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Development and test: Future-proof substation designs for the low-temperature operation of domestic hot water systems with a circulation loop

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ABSTRACT

On the transition toward low-temperature district heating (DH), generation sectors, distribution networks, and building consumers should all be adapted to low-temperature operation conditions. However, a bottleneck in lowering DH return temperatures is the domestic hot water (DHW) system with a circulation loop in multifamily buildings. Existing systems with a single heat exchanger often led to elevated return temperatures because of the reheating of the circulation loop. This study developed several innovative designs for future-proof DHW substations that decouple the heating of cold water and circulation flows, ensuring lower DH return temperatures in large multifamily buildings. First, a theoretical analysis was performed for benchmarking the return temperature for various proposed design configurations under low-temperature operation conditions; then, the proposed configurations were tested for a Danish multifamily building connected to a medium–low-temperature DH network. In the field tests, compared to a typical DHW substation with a single heat exchanger, the proposed configuration with the circulation loss booster reduced the average DH return temperature from 46.4 °C to 34.1 °C and 27.9 °C for parallel or serial connections, respectively. Economic analysis confirms the viability of the proposed solution, with a payback period ranging from 3.4 to 7.9 years.

1. Introduction

1.1. Background

The European Green Deal aims to achieve zero net emissions by 2050 [1]. In the building energy sector, this policy initiative focuses on improving the energy performance of buildings by using pricing instruments to incentivize building energy efficiency, guiding the design of buildings in line with a circular economy, increasing digitalization, and implementing strict enforcement of rules [2,3].

In Denmark, district heating (DH) accounts for 50% of the total heat demand (63% of households) [4] and includes both space heating (SH) and domestic hot water (DHW) systems in buildings. The future low-temperature DH (LTDH) system networks, defined in literature as 4th generation DH (4GDH), are expected to operate with average supply and return temperatures of 55 and 25 °C, respectively, offering a sustainable solution to realize a fossil-free energy system [5–8]. However, this requires the existing heating systems for SH and DHW to be adapted to LTDH systems [7]. Although SH remains dominant in typical Danish multifamily buildings, the share of DHW energy consumption has increased to 35% in recent years [9,10]. This share is expected to further increase up to 40%–50% of the total heat consumption owing to the low SH demand in new and renovated buildings [9–11].

The Danish green strategy for decarbonizing the DH industry aims to integrate renewable energy sources that convert fossil fuel-based central combined heat and power (CHP) units into biomass plants, use large heat pumps, and recover excess heat from local sources [12]. On the generation side of the DH system, lower DH supply temperatures increase the electrical output from CHP plants and boost the potential for heat recovery, whereas lower DH return temperatures increase the heat output from condensing flue gases in boilers and improve the overall generation efficiency [13]. In a distribution network, a lower operating temperature can minimize the distribution heat loss by 15% in municipal systems and up to 35% in low-density areas, increase the operational flexibility of the DH operators, allow access to low-grade heat

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Nomenclature

Symbols

C_p	Specific heat capacity of water J/(kg·K)
m_{aDH}	Mass flow rate of the DH supply flow entering the main HEX (kg/s)
m_{bDH}	Mass flow rate of the DH supply flow entering the auxiliary HEX (kg/s)
m_c	Mass flow rate of the DHW return flow (kg/s)
m_u	Mass flow rate of the cold water (kg/s)
T_{supDH}	Supply temperature from the DH network (°C)
T_{retDH}	Return temperature to the DH network from the whole system (°C)
T_{retHEX}	Return temperature to the DH network from the main HEX (°C)
T_{retHP}	Return temperature to the DH network from the heat pump (°C)
T_{outHEX}	Outlet temperature of the main HEX on the secondary side (°C)
T_{outPre}	Outlet temperature of the auxiliary HEX on the secondary side (°C)
T_{supCir}	Supply temperature of the DHW circulation (°C)
T_{retCir}	Return temperature of the DHW circulation (°C)

Abbreviations

CHP	Combined heat and power
LTDH	Low-temperature district heating
COP	Coefficient of performance
SH	Space heating
DH	District heating
4GDH	4th generation district heating
DHW	Domestic hot water
HEX	Heat exchanger

sources and storage units, increase the hydraulic capacity of the network, and extend the life of the pipes [6,13–15].

However, DHW standards always require a high level of high-temperature supply, which may be a constraint for lowering DH operational temperatures. For instance, based on Danish Standard DS 439 [16], hot water should be delivered at a minimum temperature of 50 °C; however, 45 °C can be acceptable during peak situations for meeting hygiene and comfort requirements. According to specific national legislation, the water temperature should be maintained in the range of 55–65 °C for DHW systems with hot water tanks [17]. Additionally, DHW systems with circulation loops are the most common solutions for multistory buildings, either with storage tanks or instantaneous heat exchangers [18]. To maintain the circulation flow at a minimum temperature of 50 °C at any point in the system, the DH return temperatures typically exceed 50 °C when there is no tapping of hot water. While circulation heat losses may be a fraction of the total DHW consumption, they represent a substantial share of up to 80% and 65% in commercial and multifamily buildings, respectively [17]. Therefore, large buildings with DHW circulation loops can be one of the main bottlenecks in the transition toward low-temperature operations in DH networks.

The primary purpose of DHW circulation systems so far has been to avoid the proliferation of *Legionella bacteria*, shorten the waiting time of users, and reduce water consumption [19]. However, the focus on circulation heat losses has recently increased because of stringent regulations on the energy performance of buildings [9,18]. Almost 80% of the heat allocated to DHW system is used in the circulation system [20]. Cholewa et al. [21] showed that the circulation heat loss is a significant part of the preparation of DHW and ranged from 56.7% to 70.1%. BasedClick or tap here to enter text. on investigation of several buildings, Kempe et al. [22] reported that hot water circulation losses in a multifamily building are in the range of 5–8 kWh/m^2·year (heated floor area) in Sweden, and increase up to 25 kWh/m^2·year in some cases [22]. In newly built or renovated buildings, the DHW circulation heat losses rarely drop below 5 kWh/m^2·year [23]. The return temperature is strongly influenced by the relationship between the energy used by the DHW circulation system and the actual energy demand [17]. In other words, the high heat loss and maintaining a stable hot water temperature in the circulation lead to a high DH return temperature.

Some studies have investigated how to fulfill the DHW temperature requirements under LTDH supply temperatures. Boesten et al. [24] proposed a solution for DHW supply to achieve the advantages of integration of low-temperature resources, bi-directional operation, decentralized energy flows, and possible energy sharing in 5th generation DH, which is a stepped heating system: the district level provides low-temperature hot water; the building energy plant sufficiently increases the temperature to suit the SH system with heat pumps; and the individual customers can further raise the temperature for DHW use with an optional booster. Zvingilaite et al. [25] presented and analyzed the feasibility of a DH consumer unit with a micro heat pump for DHW preparation in a low-temperature DH network. In a variant of this system, the supply flow of DH was divided into two flows, one entering the condenser and the other entering the evaporator, generating hot water at 53 °C with a DH supply temperature of 40 °C. Benakopoulos et al. [26] aimed to investigate the potential reduction in the operating temperatures of a DHW system with a circulation loop. One of the solutions is to redirect the return flow from the DHW system to the low-temperature SH system to cool the return temperature to below 35 °C. Another solution, involving the use of an extra heat exchanger and a micro-booster heat pump, can compensate for the circulation loss and further cool the return temperature to below 35 °C. However, the researchers theoretically investigated the potential return temperature without conducting field tests. Thorsen et al. [27] noted that realizing a low DH return temperature solely by direct heat exchange is challenging; therefore, they tested the configuration using a booster heat pump to compensate for the circulation heat loss in a Danish multifamily building connected to a DH network within a one-year testing period. The test shows that the yearly average DH return temperature decreased from 47.2 °C to 21.5 °C. However, the local DH network was characterized by medium–high supply temperatures during the test. The economic evaluation highlighted its potential attractiveness with a payback time of 5.1 years, provided a motivation tariff is part of the cost structure of the local DH operator. Motivation tariffs have been part of heating-price models in Denmark over the past two decades; however, they may not be common in other energy markets.

1.2. Problem statement and research hypothesis

Typical DHW substations with one heat exchanger and circulation in large multi-apartment buildings represent a challenge in supplying hot water under 4GDH requirements. This results in high DH return temperature due to the necessity to maintain the circulation temperature above 50 °C on the secondary side of the heat exchanger.

The proposed DHW substation design concept, decoupling the heating of circulation from the cold water with a separate heat exchanger and further cooling the return flow with a heat pump or by cascading to the SH system, offers a potential solution to address the problem. Such an approach could effectively secure DHW supply and significantly enhance DH return temperature reduction in large multifamily buildings operating under 4GDH requirements.

1.3. Novelty

This study entailed successful field tests of the future-proof DHW substation with circulation loss booster under medium–low DH supply temperatures. To the best of our knowledge, no such tests have been conducted previously under these conditions. Hence, this study provides an innovative and practical solution for DHW preparation for multifamily buildings in future low-temperature scenarios.

1.4. Article structure

In the article, Section 2 presents the methods with a concise overview of the schematics, assumptions for low-temperature operation, and the governing equations for the heat balances of all configurations investigated. Section 3 presents a case study, describing the specific building and substation that were the subjects of the experimental test. Section 4 introduces findings from both theoretical analysis and experimental tests, offering insights from energy and economic perspectives. Section 5 offers a critical assessment of these findings, pinpointing limitations of the current study and suggesting areas for future research. Section 6 wraps up the research by summarizing the investigation and emphasizing the key findings.

2. Method

This section introduces the setup of the different configurations, heat balance equations for calculating the DH return temperatures, and assumptions for low-temperature operation in the steady-state theoretical evaluation.

Four DHW configurations were investigated:

- A DHW system with the main heat exchanger only (basic configuration).
- A DHW system with a circulation loss booster for heating the circulation loop connected in series to the main heat exchanger (serial configuration).
- A DHW system with a circulation loss booster for heating the circulation loop connected in parallel with the main heat exchanger (parallel configuration).
- A DHW system with a separate heat exchanger for heating the circulation loop, and a separate heat exchanger cascading with the SH system to further cool the DH return temperature (cascading configuration).

The experimental setup was constructed in a Danish multifamily building. The flexibility of the setup allowed us to assess and compare only the first three configurations, whereas the cascading configuration was only investigated theoretically.

2.1. Typical DHW system with the main heat exchanger

Fig. 1 shows the layout of a DHW system with a single main heat exchanger. This is a typical configuration in which both the cold water and circulation flow are heated by the same large heat exchanger. In this basic configuration, on the secondary side, the return flow from the circulation loop m_c is first mixed with cold water m_u before entering the main heat exchanger. The mixed flow is heated to the desired circulation supply temperature T_{supCir} in the main heat exchanger. The DH provides heat to the heat exchanger on the primary side.

The heat balance of the main heat exchanger can be expressed by the equation (1).

$$m_{aDH}{}^{*}C_p{}^{*}\left(T_{supDH}-T_{retDH}\right)=m_c{}^{*}C_p{}^{*}\left(T_{supCir}-T_{retCir}\right)+m_u{}^{*}C_p{}^{*}\left(T_{supCir}-T_u\right) \tag{1}$$

The DH supply temperature T_{supDH} was assumed to be 55 °C. Additionally, the setpoint temperature of the hot water supplied to the circulation T_{supCir} was assumed to be 54 °C, and the return temperature of the circulation flow T_{retCir} was assumed to be 50 °C. All these temperature parameters complied with Danish standards [16,28] for hygiene and comfort. This method assumed a simplified DHW tapping profile with an hourly average of 6 kW, distributing the daily average DHW energy consumption, which was found to be constant throughout the year [29]. The circulation heat loss was assumed to be 4.5 kW, in line with the real measurements. The cold-water temperature T_u was assumed to be 10 °C.

The return temperature of the main heat exchanger T_{retDH} was assumed to be 5 °C higher than the inlet temperature of the secondary side when draw-off occurs ($m_u > 0$) and 1 °C higher when almost no draw-off occurs ($m_u \approx 0$). This is because of the draw-off, the flow in the main heat exchanger is much higher. Half of the time was considered with draw-off, and the other half was considered without draw-off. All

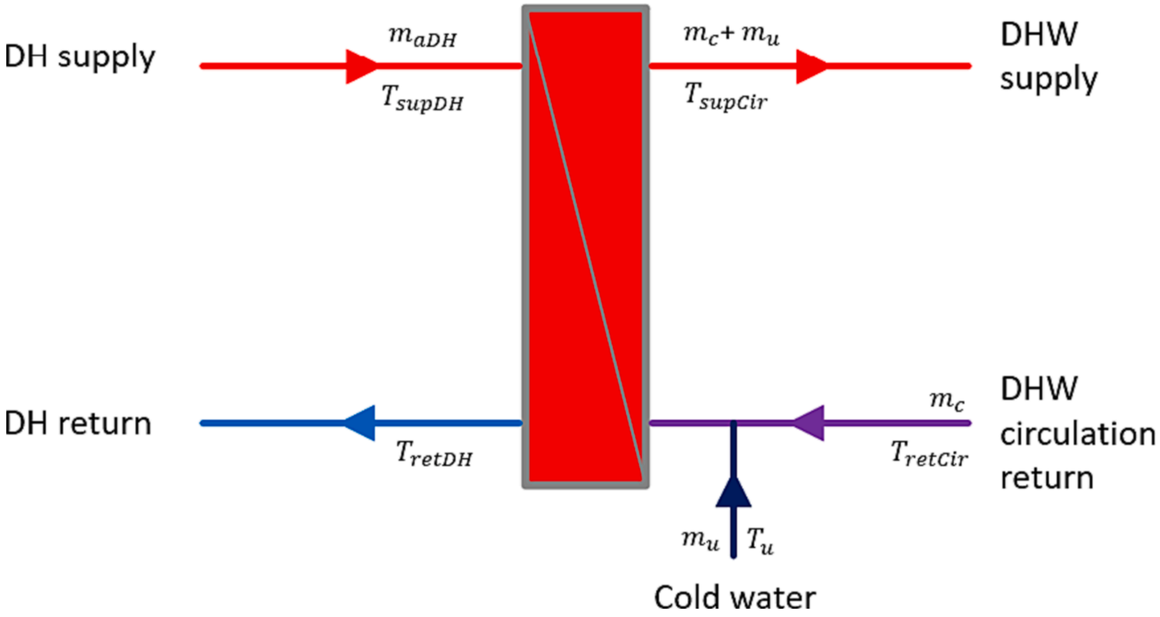

Fig. 1. DHW substation installation with the main heat exchanger.

the mass flow rates were indirect variables that were derived from the power and temperature parameters.

2.2. DHW system with the circulation loss booster connected in series with the main heat exchanger

The configuration of DHW system using a circulation loss booster connected in series with the main heat exchanger is shown in Fig. 2. In this configuration, on the secondary side, the cold water and the circulation flow still mix before entering the main heat exchanger; however, the mixed flow would be heated up only to 50 °C (T_{outHEX}) and then to 54 °C (T_{outHP}) with the auxiliary heat exchanger and heat pump. The flow heated by the heat pump is supplied to the DHW circulation. On the primary side, the heat source for the two heat exchangers is the DH supply flow, and the DH return flow from the auxiliary heat exchanger is the heat source for the heat pump.

In real-world operation, partial outlet flow from the main heat exchanger is directed to the circulation loss booster for further heating and then mixed with another part of the flow from the main heat exchanger before entering the circulation flow. In the theoretical analysis, this was simplified by having all the flow heated in the pre-heater and the booster heat pump. This simplification did not affect the heat balance of the components in the calculation.

The heat balance of the main heat exchanger is given by equation (2).

$$m_{aDH}{}^{*}C_p{}^{*}\left(T_{supDH}-T_{retHEX}\right)=m_c{}^{*}C_p{}^{*}\left(T_{outHEX}-T_{retCir}\right)+m_u{}^{*}C_p{}^{*}\left(T_{outHEX}-T_u\right) \tag{2}$$

The heat balances of the auxiliary heat exchanger and the heat pump are described by equations (3) and (4), respectively.

$$m_{bDH}{}^{*}C_p{}^{*}\left(T_{supDH}-T_{retPre}\right)=\left(m_c+m_u\right){}^{*}C_p{}^{*}\left(T_{outPre}-T_{outHEX}\right) \tag{3}$$

$$m_{bDH}{}^{*}C_p{}^{*}\left(T_{retPre}-T_{retHP}\right){}^{*}\frac{COP}{COP-1}=\left(m_c+m_u\right){}^{*}C_p{}^{*}\left(T_{outHP}-T_{outPre}\right) \tag{4}$$

The DH return temperature can be expressed as

$$T_{retDH}=\frac{m_{aDH}{}^{*}T_{retHEX}+m_{bDH}{}^{*}T_{retHP}}{m_{aDH}+m_{bDH}} \tag{5}$$

For configurations with a circulation loss booster, two sub-scenarios were created to assess the impact of the capacity of the heat pump. In the first scenario, it was assumed that the heat pump capacity was designed to deliver 4 kW of the total 4.5 kW of circulation heat loss, whereas in the second, it was reduced to 2.5 kW according to the heat pump capacity installed in the test facility. The coefficient of performance (COP) of the heat pump was assumed to be 6, on the basis of the product's technical data [30]. The return temperature of the primary side of the auxiliary heat exchanger (T_{retPre}) was assumed to be 1 °C higher than the inlet temperature of the secondary side.

2.3. DHW system with the circulation loss booster connected in parallel with the main heat exchanger

The configuration with a circulation loss booster connected in parallel to the main heat exchanger is shown in Fig. 3. In this parallel configuration, on the secondary side, the main heat exchanger is only responsible for heating the cold water to 50 °C (T_{outHEX}). The circulation loss booster heats the circulation return flow from 50 °C (T_{retCir}) to 54 °C (T_{outHP}). The primary side of the parallel configuration has the same settings as that of the serial configuration.

The heat balance of the main heat exchanger is expressed as follows:

$$m_{aDH}{}^{*}C_p{}^{*}\left(T_{supDH}-T_{retHEX}\right)=m_u{}^{*}C_p{}^{*}\left(T_{outHEX}-T_u\right) \tag{6}$$

The heat balances for the auxiliary heat exchanger and micro-booster heat pump are described in equations (7) and (8), respectively.

$$m_{bDH}{}^{*}C_p{}^{*}\left(T_{supDH}-T_{retPre}\right)=m_c{}^{*}C_p{}^{*}\left(T_{outHP}-T_{retCir}\right) \tag{7}$$

$$m_B{}^{*}C_p{}^{*}\left(T_{retPre}-T_{retHP}\right){}^{*}\frac{COP}{COP-1}=m_c{}^{*}C_p{}^{*}\left(T_{outHP}-T_{outPre}\right) \tag{8}$$

The DH return temperature can be expressed as follows:

$$T_{retDH}=\frac{m_{aDH}{}^{*}T_{retHEX}+m_{bDH}{}^{*}T_{retHP}}{m_{aDH}+m_{bDH}} \tag{9}$$

In this parallel configuration, the main heat exchanger heats only the cold water, and a lower primary-side return temperature can be expected. Hence, given a cold-water temperature of 10 °C, 15 °C was estimated to be the return temperature of the main heat exchanger (T_{retHEX}). The outlet temperature setpoint of the heat pump (or the auxiliary heat exchanger) is 54 °C. Given that the flow from the main heat exchanger (m_u) at 50 °C is relatively smaller than the circulation flow (m_c), to simplify the calculation, the temperature of the mixed flow before entering the circulation loop was assumed to be 54 °C. This also applies to the cascading configuration described in Section 2.4.

2.4. DHW system with main heat exchanger and a separate heat exchanger cascading with the space heating system

The proposed cascading configuration is shown in Fig. 4. In this configuration, on the secondary side, the main heat exchanger is only responsible for heating the cold water to 50 °C (T_{outHEX}). The separate heat exchanger heated the circulation return flow from 50 °C (T_{retCir}) to 54 °C (T_{outHP}). The two flows are then mixed and supplied to the circulation loop. The SH system in this scenario is assumed to be adapted to LTDH with supply and return temperatures of 55 and 35 °C,

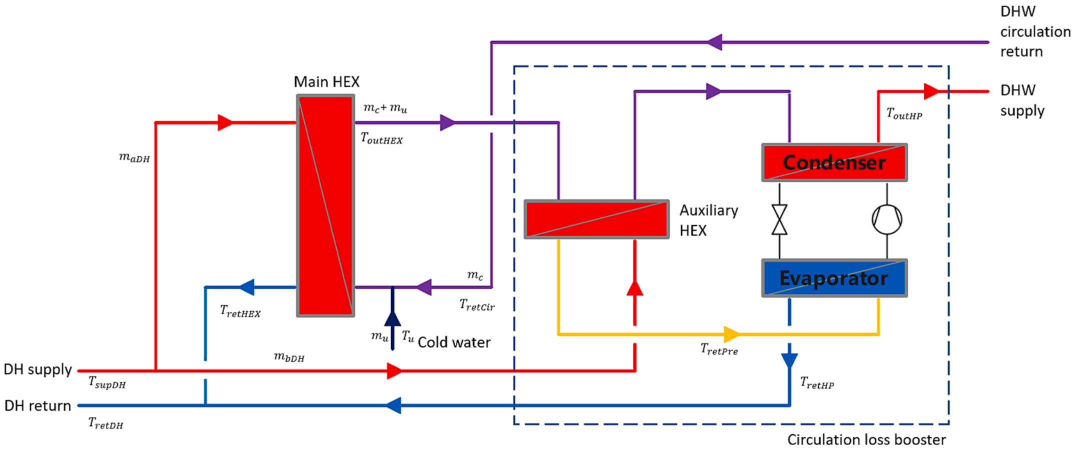

Fig. 2. DHW system with the circulation loss booster connected in series with the main heat exchanger.

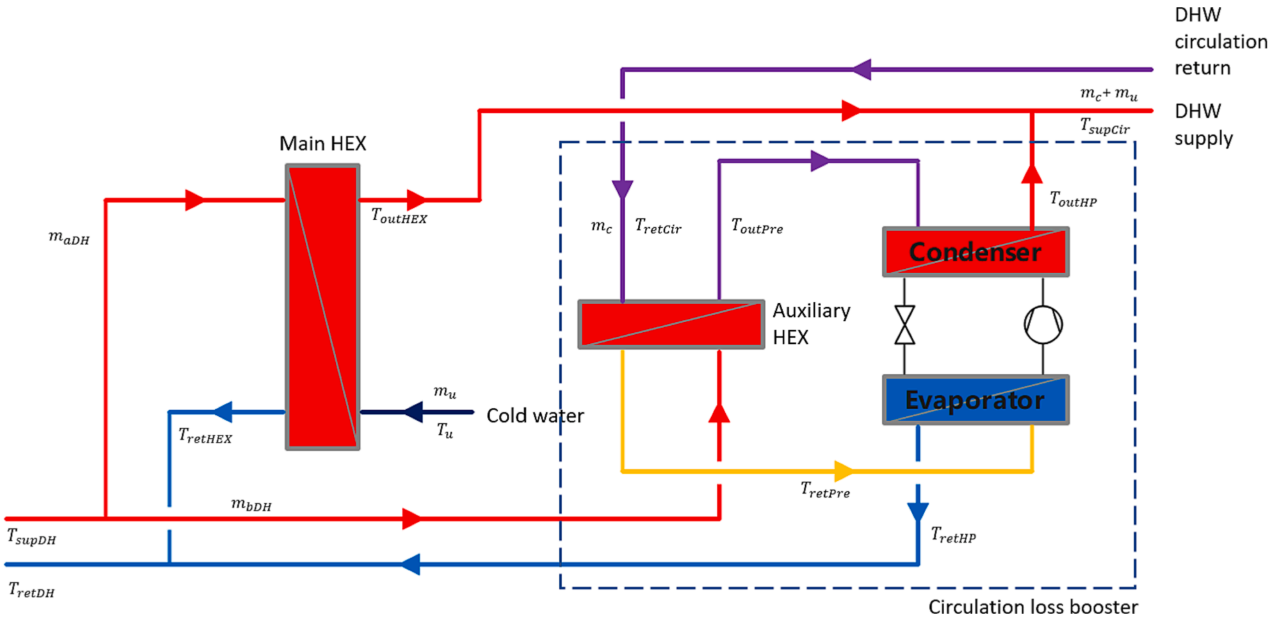

Fig. 3. DHW system with the circulation loss booster connected in parallel with the main heat exchanger.

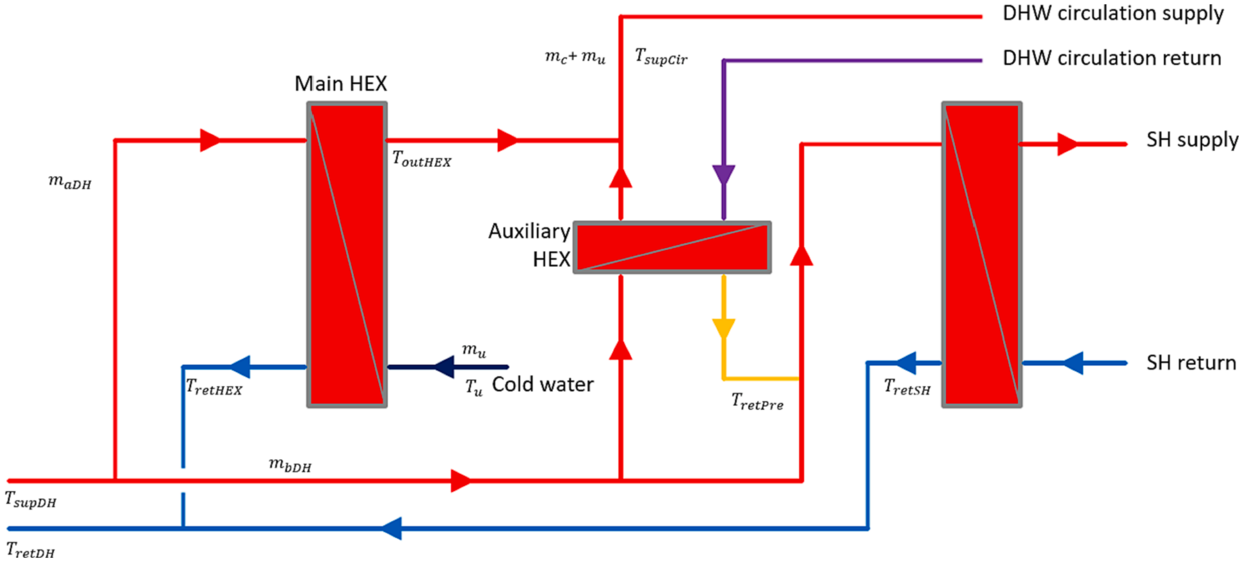

Fig. 4. DHW system with the main heat exchanger and the auxiliary heat exchanger cascading with the space heating system.

respectively. The outlet flow from the primary side of the separate heat exchanger cascades to the primary side of the SH substation. Thus, the return flow from the separate heat exchanger with a high temperature can be limited to 35 °C.

The heat balance of the primary heat exchanger is expressed as follows:

$$m_{aDH}{}^{*}C_p{}^{*}\left(T_{supDH} - T_{retHEX}\right) = m_u{}^{*}C_p{}^{*}\left(T_{outHEX} - T_u\right) \tag{10}$$

The heat balance of a separate heat exchanger is expressed as

$$m_B{}^{*}C_p{}^{*}\left(T_{supDH} - T_{retPre}\right) = m_c{}^{*}C_p{}^{*}\left(T_{outPre} - T_{retCir}\right) \tag{11}$$

The temperature of the return flow to the DH system for the DHW part can be expressed as follows:

$$T_{retDH} = \frac{m_{aDH}{}^{*}T_{retHEX} + m_{bDH}{}^{*}T_{retSH}}{m_{aDH} + m_{bDH}} \tag{12}$$

3. Case study

This study investigated a DHW system in a multifamily apartment building in Viborg, Denmark. The building was constructed in 1970 and consists of 42 apartments distributed on three floors, connected to a local DH network. Originally, the building had a DHW system that utilized a large storage tank with an internal coil and a circulation loop. In 2021, this DHW system was replaced. The newly designed system features a main instantaneous heat exchanger and a circulation loss booster to compensate for heat losses in circulation. This setup enabled flexibility in testing various DHW configurations, as outlined in Section 2.

The local DH operator aims to investigate and assess new technical solutions that could secure the reduction of the supply temperature to 55 °C in the network. In the future, these large buildings with storage tanks and circulation loops could be a bottleneck for the system, forcing the entire network to operate at higher temperatures. The heat pump installed has a nominal heating capacity of 2.7 kW and a COP of 6, given the heat source temperature of 40 °C [30]. Energy meters were installed in the system to measure the following parameters:

- Total energy delivered to the DHW system on the primary side.
- Energy delivered from the heat pump and relative electric power.
- DHW circulation heat losses, excluding the plant room and relative pipelines.

Additionally, several temperature sensors were used to measure the supply and return temperatures of the primary and secondary sides of the system.

In this building, the DH energy consumption was 315 MWh in 2022, of which the DHW system accounted for 20%. Circulation heat loss accounted for approximately 60% of the total DH energy delivered to the DHW system. The DHW circulation heat loss power was in the range of 4.0–5.0 kW. The test was performed from June to August during the summer of 2022, with the summer medium–low DH supply temperature in the range of 62–64 °C.

The hot water is circulated at a minimum of 50 °C to minimize energy consumption. This is controlled by circulation valves strategically installed in several places in the DHW system. A circulator pump is used to keep the DHW circulating at 0.2–0.25 l/s. When there is a hot water demand, the circulating pump adjusts accordingly to maintain a stable circulating water flow rate, and the opening of the tap creates an additional differential pressure, which is a signal for new hot water production.

4. Results

4.1. Theoretical results of DH return temperature

The theoretical analysis aimed at benchmarking the return temperature of different DHW substation configurations under the LTDH condition of a supply temperature of 55 °C. It was also decided to model and evaluate the impact on operations for cases with a 4-kW capacity heat pump, based on the measured circulation heat loss and an actual installation capacity of 2.5 kW.

The results in Fig. 5 show that the basic configuration, with only the main heat exchanger, had the highest DH return temperature of 50.8 °C. This is a typical effect of the heating circulation flow and cold water in the same heat exchanger. The lowest average DH return temperature of 21.0 °C was recorded in the parallel configuration with a 4-kW heat pump. This was expected because this configuration completely separated the heating of the circulation from the cold water. In addition, the heat pump secured a lower return temperature to the DH by using the outlet flow from the auxiliary heat exchanger as the heat source. The serial configuration, despite the presence of the 4-kW heat pump, showed minor improvements in lowering the DH return temperature compared to the basic configuration owing to the circulation flow being partially heated in the main heat exchanger. The analysis also indicates that a smaller heat pump capacity (2.5 kW)—given the same circulation heat losses of 4.5 kW—would lead to higher return temperatures in both parallel and serial configurations with a supply temperature as low as 55 °C. Finally, the cascading configuration can achieve a DH return temperature of 33.8 °C without the heat pump or the use of electricity.

The relationship between the heat-pump capacity and the heat-pump return temperature to the DH network was further investigated. This is highlighted in Fig. 6, where the total heat output is assumed to be 4.5 kW, which is equal to the assumed total circulation heat loss, and the return temperature is presented as a function of the thermal capacity of the heat pump. The heat pump's heat source (DH supply) and the COP were assumed to be 51 °C and 6, respectively. The heat-pump return temperature decreased as the heat pump capacity approached the circulation heat loss.

4.2. Field test with medium–low DH supply temperature during summer

Three different configurations, such as basic, serial, and parallel, were tested in the building study case during the summer from June to August 2022. Every Tuesday evening to Wednesday morning, the sterilization of the system was scheduled, and the heat pump was turned off during this period. The results are presented and compared over a five-day period to avoid interference.

5. DHW heat demand

Fig. 7 presents the average hourly measurements of the total heat power delivered to the DHW system and the circulation heat losses for the basic configuration. The average circulation heat loss was 5.0 kW during the test period. The heating power of the system was controlled

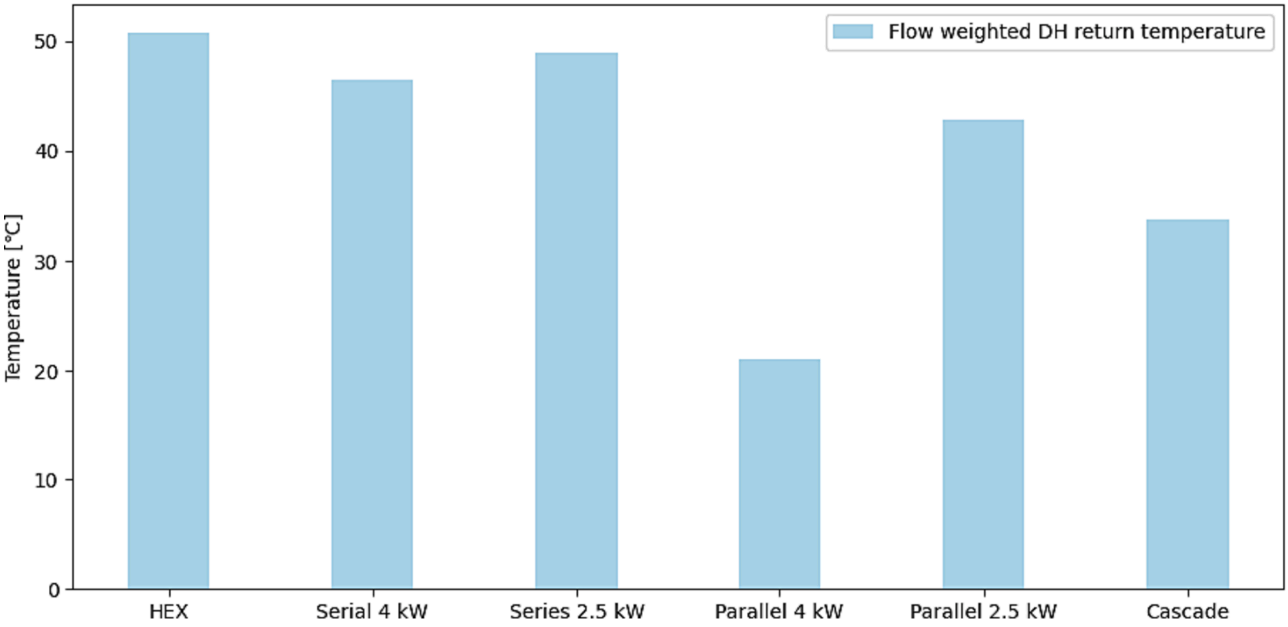

Fig. 5. Flow-weighted DH return temperatures of different cases in theoretical analysis.

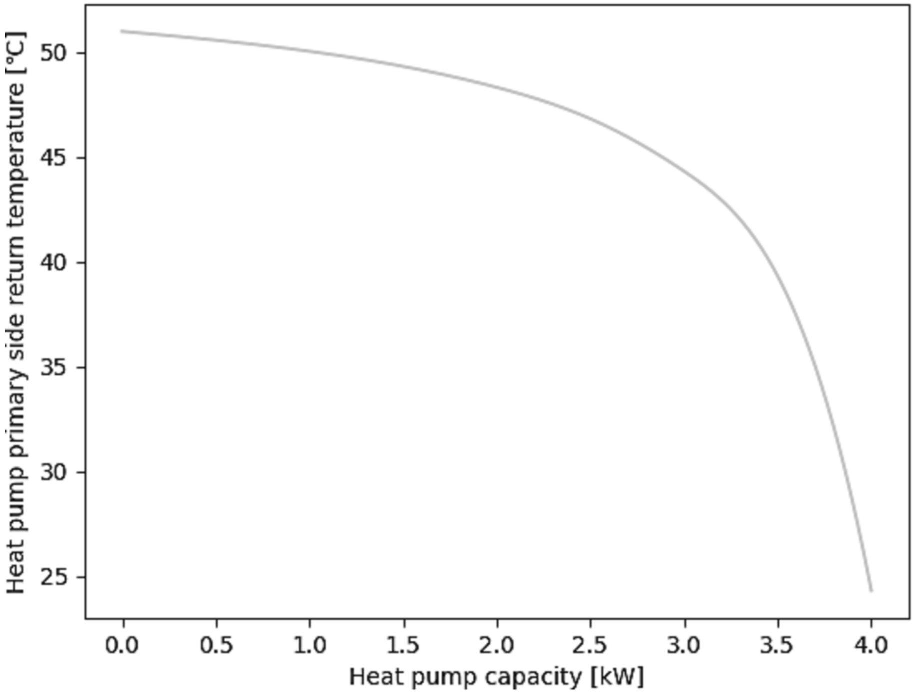

Fig. 6. Heat pump primary-side return temperature variation against the heat pump capacity in parallel configuration, heat source at 51 °C and COP at 6.

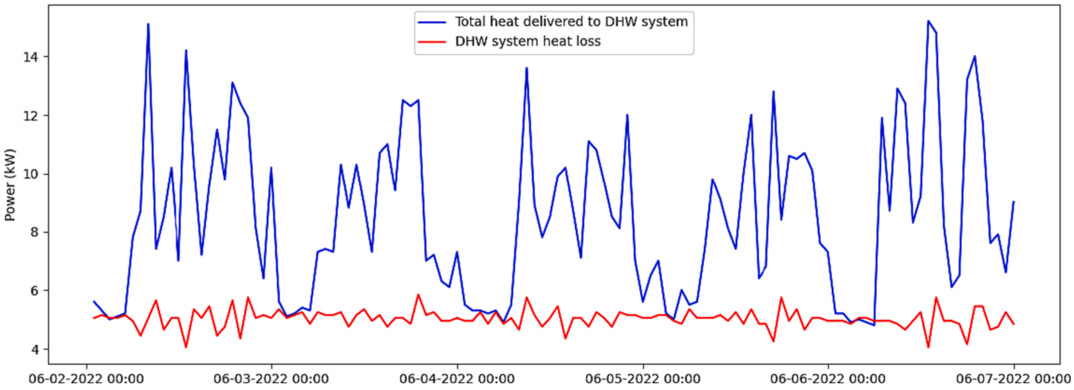

Fig. 7. The total heat delivered to the DHW system and circulation heat loss during the test for the basic configuration.

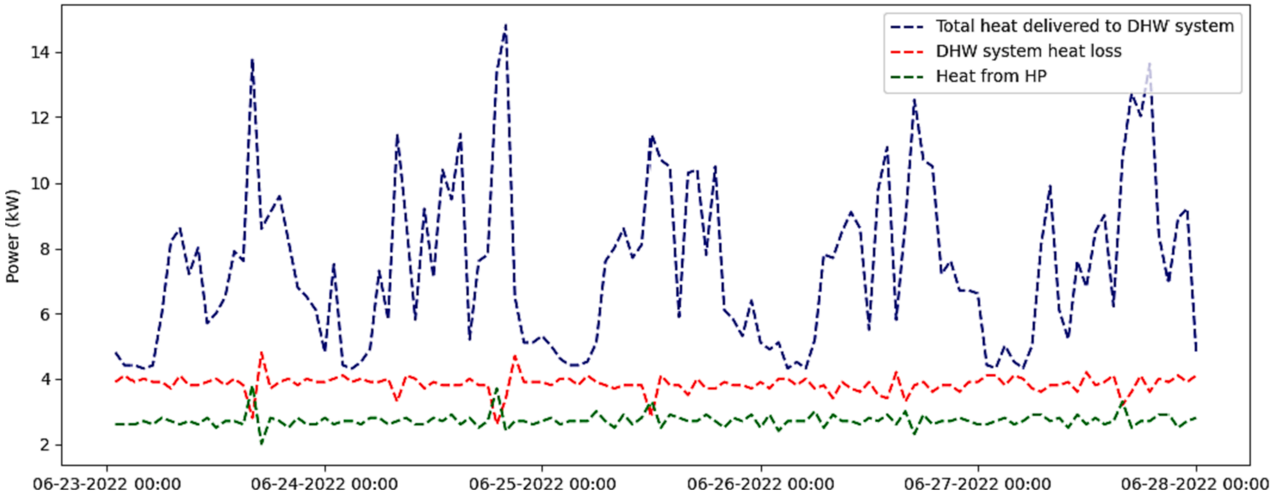

Fig. 8. The total heat power delivered to DHW system, circulation heat loss, and the heat power provided by heat pump during the test of the serial configuration.

based on the specific needs of the users. A typically high consumption of hot water occurred during the morning and dinner times. During the night, the DHW demand was related to circulation losses.

In the serial configuration test, as shown in Fig. 8, the average circulation heat loss was approximately 4.1 kW, and the heat output of the heat pump was approximately 2.5 kW.

Further, for the parallel configuration, as shown in Fig. 9, the average circulation heat loss was approximately 4.0 kW, and the heat output of the heat pump was approximately 2.5 kW. The electric power consumption of the heat pump was stable at 0.5 kW.

6. Operating temperatures in the DHW configurations

During tests, the DH supply temperatures were stable in the range of 62–64 °C. This makes the results obtained for the return temperatures in the three tests comparable, given similar heating demands. Fig. 10 summarizes the test results for the three configurations.

The return temperature profile for the basic configuration clearly suggests that it is not possible to achieve low return temperatures with one main heat exchanger heating both the cold water and circulation flow. Nonetheless, during the tapping of hot water, when the DHW heat demand is higher, the mixing of cold water with the circulation flow leads to a higher temperature difference and consequently to lower return temperatures.

The tests highlighted that the auxiliary heat exchanger and heat pump in both configurations had a positive impact on reducing the return temperatures, although the heat pump capacity was designed to deliver 2.5 kW of the total measured circulation heat loss. This was possible because of the higher DH supply temperature of 62–64 °C compared to the theoretical calculations. Overall, the lowest flow-weighted average return temperature of 27.9 °C was recorded for the parallel configuration because of the positive effect of decoupling the hot water preparation from the heating of the circulation flow. A comparison of the three configurations based on the flow-weighted average temperature is presented in Fig. 11. The basic and series layouts resulted in an average return temperature of 46.4 °C and 34.1 °C, respectively.

7. DHW substation control and heat pump performance

These tests are also important for assessing overall DHW substation control. Fig. 12 shows the relationship between the total heat delivered to the DHW system and the DH return temperature. Based on the measurements, the thermostatic control of the valve opening on the primary side of the main exchanger was accurately executed for basic and serial configurations. However, for parallel configuration, the data show scattered return temperatures, indicating problematic control, primarily during low DHW demand.

This is because the DHW circulation flow passes through the main heat exchanger in the basic or serial configuration, whereas the main heat exchanger is dedicated to heating the cold water in parallel operation, resulting in a discontinuous and substantially lower flow on the secondary side compared to the other configurations. Additionally, a temperature sensor controlling the valve of the main heat exchanger was installed at a certain distance from the main heat exchanger on the secondary side, resulting in suboptimal thermal contact with the primary side.

Hence, during parallel operation, when there was a minor or no tapping demand, the small water volume or residual cold-water flow caused the flow temperature to be lower than the sensor setpoint. This leads to unstable control with unnecessary valve openings, higher flow on the primary side, and consequently, a higher return temperature.

Another important aspect in serial and parallel configurations is the COP of the heat pump. Based on the measurements, the hourly electricity consumption was 0.5 kW, whereas the thermal heat output was approximately 2.5 kW. The resulting measured COP values were on average 5.3 and 5.1 for serial and parallel operations, respectively, as shown in Fig. 13.

7.1. Economic analysis

An analysis was performed to investigate the economic feasibility of the circulation loss booster concept, as summarized in Table 1. The DH motivation tariff is commonly integrated into the Danish pricing structure, offering bonuses in the energy billing of end users based on the reduction in the DH return temperature from a specified reference level. This approach engages end users and encourages them to operate their heating systems optimally in exchange for discounts on heating bills [31,32]. Within the Viborg local heating network, the local motivation tariff ensured a 1% reward for each degree of temperature reduction. Moreover, a 2% reward can be guaranteed if the DH supply temperature is as low as 55 °C in the future [33].

Hence, two scenarios were considered in the analysis: the current scenario, with an average DH supply temperature of 65 °C and a 1% bonus for every 1 °C decrease in the DH return temperature, and the future scenario, with a DH supply temperature of 55 °C and a doubled bonus of 2% for every 1 °C decrease. The assessment compared serial and parallel configurations with the case in which only the main heat exchanger was used as a reference. Moreover, in the future scenario, the capacity of the heat pump was assumed to be 4 kW based on the results presented in Section 4.1, as this would secure thermal comfort and

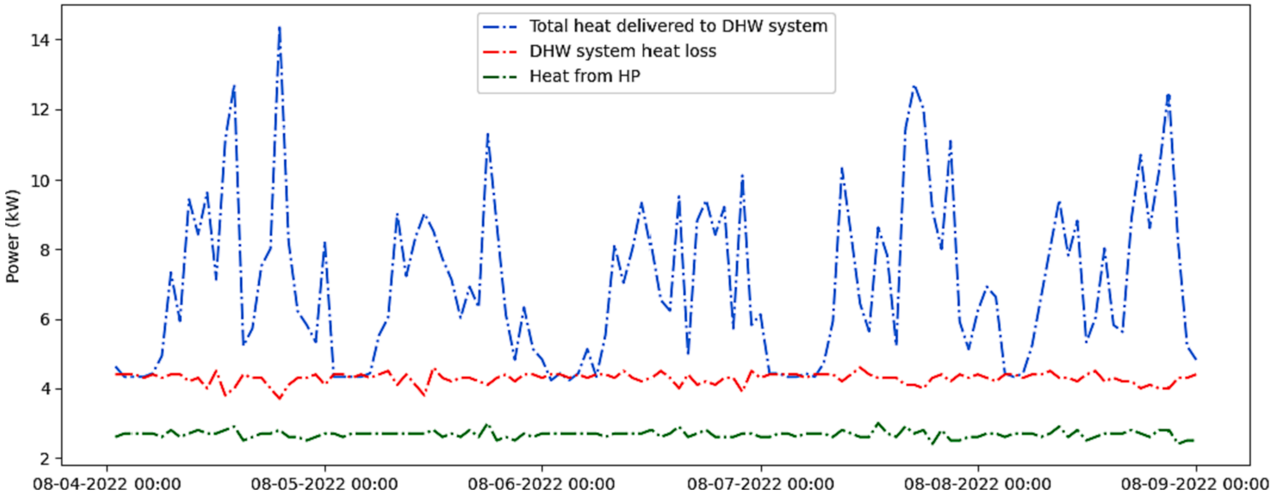

Fig. 9. The total heat power delivered to DHW system, circulation heat loss, and the heat power provided by heat pump during the test of the parallel configuration.

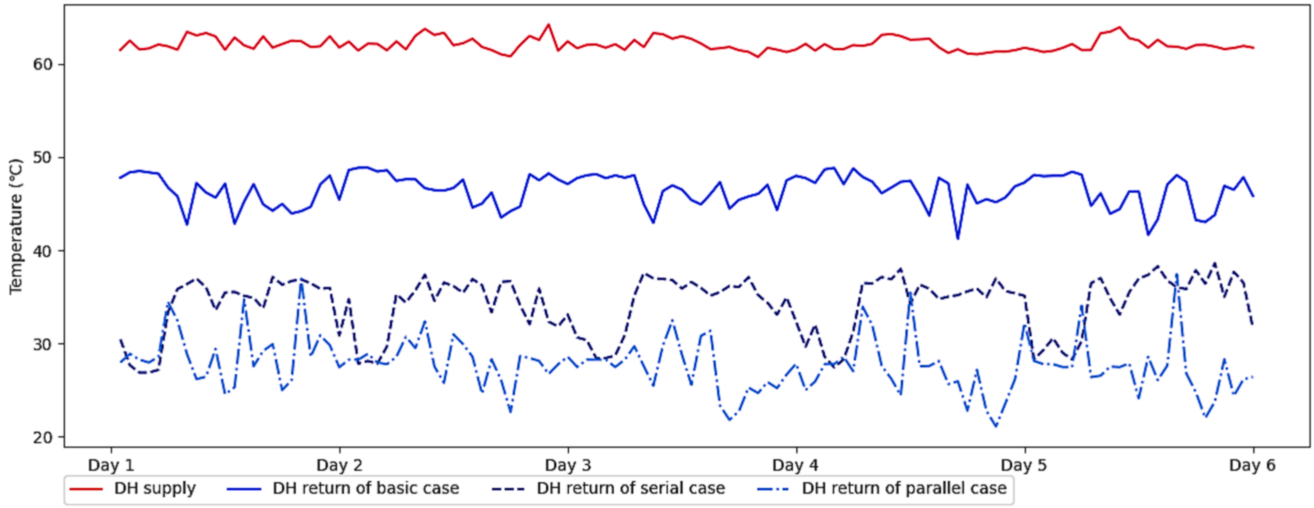

Fig. 10. Comparison of the DH return temperature from the three configurations.

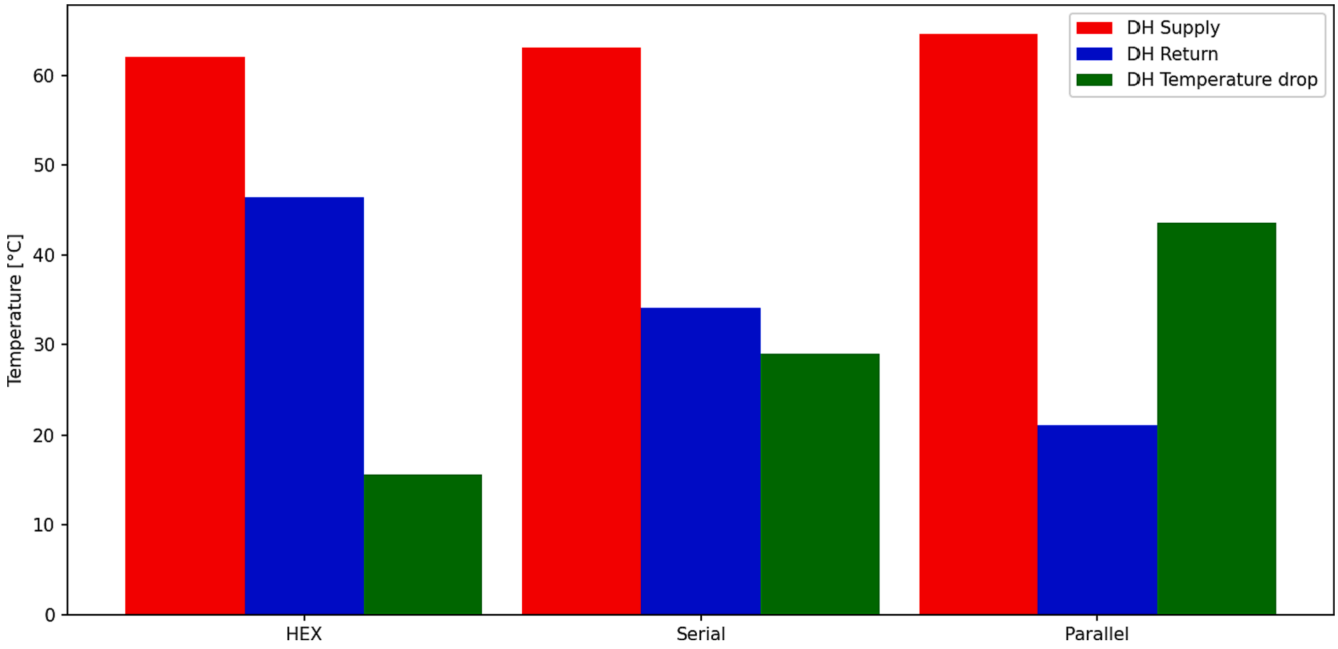

Fig. 11. Flow-weighted average DH operating temperature and temperature drop comparison of three configurations in the test period of June – August 2022.

lowest return temperature with a supply temperature of 55 °C in the network. In both scenarios, the COP of the heat pump was assumed to be 5.1–5.3, which is coherent with the field measurements; therefore, the temperature of heat source of the heat pump T_{outPre} will not change with scenario.

The economic analysis in the current scenario indicates that DHW substations with circulation loss boosters in both serial and parallel configurations have low payback periods of 3.7 and 3.4 years, respectively. In the future, despite a higher bonus rate, the payback period will increase to 7.9 and 7.2 years because of higher electricity consumption and a lower overall DH return temperature reduction. Nevertheless, the project remains financially feasible, assuming a typical booster heat pump lifetime of 15 years.

8. Discussion

8.1. Assessment of the theoretical analysis

The theoretical analysis evaluated the performance of various configurations based on DH return temperatures under future LTDH conditions with a DH supply temperature of 55 °C. Typical DHW substations with only one heat exchanger would lead to a high DH return temperature of 50.8 °C. The serial configuration could only reduce the DH return temperature by 4 °C compared to the typical installation, whereas the parallel configuration with a 4-kW heat pump could achieve the lowest DH return temperature of 21 °C. This investigation suggests that the concurrent heating of the circulation flow is the main limitation for lowering the DH return temperature in DHW systems. The lowest DH return temperature can be achieved by decoupling the heating of the circulation loop from hot water production and using a heat pump to minimize the DH return temperature after heating the circulation.

Similarly, a configuration with a separate, smaller heat exchanger for

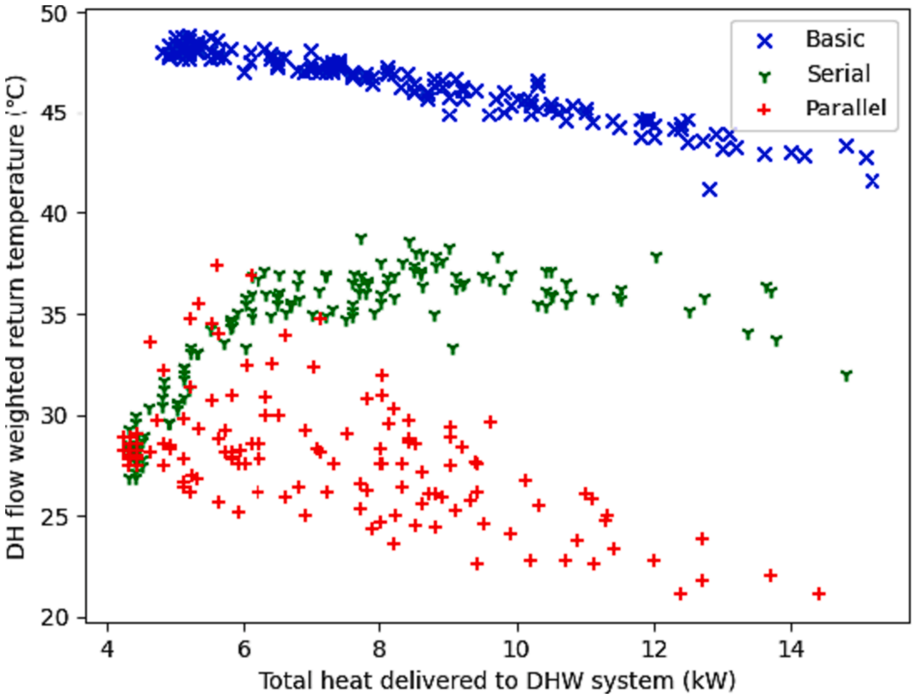

Fig. 12. Correlation of the total heat delivered to the DHW system and the DH return temperature of the three configurations.

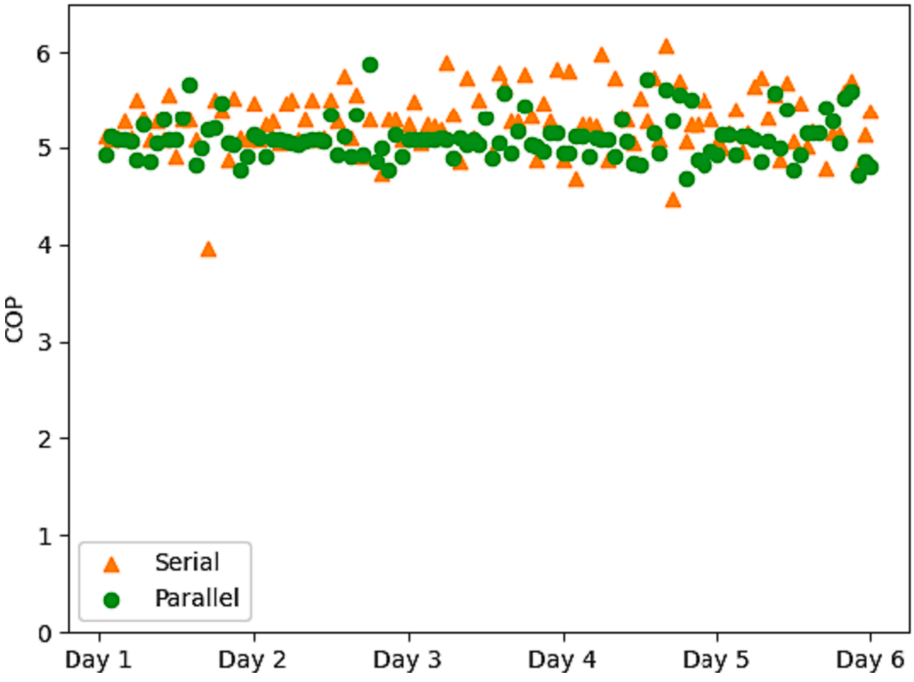

Fig. 13. COP of the heat pump in the test period of serial and parallel configuration.

DHW circulation losses, in which the return temperature flow is cascaded to the SH heating system for further cooling, could be a promising solution for the future design of DHW substations. The analysis showed a good performance with DH return temperatures of 33.8 °C; however, this was not tested in this study. The analysis revealed that the parallel configuration can secure a lower DH return temperature; however, the cascading case has the advantage of simpler implementation and lower operating costs as electricity is not required. The limiting factor is the necessity of SH systems ready for low-temperature operation as a prerequisite for ensuring low DH return temperatures.

In the theoretical analysis, a simplified DHW tapping demand based on an hourly average of 6 kW was assumed. Although the tapping profile varied dynamically over time, as presented in Section 4.2, the measurements showed that the daily DHW energy consumption was constant throughout the year, which is consistent with similar findings in [13,34]. The theoretical investigation scope was limited to benchmarking the different configurations and capabilities to safely deliver hot water with a DH supply temperature of 55 °C rather than having detailed dynamic models of the systems. Therefore, the assumptions and simplified model are appropriate for the intended purpose. Nonetheless,

Table 1
Economic analysis of circulation loss booster.

		Ref. case	Current scenario		Future scenario	
		Main HEX	Serial	Parallel	Serial	Parallel
Temperatures						
Avg. DH supply	°C	65	65	65	55	55
Avg. DH return	°C	42.0	37.8	37.8	40.1	40.2
DH return reduction	°C		4.2	4.2	1.8	1.8
Consumptions and savings						
Heat pump capacity	kW		2.5	2.5	4	4
EL Consumed.	MWh/year		4.1	4.3	6.6	6.9
DHW Cir. Loss	MWh/year	43.8	36.8	35.0	36.8	35.0
DH total Consume.	MWh/year	315.8	308.8	307.0	308.8	307.04
DH savings	MWh/year		11.1	13.1	11.1	13.1
Costs and incentives						
DH price	EUR/kWh	0.11	0.11	0.11	0.11	0.11
DH motivation tariff	%/(°C •kWh)		1	1	2	2
EL price	EUR/kWh		0.2	0.2	0.2	0.2
Investment	EUR		7000	7000	10,300	10,300
Operational cost	EUR/year		100	100	120	120
Economic benefits						
Annual savings	EUR		1827	1983	1428	1560
Payback	Year(s)		3.7	3.4	7.9	7.2

the dynamic nature of the DHW tapping profiles was assessed by experimentally testing different configurations.

8.2. Assessment of the test with medium–low DH supply temperature

During the test, which featured a medium–low DH supply temperature range of 62–64 °C, all three configurations could safely provide hot water and maintain the required circulation temperature, without any complaints from users. The basic configuration, featuring one heat exchanger, achieved a DH return temperature of 46.4 °C. Meanwhile, both the serial and parallel configurations could achieve even lower DH return temperatures, averaging 34.1 °C and 27.9 °C, respectively. The test results were consistent with the theoretical analysis, although the serial configuration achieved a relatively lower DH return temperature because of the higher DH supply temperature in the test.

The test results indicated that the control system in the main heat exchanger performed well during basic and serial operations. However, in parallel operations, the control system exhibited irregularities, as shown in Fig. 12. This suggests that the current control system in the main heat exchanger is not suitable for operation with low flow on the secondary side and cannot be directly used in the proposed parallel design. The current thermostatic controller only reacts to the temperature difference between the setpoint and secondary side flows; therefore, a more effective alternative controller is required to close the valve on the primary side without DHW tapping by integrating an additional flow switch.

The measured COP of the heat pump in the serial (5.3) and parallel configurations (5.1) indicates good performances. This was also possible because of the positive effect of the auxiliary HEX in making the best use of the heat from the DH system and increasing the temperature of the circulation flow. In [26], Benakopoulos et al. demonstrated that electricity consumption can also be reduced by 7% when the DH supply temperature is 55 °C by using a small HEX to preheat the hot water circuit before the heat pump.

Finally, the circulation heat losses in the basic configuration were 14.3% (0.8 kW) higher than those in the parallel case using a simple energy balance using measurements from the energy meters on the primary and secondary sides of the substation. This difference is associated with the higher heat losses in the main exchanger and the uninsulated pipes in the plant room. Hence, this study confirmed that losses in the plant room cannot be disregarded and can significantly contribute to the overall circulation heat losses.

8.3. Economic results

The economic analysis results indicate that the substation in this study demonstrated overall good financial performance, primarily because of the application of the DH motivation tariff in Denmark and the lower DHW circulation loss in configurations featuring circulation loss boosters. These findings are consistent with those of Thorsen et al. [27], although their substation layout differs from that used in this study, and their system includes a DHW storage tank.

The economic model used in this study relies on DH motivation tariffs, which are common in Denmark and Sweden. Consequently, the positive effects of these tariffs on billing may not be observed in other contexts in which such incentives do not exist. Additionally, the feasibility of implementing circulation loss boosters from an economic standpoint depends heavily on local electricity prices. Given that Denmark has one of the highest electricity prices worldwide, this concept can also achieve good economic performance in other countries or regions with lower electricity costs.

8.4. Limitation and future work

In the present study, the test were performed during the summer with DH supply temperatures in the range of 62–64 °C. In future, a test with a supply temperature of 55 °C will be conducted. To test the performance of the designs under LTDH conditions, a mixing loop will be installed on the primary side of the heat exchanger to blend and manage the DH supply temperature at 55 °C.

The economic analysis focuses on the economic feasibility of the substation under study at the building level. A potential future investigation will focus on conducting a more comprehensive technoeconomic analysis to assess the effects of reduced operating temperatures on the entire network. The proposed DHW substation with a circulation loss booster could be a viable solution for replacing DHW systems with large storage tanks in multifamily buildings. This would allow DH operators to remove the barriers that these buildings may pose in reducing the supply temperature to 55 °C in DH networks to comply with the comfort and hygiene requirements of DHW systems. This is relevant for the specific network in Viborg, where the DH operator phases out existing natural gas CHP power plants in favor of large heat pumps, local excess heat recovery, geothermal heating, and electric boilers. However, it is equally relevant for any DH operator in the transition toward green heat generation. A lower supply and return temperature in the network may be economically attractive because of lower energy generation costs and reduced distribution losses. In Denmark, owing to motivational tariffs, other studies found that this could have an attractive payback period for end users [27]. However, even if the solution might not have a short payback for the end users in other DH markets, the DH operators could secure some financial incentives for specific users, offsetting the extra cost with the potential savings from lower heat generation costs.

9. Conclusion

DHW systems with circulation loops in large multifamily buildings are one of the main bottlenecks in achieving low-temperature operation in DH networks. This study demonstrated innovative and economically feasible DHW substation designs that effectively decouple the heating of circulation and cold water, ensuring thermal comfort, hygiene requirements, and a low DH return temperature.

The steady-state theoretical analysis results demonstrate that the parallel configuration with the circulation loss booster and the cascading configuration with the SH system have the potential to achieve low DH return temperatures of 21 °C and 33.8 °C, respectively, with a DH supply temperature of 55 °C. In the field test at a Danish multifamily building under medium–low DH supply temperatures of 62–64 °C, the booster heat pump configuration can reduce the DH return temperature from 46.4 °C to 33.1 °C and 27.9 °C in the serial and parallel configurations, respectively, compared to a typical DHW substation with a single heat exchanger. Additionally, the heat pump exhibited a COP of 5.1–5.3. According to the economic analysis, the circulation loss booster concept has a short payback period ranging from 3.4 to 7.9 years, depending on the specific scenario conditions under consideration. However, given the expected lifetime of 15 years, this concept is economically attractive.

Although the field test and economic analysis indicate that the parallel connection of the circulation loss booster exhibits excellent performance in terms of low DH return temperatures and short payback periods, the control system must be sufficiently robust to handle low-temperature and low-flow targets that are likely to become more prevalent in future low-temperature operations. Future research may focus on refining experimental setups and control strategies to test various configurations at a DH supply of 55 °C and conducting an economic analysis to assess the impact of these new configurations on the entire DH network.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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