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Impact of System Control on the Performance of a Water-Loop Heat Pump System: A Detailed Analysis

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Abstract

This work focuses on a cascade heat pump system developed to deliver space heating, cooling and Domestic Hot Water to existing small Multi-Family Houses, as this building typology represents the most common in the EU context.
The system analysed integrates centralised air-to-water heat pumps maintaining a water loop's temperature in a range of 20-35 °C. The water loop acts as a thermal source for room-level water-to-air heat pumps, which provide space heating and cooling to a ten-apartment Multi-Family home. Additionally, a water-to-water heat pump connected to the loop supplies Domestic Hot Water.
Dynamic simulation models, validated using monitoring data and laboratory measurements, were used to develop an optimised rule-based control strategy. This adjusts the set temperatures of the storage units and the distribution system to maximise the instantaneous system COP.
Hourly and daily evaluations were carried out to identify the effect of system components sizes and dynamic set points on the overall system performance. In particular, we noticed that: increasing the storage volume (500-2000 l) reduces centralised heat pumps ON-OFF cycles. Moreover, implementing a specific climatic control for both the storage tank and the water loop can improve the system's COP up to 20% on specific days. This control aims to align the COP of the two heat pumps, as, in cascade systems, this maximises the system's COP. In addition, the cascade system's daily COP, calculated in a specific winter week, is compared with the system COP of a reference heat pump system. Lastly, during summer, the combined operation of water-to-water heat pump (which extracts thermal energy from the loop) and water-to-air heat pumps (which reject thermal energy to the loop) tends to complement each other. This reduces the use of the centralised heat pumps, which could remain off for up to two consecutive days.

Keywords: Building renovation; Cascade Heat Pump systems; Optimised system control.

1. Introduction

To reduce fossil fuel dependence in the building sector and cut associated CO_2 emissions, one of the most promising and currently adopted solutions involves electrifying systems that meet users' thermal needs—such as space heating (SH), cooling (SC), and domestic hot water (DHW)—by using heat pump (HP) systems.

The HP systems are more efficient in those applications (typically new and renovated buildings) where the terminal units allow for the use of low supply water temperatures (often in the range of 30-45 °C).

However, the yearly building renovation rate is currently around 1 % and should double to meet the EU targets [1]. Focusing solely on new or renovated buildings is therefore insufficient. On this basis, HP systems development should also consider existing non-renovated buildings, characterised by high specific SH peak thermal demand (in the range of 100 W/m^2). In such buildings, the replacement of fossil fuel heat generators with HP systems is challenging, particularly when high supply water temperature (around 60-70 °C) is needed.

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This, however, is common in existing small Multi-Family Houses (sMFHs) in the EU context, especially in the EU Continental climate, the focus of this work, where radiators are the most adopted terminal units.

Another increasingly critical aspect is the covering of SC thermal demand in residential buildings. This is also valid in milder climates, such as the EU Continental one. Since radiators cannot meet the SC demand, often, a second independent system (typically an air-to-air HP system) is installed.

One solution developed to address these challenges is the cascade HP system with room booster HPs, which has been developed within the HAPPENING project [2] and installed in one of the project's demonstrator buildings. In this system, three Air-to-Water HPs (AWHPs) maintain a distribution circuit (water loop) in the range 20-35 °C. This water loop acts as a thermal source (or thermal sink) for one Water-to-Water HP (WWHP) and a series of Water-to-Air HPs (WAHPs) that cover the SH, SC and DHW users' thermal needs.

Using the existing distribution system at notably lower temperatures (in the range of 20-35 °C instead of the typical 60-70 °C for systems with radiators) reduces distribution system thermal losses to nearly zero. Moreover, in summer, the WAHPs working in cooling mode reject heat to the water loop, while the WWHP extracts heat from the loop. This could result in the thermal balance of these two contributions, with the AWHPs remaining switched OFF.

The specificities of the cascade system imply a proper study of the system control logic and components' sizes to maximise the system COP. In this work, dynamic simulations, performed with models validated against monitored data (obtained using RTD1000 sensor for tank's temperature measurements and calibrated calorimeters for measuring the thermal energy in different control sections identified with the letter "P" in green in Figure 1) and laboratory measurements, are used to identify the effect of system components sizes and dynamic temperature set points on system COP. This is done at hourly/daily time horizons.

This work is organised in different sections: section 2 discusses the model considered and the assessments performed, section 3 presents the main results after applying the discussed control logic, while section 4 summarises the main conclusions.

2. Method

2.1. Building and cascade system model description

The dynamic simulations of the building and the cascade system are performed in TRNSYS [3]. The simulations account for the EU Continental climate as defined in the iNSPiRe project [4]. In this context, Stuttgart is used as reference location and its climatic data are taken from Meteonorm [5].

The building considered is a sMFH with 2 dwellings per floor, characterised by a net floor area of 50 m^2 each, and five floors, for a total net floor area of 500 m^2 and a SH demand in the range of 70 $kWh/(m^2 \cdot y)$. Each apartment is modelled as two thermal zones, representing the living and sleeping zones, to account for their different usage patterns. In terms of indoor temperature control, one thermostat per dwelling is considered. The thermostat's measurement is the weighted average of the living room and sleeping room air temperatures, weighted based on the net floor area of the two thermal zones. The indoor temperature set points are 20 °C and 26 °C in winter and summer, respectively, according to [6]. In winter, the system is switched OFF during nights (22:00-06:00).

Figure 1 shows the Piping and Instrumentation Diagram (P&ID) of the considered cascade system. In this figure, it is possible to note the two cascade systems. In fact, the AWHPs can work in cascade with the WWHP or with the WAHPs, depending on which of the machines are active.

Three 15 kW_{th} R32 AWHPs, connected in parallel, condition the buffer tank (BUF in Figure 1).

Different buffer tank sizes, ranging from 500 to 2000 l, have been considered in the simulations. This aims to identify how a larger buffer tank reduces the number of AWHPs activations. The buffer tank is also connected to the distribution system (water loop), which consists of a first common part, extending to the collectors Dist_HJS and Dist_HJR in Figure 1, and then divided into two separate parts. The first is the DHW distribution system, which connects the collectors to the 9 kW_{th} R410a WWHP. The second is the SH/SC distribution system, which connects the same collectors to the 2.1 kW_{th} R290 WAHPs (one per building's thermal zone).

The WWHP charges the 1100 l DHW tank (TES in Figure 1) maintaining the temperature measured at 60 % of the tank's height starting from the bottom in the range 55-60 °C using the water loop as a thermal source. The TES is also connected to the users through a recirculation circuit (DHW recirculation system in Figure 1) to ensure the delivery of DHW to the users in a short time.

The WAHPs, instead, deliver SH and SC to the building using the water loop as a thermal source (in heating mode) or as a thermal sink (in cooling mode).

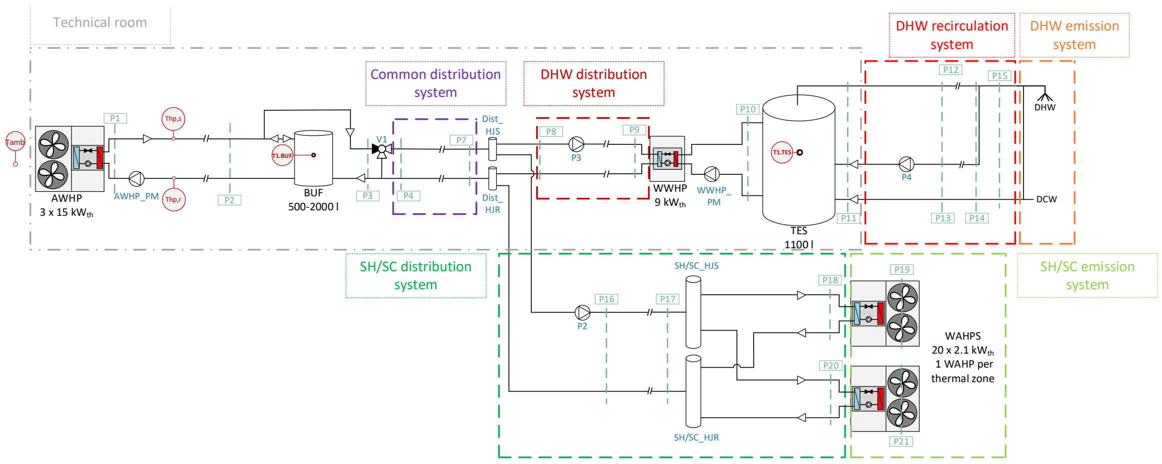

Figure 1. Simplified P&ID of the cascade system with room booster HPs.

The system control logic differs between winter and summer. However, the AWHPs activation is always based on the same buffer temperature sensor placed at 60 % of the tank's height from the bottom.

In winter, the buffer tank temperature, and thus the AWHPs operation, is controlled using a dynamic temperature set point following an inverse climatic curve. This is because a generic cascade system COP has a theoretical upper limit calculated according to Eq. (1), which has a maximum when COP_1 is equal to COP_2:

$$SYS\_COP_{theo} = \frac{COP_1 \cdot COP_2}{(COP_1 + COP_2 - 1)} \quad (1)$$

Where COP_1 and COP_2 are the COPs of the machines in cascade.

In the considered cascade system, the AWHPs show the largest COP variation due to the wide source temperature range in which they operate, making them the main factor influencing system COP among the three types of HPs. The AWHPs set point temperature varies linearly (Figure 2, left) to sustain its COP also at low ambient temperatures. A similar dynamic temperature set point is used for the water loop (Figure 2, right).

The differences in terms of system control in summer regard the management of the buffer temperature, and, therefore, the activation of the AWHPs, and the management of the water loop temperature.

In summer, the objective of the system control is to let the WWHP and the WAHPs (working in cooling mode) to thermally balance themselves, using the water loop and the buffer tank to accommodate eventual temporal thermal imbalances before activating the AWHPs in heating or cooling mode.

For this reason, in summer, the buffer temperature is allowed to vary between 25 °C and 38 °C (Figure 2, left). Temperatures outside this range cannot ensure an efficient operation of both WWHP and WAHPs in cooling mode. The water loop set point temperature varies in the range 35-25 °C (Figure 2, right). During milder summer days, SC thermal demand is limited or absent, while the DHW demand is always present. The water loop set point temperature is, in these conditions, in the range of 30-35 °C to optimise the cascade system AWHPs-WWHP operation. On the other hand, the water loop set point temperature decreases at high ambient temperatures in summer (hot days), when the SC load is the highest building thermal demand. In this way, the operation of WAHPs (which, in cooling mode, benefit from a lower water loop temperature) is optimised and, considering the higher contribution of the WAHPs with respect to the WWHP in hot days, this results also in an improved system COP.

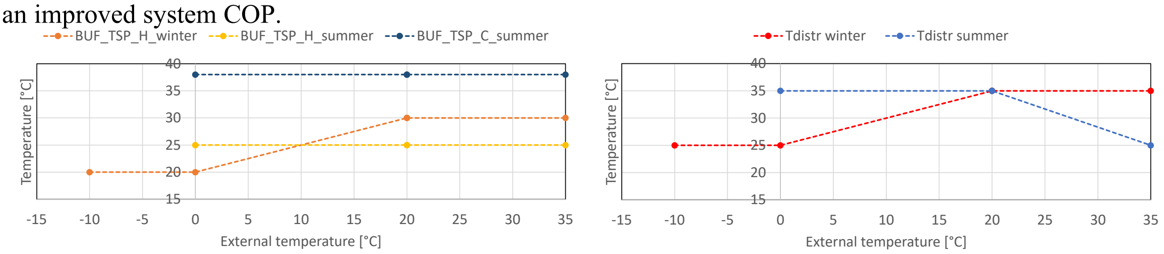

Figure 2. Left figure: buffer tank set point temperature in winter (orange), and summer (heating: yellow, cooling: dark blue). Right figure: water loop temperature set point in winter (red) and summer (blue).

2.2. Reference period and system considered for the results assessment and COP calculation method

As the focus of this work is to analyse the effect of system components sizes and dynamic set point temperatures on system COP on short (hourly/daily) time horizons, the analysis reported in the section 3 focuses on two weeks considered representative of the typical system operation in winter (period 1-7 January) and summer (period 22-28 June).

The daily COP of the cascade system is compared, for the selected winter week, with the COP of a reference system, sized to cover the thermal demand of the considered building, consisting of a single AWHP that supplies SH (using radiators) and DHW. This comparison provides a benchmark against a standard solution typically used in renovations of this type of building. The reference HP system control logic in SH mode follows a climatic curve, supplying water to the SH distribution circuit at 60 °C when the outdoor temperature is −12 °C and at 30 °C when it is 20 °C, while the management of the DHW tank's temperature is the same already reported above.

Moreover, the daily COP of the cascade system with dynamic set point temperatures is compared with the one obtained for the same cascade system with a fixed set point temperature.

The COP calculation of the various machines and of the cascade system is based on Eq. (2).

$$COP_i = \frac{Q_{th,i}}{W_{el,i}} \quad (2)$$

For the COP calculation of the single machines, the subscript i indicates the COP of the considered HP, the thermal energy delivered by the machine (Q_{th}) and the related electric consumption (W_{el}). For the system COP calculation, the same subscript i indicates the system COP, the thermal energy delivered for SH, SC and DHW to the users (measured at control sections P19, P21 and P15 in Figure 1) and the related system electric consumption (including the electric consumption of the compressor, the fan and the circulating pumps).

In the calculation of the cascade system COP, the system COPs of the two cascades (AWHPs-WWHP and AWHPs-WAHPs) are combined, weighting them based on the thermal energy delivered by the WWHP and the WAHPs. The same averaging procedure is also used for the calculation of the theoretical system COP.

3. Results and discussion

As shown in Figure 3, a larger buffer tank reduces the number of daily AWHPs activations, increases the operational time within the specific charge (aspect not visible in Figure 3) and the interval between two consecutive AWHPs activations. The figure presents the daily integrated number of AWHPs activations for the considered winter week with the 500 l (gold line) and the 2000 l (green line) buffer tank.

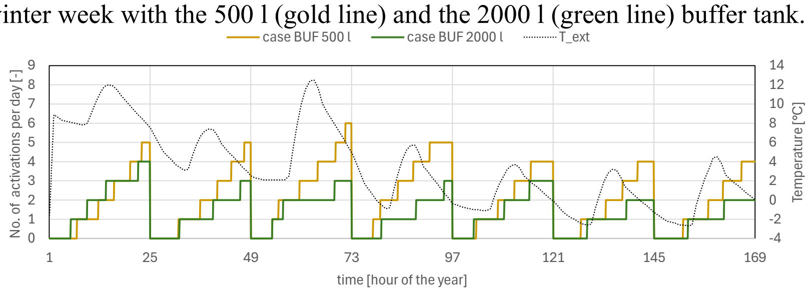

Figure 3. On the left y-axis: daily integrated number of AWHPs activations considering a buffer tank of 500 l (gold line) or 2000 l (green line). On the right y-axis: ambient air temperature (black dotted line). Period 1-7 January.

Figure 4 shows the AWHP COP in heating mode (black triangles), the WWHP COP (red crosses) and the WAHPs COP (green squares). From this figure, it can be noted that the AWHPs COP and the WAHPs COP are similar, leading to almost optimal operation for this cascade.

On the other hand, the WWHP COP is almost always lower than the AWHPs COP, indicating that the operation of the cascade AWHPs-WWHP could be, in principle, improved. However, it has been verified that the main factor limiting the WWHP COP is not the low water loop temperature, but, instead, the high temperature at the load side. In fact, this machine is responsible for charging the DHW tank, working with supply water temperature up to around 60 °C.

Figure 4 also shows the thermal power delivered to the users for DHW (dark red line), SH (red line) and the total system electric consumption (orange line). From these profiles, it can be noted the effect of the reduced night indoor temperature set point during the night.

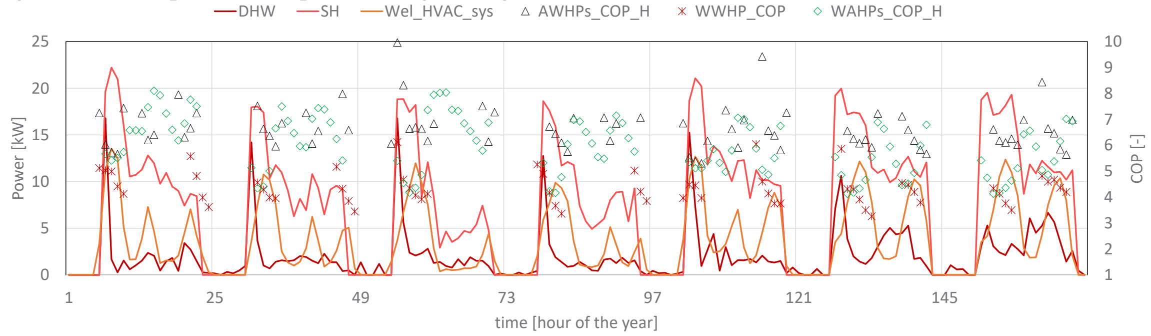

Figure 4. On the left y-axis: thermal power delivered to the users for DHW (dark red line), SH (red line) and the system electric consumption (orange line). On the right y-axis: AWHPs COP in heating mode (black triangles), WWHP COP (red crosses) and WAHPs COP in heating mode (green squares), Period: 1-7 January.

Figure 5 presents the daily thermal energy calculated as the integral of the thermal and electric power visible in Figure 4, the daily COP for the different types of HPs and the system COP (purple circles). In addition, the theoretical system COP and the reference HP system COP are shown (purple empty circles and squares). As can be noted, the system COP is in the range 2.6-2.9 in the considered period, a value similar to the upper theoretical limit. This is because, in the considered week, SH is the main building thermal demand, and the cascade AWHPs-WAHPs presents high and similar COPs for the two types of machines.
Compared with the reference HP system, the cascade system presents a higher daily system COP, with differences of 0.4-0.8, except on the first day, where the reference system exhibits a higher COP due to the different buffer and DHW tank temperatures between the beginning and the end of that day. The cascade system achieves higher COPs, particularly on the coldest days, due to the high supply temperatures required by the reference HP system to meet SH demand.
Moreover, in comparison to a cascade system using a standard control logic with a fixed set point temperature, the advantages, in terms of cascade system COP, are higher in the milder period, profiting from the possibility to increase the buffer tank and water loop set point temperatures, and therefore the WWHP and WAHPs COPs, maintaining a high AWHP COP, similar to the WWHP and WAHPs one. The improvement in the daily system COP can reach up to around 20 %.

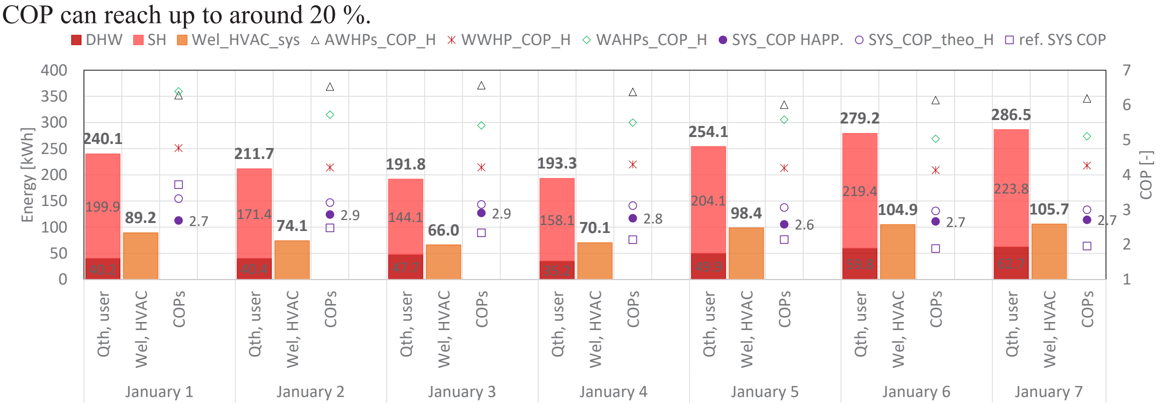

Figure 5. On the left y-axis: thermal energy delivered to the users for DHW (dark red bars), SH (red bars) and the system electric consumption (orange bars). On the right y-axis: AWHPs COP in heating mode (black triangles), WWHP COP (red crosses), WAHPs COP in heating mode (green squares), system COP (filled purple circles), theoretical system COP in heating mode (empty purple circles) and reference HP system COP (empty purple squares). Period: 1-7 January.

The positive interaction between the WWHP and the WAHPs working in SC mode in summer is presented in Figure 6. In this figure, the red and light blue filled bars represent the thermal energy extracted by the WWHP and rejected to the water loop by the WAHPs, respectively.

The red or light blue empty columns in the same figure represent the thermal energy delivered by the AWHPs, which can work in heating (red empty bars) or cooling (light blue empty bars) mode, depending on the buffer temperature. As visible in the figure, the AWHPs deliver only part of the thermal energy used by the WWHP and WAHPs, with days in which the AWHPs are not activated as the operation of the WWHP and the WAHPs, together with the thermal capacity given by the water loop and the buffer tank, thermally balance themselves. Although it is not visible in Figure 6, the AWHPs can remain off for up to two consecutive days. The labels P1, P8 and P16 refer to the control sections in Figure 1.

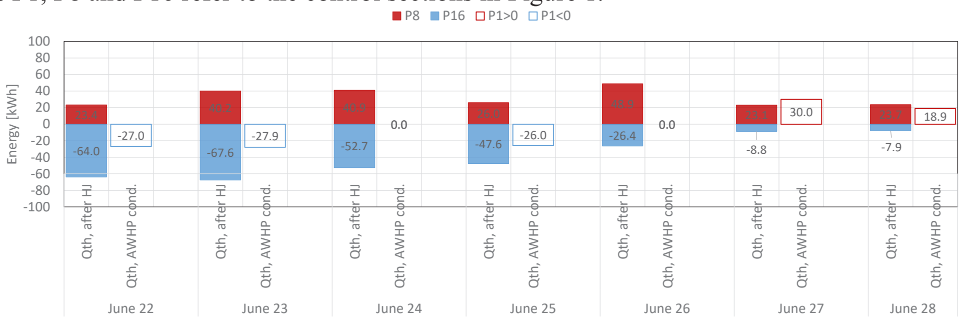

Figure 6. Thermal energy extracted by the WWHP (red filled bars) and rejected by the WAHPs (light blue filled bars) from/to the water loop; AWHPs contribution in heating (red empty bars) or cooling (light blue empty bars) mode. Period: 22-28 June.

4. Conclusions

This work has demonstrated that a larger buffer tank has a positive effect on the reduction of the AWHPs number of cycles.

Moreover, the adopted dynamic temperature set point for both the buffer tank (and thus the AWHPs) and the water loop resulted in an increased system COP in comparison to a fixed set point temperature on the same cascade system in milder days. If compared to a reference HP system with a centralised AWHP sized to cover the same building's thermal loads, and radiators as terminal units, the cascade system shows daily COPs slightly higher, especially on the coldest days, in the considered winter week.

Another advantage of the studied cascade system is the possibility to exploit the positive synergies between the WWHP and the WAHPs working in cooling mode during summer. In fact, the operation of these two HP types tends to thermally balance themselves in summer, resulting in a lower contribution of the AWHPs and, therefore, in a reduced system electric consumption.

Acknowledgements

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