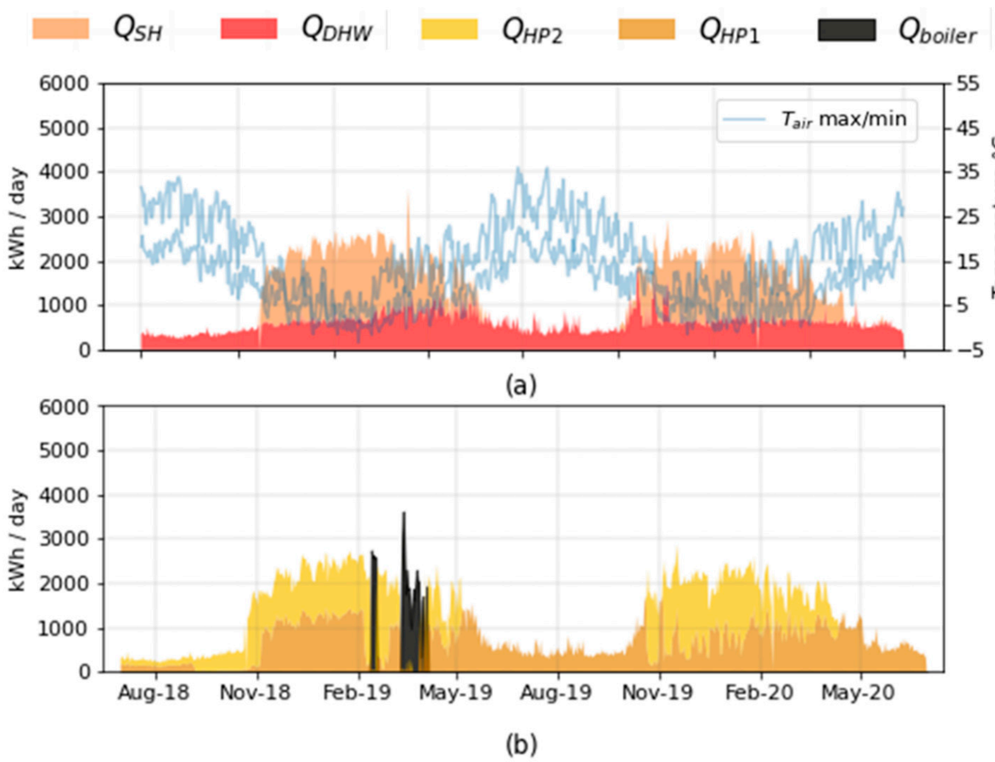

Figure 8. Monovalent ASHP system: (**a**) Daily SH and DHW production, as well as minimum/maximum outdoor temperature and (**b**) Daily HP and boiler production, over two years of operation in kWh_{th}/day (July 2018–June 2020).

Over these first two years of operation, the demand was almost entirely covered by the two ASHPs, as shown in Figure 8b. In the middle of the 2018–2019 winter, the ASHP system suffered two breakdowns (February and March 2019), and the oil boiler was exceptionally turned on. The ASHP breakdown took an entire month to be solved, due to the necessity to wait for a trained technician from another region of the country. During the first summer (up to September 2018), both ASHPs were operated in parallel, while from the second summer onwards, priority was given to one HP in order to improve the load factor, as well as to reduce auxiliary electricity.

Furthermore, during this period the heat production temperatures were optimized as follows (see Appendix C for more details):

- In SH mode: during the first year of operation, the SH production temperature always remained above 50 °C, not taking into account the heating curve defined at the level of the centralized automation; the latter was fixed for the second year, during which the heating curve was also was reduced by approximately 5 K.
- In DHW mode: during the second year, adjustments in the DHW setpoint also helped to decrease the distribution temperature, and hence the HP production, by about 3–5 K each.

4.3. HP Capacity and Heat Load

Figure 9 shows the observed load (by bins of outdoor temperature of 5 °C), in relation with the related HP capacity (for a production temperature of 60 °C). As a complement, Appendix D provides information concerning the respective SH and DHW shares, as well as the actually observed HP production temperature.

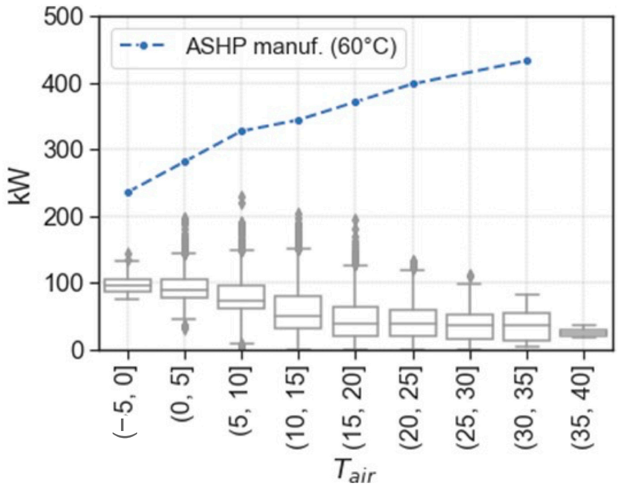

Figure 9. Monovalent ASHP system: Hourly heat load (kW_{th} by bins of outdoor temperature of 5 °C), in relation to the HP capacity (July 2019 to June 2020). The heat load is represented by boxplots, with 50% of the hourly heat load within the box (median +/−25%), 80% within the upper and lower marker, and the 10% min and max outliers represented by dots.

As expected, the median HP load decreases with rising outdoor temperatures and the related drop of the SH load (from around 100 kW_{th} in the 0–5 °C range, down to around 45 kW_{th} in the 15–20 °C range). In contrast, the rated HP capacity rises from 235 kW in the lowest bin (−5 to 0 °C), up to 433 kW_{th} in the highest bin (30 to 35 °C). As a result, the installed HP capacity remains in all bins much higher than the observed peak load. In the 0–5 °C range, where the difference between HP capacity (280 kW_{th}) and peak load (196 kW_{th}) is the smallest, the capacity/load ratio hence still amounts to 143%.

The latter analysis leads to the following insights: (i) at the design stage, the only available data were the historic annual oil consumptions, from which the heat demand was only roughly estimated based on an expected boiler efficiency; the latter points to the added value which can be brought by heat metering over a few weeks or months during the project design phase, for better estimation both of the overall demand and its separation in SH and DHW components; (ii) as observed in Appendix D, the highest loads only occur during very few hours of the year, which leads to a reflection concerning possible downsizing of the HP capacity and related investment to lower values (in this case possibly by a factor 2), with sporadic peak complements covered by an electric rod.

4.4. ASHP Performance

The evolution of the ASHP system performance during the monitored period is depicted in Figure 10. Summer 2018 is characterized by the lowest COP_2, below 1.5, despite high outdoor air temperatures. The following reasons for the low performance were identified:

- During this period, one of the ASHP had its circulation pump constantly activated, even when the production was off. This error caused an electricity overconsumption of 72 kWh_{elec}/day without production, which degraded the COP_2 from 2.1 to 1.5 during summer 2018. This overconsumption represents 31% of the ASHP system's daily electricity consumption in summer. It becomes less important in the winter (5%).
- In the case of DHW production, the large flowrate in the ASHPs as compared to the one in the DHW heat exchangers (see Section 2.2.1) resulted in high return temperatures to the ASHPs, which reduced their performance. The problem was eventually solved by letting the entire flow from the ASHP circulate through the heat exchangers.

These adjustments resulted in a significant increase of COP_2 , which from May 2019 onwards reached values equal to 2 or higher, up to 3.1 when the outdoor temperature was highest. During the second year of operation, performance generally followed the outdoor temperature fluctuations.

As a complement, Appendix E shows the daily measured COP_2 and COP_1 as a function of the HP temperature increase (difference between HP production and outdoor). Unlike COP_2, which includes auxiliaries, COP_1 values follow the ones given by the manufacturer, which confirms that the low system performance observed during the first summer was indeed not due to a deficiency of the ASHP units, but to non-optimal system operation.

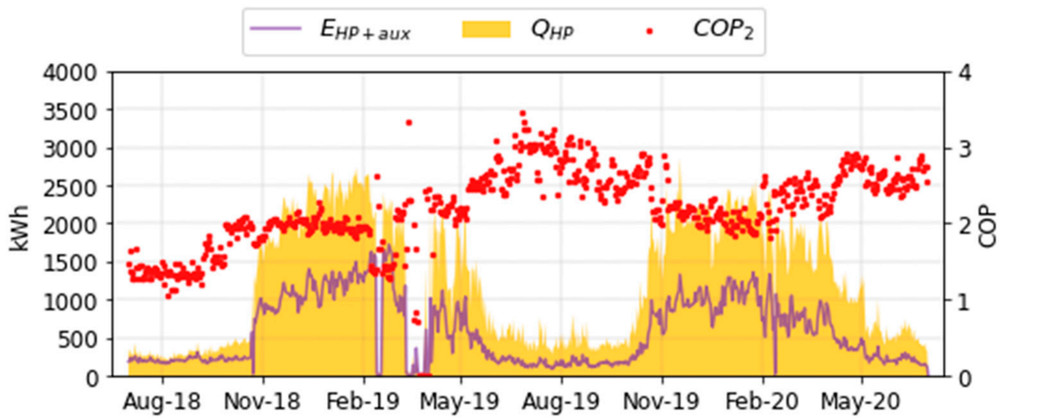

Figure 10. Monovalent ASHP system: Daily heat production (kWh_{th}/day) and electricity consumption (kWh_{elec}/day) of the two ASHP as well as COP_2 (performance during the breakdown period is not considered).

5. Results—Hybrid System

5.1. Annual Energy Balance, CO_2 Emissions, and Renewable Energy Fraction

In the case of the hybrid system, the annual heat production of the second year is 94 $kWh_{th}/m^2/yr$, of which the ASHP covers 67% with a SPF_{sys} of 2.3 (including auxiliaries and excluding ASHP distribution losses), as shown in the Sankey diagram in Figure 11. The gas boiler provides the rest with a monitored annual efficiency of 69% (relative to the higher heating value, HHV). This efficiency is relatively low but typical for a non-condensing boiler, dating from the construction of the building. The overall system performance, including ASHP and boiler efficiency (SPF_{global}), is equal to 1.28. This value is relatively low but is explained by the malfunctioning described below. With a boiler efficiency of 90% (on HHV) and without ASHP breakdowns, the SPF_{global} of this system would increase up to 1.7. The total annual heat demand is composed of 68% for SH (64 $kWh_{th}/m^2/yr$) and 32% for DHW production (30 $kWh_{th}/m^2/yr$).

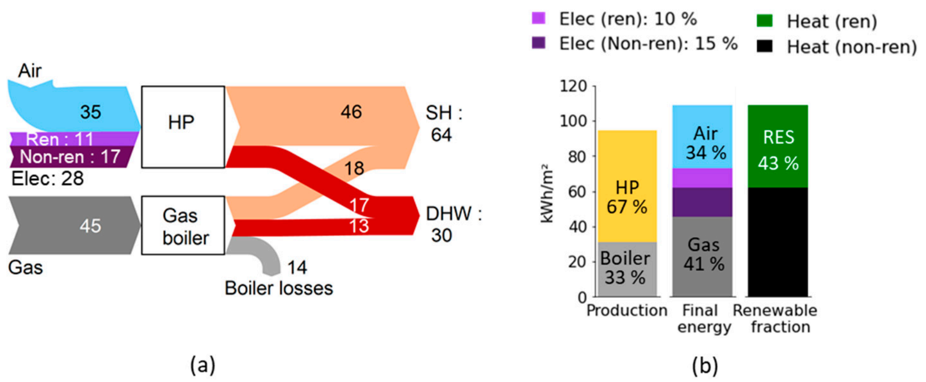

Figure 11. (**a**) Sankey diagram of the hybrid ASHP system in $kWh/m^2/yr$. (**b**) Heat production, decomposed by source, and renewable/non-renewable energy share. Second year of operation, from July 2018 to June 2019 ($kWh/m^2/yr$). The ASHP measured production does not take into account ASHP distribution losses.

As shown in Figure 11b, 43% of the annual heat production (46 $kWh_{th}/m^2/yr$) turns out to be renewable, of which 34% is extracted from the air and 9% of electricity originates from renewable sources (as given by the hourly electricity mix).

Figure 12 represents the evolution of the heat production over the 2010–2018 period, normalized to standard weather, and subdivided by heat supply system (boiler + HP). The heat production is given by the measured heat production of the boiler (entire period) and the HP (2017 and 2018). In contrast to the first project, the normalized heat production in 2017 and 2018 (98 $kWh_{th}/m^2/yr$ and 102 $kWh_{th}/m^2/yr$) was 29% and 26% lower, respectively, than average over the 2010–2016 period (138 $kWh_{th}/m^2/yr$).

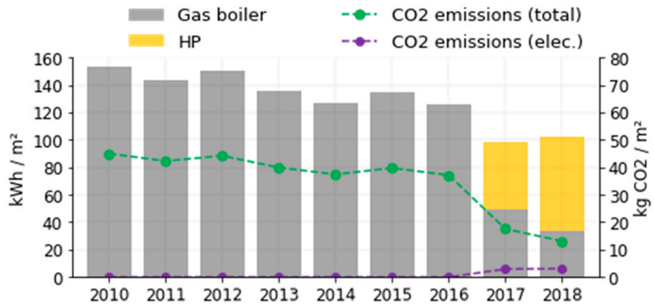

Figure 12. Hybrid ASHP system: Evolution of the heat production (normalized to standard weather) in $kWh_{th}/m^2/yr$ and CO_{2eq} emissions in $kgCO_{2eq}/m^2/yr$, over the 2010–2018 period. Each year runs from July to June (e.g., 2018 = 1st July 2018 to 30th June 2019).

Figure 12 also indicates the evolution of the CO_{2eq} emissions (HP + boiler). While we observe average emissions of 40 $kgCO_2/m^2/yr$ during the 2010–2016 period, this value drops to 18 $kgCO_2/m^2/yr$ during the first year of HP operation (57% savings) and to 13.1 $kgCO_2/m^2/yr$ during the second year of HP operation (68% savings) as a result of adjustments and optimization explained below. As for the monovalent case, the savings of CO_{2eq} (68%) are higher than the renewable energy share (43%) due to the share of nuclear electricity in the Swiss mix (average of 41% in 2018).

5.2. Heat Demand and Production

Figure 13 represents the daily heat demand and production over the first two years of operation (July 2017—June 2019). Overall, the DHW production is very similar for both years (31.3 and 30.3 $kWh_{th}/m^2/yr$), which is also the case for the seasonal pattern. Due to similar weather constraints, SH for the first year of operation (61.1 $kWh_{th}/m^2/yr$, for 2431 HDD) is also comparable to the second year (64.2 $kWh_{th}/m^2/yr$, for 2368 HDD). However, with regard to the seasonal pattern, we observe especially high SH peaks during the first winter due to outdoor temperature dropping to −9.8 °C in February 2018, but otherwise unexplained. Also note two failures in the monitoring system, during 5 days in April 2018 and 3 days in June 2019.

While the hybrid ASHP system was sized to cover 80% of the annual demand with the HPs, it only amounted to 50% during the first year of operation, with an increase up to 67% during the second year (Figure 13b). This can be explained by the following malfunctioning and the related adjustments:

- In SH mode: during the first year of operation, the system suffered several HP shut-downs when the boiler was activated, caused by high SH return temperatures being directed to the HP storage tank (see Figure 5), which in turn was causing high-pressure alarms on the HPs. The problem was eventually solved by: (i) implementation of a three-way valve on the SH return flow which, when the SH return temperature is too high for the HP, is now redirected towards the boiler instead of the HP storage tank; (ii) increased delay for boiler switch-on, leaving more time for the HPs to operate in stand-alone mode.

- In DHW mode: during the first year of operation, the "manual" cascading of the 3 dedicated HPs was causing a slow thermal response of the storage tank, leading to complementary switch on of the boiler for reaching of the desired DHW temperature. The problem could eventually be solved by defining identical on/off setpoints in each HP, getting rid of the cascading effect (all 3 HPs switched on and off at the same time), reducing the thermal response of the storage. However, this adjustment induces shorter and numerous HP on/off cycles, which reduces the life expectancy of the machine and decreases the performance, as shown in several studies [46,47].
- At the beginning of the second heating season, in November 2018, SH is provided only by the boiler, due to a manual valve which remained closed, preventing heat distribution by the HPs. Between March and April 2019, SH is again provided only by the boiler, due to a breakdown of the HPs.

Additionally, during this period the heat production temperatures were adjusted as follows (see Appendix C for more details):

- In SH mode: during the second year of operation, the heating curve was limited to a maximum of 50 °C, compatible with the maximum HP production temperature of 55 °C, so that the boiler had to not be activated for insufficient temperature, but only for missing capacity.
- In DHW mode: during the second year, adjustments in the setpoints allowed to increase the HP production temperature and reduce the temperature of the boiler, contributing to an increase of the HP share in DHW production.

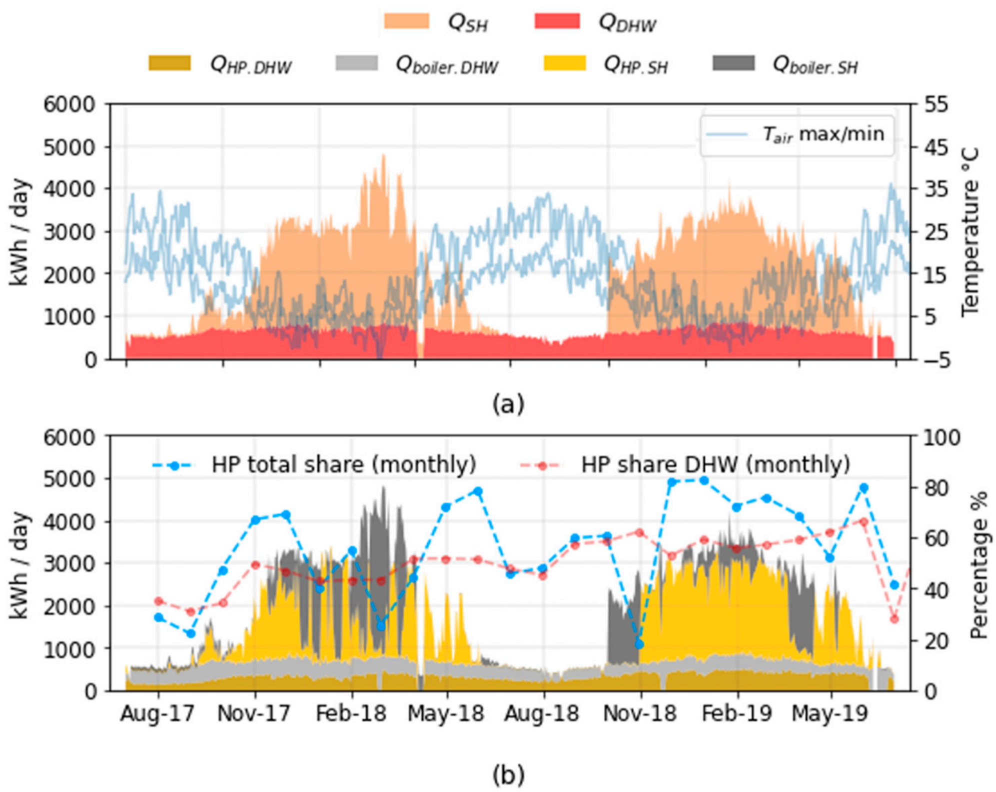

Figure 13. Hybrid ASHP system: (**a**) Daily SH and DHW production (kWh_{th}/day), as well as minimum/maximum outdoor temperature and (**b**) Daily HP and boiler production (kWh_{th}/day), segmented between SH and DHW (left axis), as well as ASHP share (rigth axis), over two years of operation (July 2017–June 2019).

5.3. HP Capacity and Heat Load

Figure 14 shows the observed load (by bins of outdoor temperature of 5 °C) in relation with the related HP capacity (for a production temperature of 50 °C), as well as with the complementary capacity of the boiler. As a complement, Appendix D yields information concerning the respective SH and DHW shares, as well as the actual observed HP and boiler production temperature.

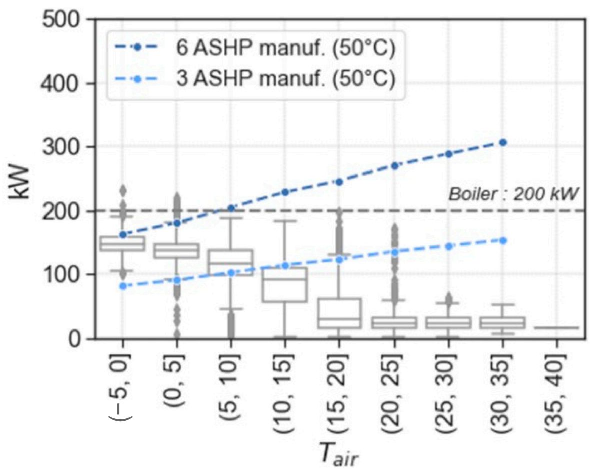

Figure 14. Hybrid ASHP system: Hourly heat load (kW_{th} by bins of outdoor temperature of 5 °C), in relation with the HP and boiler capacity (July 2018 to June 2019). The heat load is represented by boxplots, with 50% of the hourly heat load within the box (median +/−25%), 80% within the upper and lower marker, and the 10% min and max outliers represented by dots.

Again, the median HP load decreased with rising outdoor temperatures and related drop of the SH load (from around 130 kW_{th} in the 0–5 °C range, down to 20 kW_{th} in the 15–20 °C range).

In the range from −5 to 0 °C, the ratio between capacity (138 kW_{th}) and load (232 kW_{th}) only amounts to 59%, but this bin represents less than 3% of the annual delivered heat. At first sight, it looks like the HP capacity should cover the overwhelming part of the annual load, almost down to the 0 °C outdoor threshold, which should in principle lead to higher coverage than the observed value of 67%. The interdependencies are, however, more complex, in particular in DHW mode, during which: (i) the 55 °C temperature HP limitation actually limits the contribution of the HP to pre-heating; (ii) the 3 remaining HP units (i.e., half of the total capacity) can by far not cover the SH load at low outdoor temperatures (in the range between −5 and 0 °C), since they add up to a total capacity of around 80 kW_{th}, which cannot even satisfy the lowest observed load in this bin; in the range between 0 and 5 °C, they add up to around 100 kW_{th}, representing 10% of the observed loads. Disentangling of these effects and estimation of the optimal expectable HP coverage is unfortunately not possible with the available monitoring data (namely due to missing SH return temperature and/or related flowrate) and will hence be addressed in a later stage by way of numerical simulation.

Finally, the 200 kW_{th} boiler capacity exceeds by far in all cases the missing HP production. However, since the boiler is pre-existing, this can not be seen as an oversizing or over-investment issue.

5.4. ASHP Performance

In the first year of operation, the COP_2 varies widely due to the ASHP breakdowns, changes in the hydraulic configuration, as well as optimization of the regulation (Figure 15). In contrast, in the second year, the COP_2 varies between 2 and 3 and follows the outdoor temperature fluctuations, except for some malfunctioning periods.

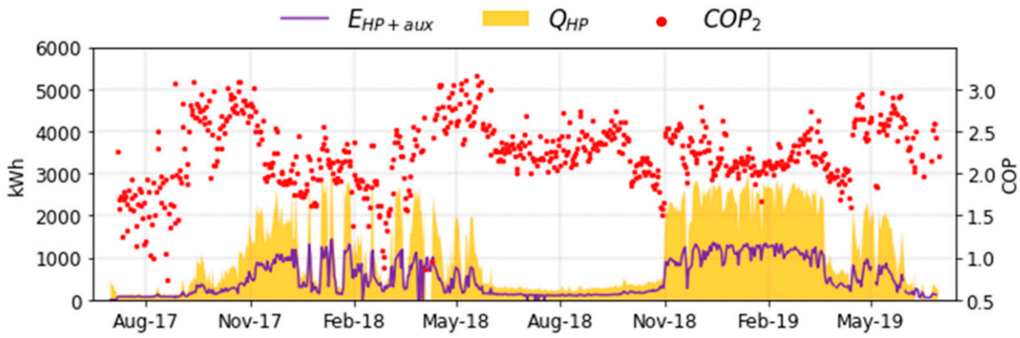

Figure 15. Hybrid ASHP system: Daily heat production (kWh_{th}/day) and electricity consumption (kWh_{elec}/day) of the two ASHP, as well as COP_2 of 6 heat pumps (including auxiliary electricity).

As a complement, Appendix E shows the daily measured COP_2 and COP_1 as a function of the HP temperature lift (difference between HP production temperature and outdoor temperature). As for the monovalent system, the COP_1 values are closer to the ones given by the manufacturer. However, the extensive pipe system connecting the ASHP on the roof to the boiler room (see Figure 4b) induces relatively large heat losses (not taken into account by the monitoring system, see Figure 5). During a specific monitoring campaign over two winter weeks in November 2018 (with outdoor temperatures between 0 and 10 °C), these losses were estimated at 760 kWh_{th}/day, representing 24% of total daily delivered heating during this period. When taking these losses into consideration, the COP_1 values follow the ones given by the manufacturer, which confirms proper functioning of the ASHP units.

6. Discussion

6.1. Synthetic Comparison of the Case Studies

The main results of both case studies are summarized hereafter, in terms of heat demand and production, as well as system performance and environmental performance (for the latter, see Table 2).

Table 2. Summary of the main results of the two pilot projects.

	Monovalent	Hybrid
SPF_{sys}	2.29	2.28
SPF_{global}	2.29	1.28
HP fraction	100%	67%
Renewble energy fraction ($\eta_{Heat.yr}$)	75%	43%
Emissions before ASHP renovation	42 $kgCO_{2eq}/m^2/yr$	40 $kgCO_{2eq}/m^2/yr$
Emissions after ASHP renovation	3.4 $kgCO_{2eq}/m^2/yr$	13.1 $kgCO_{2eq}/m^2/yr$
Emissions savings	92%	68%

In each case, the results concern the second year of operation. For comparison between the 2 cases (with distinct heated surface) as well as benchmarking with other buildings, the annual energy demand as well as the HP and boiler design capacities are expressed per m^2 of heated surface.

When normalized to standard weather conditions, both buildings have similar SH demands (76.8 vs. 72.1 $kWh_{th}/m^2/yr$) and are representative of non-retrofitted MFB, although within the lower range of the overall distribution for their respective construction periods. They notably differ in terms of DHW production (54.1 vs. 30.3 $kWh_{th}/m^2/yr$), representing very high vs. average to low values when compared to benchmark values.

The first building is equipped with a monovalent ASHP system (58 W_{th}/m^2 for design conditions of −10 °C outdoor and 60 °C heat production), which turns out to be largely oversized when compared to actual peak loads (with an oversizing ratio of around 140%).

The second building is equipped with a hybrid ASHP system (18.2 W_{th}/m^2 for design conditions of −10 °C outdoor and 50 °C heat production) with a complementary gas boiler (26.4 W_{th}/m^2). At an outdoor temperature below 0 °C, the ratio between HP capacity and observed heat load amounts to 59%, but rises very quickly with temperature, reaching 90% in the 0–5 °C range and more than 100% above 5 °C.

As a result, the annual heat share supplied by the HP amounts to 100% in the first case, as opposed to 67% in the second case. The latter value is lower than the expected 80%, due to accidental switch-off, temporary breakdown of some HP units, as well as complex master/slave control.

The SPF_{sys} of the HPs (including auxiliary electricity for circulation from the HP units to the technical room) amounts in both cases to 2.3, but the renewable energy fraction (air source + renewable fraction of electricity, taking into account the hourly mix) differs significantly, i.e., 75% in the first case, as opposed to 43% in the second case, due to complementary use of gas. Finally, the related CO_{2eq} emission savings amount to 92% for the monovalent system, and up to 68% for the hybrid system.

While the CO_{2eq} savings are particularly impressive with the present Swiss electricity mix, with an SPF_{sys} of 2.3 as measured here, with the EU28 annual electricity mix (294 g/kWh_{elec}) the savings would still amount to around 66% with the monovalent system and to only around 55% for the bivalent one [20], which indicates the need to further reduce the gap between project and implementation (as is also the case for SFBs), as well as to further improve the intrinsic performance of ASPF units. This is even more important since, in parallel to the rapid development of renewable electricity, electrification is progressing in other sectors, in particular mobility.

6.2. Issues Identified

While both systems are able to provide the entire heat demand of the non-retrofitted buildings, both in terms of load and of temperature, the following issues were identified:

- Monovalent system: The two industrial ASHP models are able to fully supply the current heat demand of the non-retrofitted MFB, however the following issues which occurred during the first year of monitoring had to be solved: (i) internal setpoints of the industrial ASHP, which were not considering the heating curve defined at the level of the centralized automation; (ii) constantly activated circulation pumps, even when the production was off; (iii) high return temperatures to the ASHP, due to incompatibilities between HP units and DHW heat exchanger; (iv) HP breakdown during an entire month, due to lack of a trained technician who ultimately came from another region of the country.
- Hybrid system: Compared to the monovalent project, this project has a high level of complexity in terms of hydraulic concept and regulation, since it was necessary to combine the operation of smaller ASHP units in cascade, along with the old existing boiler. Several types of malfunctioning were identified and solved: (i) high return temperatures causing heat pump failures when operating in parallel with the boiler; (ii) limited master-slave control and related cascade of HP units and boiler; (iii) heat losses in the pipes connecting the ASHP located on the roof to the boiler room. Furthermore, residents of an apartment on the top floor of the building reported excessive noise from the HP, which could be heard from open windows. This was confirmed acoustic measurements, after which the air inlets and outlets of the heat pumps were equipped with adequate sound absorbers.

7. Conclusions

This study concerns the actual performance of two non-retrofitted multi-family buildings, whose original fossil fuel boilers were replaced by a monovalent air source heat pump system in the first case and a hybrid system with a complementary gas boiler in the second case. Based on a detailed monitoring campaign covering two years of operation each, the main findings show that, even in non-retrofitted buildings, both systems are able to supply the required temperature levels and cover the entire heat demand (space heating and domestic hot water). A close follow-up of these pilot projects allowed us to identify issues and constraints linked to integration and operation of such systems in large existing buildings. Optimization measures enabled us to significantly increase the COP of the monovalent system, from 1.3 up to 3.4 during the last summer, with an optimized SPF of 2.3. For the hybrid system, the HP share was increased from 50% to 67%, allowing to reach an optimized SPF of 2.3. Both systems offer major progress in terms of CO_2 savings (92% and 68%) and increased renewable energy share (75% and 43%), taking into account the actual Swiss electricity mix and its CO_2 content at hourly level.

It should be noted that the two case studies differ both in terms of system setup (monovalent vs. hybrid) and choice of HP units (large industrial units vs. small units designed for SFB). However, the system setup and the HP type are not intrinsically related: in principle large HP units could also be used in bivalent setups, or small units in monovalent mode. When making a choice, the following features of the various options should be considered:

- Monovalent systems are in principle easier to integrate and to regulate, in particular regarding interaction between HPs and boiler and related operating temperatures. They are, however, easily subject to oversizing (and related overinvestment), due to the targeted 100% share. The latter raises the question whether to consider "monovalent" HP systems with direct electric heating for extreme peak loads. This should be further analyzed in terms of the related energy mix, grid connection capacities, as well as cost aspects.
- Besides a comparative advantage in terms of cost and space, hybrid systems represent a flexible option for existing buildings, in view of forthcoming retrofit and the related decrease of heat load.
- Large industrial HPs need less space and hydraulics, with the complementary advantage of reduced heat losses, but they currently require specific constructive measures in terms of noise reduction and possibly for structural reasons linked to their weight.
- Bundling of small HPs developed for the SFB market offers an advantage regarding weight distribution on the roof. Currently (at least based on this project), their integrated control systems are not yet suitable for integrating a large number of units and their production temperature does not always meet the requirements.

Finally, most of the malfunctioning observed in the two pilot projects was due to incorrect information/parameterization of the devices, which could be corrected by optimizing the system regulation, but in some cases non-optimal hydraulic configuration was also encountered, which was adapted as far as reasonably possible.

As these pilot projects show, the implementation of such systems requires adequate professional training and careful execution, linked to specificities of HP systems as compared to fossil fuel boilers (namely in relation with temperature issues). Particular attention must be paid to the design of the hydraulic circuit and the regulation to ensure the efficiency, reliability, and durability of such systems, especially in the case of hybrid systems. The adequacy of the hydraulic integration should also be verified at each stage of the project (pre-design, design, implementation, commissioning, follow-up).

As an outlook, future research will deal with the following aspects:

- Sensitivity analysis by way of numerical simulation, in order to derive robust sizing and integration rules.
- Specific focus on control strategies and cascading, with the objective of robust and flexible control strategies for heat pump manufacturers and engineering firms.
- Alternative and/or complementary system integration, i.e., by combination of heat pump systems with photovoltaics (PV) or hybrid photovoltaic thermal solar collector (PV-T).
- Optimal/flexible strategies for combined fuel-switch and envelope-retrofit, in terms of energy performance, CO_2 savings, cost, and architectural constraints.

Author Contributions: Conceptualization: O.M., P.B., S.C., C.F., M.R., E.V., N.C., F.R. and P.H.; methodology: O.M., P.B., S.C., C.F. and P.H.; formal analysis: O.M., P.B. and S.C.; software: O.M., P.B. and S.C.; investigation: O.M., P.B., S.C. and C.F.; data curation: O.M., P.B., S.C. and C.F.; writing—original draft preparation: O.M., P.B. and P.H.; writing—review and editing: O.M., P.B., S.C., C.F., N.C., F.R., M.P. and P.H.; visualization: O.M., P.B., S.C. and P.H.; supervision: P.B., F.R., M.P. and P.H.; project administration: M.R., N.C. and P.H.; funding acquisition: M.R., F.R. and P.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was co-funded by SIG (within a pluri-annual partnership related to critical analysis of innovative energy systems in actual condition of use), the Swiss Federal Office of Energy (within the "AirBiVal" project), as well as Innosuisse–Swiss Innovation Agency (within the "Renowave" project).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request to the corresponding author.

Acknowledgments: The authors would like to thank the diverse stakeholders (building owners, engineers, technicians, HP manufacturers) for participating in the follow-up and exchange group related to these case-studies.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Acronyms	
ASHP	Air-Source Heat Pump
DHN	District Heating Network
DHW	Domestic Hot Water
HDD	Heating Degree Days
HP	Heat Pump
MFB	Multi-Family Buildings
SFB	Single Family Buildings
SH	Space Heating
Symbols	
C_{elec}	Annual emissions from HP electricity consumption ($kgCO_{2eq}$)
C_{fossil}	Annual emissions from boiler consumption ($kgCO_{2eq}$)
C_{global}	Annual total emissions of the system from electricity and gas consumption ($kgCO_{2eq}$)
COP	Coefficient of performance of the heat pump
COP_1	Daily coefficient of performance of the heat pump without auxiliaries
COP_2	Daily coefficient of performance of the heat pump with auxiliaries
E_{HP}	Heat pump electricity consumption without auxiliaries (kWh_{elec})
E_{HP+aux}	Heat pump electricity consumption with auxiliaries (kWh_{elec})
$E_{HP+aux.h}$	Hourly heat pump electricity consumption with auxiliaries (kWh_{elec})
E_{REN}	Annual renewable energy from ASHP electricity consumption (kWh_{elec})
E_{fossil}	Gas or oil boiler consumption (kWh_{th})
Q_{DHW}	DHW demand including storage and distribution losses (kWh_{th})
Q_{HP}	Heat pump production (kWh_{th})
$Q_{HP.DHW}$	HP production for DHW (kWh_{th})
$Q_{HP.SH}$	HP production for SH (kWh_{th})
Q_{HP1}	Heat pump production of the first machine (kWh_{th})
Q_{HP2}	Heat pump production of the second machine (kWh_{th})
Q_{SH}	SH demand without storage losses (kWh_{th})
Q_{air}	Heat extracted on the air source (kWh_{th})
Q_{boiler}	Boiler heat production (kWh_{th})
$Q_{boiler.DHW}$	Heat boiler production for DHW (kWh_{th})
$Q_{boiler.SH}$	Heat boiler production for SH (kWh_{th})

SPF_{global}	Overall seasonal performance of the heat pump and boiler
SPF_{sys}	Annual seasonal performance factor of HP with auxiliaries
$T_{DHW.dis}$	DHW distribution temperature at the storage outlet (°C)
T_{HP}	Temperature at condenser output (°C)
$T_{HP.DHW}$	DHW temperature at the heat exchanger inlet (°C)
$T_{HP.SH}$	SH temperature before the mixing valve or before the tank (°C)
$T_{SH.dis}$	SH distribution temperature after the mixing valve (°C)
T_{air}	Outdoor temperature (°C)
$T_{boiler.DHW}$	DHW temperature of the boiler before the tank (°C)
$T_{boiler.SH}$	SH temperature of the boiler before the tank (°C)
$f_{elec.h}$	CO_2 content of Swiss electricity mix in hourly values (gCO_2eq/kWh_{elec})
f_{fossil}	Emissions factor from gas or oil consumption ($kgCO_2/kWh_{th}$ of gas)
$\beta_{Heat.REN}$	Annual renewable share of total heat production (%)
$\phi_{Elec.h}$	Hourly Swiss electricity share produced from renewable sources (%)

Appendix A. Control and Cascading of the HP Units and Gas Boiler (Hybrid System)

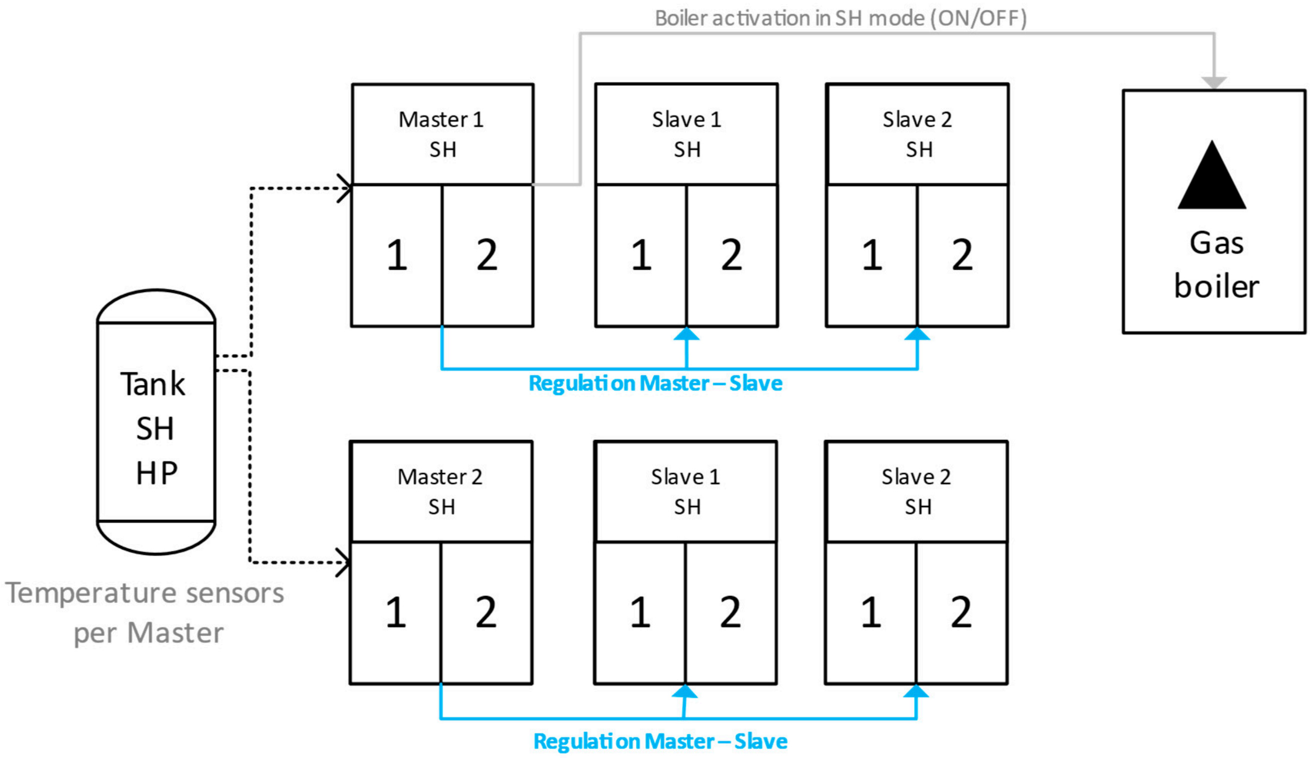

Figure A1. Control and cascading of the hybrid system, SH mode. Numbers 1 and 2 refer to the two compressors of each HP.

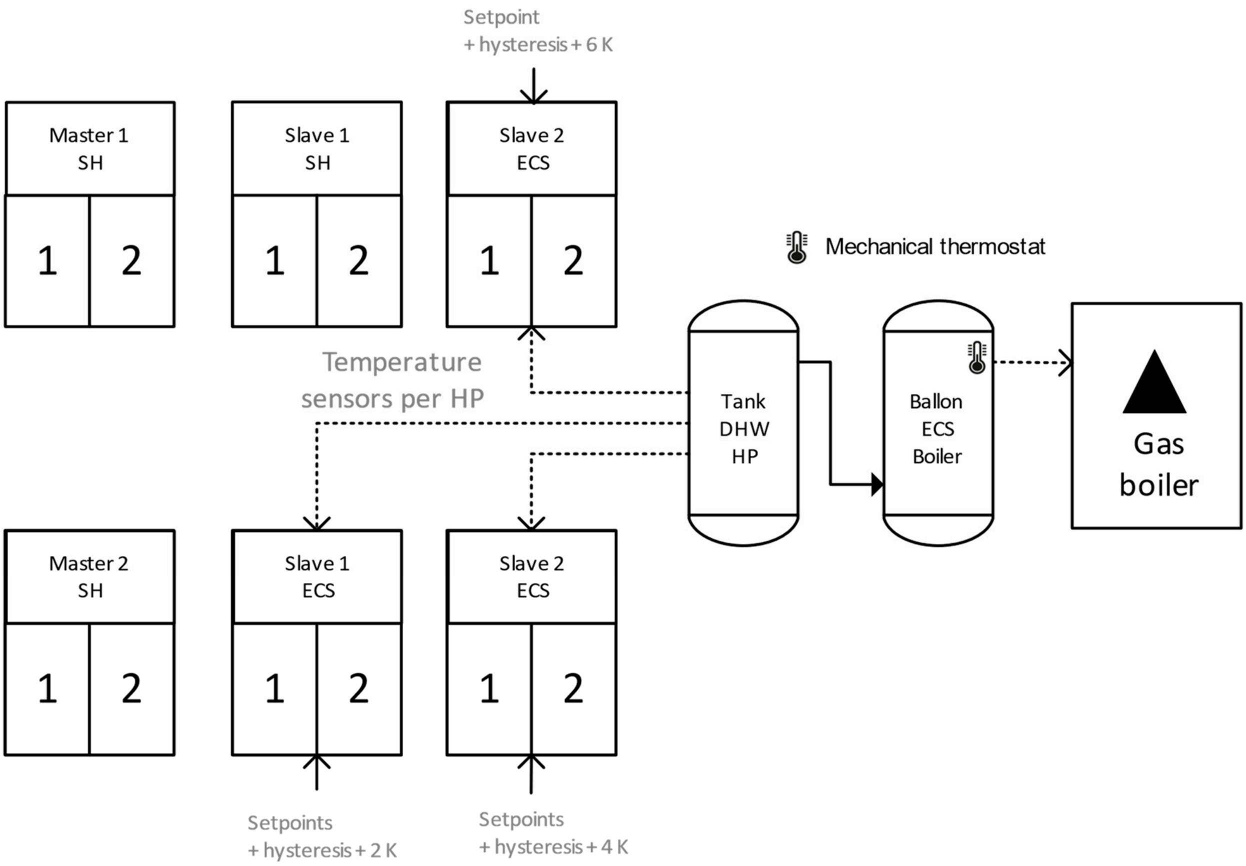

Figure A2. Control and cascading of the hybrid system, DHW mode. Numbers 1 and 2 refer to the two compressors of each HP.

Appendix B. Carbon Emissions and Renewable Energy Fraction of the Swiss Electricity Mix

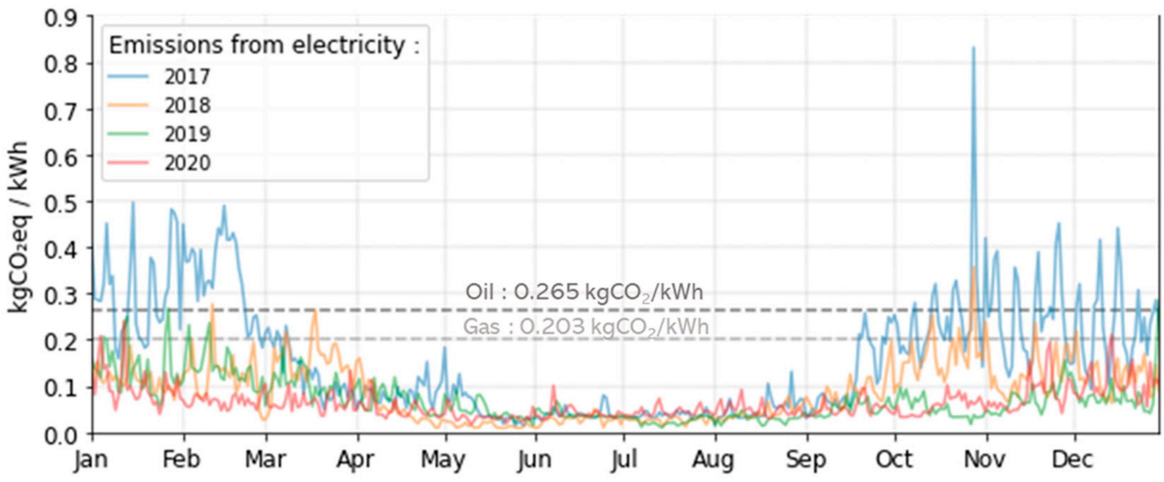

Figure A3. Daily CO_{2eq} content of Swiss electricity consummer mix, 2017 to 2020. Source: Romano et al. [43].

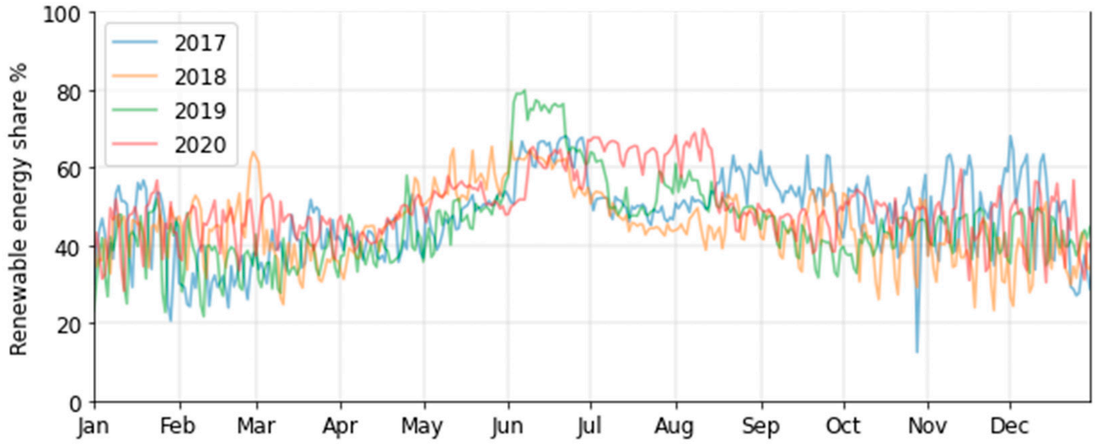

Figure A4. Daily renewable energy share of the Swiss electricity consummer mix, 2017 to 2020. Source: Romano et al. [43].

Table A1. Annual CO_{2eq} content and renewable energy share of the Swiss electricity consumer mix, 2017 to 2021. Source: Romano et al. [43].

	2017	2018	2019	2020	Average
Average annual Emissions ($kgCO_{2eq}/kWh_{elec}$)	0.156	0.088	0.070	0.063	0.096
Average Swiss electricity share from renewable sources	47.7%	45.2%	45.5%	49.8%	47.0%

Appendix C. ASHP Production and Distribution Temperatures

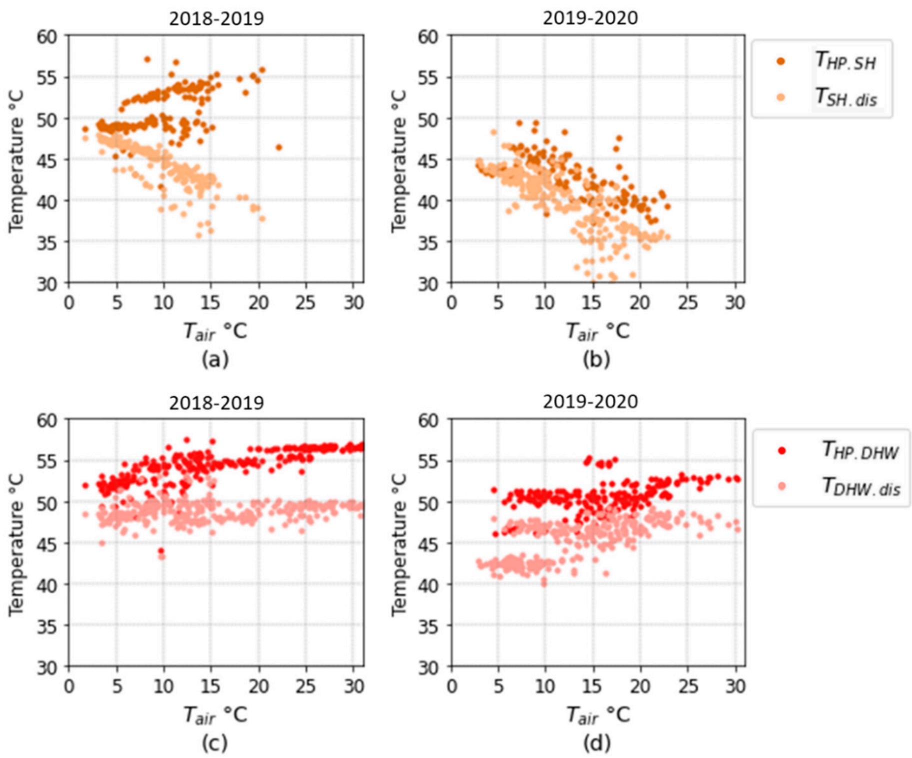

Figure A5. Monovalent system: Daily production and distribution temperatures for SH in the (**a**) first and (**b**) second year of operation. Daily temperatures for DHW in the (**c**) first and (**d**) second year of operation.

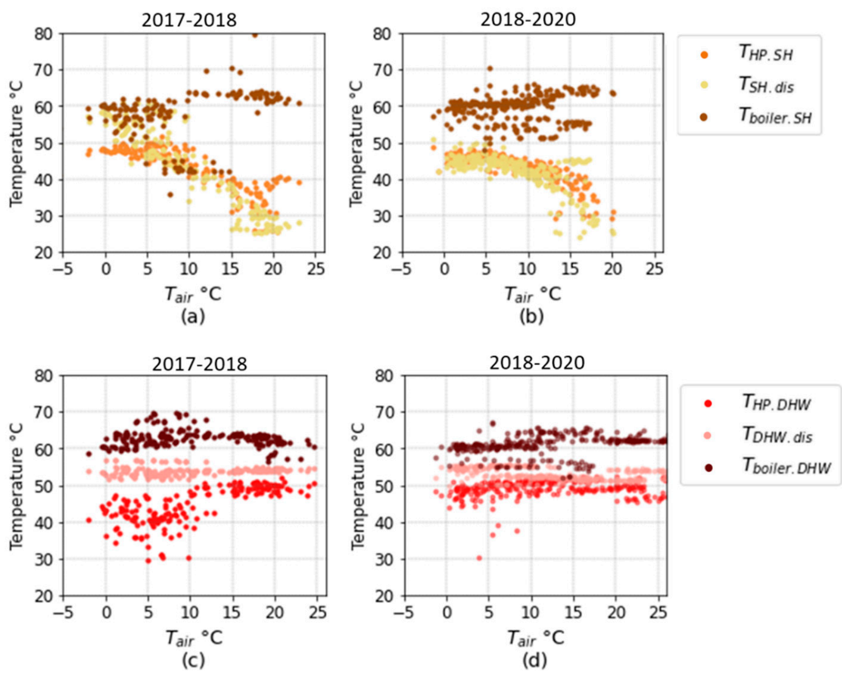

Figure A6. Hybrid system: Daily production and distribution temperatures for SH in the (**a**) first and (**b**) second year of operation. Daily temperatures for DHW in the (**c**) first and (**d**) second year of operation.

Appendix D. Heat Production of Monovalent and Hybrid System

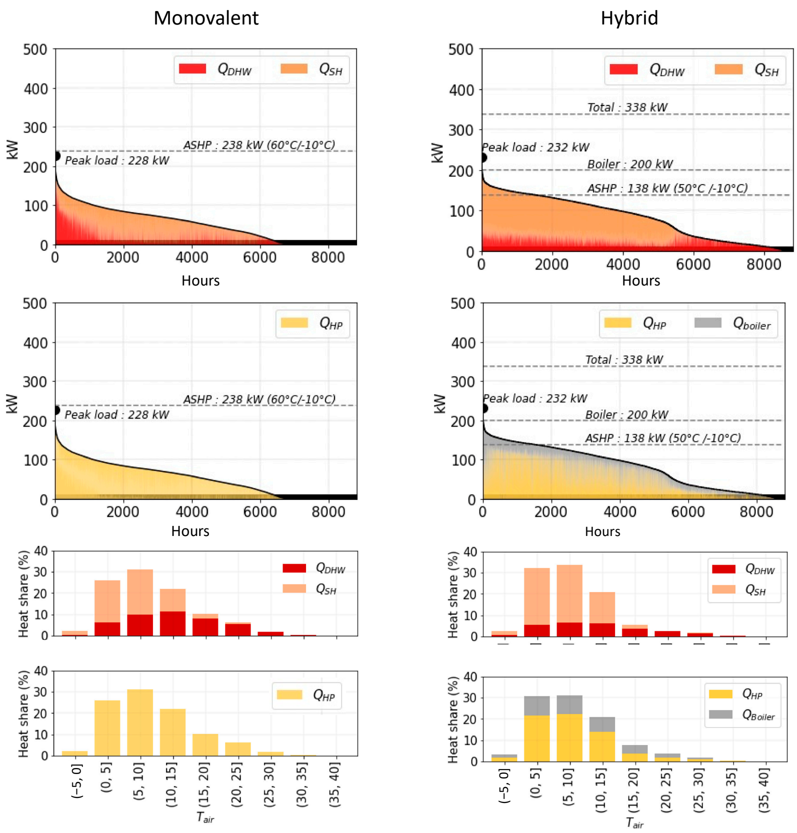

Figure A7. Monovalent and hybrid system; (**Top**) Sorted hourly heat production, decomposed in DHW and SH, as well as in HP and boiler, with related design capacities (kW_{th}); (**Bottom**) Heat share (by bins of outdoor temperature of 5 °C), segmented in SH and DHW, as well as in HP and boiler.

Note: For the hybrid system, the increase of DHW after hour 6000 relates to an unexplained malfunctioning at the end of the heating season (17 days in June 2019), during which activation of the boiler induces peaks in charging of the DHW tank, with related overheating (above the DHW set point).

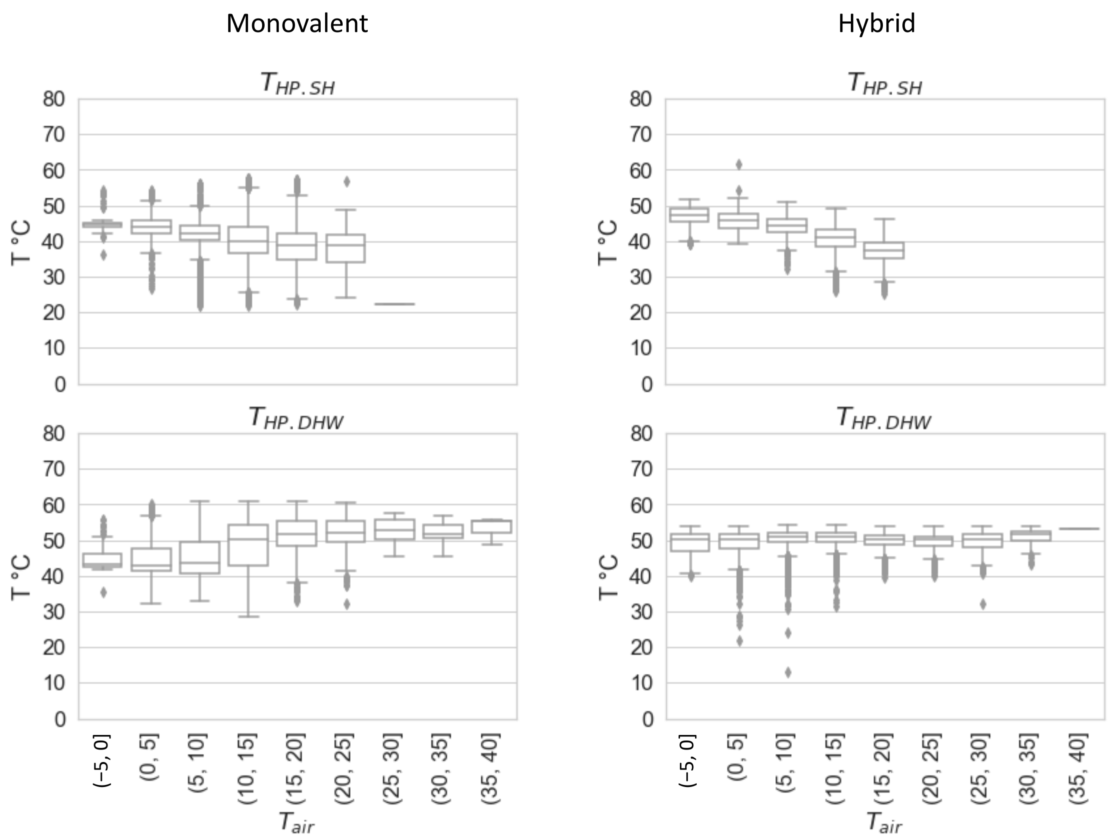

Figure A8. Monovalent and hybrid system, HP production temperature (by bins of outdoor temperature of 5 °C); (**Top**) SH mode; (**Bottom**) DHW mode. The temperature spread is represented by boxplots, with 50% of the hourly heat load within the box (median +/−25%), 80% within the upper and lower marker, and the 10% min and max outliers represented by dots.

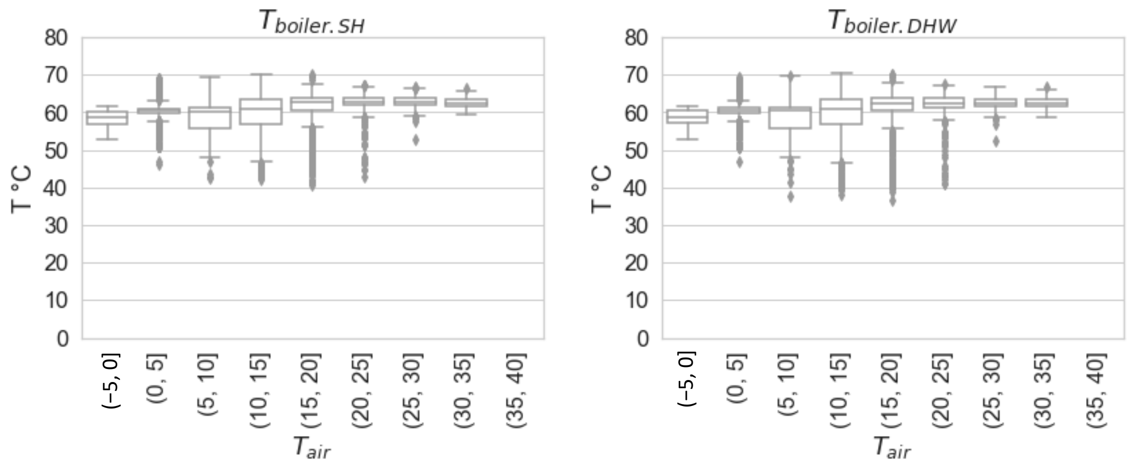

Figure A9. Hybrid system, boiler production temperature (by bins of outdoor temperature of 5 °C), SH mode, and DHW mode. The temperature spread is represented by boxplots, with 50% of the hourly heat load within the box (median +/−25%), 80% within the upper and lower marker, and the 10% min and max outliers represented by dots.

Appendix E. Comparison between the Actual Performance and Manufacturer

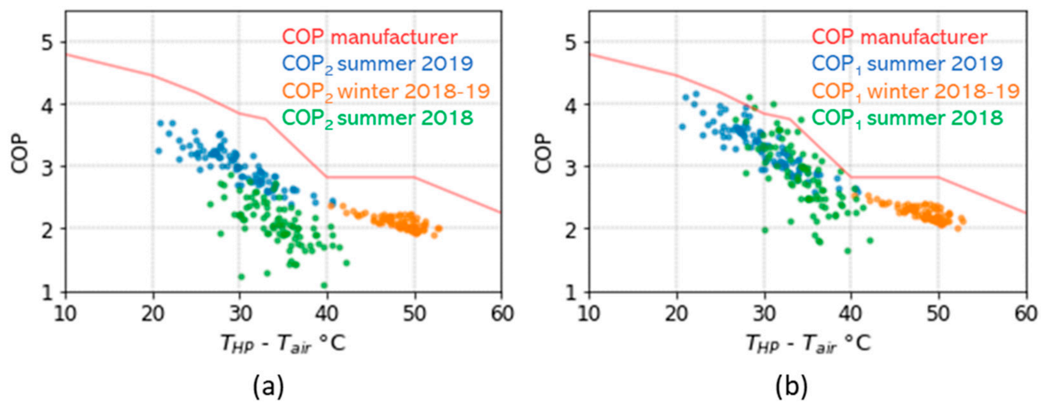

Figure A10. Monovalent system: (**a**) COP_2 measured with (**b**) COP_1 without auxiliaries as a function of operating temperature difference, between the outlet temperature and the outside air temperature for each season. The actual performance is compared to the performance announced by the manufacturer at condenser outlet temperature of 45 °C (Summer: 1 June–31 August; Winter: 1 September–31 January).

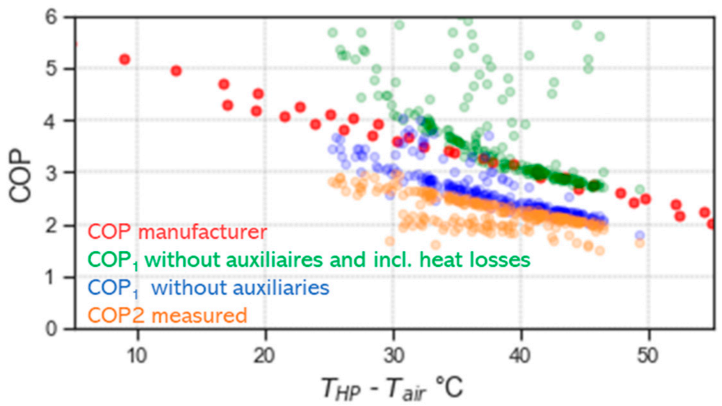

Figure A11. Hybrid system: COP_2 mesured as a function of the operating temperatures (T_{HP}-T_{air}) during the winter of 2018–2019, without auxiliaries (blue dots) and including heat losses (green dots). The actual performance is compared to the performance announced by the manufacturer at condenser outlet temperature of 50 °C (red dots).

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