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Laboratory investigation of control strategies of a cascade heat pump system with intermediate water loop

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Abstract

A water-loop, cascaded heat pump system has been designed targeting the renovation of buildings originally heated by a central gas boiler. The project included the control development, laboratory tests and installation and monitoring of the system at a demonstration site.

The system uses the existing water distribution loop to connect a central to room heat pumps: central heat pumps provide low-temperature heat to the water-loop, which supplies booster heat pumps covering domestic hot water, space heating and cooling demands. The control of all the components is crucial for the effective operation of the whole system.

The paper presents the laboratory characterization of the system, while in operation under four different rule-based controls. In the first case, we considered the same control implemented on board of the system installed at the demonstration site, while the others explore potential improvements.

The system has been set up in three adjacent climatic chambers: one hosted the external unit (representing the outdoor ambient), one the water-loop and the storages (technical room) and one the internal units (indoor ambient). The tests were conducted by producing dynamic air temperature and humidity in the chambers, by emulating domestic hot water space draws, hence allowing to test the system under a range of real-like operating conditions. The results demonstrated the control strategies effectiveness: the importance of the control of the source heat pump which COP affects the cascade COP and the importance of the control of the water loop that affects the thermal losses and the auxiliary consumptions. From the base control the system COP has been improved by 2% to 80% with the different controls. The cascade system has been compared with an air-to-water heat pump that feeds fan-coils or radiators. The cascade system COP is 40% higher than the single stage unit with fan-coil.

Keywords: water loop; cascade heat pump system; laboratory test; control strategies;

1. Introduction

The heating and cooling demands cover near the 50% of the heat demand and the decarbonization of buildings' thermal loads plays a key role for the achievement of the energy and climate targets [1]. In this transition of the electrification of thermal loads, the heat pumps cover an important role [1–3].

The design of the heat pump is important for the field performance, and this will be reflected in the operational costs, comfort of the user, lifetime of the unit. As example, the evaluation of the monitored data performed by Miara et al showed a wide range of COP for different heat pump [4]. Regarding the design of the system, Li et al. [5] identified in 30-40 l/kW as optimal size for the storage in relation to the heat pump

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capacity for fixed-speed units. Proper control of the system is crucial for performance. Advanced control strategies can improve the COP in a range of 5 to 20% [6–10].

Implementing a heat pump system in a newly constructed building is more straightforward than in a renovation project. This is because the design of a new building allows for integrated planning: thermal loads are minimized, dedicated space is allocated for technical equipment, and the distribution circuit can operate at low temperatures, efficiently supplying both heating and cooling needs. For these reasons in a new building a single-stage heat pump can achieve a high coefficient of performance. Instead, renovating a building involves multiple obstacles, and a single-stage heat pump cannot meet all renovation needs.

For the cases with high temperature lifts (high heating load or industrial processes), cascade heat pump systems have emerged as a promising approach for applications requiring large temperature lifts or simultaneous heating and cooling [11]. By integrating multiple stages of compression, the refrigerant of the first stage exchanges heat directly with the refrigerant of the second stage through an intermediate heat exchanger. These systems can achieve improved performance and flexibility compared to conventional single-stage units when used with high temperature side. On the other side at low or medium temperatures a single stage heat pump can reach higher COP than a cascade heat pump [12–15].

A critical component in optimizing the operation of cascade systems is the intermediate loop. This configuration enables better control of heat transfer, stabilizes system dynamics, and enhances overall energy efficiency [16]. However, the complexity introduced by multiple stages and intermediate loops necessitates robust control strategies to ensure reliable operation under varying load conditions [13].

Despite the theoretical advantages, practical implementation of these strategies requires thorough validation under controlled conditions. Laboratory testing provides an essential platform to evaluate system behavior, identify operational challenges, and refine control algorithms before deployment in real-world applications. Previous studies have focused on component-level optimization, but comprehensive investigations into integrated control approaches for cascade systems remain limited [13,15–17].

A cascade heat pump system with intermediate water-loop has been developed in the H2020 project HAPPENING for the retrofit of existing buildings [18]. The proposed system offers several advantages for building renovation, including neutral distribution temperatures that minimize thermal losses and improve efficiency, retention of the existing distribution system to reduce investment and enable independent room cooling, balancing domestic hot water and cooling demands in summer, decoupling the source heat pump from those serving the loads, and flexible management of storage. Advanced controllers can improve the system performance acting in these last two points.

This paper presents a laboratory investigation of control strategies for the cascade heat pump system with an intermediate water loop. The study aims to assess the impact of different control schemes on system performance. The starting point was the settings implemented in the demo case and then different variations were proposed to improve the system COP. The system installed in laboratory was the system of the demo case in a smaller scale. This activity was also used to validate the model predictive control developed within the project framework [19]. The paper presents the comparison of the performance of the cascade system with an air-to-water heat pump that feeds fan coil or radiators.

Section 2 presents the cascade heat pump system, the control strategies implemented to control it, the test method and the KPIs. In section 3 we discuss the results of the test with different control strategies in terms of system and sub-system COPs and power input.

2. Method

2.1. Cascade heat pump system

In the HAPPENING project a cascade heat pump system with intermediate water loop was designed for the renovation of buildings originally heated by a gas boiler. The aim is to replace the gas boiler minimizing the construction works in the building: the distribution system of the building is maintained while the generation system and the heat emission terminals are replaced by heat pumps. In the project Innova developed the prototypes of the air-to-water, water-to-water and the water-to-air heat pumps. Those units were developed selecting refrigerants according to the phase down foreseen by EU F-Gas Regulation.

The same system has been installed in a demo case with 15 dwellings and reproduced in the Heat Pumps Lab of Eurac Research [20] on a smaller scale. While the demo case has three centralized air-to-water heat pumps connected in parallel, in the laboratory we installed one unit; the demo case has 15 dwellings, and the laboratory reproduced one dwelling. The capacity of the buffer and thermal energy storage has been proportionally reduced. It was not possible to maintain the same proportion between the air-to-water heat pump and the water-to-air heat pumps in terms of installed capacity due to lack of availability of water-to-air prototypes. Therefore, the system reproduced in laboratory presents a central heat pump oversized in relation to the loads. In addition, the thermal insulation of the system was not optimized: all the pipes and the storages were insulated according to the manufacturer specifications while some valves were not insulated representing a "medium quality" installation.

Figure 1 presents the layout of the system installed in the laboratory and the KPIs boundaries that will be described in the following section. An air-to-water heat pump (green dotted line) is connected to a 500 L buffer and delivers heat at low-temperature to the water-loop. The water loop is the source for booster heat pumps. The temperature of the water-loop is controlled by a three-way. A water-to-water heat pump produces domestic hot water charging thermal energy storage (200 L) while two water-to-air heat pumps cover the heating and cooling loads controlling the indoor temperature. In the figure it is represented only one for simplify the representation.

The blue dashed lines show the control logic dependencies which will be described in the following section.

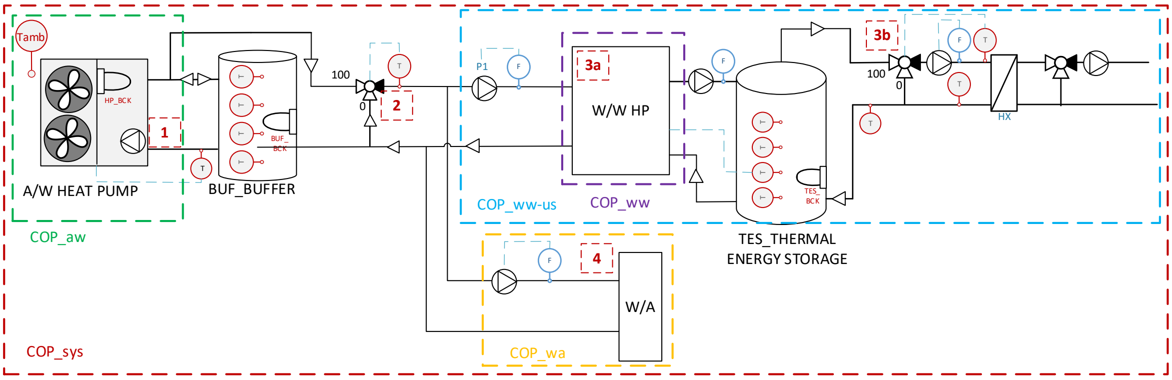

Figure 1. System scheme and KPIs boundaries.

To build the system in the laboratory, we used hydraulic modules (called energy hubs EH) which have a double function: control of temperatures and flows and energy metering. EH1 meters the capacity of the air-to-water heat pump, EH7 controls the water-loop temperature, EH9 and EH10 control the flow rate of the water-to-air HPs, EH8 and EH3 control the flow rates of evaporator and condenser of the water-to-water HP, EH2 controls the distribution of DHW and connects the system to the draw-offs. EH2 on the secondary circuit simulates the DHW tapping, while in the primary circuit was configured with different controls.

Figure 2 presents the installation prepared in laboratory: in the climatic chamber A2 (left part of the figure) there is the external unit of the air-to-water heat pump; the chamber A1 (middle) represents the technical room with the internal unit of the air-to-water heat pump, the buffer and the thermal energy storage, hydraulic modules; in the calorimeter I (right part) there are the two water-to-air heat pumps with the relative pumping hydraulic modules.

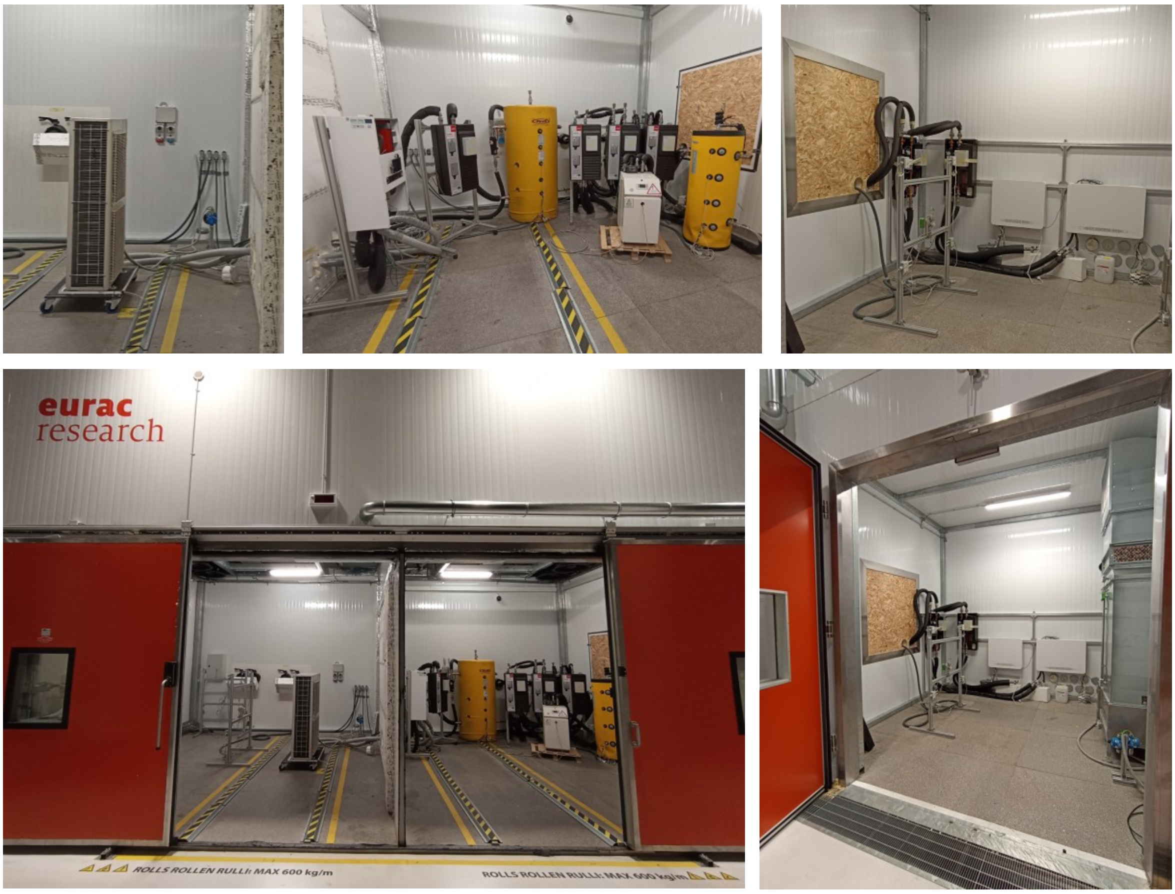

Figure 2. Installation of the system in laboratory.

2.2. Control strategy

Different control logics were implemented throughout the test phase to reproduce the common traditional controls that are implemented in the heat pump system. Table 1 presents the controls of the different circulators while Table 2 presents the controls of temperatures done with the units or with the three-way valves. In the tables there are indicated the control points as reported in Figure 2 (red numbers with dotted border) representing:

- 1 – Central A/W heat pump. The flow rate and the return temperature are set on the unit. The pump has three speeds manually selectable, and the unit controls the activation of the pump according to the different strategies available for the user. For this test we selected the “Eco mode” which stops the pump when the compressor is not working; the circuit was balanced in order to have 1.95 m3/h when the pump is active. The unit controls its modulation with the return temperature; for the test different temperatures were set and compared.
- 2 – Water loop. The temperature of the water loop is controlled by the three-way valve of the EH and during the test different temperatures were set as the A/W heat pump.
- 3a – W/W heat pump. The heat pump was without the internal circulator, and the control of the flow has been performed with the EHs. The flows are the nominal ones. The heat pump controls the DHW storage temperature with a constant set point and default hysteresis.
- 3b – DHW distribution system. The flow and temperature of the DHW distribution system was controlled with an EH. The flow rate was calculated according to the design of the heat exchanger. The temperature control was considered in two cases: no control (valve fully open) or fixed set temperature of 45°C.
- 4 – Rooms’ W/A heat pumps. The EHs controlled the flow of the W/A heat pumps with a continuous flow rate, and the room temperature was controlled by the unit.

The control logic A reproduces the control of the system that the local installer of the system implemented in the demo case. Then, the control logic B, C, D represents possible improvements that the installer can perform without changing the control hardware.

The activation of W/W, DHW circulators "on request" is controlled by the thermostat of the DHW storage which normally controls the water-to-water heat pump.

Table 1. Controls of circulators

Logic n.	A/W circulator	W/W circulator – source	W/W circulator – load	DHW storage circulator	W/A circulator
Control point	1	3a	3a	3b	4
A	Eco mode 1.95 m3/h	Continuous 1.65 m3/h	Continuous 1.30 m3/h	Continuous 1 m3/h	Continuous 0.30 m3/h
B	Eco mode 1.95 m3/h	Continuous 1.65 m3/h	Continuous 1.30 m3/h	Activated on request 1 m3/h	Continuous 0.30 m3/h
C	Eco mode 1.95 m3/h	Activated on request 1.65 m3/h	Activated on request 1.30 m3/h	Activated on request 1 m3/h	Continuous 0.30 m3/h
D	Eco mode 1.95 m3/h	Activated on request 1.65 m3/h	Activated on request 1.30 m3/h	Activated on request 1 m3/h	Continuous 0.30 m3/h

Table 2. Control of set temperatures

Logic n.	A/W return temperature	water loop temperature	W/W supply temperature	DHW loop valve	W/A room temperature
Control point	1	2	3a	3b	4
A	20 / 30 / 50 °C	20 / 25 / 43 °C	54 °C with default hysteresis	No control / fully open	22 °C
B	20 / 30 / 50 °C	20 / 25 / 43 °C	54 °C with default hysteresis	No control / fully open	22 °C
C	20 / 30 / 50 °C	20 / 25 / 43 °C	54 °C with default hysteresis	No control / fully open	22 °C
D	20 / 30 / 50 °C	20 / 25 / 43 °C	54 °C with default hysteresis	Tset 45 °C	22 °C

2.3. Comparison with a reference system

The performance of the cascade heat pump system with intermediate water loop was compared with a heat pump system composed of a single-stage air-to-water heat pump with the same configuration of buffer and domestic hot water storage. In this case, the KPIs boundaries are simplified: COP of the air-to-water heat pump, the COP of the domestic hot water that includes the boundary from the air-to-water heat pump to the hot water use, and the COP of the space heating that includes the boundary from the air-to-water heat pump to the heat emission system. For this purpose, we considered two possible heat emission systems: fan coil and radiators. The set temperatures were respectively 50°C and 60°C to have the system working at 45°C and 55°C.

Regarding the control strategies we considered the "A" and "D" strategies. The space heating and domestic hot water loads are the same as the cascade system.

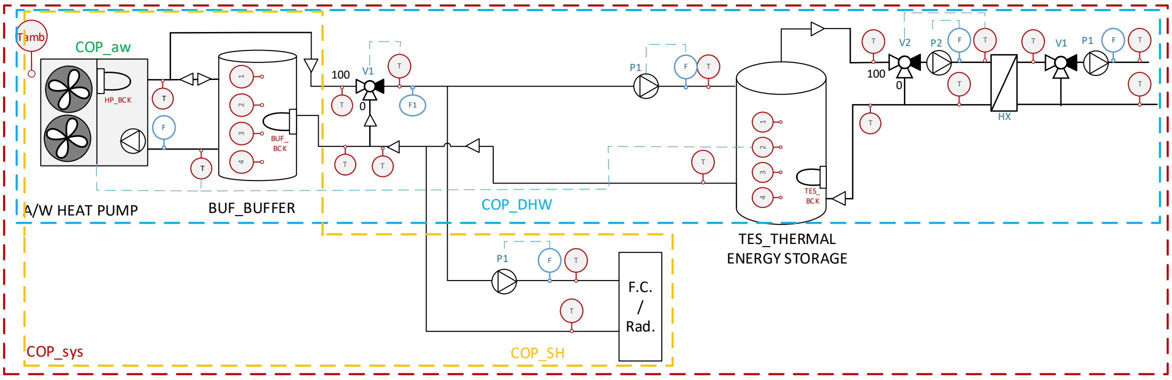

Figure 3. System scheme and KPIs boundaries of the reference system.

2.4. Test method and calculation of KPIs

The tests were carried out at the Heat Pumps Lab of Eurac [20]. The authors initially programmed to perform a dynamic test according to the PLPE method developed by Eurac [21] or the hardware-in-the-loop with TRNSYS as simulation model. However, the number of combinations of test (four control logics and three water set temperatures) would have request a long test campaign and the authors decided to simplify the test method.

The test duration was 12 h considering different boundary conditions. The boundary conditions were combined with control logics described in the previous section.

- The climatic chamber “A2” reproduced the external air temperature ranged between -5 °C and 8 °C, while the RH values ranged between 65 % and 85 %.
- The HVAC system of the calorimeter “I” emulated a variable load ranging between 1.6 kW and 2.6 kW with a fixed profile of total energy of 24.4 kWh (the same profile was applied to all tests). The profile is reported in Figure 4.
- The DHW load was performed with load profiles similar to “M” and “L” profiles of EN 16147:2017. As the test was 12h (from 07:00 until 19:00) and the standard defines a longer duration (from 07:00 until 21:45), the version implemented in the laboratory considered the same energy but extracted in 12 h. In all the tests the DHW storage was preconditioned at the same level of energy. The profiles are reported in Figure 4.

The KIPs were defined considering the different boundaries presented in the Figure 1 and Figure 3. The heating capacity was measured with the water enthalpy, and the COPs considered the units and the sub-systems.

$$\dot{Q}_i = \dot{m}_w \cdot \rho \cdot \left(c_{p,out} \cdot \vartheta_{out} - c_{p,in} \cdot \vartheta_{in}\right) \tag{1}$$

$$COP_{sys} = \frac{Q_{SH}+Q_{DHW}}{\sum_i W_i} \tag{2}$$

$$COP_{AW} = \frac{Q_{AW}}{W_{AW}} \tag{3}$$

$$COP_{WW} = \frac{Q_{WW}}{W_{WW}} \tag{4}$$

$$COP_{WW-US} = \frac{Q_{DHW}}{W_{WW}+W_{p,s,WW}+W_{p,l,WW}+W_{p,DHW}} \tag{5}$$

$$COP_{WA} = \frac{Q_{WL}}{W_{WL}+W_{p,WL}} \tag{6}$$

where:

- $\dot{Q}_H$ is the heating capacity, expressed in kW;
- $\dot{m}_w$ is the indoor heat exchanger flow rate, expressed in m^3/h;

- ρ is the density, expressed in kg/m^3;
- cp is the specific heat at constant pressure, expressed in kJ/(kg K);
- ϑ is the temperature, expressed in °C.
- Q_{SH} is the space heating load, expressed in kWh.
- Q_{DHW} is the domestic hot load, expressed in kWh.
- W is the electric consumption, expressed in kWh. The subscript “p” represents the pump consumption, “s” the source side, and “l” the load side. W_{AW}, W_{WW}, W_{WL400}, W_{WL200} are the electric consumption of air-to-water, water-to-water, and the water-to-air WL400 and WL200 heat pumps.
- Q_{AW}, Q_{WW}, Q_{WL}, are the heats of the indoor heat exchangers (load side) of air-to-water, water-to-water, and the water-to-air WL heat pumps, expressed in kWh.

The thermodynamic properties of water are defined as a function of temperature according to the tables in the "Perry's Chemical Engineering Handbook, 7th Edition, 1997".

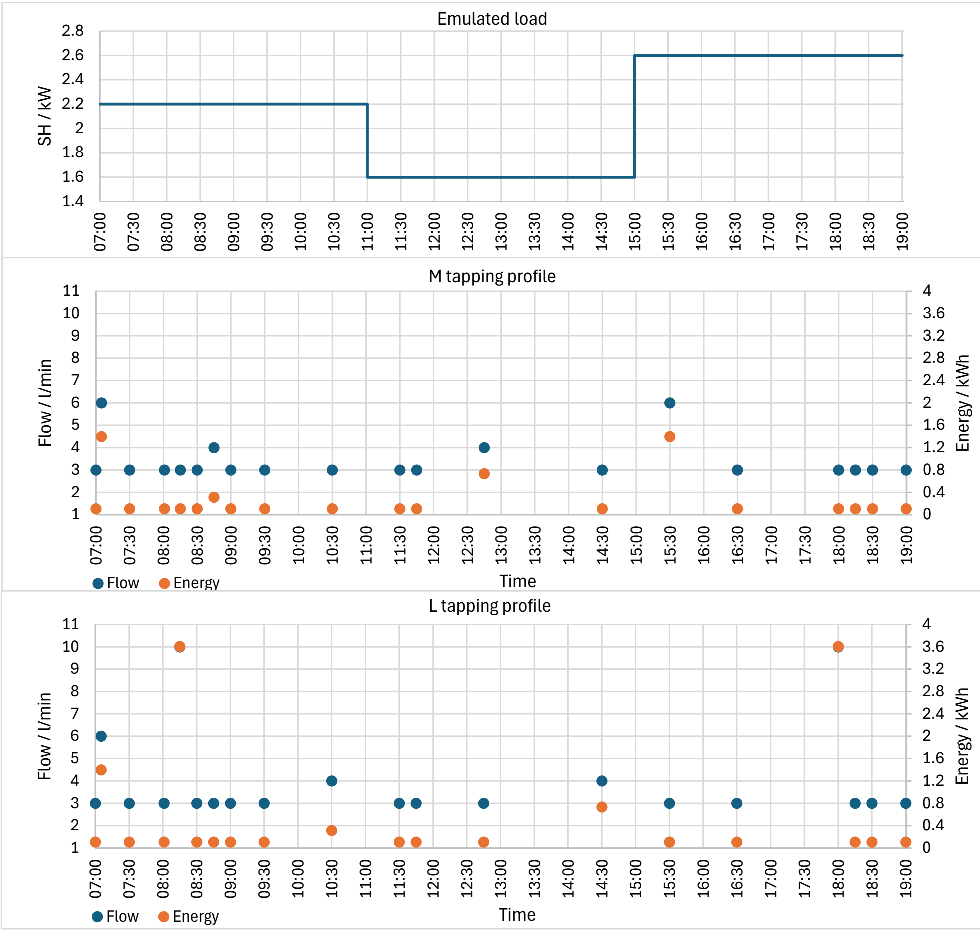

Figure 4. Load profiles.

3. Results and discussion

The laboratory performed tests with different profiles of external temperature. In this paper we report only the test with an average external air temperature of 5°C in order to simplify the presentation of the results. The tests were done with the space heating and domestic hot water profiles presented in the previous section. The different figures report in the title the “M” and “L” letters that represent DHW profiles. In the first case the system provided 32.2 kWh of useful load subdivided in 26.5 kWh for the space heating and 5.7 kWh for the domestic hot water. In the second case the system provided 37.9 kWh corresponding to the same space heating load and to 11.4 kWh of domestic hot water.

In order to simplify the understanding of the reader, the following figures present the KPIs as a function of the set temperature of the air-to-water heat pump with different data series for the four control logics; the figures present a data label which indicates the control of the water-loop temperature. The control logics with the indication "-SS" refers to the single stage system; in this case there is no label as the water loop temperature is useless.

Figure 5 presents the system COP calculated according to Eq. (2). The system COP is higher for the L profile compared to the M profile and decreases with the increase of the temperature set of the air-to-water heat pump or the set of the water-loop temperature. The strategies with continuous operation of the circulators present a lower COP. The single-stage heat pump must work with a high temperature of the distribution system. The cascade system, when controlled with a neutral temperature, performs better than the single stage system which is affected by the thermal losses of the circuit.

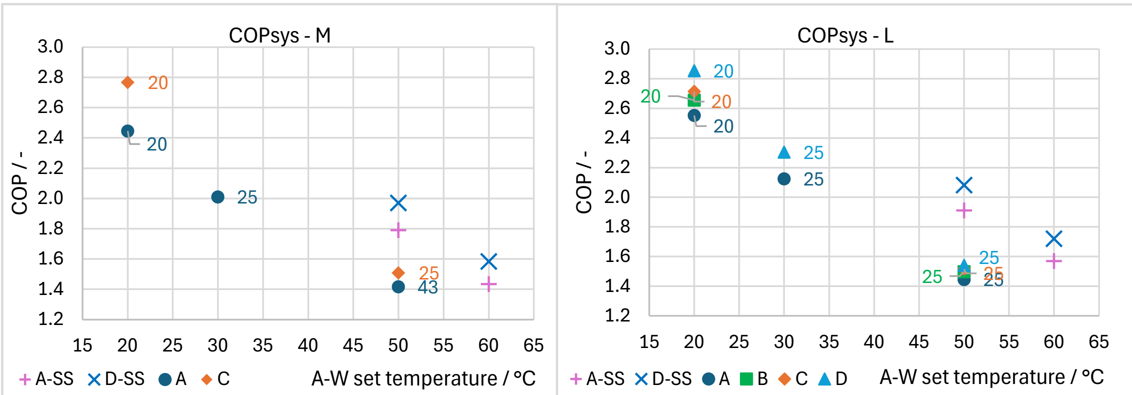

Figure 5. COP of the system as a function of the A/W HP set temperature for the different control strategies. The data label indicates the control of water-loop temperature.

Figure 6 presents the COP of the air-to-water heat pump calculated according to Eq. (3), the COP of the DHW calculated according to Eq. (5) and the COP of the space heating according to Eq. (6). The figure reports only the KPIs of the cascade system as the single stage system does not have the water-to-water heat pump and the water-to-air heat pumps and the comparison would not be fair. The air-to-water heat pump set temperature has a clear influence on the heat pump COP and the range of variation is from 6.6 to 3.1. The first occurs when operates with a return set temperature of 20°C while the second value occurs when the unit operates with 50°C return temperature. The COP of the DHW circuit depends on the water loop temperature and the control strategy of the auxiliaries. This COP is calculated as the useful DHW load divided by the electrical consumption of the water-to-water heat pump summed to the circulators' consumption. When the water-loop operates with higher temperatures the COP of the water-to-water unit is higher, but the total COP is penalised if the circulator operates continuously. The example can be seen in the point of M profile with strategy A, 43°C of loop temperature versus strategy C and loop temperature of 25°C: the continuous operation of the circulator penalizes the higher COP of the water-to-water unit in terms of thermal losses and electrical consumption. At the same time, even the water-to-air heat pump reaches the maximum COP when the water-loop temperature is higher, but this effect cannot be reflected to the system COP for the mentioned reasons.

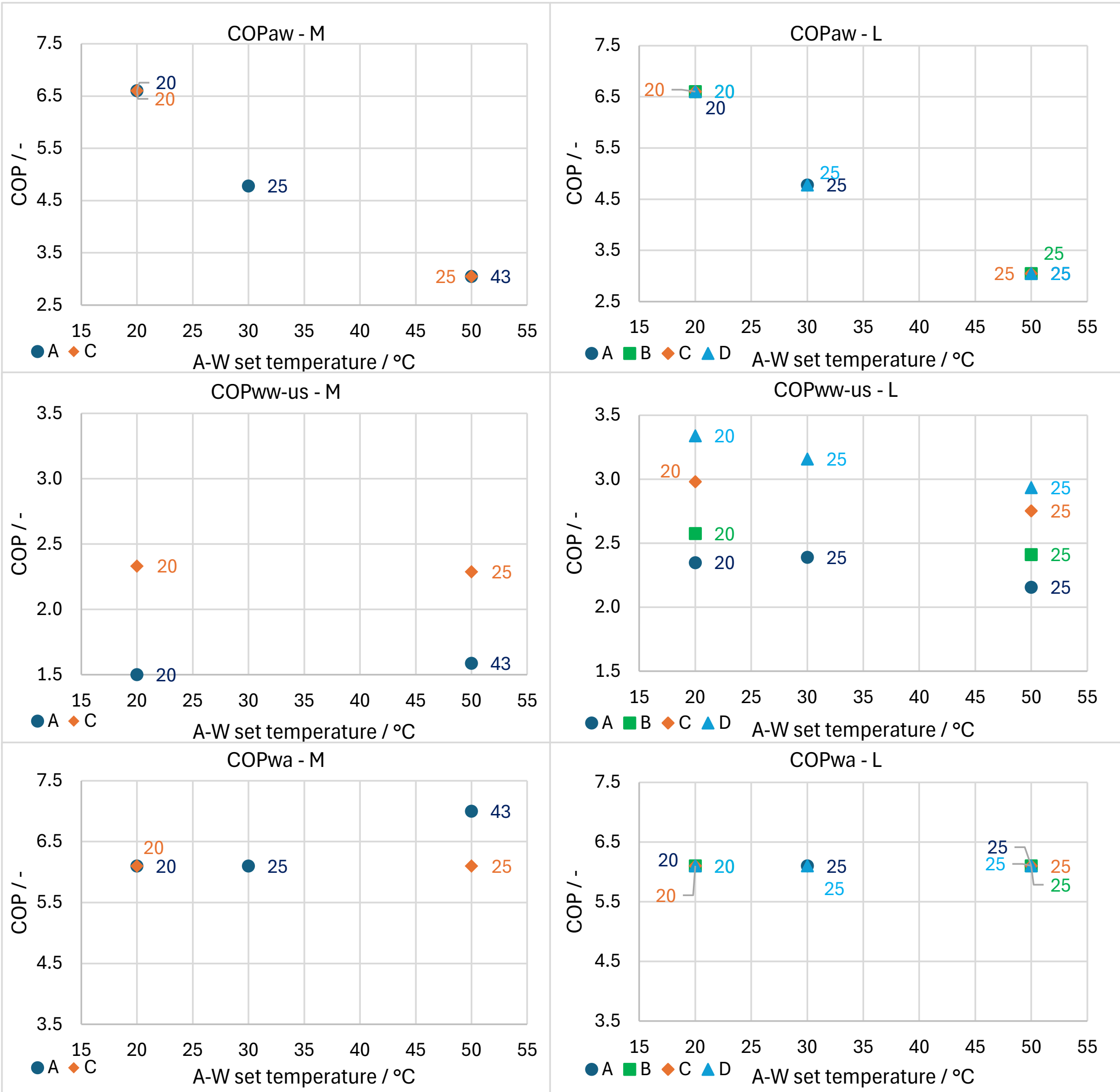

Figure 6. COP of the sub-systems as a function of the A/W HP set temperature for the different control strategies. The data label indicates the control of water-loop temperature.

Figure 7 and Figure 8 present in more detail the effects of the different control strategies.

Figure 7 shows the electrical consumption of the whole system and the electrical consumption of all the auxiliaries. The effect of the different control strategies in terms of circulators control is clearly shown in the auxiliaries' consumption. If the circulators are continuously active, they consume about 2.2 kWh while the consumption is about 0.5 kWh when are activated on request. The single stage system has a lower consumption of circulators as there is one less circuit: 1.4 kWh with continuous activation and 0.4 kWh with activation on request. The other effect that can be seen in this figure is the correlation between the air-to-water and water-loop temperatures with the system consumption. With higher temperatures the thermal losses of the system increase requiring higher heat production from the air-to-water heat pump.

The consumption of the single stage heat pump is lower than the cascade system when it is compared at the same water loop temperature as the COP of a single stage is always higher than a cascade COP (as demonstrated in [18]). However, it should be considered that the single stage system cannot provide heat at 20°C while the water loop circuit can do it. The cascade system performs better with lower water loop temperatures. In other words, the cascade system should be controlled with water loop at 20 °C and this will provide higher system COP and lower consumption than the single stage heat pump. In the M profile, the cascade system with water loop temperature of 20°C has a COP of 2.8 compared to 2.0 of the single stage coupled with the fan coil (50°C of air-to-water supply temperature) corresponding to 40% of higher COP.

Figure 7. Electrical consumption of the whole system and of the auxiliaries as a function of the A/W HP set temperature for the different control strategies. The data label indicates the control of water-loop temperature.

Figure 8 shows the thermal losses of the water-loop circuit. These are calculated as the difference between the heat produced by the air-to-water heat pump and the source sides of the water-to-water heat pump and the water-to-air heat pumps. This means that the buffer and the pipes are included in the losses' calculation. The status of charge of the buffer is the same at the end and start of the test. The losses of the water-loop depend on the air-to-water supply temperature and the control of water-loop temperature. The highest influence is given by the heat pump as the control of the water-loop temperature is done after the buffer. The losses are very small at 20°C and increase up to 16 kWh when the loop temperature is 43°C and arrives at 20 kWh in the case of the single stage system coupled with radiators (loop at 60°C).

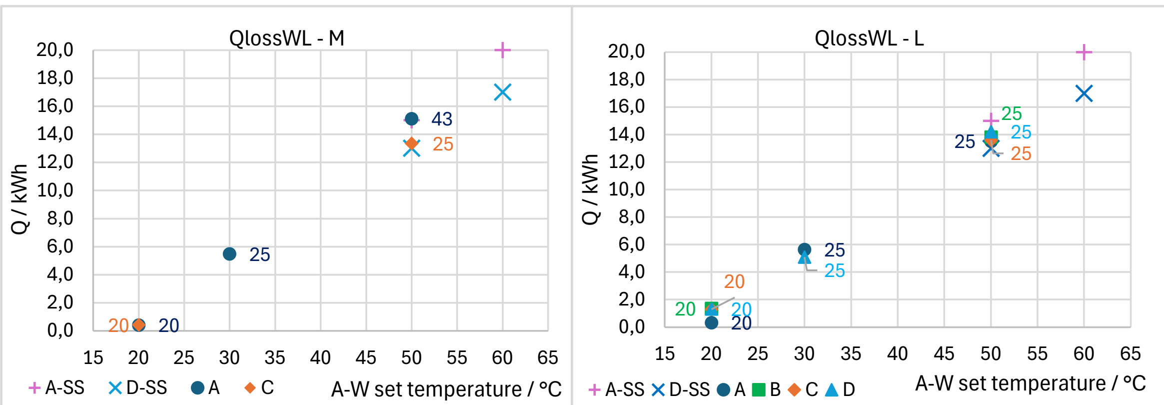

Figure 8. Thermal losses of the water loop as a function of the A/W HP set temperature for the different control strategies. The data label indicates the control of water-loop temperature

As mentioned in the section 2.1, the central heat pump was oversized in relation to the loads and the thermal insulation of the system was not optimized. Those two factors impacted the performance with higher thermal losses and higher number on/off cycles of the air-to-water heat pump. A proper size of the air-to-water heat pump would give more efficient part-load operation than the tested conditions. The higher size would also reduce the lifetime of the system that cannot be observed in a short test but in years of operation.

4. Conclusions

This study evaluated the performance of a cascade heat pump system with intermediate water loop used for retrofitting existing building, focusing on the impact of various control strategies and operational set points. The study also compared the performance of the cascade system with one with single stage. The research analysed both overall system performance and sub-system efficiencies by varying the air-to-water heat pump set temperature and the water-loop temperature, and by testing different strategies for circulator operation. The control strategies implemented started from the initial configuration in a demo case and changed optimizing the operation of the system.

Key findings indicate that system COP is strongly influenced by the set temperature of the air-to-water heat pump as well as the control approach for the circulators and water loop. The system COP was improved from 1.4 of the initial setting to 2.7 at the final configuration. Specifically looking at the sub systems, the COP of the air-to-water heat pump ranged from 6.6 at a return set temperature of 20°C down to 3.1 when operating at 50°C, the domestic hot water generation from 1.5 to 3.3 and the water-to-air heat pump was higher than 6.0. Similarly, the electrical consumption of the circulators demonstrated clear differences: continuous circulator operation resulted in energy usage about 2.2 kWh, whereas demand-based operation reduced consumption to about 0.5 kWh in the same interval.

Thermal losses in the water-loop circuit were also highly dependent on the loop temperature; losses were minimal at 20°C but increased substantially, up to 16 kWh, as the loop temperature rise to 43°C. The single stage system required 50°C or 60°C of distribution temperature which brings the losses up to 20 kWh.

Overall, the results reveal that lower temperature set points of the water loop and intermittent auxiliary operation are essential for achieving higher system efficiencies. Optimizing control strategies, particularly by limiting unnecessary auxiliary consumption and managing operational temperatures, can result in substantial energy savings and improved thermal performance. Integrated system design and proper controls are therefore crucial for maximizing the benefits of heat pump installations in existing multi-family buildings.

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