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Investigation of the effect of storage operation in Single-Family Homes with Separate Tanks for Space Heating and DHW

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Abstract

While heat pump systems in existing residential buildings already achieve significant CO_2-savings compared to fossil heating systems, field measurements still show optimization potential regarding their performance. One key factor influencing the operation of heat pump systems is the integration and operation of the thermal energy storage, as it couples heat generation and heat demand side. This study investigates a typical heat pump system hydraulic, comprising a parallel buffer storage for space heating (SH) and a domestic hot water (DHW) tank.

The analysis is based on monitoring data of single-family houses in Germany. It involves a total of seven heat pump systems from five different manufactures, consisting of four air source heat pumps and three ground source heat pumps, all with a nominal thermal capacity of less than 12 kW and inverter-controlled compressors. The measurements and evaluations were conducted throughout the year 2023. The measurement concept was designed to monitor the efficiency and operational behavior of heat pump systems. To achieve this, all necessary energy flows are recorded with minute-by-minute precision. The cooling mode available in part of the installations was not evaluated.

The results reveal a tendency for the heat pumps to produce heat at a rate exceeding the actual heating load of the houses, suggesting that the systems may be overdimensioned and/or that modulation control is suboptimal. Additionally, the analysis uncovered unbalanced flow rates between tank charging and discharging. These imbalances can cause unfavorable thermal conditions within the storage, including mixing effects and poor thermal stratification, ultimately compromising the overall performance of the heating system and leading to unfavorable operation with frequent on/off cycling of the heat pump. To further understand this behavior, simulations were conducted to evaluate smoother and favorable operational.

Keywords: heat pump; thermal energy storage; heat pump system measurements

1. Introduction

The necessity of transitioning to climate-neutral energy systems highlights heat pumps (HPs) as critical technology for decarbonizing the residential heating sector. While monitored HPs already achieve significant emissions reductions over fossil technologies, their operational effectiveness is often limited by real-world factors, including system integration, and control strategies. A key factor influencing operational efficiency is the integration and management of thermal energy storage components, which serves not only as a heat storage but also to decouple heat generation from heat consumption, facilitating smoother operation and aiding in the reduction of heat pump cycling [1]. However, issues such as hydraulic imbalances around buffer tanks can undermine overall system efficiency and heat pump cycling. Such issues are aggravated by factors such as mismatches between the heat pump's generation capacity and the building's thermal demand. For instance,

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Brudermueller et al. (2023) [2] utilized Smart Meter Data to monitor heat pump cycling across 503 Swiss houses, finding that inadequate sizing or configurations often result in short and frequent cycles.

To address these challenges, this study investigates the operational behavior of a commonly used residential HP system. Measurement data were collected throughout 2023 from seven single-family houses in Germany, as part of project “WP-QS im Bestand” [1]. The analysis focuses on system configurations that include both a space heating (SH) buffer storage tank and a domestic hot water (DHW) storage tank. And aims to understand the interactions between heat pump, thermal energy storages and house heat consumption, providing insights for improved design and operation of these residential HP systems.

2. Methodology and Approach

2.1. Overview of Measured Heat Pump Systems

The analysis utilized one-minute measurement data collected throughout 2023 from heat pump systems installed in seven single-family German houses. The monitored installations included four air-source heat pumps (ASHPs) and three ground-source heat pumps (GSHPs). Figure 1 provides a simplified schematic of a heat pump system, presenting the typical layout used in all monitored buildings. All systems featured a buffer tank for space heating and a separated DHW storage tank. System configurations varied in heat distribution, employing radiators, underfloor heating, or a combination of both. The different characteristics of the monitored house systems are presented in Table 1. The system hydraulics were equipped with heat meters to determine the heat flow between components (Figure 1). No measurements were made inside the components, for example, the temperature inside the storages were not measured. Finally, the electricity consumption of the heat pump, auxiliar heater and flow pumps were measured.

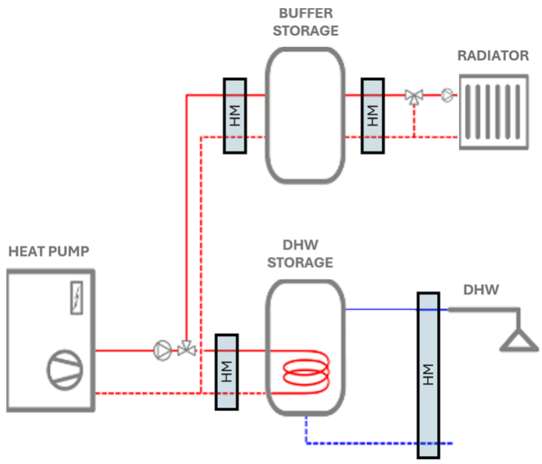

Figure 1. Simplified schematic of heat pump system featuring a buffer tank for space heating and a separate DHW storage tank. Heat meters (HM) measure the heat flow, volume flow, and supply and return temperatures.

The focus of this study is on heat pump systems operating under standard demand-driven control, where heat generation is regulated according to the heating demand of the building. However, houses 593 and 599 were equipped with photovoltaic (PV) systems and featured PV-optimized control. This distinction is relevant when interpreting the measurement results, as PV-driven systems may exhibit different operational behavior compared to purely demand-oriented systems.

In addition, two systems exhibited control-related faults that affected their operation:

- House 532: A defect in the three-way valve responsible for switching between SH and DHW charging caused both circuits to be active simultaneously, allowing flow through both SH and DHW loops in parallel.
- House 599: A control malfunction occasionally caused the circulation pump in the HP circuit to operate independently of the compressor, sometimes for extended periods when compressor was off. This desynchronization led to unwanted mixing within the buffer tank, as cooler return water from the lower tank region was circulated into the upper, warmer section.

2.2. Evaluation Methodology

The core of this study focuses on the operation of the system around the thermal storage components: the space heating buffer tank and the domestic hot water storage tank. These storage units serve not only as thermal reservoirs but also as hydraulic separators, decoupling heat generation from heat consumption. In addition, for ASHP, the buffer tank serves as a heat source for the reversed cycle defrosting. To evaluate the influence of the storage tanks on overall system performance and operation, a comparative analysis was carried out between the two sides separated by the storage:

- Generation side (charge side): representing the HP charging a storage tank.
- Consumption side (discharge side): representing the house's heating demand, discharging a tank.

Comparing these two sides allowed the identification of hydraulic imbalances and thermal inefficiencies.

Because the system includes two distinct storages, the HP operates in two separate, time-dependent modes. Accordingly, the evaluation method distinguishes between these operating modes:

- Domestic Hot Water (DHW) Mode: In this mode, the HP delivers heat to the dedicated DHW storage tank. DHW preparation typically involves shorter, more frequent cycles at higher supply temperatures (50–60 °C), differing significantly from space heating operation.
- Space Heating (SH) Mode: In this mode, the HP delivers heat from the condenser to the SH buffer storage, which subsequently supplies the building's heating distribution system.

For three of the seven houses, it was not possible to install sensors between the HP and the DHW storage, as both components were integrated in a single product casing. Additionally, in three houses, no sensors could be installed between the DHW storage and the tapping points, preventing measurement of tank discharge. Measuring DHW discharge flow also proved difficult due to the oftentimes short and unsteady nature of DHW tapping events. Given these measurement limitations, the evaluation presented in this work focuses almost exclusively on the space heating (SH) mode. Only two houses could be partially evaluated in DHW mode, and only on the generation side due to uncertainties of discharge measurements.

Table 1. Monitored houses characteristics. The HP nominal heat power [kW] and COP [-] values were obtained from the heat pump datasheet (according to EN-14511). For ASHP, the nominal point is A2/W35, and for BSHP, it is B0/W35. The space heating load [kW] and HP supply [°C] at 0°C outdoor temperature were derived from measurements.

	House 532	House 522	House 547	House 554	House 558	House 593	House 599
Heating area [m²]	198	210	100	155	180	148	120
Space heating demand [kWh/m²a]	49	86	99	55	74	85	45
Space heating load at 0°C outdoor [kW]	3,1	5,4	2,6	2,4	3,7	3,5	1,6
Space heating HP supply at 0°C outdoor [°C]	37,2	49,1	35,6	41,8	46,5	41,7	43,7
Space heating system	mostly floor heating	mostly radiator	radiator and floor heating	mostly radiator	radiator and floor heating	floor heating	mostly radiator
HP heat source	ASHP	GSHP	ASHP	ASHP	GSHP	GSHP	ASHP
HP nominal power [kW]	12,0	5,1	4,3	4,3	7,5	10,4	5,0
COP nominal [-]	3,4	4,8	4,3	4,3	4,6	5	3,7
Buffer storage vol. [L]	750	700	200	200	120	200	200
DHW storage vol. [L]	280	800	390	300	185	170	165

2.2.1. Seasonal Performance Factor

The Seasonal Performance Factor (SPF) characterizes the energetic performance of the heating system over a longer period, here the 2023 year. The SPF is defined as the ratio of the total provided thermal energy to the total consumed electrical energy. For a consistent basis for benchmarking and comparison, the SPF can be evaluated within different system boundaries. This study specifically utilizes definition for SPF3, as categorized on references [3, 10]. SPF3 extends the system boundary to the entire HP system and also includes the electricity input for electrical resistance heaters as backup units and their corresponding heat output. SPF3 balances the useful heat supplied to the buffer storages.

2.2.2. Heat Pump Operation Duration and Start Counts

To quantify system cycling behavior, two key operational metrics were analyzed: Heat Pump Operation Duration (Runtime) and Heat Pump Mode Start Counts (HP Starts). These metrics were derived from measured data and the labeled heat pump operating mode, indicating when and in which mode the HP was active.

- Operation Duration (Runtime): The total cumulative time the heat pump compressor was actively running, separated by operating mode (SH or DHW).
- Heat Pump Mode Start Counts: The number of times the heat pump switched modes. For example, each activation of SH mode is counted as one SH start.

Analyzing runtime and cycling frequency is essential for assessing both system control and equipment longevity. Frequent, short cycles—characterized by a high number of starts combined with short runtimes—indicate frequent compressor on-offs, often caused by HP oversizing or suboptimal control strategies. Minimizing the number of compressor starts is particularly important to prolong equipment lifetime and quantify the operational stress imposed by current control strategies.

For ASHPs, the count of mode starts is also influenced by the occurrence of defrost cycles. In this analysis, defrost operation was not classified as part of either the SH or DHW mode. Consequently, when, for example, the HP temporarily interrupts SH operation to perform defrosting and then resumes SH mode, this resumption is registered as an additional SH mode start.

2.2.3. Statistical Evaluation of Measurements as Function of Outdoor Climate

To systematically assess the impact of external climate on system operation, measurements were grouped into 1 Kelvin wide bins based on the recorded outdoor temperature. This statistical evaluation allows for the characterization of system behavior as a direct function of the ambient environment.

The procedure involved:

- Bin Construction: Measurements were grouped after outdoor temperature bins of 1 Kelvin width. For example, between -0,5°C and +0,5°C outdoor temperature.
- Filtering Active Operation: To focus the analysis on meaningful operating conditions, a filtering procedure was applied. On the generation side, only periods when the heat pump was operating were considered, while on the consumption side, only data points with a volume flow exceeding 5,0 L/h were included.
- Statistical Analysis: Within each bin, the mean, 10th–90th percentile bands, and interquartile ranges (25th and 75th percentiles) were computed. These statistical values were used to demonstrate the variability and spread of system behavior at different external temperature intervals.

An example of such results is presented in Figure 2. The average HP heat generation rate, *Q_cond* [kW] and the average house heat consumption rate, *Q_load* [kW] were evaluated in groups of 1 Kelvin temperature bins, and the dotted line represents these groups average values, while the dark/light transparent bands represent the limits of the 25th and 75th percentiles, and 10th–90th percentile. Additionally, the average heat output rate of the heating rod, *Q_rod* [kW] is presented.

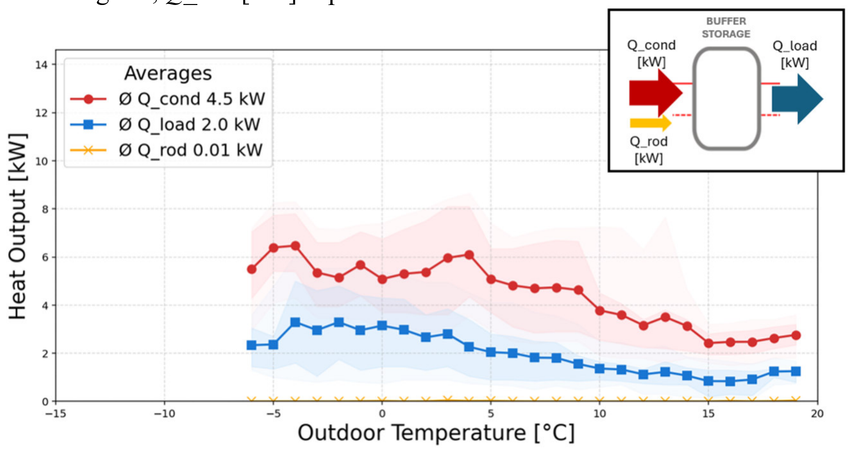

Figure 2. Average heat generation rate from HP, *Q_cond* and heating rod, *Q_rod* supplied to the buffer storage (charging), and heat consumption rate (discharge) of the house, *Q_load* as function of outdoor temperature. With 10th–90th and 25th–75th percentile bands. And annual averages indicated in the legend.

2.3. Simulation of Heat Pump Systems

To further analyze the system behavior, a numerical simulation of the houses HP systems was conduct. This simulation framework, built in Python programming language, focused exclusively on space heating mode, while domestic hot water operation was not modeled. Periods in the measurements when the HP operated in DHW mode were represented in the simulation as times when the HP was inactive.

The heat pumps were modeled using a generic performance table. Two types of heat pumps were represented: an ASHP [4] and a GSHP for ground-coupled systems [5]. The heat output from the table was scaled to match the known nominal power of each HP, as exact real performance points were not available. For ASHPs, evaporator defrosting was not simulated. From the measured data, a heating curve representing the supply temperature to the house as a function of outdoor temperature was derived and used as the HP condenser outflow temperature setpoint. HP power modulation was implemented via a PI controller by varying the HP compressor rotational speed between 20% and 100% of its maximum speed, while the compressor on/off signals were defined based on buffer tank temperature hysteresis.

The buffer storage was modeled using a discretized node approach with 8 nodes, based on the Mosaik hot water tank model [6], and incorporated the actual tank geometry and hydraulic connections positions. The house side (consumption side) was represented as a simple heat sink, with the measured house heat load prescribed as input to the model.

3. Results and Discussion

3.1. Monitored Systems Results

Table 2 presents the SPF and cycling results, separated between SH mode and DHW mode. For the seven houses the SPF during SH mode varied between 2.9 to 4.9, while smaller SPF values for DHW mode were found: 3.0 and 2.4. Many factors can influence the system performance, but this is normally highly correlated to the operating temperatures [7]. The low SH mode SPF of 2,9 for house 532 was likely caused by the three-way-valve defect. The number of SH mode starts shows a large variation range, from 1420 to 3356 starts. Similarly, the duration at which the HP operates in SH mode varied between 1572 hours to 3056 hours. In contrast, the total runtime and start counts are smaller in DHW mode than for SH mode.

Table 2. Monitored system 2023 results for SPF, counts of starts and duration, separated by HP operation mode.

		House 532	House 522	House 547	House 554	House 558	House 593	House 599
SH mode	SPF [-]	2.9	4.0	4.9	4.5	4.2	4.4	3.1
	Counts starts [-]	2009	3356	2101	1420	1950	2062	2030
	Duration [hours]	2505	3299	3056	2369	2256	2249	1572
DHW mode	SPF [-]	na	na	3.0	2.4	na	na	na
	Counts starts [-]	209	398	718	260	902	249	244
	Duration [hours]	279	461	384	375	605	240	230

Figure 3 shows the results for the charging and discharging of the buffer storage. The HP heat output *Q_cond*, is calculated only when the HP operates in SH mode, while the house heat consumption *Q_load*, is calculated only when the building is actively consuming heat. The average HP heat output *Q_cond*, is consistently higher than the average house heat consumption *Q_load*. This outcome is expected, as the HP must charge the buffer storage at a higher rate than the house discharges it, since the HP is not solely operating to cover the instantaneous SH demand of the house but also to supply DHW, to charge the buffer, and, in the case of ASHPs, defrosting the evaporator. However, the magnitude of the observed differences suggests possible mismatches in system operation, such as poor HP modulation or oversizing of the HP relative to building's heating load. This interpretation is supported by the fact that, with the exception of house 522, all systems feature HPs with nominal heating capacities *Q_hp_nom* greater than the average heat consumption rates *Q_load*, in particular, for houses 532, 554, 593 and 599. It should be noted, however, that *Q_hp_nom* refers to the nominal heating capacity at standard test conditions (EN 14511). Therefore, this comparison serves as an indicative assessment of relative sizing rather than a direct comparison of absolute power levels.

It is worth noting that the electric heating rod *Q_rod* remained inactive in most houses, with only minor and negligible operation observed in houses 558 and 599.

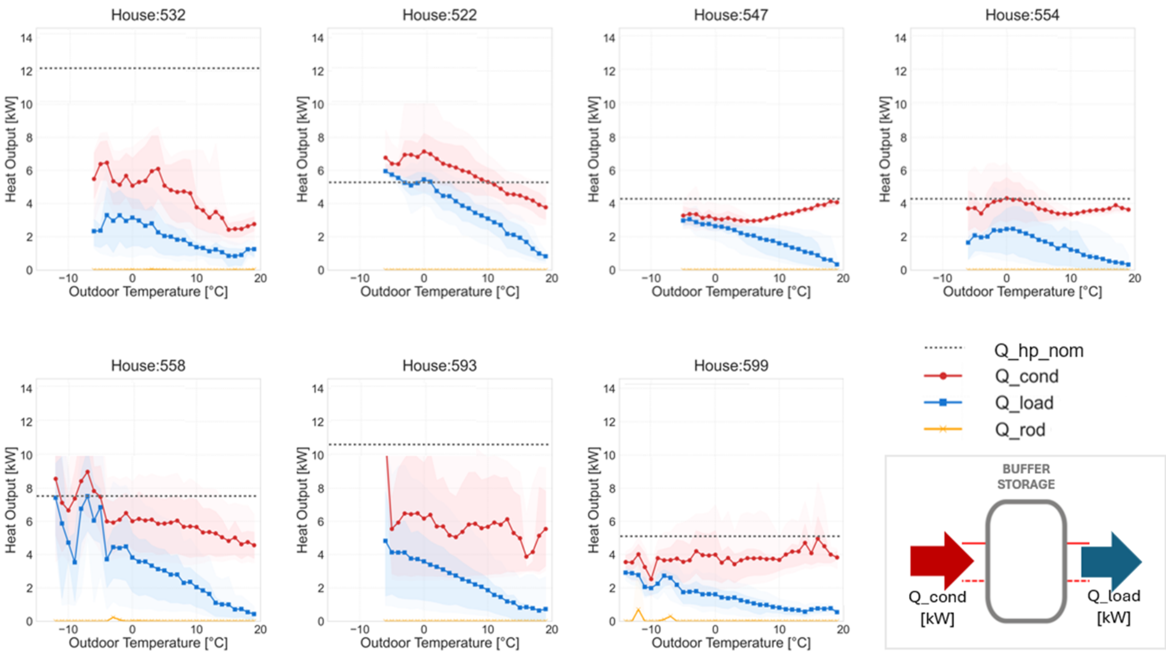

Figure 3. Average buffer storage charging and discharging rates (kW) as a function of outdoor temperature. The charging rate is determined by the heat pump condenser heat output, *Q_cond* and, when active, the electric heating rod, *Q_rod*. The building heat consumption rate, *Q_load* represents the discharging rate of the buffer storage. The nominal heat pump capacity *Q_hp_nom*, as specified in the manufacturer's datasheet, is also shown for reference.

Analyzing the volume flows (Figure 4), it can be observed that the average charging volume flow *VF_cond* is higher than the average discharging volume flow *VF_load* for all houses, except for house 554, where both flows are approximately equal. A higher charging volume flow promotes a net downward flow inside the buffer tank, which helps to ensure that hot water supplied by the HP reaches the consumption side without excessive mixing.

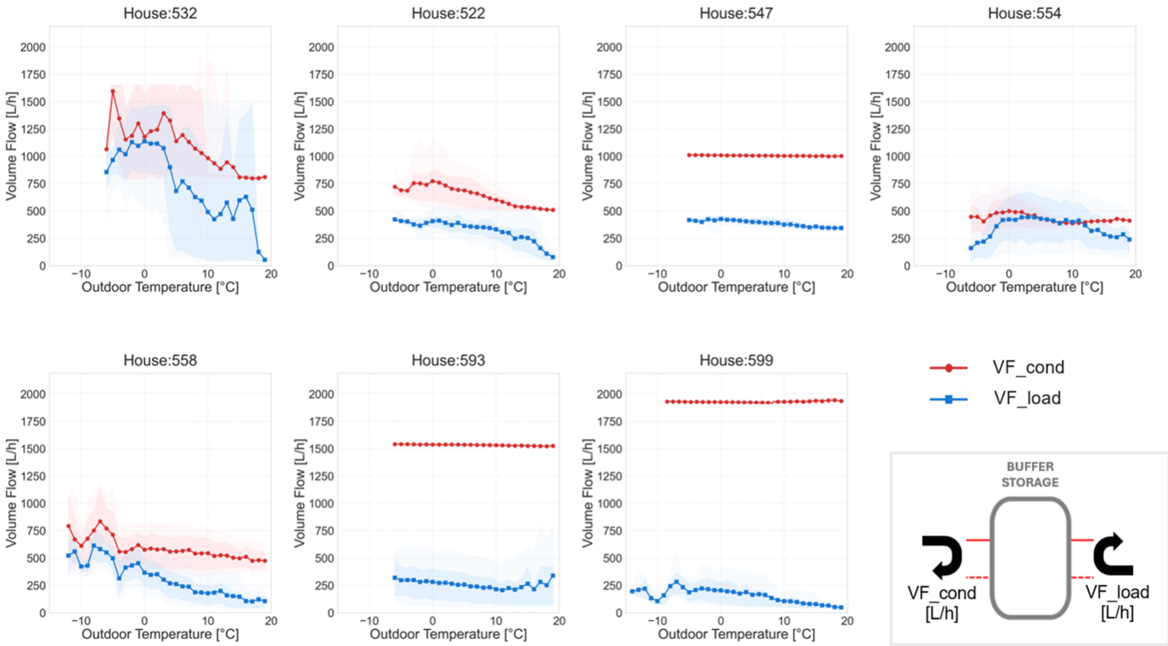

Figure 4. Average charging and discharging volume flow (L/h) as function of outdoor temperature. The charging flow *VF_cond* represents the volume flow between the HP condenser and the buffer tank, while the discharging flow *VF_load* corresponds to the volume flow between the buffer tank and the building's heat distribution system.

The effect of the charging and discharging volume flows can be assessed by comparing the charging flow temperature with the discharging flow temperature during periods when the buffer tank is simultaneously charged and discharged. Ideally, these two temperatures should be nearly identical, indicating minimal thermal mixing within the tank and thus avoiding exergy losses due to temperature degradation. Figure 5 shows the temperature difference between the HP supply to the tank and the buffer tank discharge temperature. In theory, this difference should be close to zero, since during simultaneous operation the charging volume flow is generally much higher than the discharging flow, as shown in Figure 4. The only exception is house 554, which exhibited similar charging and discharging flows. In practice, however, temperature differences of up to 2.5 K on average are observed, likely due to partial mixing within the tank, thermal losses and/or heat meter accuracy limitations.

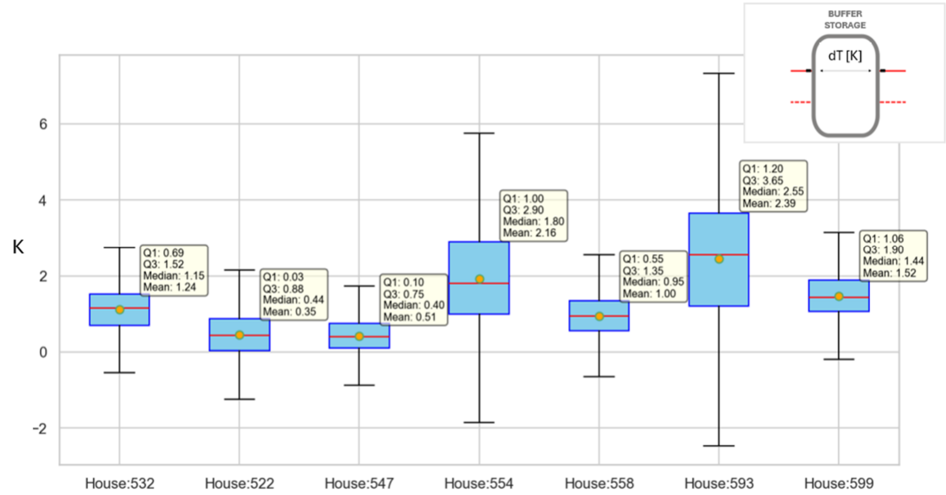

Figure 5. Temperature difference [Kelvin] between charging and discharging flow temperatures during periods when the buffer tank is simultaneously charged and discharged. The components of the rectangular box include the median, the first quartile (Q1) (25th percentile) and the third quartile (Q3) (75th percentile). The candle limits represent the interquartile range (IQR). The circle marker indicates the mean value.

Figure 6 shows the buffer storage charging temperature and discharging temperature. The average charging temperature is consistently higher than the discharging temperature. Nevertheless, unlike Figure 5, these temperatures were not calculated specifically for periods of simultaneous charging and discharging.

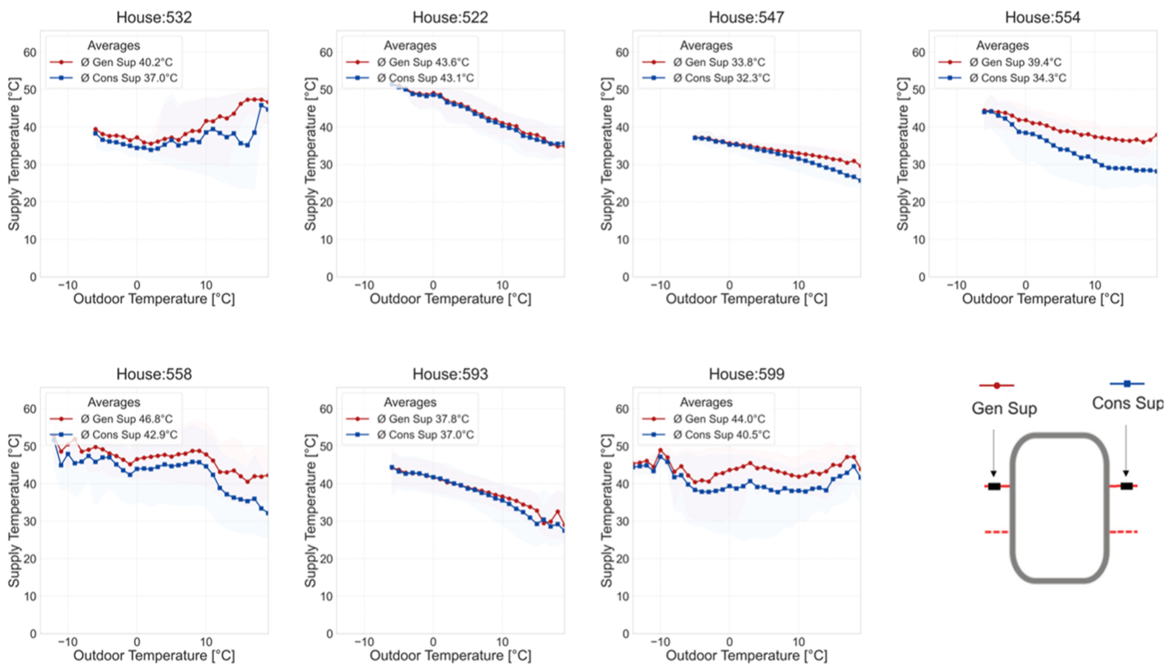

Figure 6. Buffer storage charging temperature (generation side, *Gen Sup*) and discharging temperature (consumption side, *Cons Sup*), with annual averages indicated in the legend.

Figure 7 illustrates the temperature differences between supply and return on both the heat pump (generation) side and the consumption side, as depicted in the schematic. The temperature difference on the HP side, representing the HP condenser temperature lift, was below 10 K for all houses. This difference shows little variation across different outdoor temperatures, with a narrow range indicating that the temperature lift is a controlled value. In contrast, the temperature difference on the consumption side varies significantly with outdoor temperature and exhibits a much wider range.

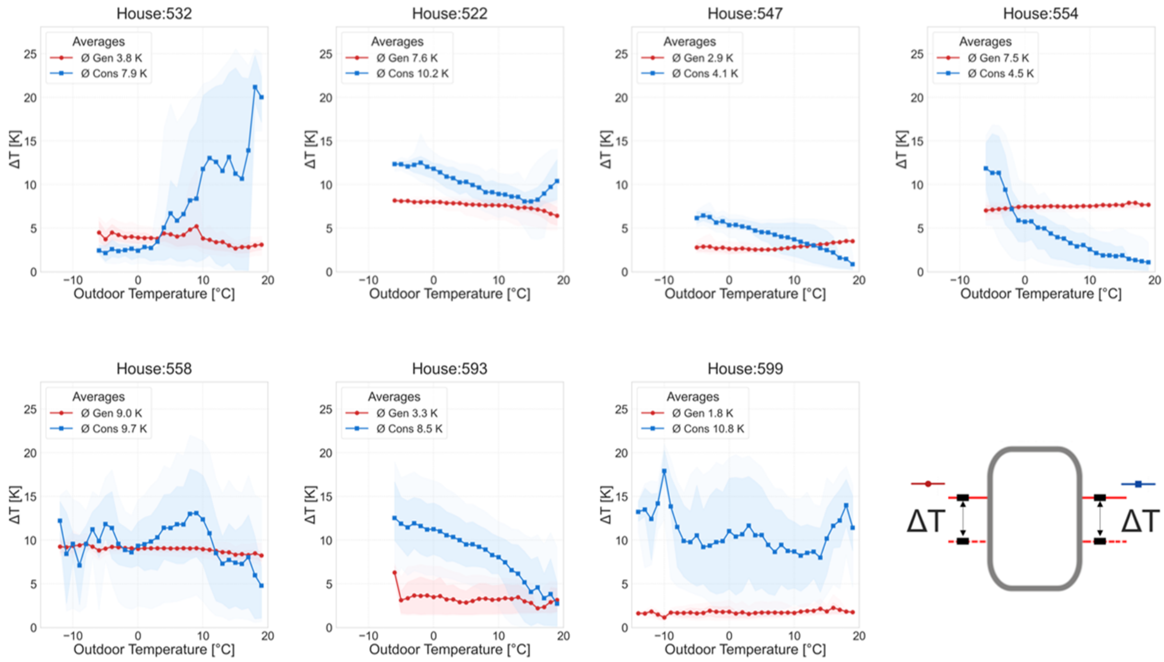

Figure 7. Temperature difference [Kelvin] between supply and return on the heat pump (generation) side and consumption side, with annual averages in the legend.

3.2. Comparison Simulation and Measured Systems

The simulation results provide valuable insights into the effects of control strategies and component sizing on the overall system performance. In particular, the simulated data show that the difference between the HP heat output rate *Q_cond* and the building heat consumption rate *Q_load* tends to be smaller than in the measured results. As illustrated in Figure 8, the simulated HP heat output *Q_cond* tends to follow the building load, *Q_load* more closely as the outdoor temperature decreases, indicating a smoother and more effective modulation behavior.

This improved modulation performance in the simulation reflects the presence of a well-tuned control algorithm and an idealized representation of system dynamics. In contrast, the measured results suggest that the real HPs experience less effective modulation control, likely resulting in higher cycling frequencies and reduced efficiency [8]. It should be noted, however, that the better alignment between *Q_cond* and *Q_load* in the simulated case does not necessarily imply that the real HPs could achieve similar modulation. Differences in the HP performance maps used in the simulations may lead to lower minimum modulation levels than those achievable by the real units. Furthermore, intrinsic numerical simplifications—such as the idealized modeling of the buffer tank and control response—can reduce dynamic effects like temperature stratification losses or controller delays, which are present in the real systems.

Focusing on the effect of buffer tank size, no clear relationship between tank volume and system performance could be identified from the results presented in Table 2. Because the houses differ considerably in their characteristics and operating conditions, the influence of tank sizing cannot be directly inferred from the measured data. To isolate the impact of tank size, a parametric study was conducted for each house by varying the buffer storage volume to 50% and 150% of the original size. The results also indicate that both the seasonal performance factor (SPF) and the runtime duration of the HP remain largely unaffected by changes in tank volume. However, the number of SH mode starts varies significantly, as shown in Figure 9. In most cases, halving the tank size leads to a notable increase in the number of SH starts. Houses 558 and 593 are the most affected by the reduced tank size, as their buffer volume–to–HP nominal power ratios were already among the lowest of all analyzed systems. Specifically, house 558 has 16 l/kW and house 593 has 19 l/kW, whereas the other houses exhibit ratios above 40 l/kW. For reference, according to DIN EN 15450, buffer tanks should be installed with a volume between 12 and 35 l/kW of the maximum HP capacity. While according to VDI 4645, the volume should be 20 l/kW at the design point. [9, 11, 12].

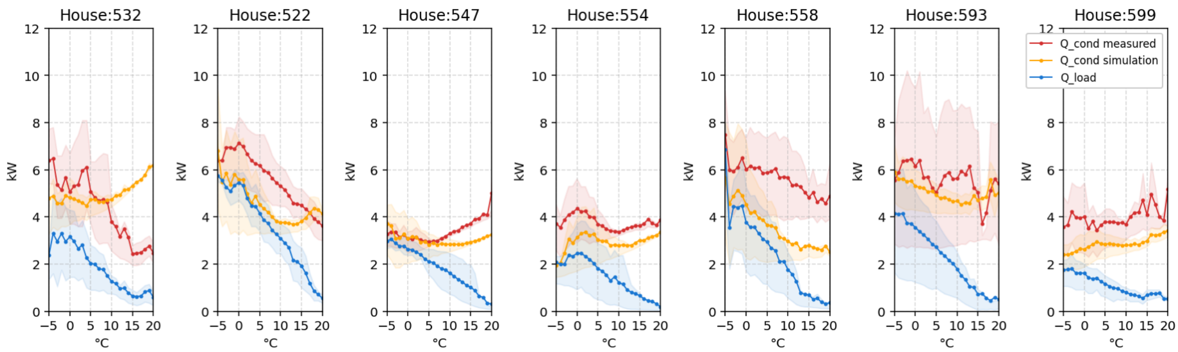

Figure 8. Measured and simulated average buffer storage charging rate *Q_cond* (kW). The average discharging rates, *Q_load* (kW) represents the building heat consumption rate, and is identical to the measured values in the simulation.

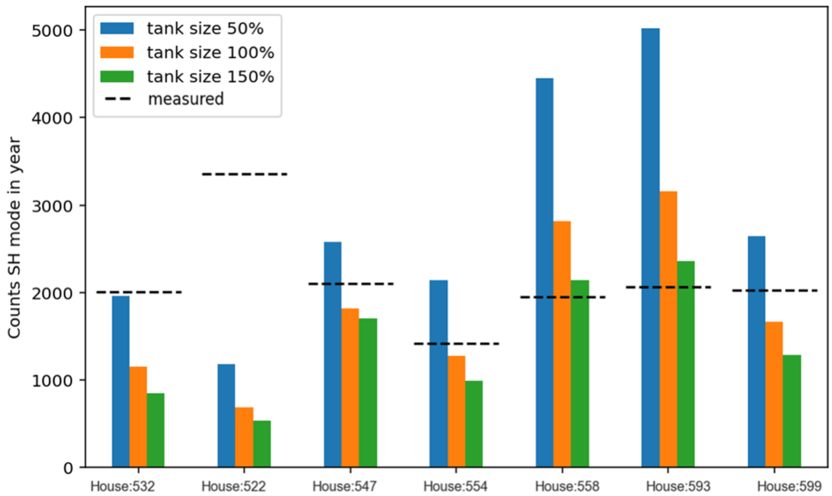

Figure 9. Impact of buffer tank size on the number of space heating (SH) mode starts. Tank volume was varied to 50% and 150% of the original size for each house. *Tank size 50%, 100% and 150%* are simulation results. While dotted line represent the number of SH starts measured.

Overall, while the simulations are useful for understanding the potential behavior under ideal control and sizing conditions, the measured results highlight the practical challenges associated with real HP operation, including suboptimal modulation control and increased cycling frequencies.

4. Conclusions

The analysis shows that the HP heat output rate is generally higher than the building heat load, suggesting that the HPs may be oversized and/or that their modulation control is suboptimal. This behavior leads to increased on/off cycling, which can reduce compressor lifetime. In most cases, the charging volume flows exceed the discharging flows, which in theory helps maintain the supply temperature to the house close to the HP output, minimizing exergy losses. However, temperature differences of up to 2.5 K on average are observed. Implying a potential to increase efficiency, as the HP often delivers heat at a higher temperature than required. Simulations indicate smoother HP modulation, but it remains unclear how much worse the real systems are modulated due to performance map differences and numerical simplifications. Finally, buffer tank size becomes critical only when very small, as undersized tanks significantly increase HP start counts, potentially affecting system longevity and performance.

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