

Article

Overview of Solutions for the Low-Temperature Operation of Domestic Hot-Water Systems with a Circulation Loop

Theofanis Benakopoulos ^{1,2,3,*} , William Vergo ³ , Michele Tunzi ³ , Robbe Salenbien ^{1,2} 
and Svend Svendsen ³ 

¹ Energy Technology Unit, Flemish Institute for Technological Research (VITO NV), Boeretang 200, 2400 Mol, Belgium; robbe.salenbien@vito.be

² EnergyVille, Thermal Systems Unit, Thor Park 8300, 3600 Genk, Belgium

³ Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118, 2800 Kongens Lyngby, Denmark; s144561@student.dtu.dk (W.V.); mictun@byg.dtu.dk (M.T.); ss@byg.dtu.dk (S.S.)

* Correspondence: thebena@byg.dtu.dk

Abstract: The operation of typical domestic hot water (DHW) systems with a storage tank and circulation loop, according to the regulations for hygiene and comfort, results in a significant heat demand at high operating temperatures that leads to high return temperatures to the district heating system. This article presents the potential for the low-temperature operation of new DHW solutions based on energy balance calculations and some tests in real buildings. The main results are three recommended solutions depending on combinations of the following three criteria: district heating supply temperature, relative circulation heat loss due to the use of hot water, and the existence of a low-temperature space heating system. The first solution, based on a heating power limitation in DHW tanks, with a safety functionality, may secure the required DHW temperature at all times, resulting in the limited heating power of the tank, extended reheating periods, and a DH return temperature of below 30 °C. The second solution, based on the redirection of the return flow from the DHW system to the low-temperature space heating system, can cool the return temperature to the level of the space heating system return temperature below 35 °C. The third solution, based on the use of a micro-booster heat pump system, can deliver circulation heat loss and result in a low return temperature below 35 °C. These solutions can help in the transition to low-temperature district heating.

Keywords: domestic hot water systems; low return temperature; circulation heat loss; storage tank; heat exchanger; micro-booster heat pump



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1. Introduction

1.1. Low-Temperature District Heating

According to the European Green Deal, the district heating (DH) sector, among others, must integrate renewable sources, increase energy efficiency, and implement other sustainable solutions to achieve decarbonization by 2050 [1–3]. Low-temperature district heating (LTDH) systems, with supply and return temperatures of approximately 55 and 25 °C, respectively, offer an economical solution to realize a fossil-free energy system [4–8].

LTDH systems can only be realized by securing the low-temperature operation of the existing buildings heated by DH [6]. DH networks deliver heat to both the space heating and domestic hot water (DHW) systems of existing buildings. There is great potential for the low-temperature operation of space heating in existing buildings [6,7]. These systems have been designed for ambient conditions that rarely occur [9–14]. In addition, the heat demand is reduced throughout the year due to the improved insulation of building envelopes [15]. As a result, the design condition can be characterized as conservative for the current actual operating conditions.

In typical Danish dwellings, while the space heating demand is decreasing, the share of the DHW demand in the overall heat delivered has increased up to 35% [16,17]. As a result, it is of great importance to secure the efficient and low-temperature operation of DHW systems in existing buildings.

1.2. Domestic Hot-Water Systems with Circulation

The two central DHW configurations with hot-water circulation that are typically used in existing buildings are illustrated in Figures 1 and 2. The hot-water circulation in DHW systems ensures that DHW is ready for use at comfortable temperatures in taps and showers, but the DHW in the circulation loop needs to be kept at a minimum temperature of 50 °C to prevent the growth of bacteria such as *Legionella*.

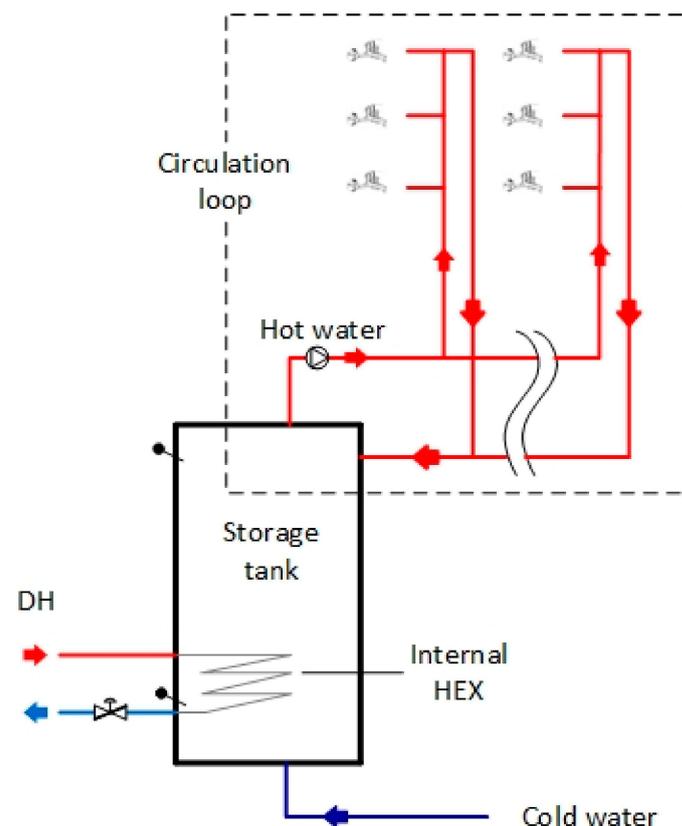


Figure 1. Typical DHW configuration with a storage tank with an internal heat exchanger and a distribution system with a circulation loop.

The first configuration is a DHW system with a hot-water storage tank [18]. Hot water is produced and stored inside the tank by a coil type of heat exchanger. Hot water is supplied from the top of the tank in a distribution system to the taps and showers in the building. The distribution system includes a circulation loop back to the upper part of the tank to keep the water in the distribution system at a temperature above 50 °C, controlled by a thermostatic valve. When hot water is needed, cold water enters at the bottom of the tank and is gradually heated to 55 °C by the heating coil on the way up to the top of the tank. The heating coil also heats up the circulation flow in the upper part of the tank. This system can be seen in Figure 1. Variations of this system can also be found. In a typical variation, the heat exchanger is a plate heat exchanger, and it is placed outside of the tank.

The second configuration is the instantaneous heat exchanger-based system without a storage tank [18]. This system can be seen in Figure 2. The heat exchanger separates the DHW system from the DH network. There is continuous hot-water circulation on the secondary side as well to maintain thermal comfort. Hot water is instantaneously prepared by the heat exchanger upon demand. When hot water is needed, cold water enters the

circulation loop before the heat exchanger. A variant of the systems has separate heat exchangers for DHW use and circulation heat loss.

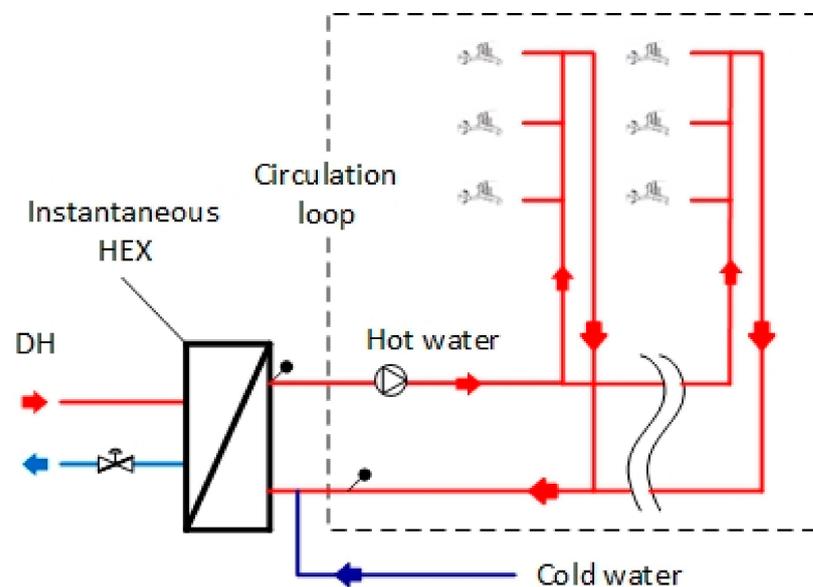


Figure 2. Typical DHW configuration with an instantaneous heat exchanger without a storage tank and a distribution system with a circulation loop.

1.3. DHW Hygiene and Comfort Requirements

According to Danish standards [19,20] and recommendations by the Danish Technologic Institute [21], to prevent Legionella growth in DHW systems based on temperature sterilization, the temperature in the circulation loop should always be above 50 °C during normal operation, and at peak demand, a minimum temperature of 45 °C can be accepted. Additionally, minimum temperatures of 45 °C in the kitchen and 40 °C in the shower within 10 s are necessary for thermal comfort.

1.4. Problem Identification

According to the regulations for hygiene and comfort, the operation and design of current DHW systems are an obstacle to reducing the operating temperatures to be suitable for LTDH systems [22–24].

1.4.1. Problems Regarding the DH Supply Temperature

To maintain 50 °C in the circulation loop according to the temperature sterilization requirements and to compensate for the temperature reduction in the loop due to circulation heat loss, the hot-water supply temperature is set to a higher value of approximately 55 °C. The DH supply temperature for heating the storage tank or the instantaneous heat exchanger should be even higher than 55 °C. This is in contrast with a DH supply temperature of 55 °C, according to the temperature requirements of LTDH. As a result, the design and operation of the DHW systems need to be improved to comply with the LTDH temperature requirements.

1.4.2. Problems Regarding the DH Return Temperature

When there is a hot-water draw-off in the building, hot water at 55 °C leaves the tank from the top. At the same time, cold water at 10 °C enters the tank from the bottom. According to the regulations and guidelines for sizing DHW systems in Copenhagen [20,25], the DHW system should be dimensioned for a pressure difference of 50 kPa on the primary side for a DH supply temperature of 65 °C in order to ensure a hot water temperature of 55 °C. However, in most cases, the real pressure difference may be up to 500 kPa, and the real supply temperature may be up to 95 °C. These typical high DH supply temperatures

and pressure differences make it possible to charge the tank within a short period with high power. This results in a low DH return temperature, but only for the short heating period.

When there is no hot-water draw-off, the tank is constantly charged to supply only the circulation heat loss of the system. More specifically, the temperature of the return circulation flow is 50 °C, according to the temperature requirements. At the same time, there is no cold water entering the tank from the bottom. As a result, the temperature stratification of the tank is not maintained, and the cooling of the DH flow is not sufficient. This results in a DH return temperature that is slightly higher than 50 °C.

1.4.3. Circulation Heat Loss

The majority of the energy loss in the DHW system occurs in both the circulation and distribution pipelines [23]. The type of building involved also has an influence on the circulation and distribution of heat loss. In apartment buildings in Denmark, the efficiency of the DHW system can be as low as 30% [16]. This is equivalent to a ratio of circulation loss to DHW use of two to three. A long-term investigation in 12 multi-family buildings in Poland found that the DHW circulation losses varied between 57% and 70% [26]. The ratio of circulation loss to the energy delivered for hot-water production can be from 25% in well-insulated systems to up to 300% in old buildings with poor pipe insulation.

1.5. Aim of the Study

Our aim is to investigate the potential reduction in the operating temperatures of different DHW systems with hot-water circulation for large multi-family buildings with DH. Only DHW systems with temperature sterilization are investigated in this article. The investigation focuses on expressing the DH return temperature as a function of the DH supply temperature, the ratio of the circulation heat loss to the hot-water energy use, and the ratio of circulation heat loss to the energy use for space heating.

1.6. State-of-the-Art

To fulfill the DHW temperature requirements for hygiene under an LTDH supply temperature, the use of hot-water temperature boosters in the form of localized heat pumps or electrical heaters has been investigated in the literature. Local electrical heater or booster heat pumps for DHW preparation were investigated in building cases in Austria [27]. The use of an instantaneous heat exchanger for DHW production at a lower temperature than 50 °C, without hot-water storage to avoid Legionella risk, was tested in Danish dwellings [28]. There were no complaints regarding poor thermal comfort.

For buildings that use heat pumps for DHW production, several state-of-the-art heat pumps have been investigated in the literature. The development of a new CO₂ air/water heat pump for the production of DHW in residential buildings was described in one study [29]. The use of a storage tank with temperature stratification as an addition to the heat pump can secure a higher Coefficient of Performance (COP) in the heat pump: simulations and tests conducted for DHW temperatures of 70 and 80 °C resulted in a COP of around 3. A prototype of a dual-source heat pump for DHW was presented in another study [30]. The highest efficiency of the heat pump was achieved by producing hot water at 55 °C. A new step-based heating concept was specially developed for DHW production at 55 °C through a ground-source heat pump [31]. A COP of 3.8 and a 50% increase in energy efficiency were achieved.

There have also been attempts to achieve a low DH return temperature without lowering the DH supply temperature. These solutions are relevant for DH networks that focus on ensuring a low DH return temperature as the first step towards LTDH [5]. A new control strategy for the DHW storage tank based on multi-mode charging methods considering the periodical characteristics of the load pattern is presented in one study [32] to achieve a low DH return temperature. This strategy was tested [33] under two innovative layouts with a storage tank: one with an external heat exchanger and another with a micro heat pump. Reductions of 4.9 and 16.4 °C were achieved in the DH return temperature

under the two layouts, respectively. A new capacity limitation functionality for DHW tanks was tested in a new building under the EnergyLab Nordhavn project [34]. According to the results, the peak load from the DHW tank was reduced from 70–80 kW to 25 kW, and an average reduction of 10 °C in the return temperature was achieved. However, this capacity limitation function resulted in a temperature drop in the tank during periods of high DHW demand. As a result, an additional security function to increase the heating power of the tank when needed is necessary to secure thermal comfort during high DHW demand periods, such as New Year's Eve. A new innovative solution for reducing the DH return temperature from the DHW circulation system was designed and tested under the EnergyLab Nordhavn project [35] in a multi-family building. This solution heats the circulation water from 50 to 55 °C using a direct heat exchanger and a booster heat pump. However, a DH supply temperature of between 65 and 90 °C was used for the demonstration instead of LTDH. The demonstration resulted in a low return temperature of 25 °C.

1.7. Novelty

The article presents a general overview of concepts suitable for the low-temperature operation of DHW systems that has not been presented earlier in the scientific literature. Furthermore, a novel control system for heating the DHW storage tank was developed and tested in a new building in Nordhavn, Denmark. The novelty of this control system is a new security function that will switch off the power limitation based on critically low temperatures measured in the tank.

2. Material and Methods

In this section, different DHW concepts with hot-water circulation are presented and investigated under LTDH conditions. These concepts are:

- DHW system with a storage tank with an internal heat exchanger;
- DHW system with separate heat exchangers for hot water use and a hot-water circulation loop;
- DHW systems with micro-booster heat pumps to cool the return of district heating and heat the circulation loop;
- The coupling of the district heating return flow from DHW systems to a space heating system with low return temperatures for the further cooling of the district heating return flow as an additional function compared to the previous systems.

2.1. Assumptions of Ideal Performance of Components

The investigation of the DHW concepts was based on assumptions regarding the ideal performance of the components. In this way, it was possible to calculate, evaluate, and compare the potential for a low DH return temperature among the different solutions under the same reference conditions. The results can suggest whether or not these concepts can be used successfully under LTDH conditions.

Uncertainties and variations regarding the DHW demand over the year, the actual heat losses in the circulation loop, the return temperature from the space heating system, and the actual performance of the components may affect the DH return temperature in real operation.

The assumptions used to simplify the modeling of the different concepts are:

- The temperature of the hot water supplied to the circulation loop is 54 °C and the return temperature is 50 °C. This is in accordance with the Danish standards [19,20] and the recommendations by the Danish Technologic Institute [21] to prevent Legionella growth in the DHW system based on temperature sterilization;
- The operation of the DHW circulation loop is continuous and the circulation heat loss is the same each day. Again, according to the standards presented above, there must be a continuous circulation flow to secure thermal comfort;

- The DHW tank can be assumed to be big enough and be ideally stratified to supply the energy for heating DHW and for the circulation loop at a constant power equal to the daily average;
- The operation of the space heating system is in accordance with the LTDH requirements, with a return temperature of 30 °C from the secondary side;
- The temperature pinch between the primary outlet flow and the secondary inlet flow of the heat exchanger is assumed to be 1 °C for heat exchangers in the circulation loop.

Regarding the last assumption, the equation describing the heat transfer (Q) from the primary to the secondary side of the counter-flow heat exchanger is:

$$Q = UA\Delta T_{lm} \quad (1)$$

$$\Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} \quad (2)$$

$$\Delta T_1 = T_{sup, primary} - T_{ret, secondary} \quad (3)$$

$$\Delta T_2 = T_{ret, primary} - T_{sup, secondary} \quad (4)$$

According to the actual heat exchanger [36], for a heating capacity (Q) of 32.3 kW, the supply ($T_{sup, primary}$) and return ($T_{ret, primary}$) temperatures on the primary side are 55/21.8 °C, respectively, and the supply ($T_{sup, secondary}$) and return ($T_{ret, secondary}$) temperatures on the secondary side are 45/10 °C, respectively. From Equations (1)–(4), the heat exchanger coefficient (UA) is calculated to be 2.97 kW/K. With the same heat exchanger, a smaller heating capacity (Q) of 3 kW, secondary temperatures of 54/50 °C, and a primary supply temperature of 55 °C, the primary return temperature can be calculated to be approximately 51 °C, which is 1 °C higher than the 50 °C temperature of the secondary supply.

2.2. DHW System with Storage Tank with Internal Heat exchanger

The conventional DHW configuration with a storage tank that has an internal heat exchanger and hot-water circulation can be modeled as two heat exchangers coupled in series on the primary side, as presented in Figure 3, to calculate the potential low DH return temperature. This assumption represents the ideal operation of a DHW tank that it is perfectly stratified and the capacity is large enough to compensate for the daily DHW use. Under real operating conditions, these assumptions cannot be applied, and the return temperature from the tank cannot be as low as under ideal conditions. This assumption is relevant only for calculating the potential of achieving a low-temperature operation from a conventional DHW system with a storage tank. The bottom heat exchanger delivers energy to heat the hot water from 10 °C to 50 °C. The top heat exchanger delivers heat to compensate for the heat loss in the hot-water circulation loop.

It is assumed that the heat exchangers are large enough to deliver the required energy to the circulation loop (P_{circ}) and the energy required for the hot-water production (P_{use}), resulting in primary return temperatures that are 1 and 5 °C higher than the secondary return temperature if the necessary flow in both heat exchangers is the same.

Equation (5) describes the total DH heat delivered to the top heat exchanger to compensate for the circulation losses (P_{circ}), and Equation (6) describes the total DH heat delivered to the bottom heat exchanger regarding the DHW production (P_{use}):

$$P_{circ} = \dot{m}_{DH} C_{water} (T_{sup, DH} - T_1), T_1 \geq 51^\circ\text{C} \quad (5)$$

$$P_{use} = \dot{m}_{DH} C_{water} (T_1 - T_{ret, DH}), T_{ret, DH} \geq 15^\circ\text{C} \quad (6)$$

where \dot{m}_{DH} is the district heating flow, C_{water} is the thermal capacity of the water, $T_{sup, DH}$ is the district heating supply temperature, $T_{ret, DH}$ is the district heating return temperature, and T_1 is the temperature of the flow from the top to the bottom of the heat exchanger.

From Equations (5) and (6), the potential for low $T_{ret,DH}$ can be expressed as a function of $T_{sup,DH}$, T_1 , and the ratio of the circulation loss to the DHW use (P_{circ}/P_{use}):

$$\frac{P_{circ}}{P_{use}} = \frac{T_{sup,DH} - T_1}{T_1 - T_{ret,DH}} \leftrightarrow T_{ret,DH} = T_1 - \frac{T_{sup,DH} - T_1}{P_{circ}/P_{use}} \quad (7)$$

when T_1 is 51 °C, this represents a balancing point where the values of the ratio P_{circ}/P_{use} and $T_{sup,DH}$ make it possible to cool the \dot{m}_{DH} flow to 15 °C ($T_{ret,DH}$). Equation (8) represents the critical value of the ratio P_{circ}/P_{use} for each $T_{sup,DH}$, where the necessary \dot{m}_{DH} flow is cooled to 15 °C after the bottom heat exchanger.

$$\frac{P_{circ}}{P_{use}} = \frac{T_{sup,DH} - 51}{51 - 15} \quad (8)$$

For bigger values of P_{circ}/P_{use} than the critical one for each $T_{sup,DH}$, the \dot{m}_{DH} flow will be cooled to $T_1 = 51$ °C after the top heat exchanger, but this will result in a higher $T_{ret,DH}$ than 15 °C after the bottom heat exchanger, according to Equation (7). For smaller values of P_{circ}/P_{use} than the critical for each $T_{sup,DH}$, the \dot{m}_{DH} flow must be larger, and the temperature T_1 will obtain higher values than 51 °C, resulting in a $T_{ret,DH}$ of 15 °C.

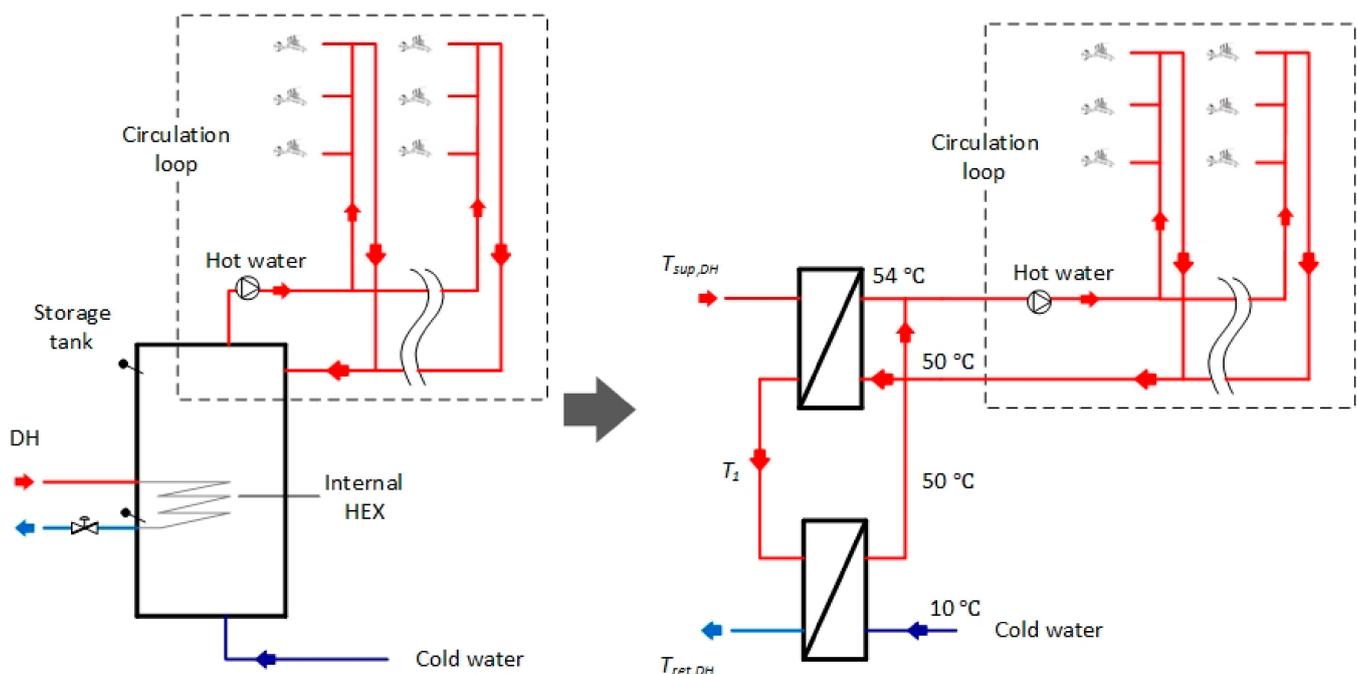


Figure 3. DHW system with a storage tank modeled as two ideal heat exchangers.

Capacity Limitation Functionality of the Storage Tank with Extra Safety Functionality

As was explained in Section 1.4, one of the main problems with the storage tank system is that the short heating periods requiring a high heating power to heat up the cold water in the tank after major usage results in high return temperatures when the circulation loss has to be supplied all the time.

To extend the heating time, a heating power limitation functionality can be implemented in the thermostatic controller of the heating process of the storage tank. The instantaneous heating power measured by an electronic heat meter on the district heating supply to the DHW tank is used as an input signal to limit the heating power accurately. This capacity limitation functionality was tested in a multi-family building in Copenhagen [34]: the peak load from the DHW tank was reduced from 80 to 25 kW, and a DH return temperature below 30 °C was achieved. However, the demonstration of this func-

tionality showed that the temperature of the tank becomes critically low during periods with unusually high hot-water demand, such as New Year's Eve.

A new safety functionality was developed and tested in the same building case to overcome the issue of a critically low DHW temperature during periods of high heat demand. The novel safety functionality works in the following way: when the temperature of the tank becomes critically low, below 45 °C, the limitation function will be switched off, allowing the heating power to be increased to maintain the temperature of the tank close to 55 °C. When the temperature of the tank is not critical anymore, the safety mechanism will switch on again the heating power limitation functionality. The heating power limitation functionality, including the new safety functionality, was tested in the same building case as in [34] during the heating season of 2020. The results of this demonstration are presented in Section 3.2.

2.3. DHW System with Separate Heat Exchanger for Heating the Circulation Loop

In this system configuration, the production of hot water and the energy delivered to the circulation loop is performed by two heat exchangers with separate supplies of district heating. As presented in Figure 4, the top heat exchanger produces hot water by heating cold water, while the bottom heat exchanger delivers the necessary heat to compensate for the circulation heat loss.

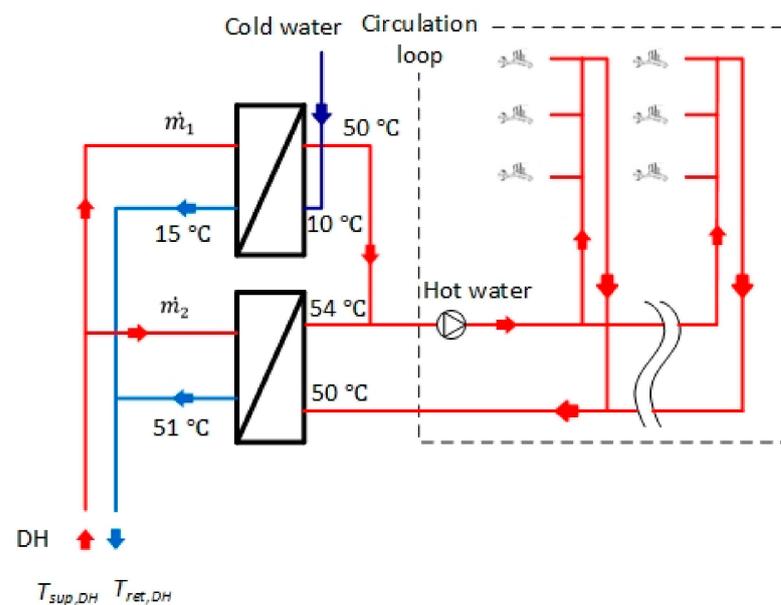


Figure 4. A DHW system with two separate heat exchangers.

The DH return temperature from the top heat exchanger can be expected to be approximately 15 °C due to the heating of cold water at 10 °C and the heat transfer capacity of the heat exchanger. The DH return temperature from the bottom heat exchanger is expected to be close to 51 °C, due to the return temperature of the circulation loop of 50 °C and the relatively small heating power needed for the circulation loss. The heat delivered to the top (P_{use}) and bottom (P_{cir}) heat exchangers can be described by Equations (9) and (10), respectively. The DH flow is divided into the individual \dot{m}_1 and \dot{m}_2 for the two heat exchangers, according to Figure 4.

$$P_{use} = \dot{m}_1 C_{water} (T_{sup,DH} - 15) \quad (9)$$

$$P_{cir} = \dot{m}_2 C_{water} (T_{sup,DH} - 51) \quad (10)$$

The overall daily average DH return temperature of the system can be calculated from the mixing of the return flows from the two heat exchangers according to Equation (11):

$$(\dot{m}_1 + \dot{m}_2)C_{water}T_{ret,DH} = \dot{m}_1C_{water} \cdot 15 + \dot{m}_2C_{water} \cdot 51 \tag{11}$$

From Equations (9)–(11), the DH return temperature ($T_{ret,DH}$) can be expressed as a function of $T_{sup,DH}$, P_{use} , and P_{cir} :

$$T_{ret,DH} = \frac{15(T_{sup,DH} - 51) + \frac{P_{cir}}{P_{use}} \cdot 51(T_{sup,DH} - 15)}{(T_{sup,DH} - 51) + \frac{P_{cir}}{P_{use}}(T_{sup,DH} - 15)} \tag{12}$$

2.4. DHW Systems with Micro-Booster Heat Pump for Hot-Water Circulation

In this section, different DHW configurations that include a micro-booster heat pump are introduced. The micro-booster heat pump cools the district heating return and heats the circulation loop. The micro-booster heat pump may be used alone or in combination with heat exchangers. The hot water for use is produced by a separate heat exchanger.

2.4.1. DHW System with Micro-Booster Heat Pump

In this DHW configuration, a heat exchanger is responsible for heating the DHW for use from 10 to 50 °C, and a micro-booster heat pump is responsible for maintaining the temperature of the circulation loop. This configuration is illustrated in Figure 5. The return temperature T_2 is a parameter set by the control of the heat pump. T_2 was set to 41 °C with a COP of 6, according to the performance data of an existing heat pump on the market with a heat source at 40 °C and DHW temperature at 10–53.5 °C [37]. The DH flow is divided into the individual \dot{m}_1 and \dot{m}_2 for the heat exchanger and heat pump, respectively.

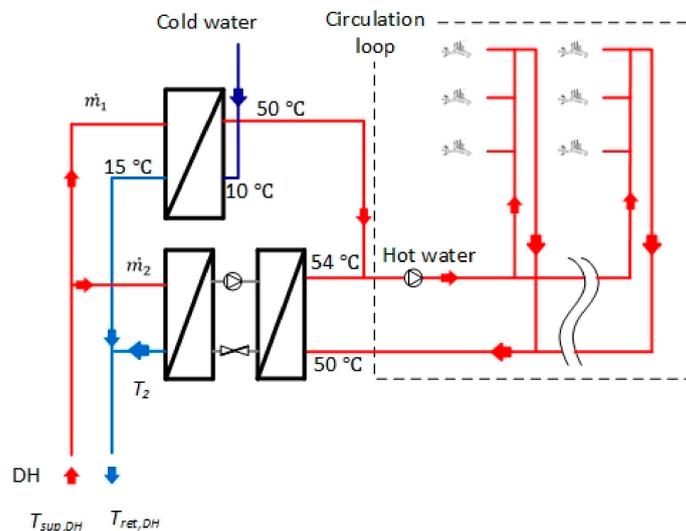


Figure 5. A DHW system with a heat exchanger and a micro-booster heat pump.

The heat delivered to the heat exchanger can also be described by Equation (9). The heat delivered to the micro-booster heat pump ($P_{cir} - P_{el}$) can be described by Equation (13):

$$P_{cir} - P_{el} = \dot{m}_2C_{water}(T_{sup,DH} - T_2) \tag{13}$$

where T_2 is the return temperature from the heat pump that can be set in the control of the flow to the heat pump and P_{el} is the electrical power for the operation of the pump. The coefficient of performance (COP) of the heat pump is calculated by Equation (14):

$$COP = \frac{P_{cir}}{P_{el}} \tag{14}$$

The overall DH return temperature of the system can be calculated from the mixing of the return flows from the heat exchanger and the heat pump:

$$(\dot{m}_1 + \dot{m}_2)C_{water}T_{ret,DH} = \dot{m}_1C_{water} \cdot 15 + \dot{m}_2C_{water}T_2 \quad (15)$$

From Equations (9) and (13)–(15), the DH return temperature ($T_{ret,DH}$) can be expressed as a function of $T_{sup,DH}$, T_2 , COP , P_{use} , and P_{cir} :

$$T_{ret,DH} = \frac{15(T_{sup,DH} - T_2) + \frac{P_{cir}}{P_{use}}(1 - (\frac{1}{COP}))T_2(T_{sup,DH} - 15)}{(T_{sup,DH} - T_2) + \frac{P_{cir}}{P_{use}}(1 - (\frac{1}{COP}))(T_{sup,DH} - 15)} \quad (16)$$

From Equation (14), the ratio of electrical power to DHW use P_{el}/P_{use} can be expressed as:

$$\frac{P_{el}}{P_{use}} = \frac{P_{cir}}{P_{use}} \frac{1}{COP} \quad (17)$$

2.4.2. DHW System with a Heat Exchanger Before the Micro-Booster Heat Pump in the Circulation Loop

In this configuration, once again, a heat exchanger is responsible for heating hot water from 10 to 50 °C. To maintain the temperature of the circulation loop, a micro-booster heat pump is connected in a row with an additional heat exchanger, as illustrated in Figure 6. The return flow from the circulation loop is heated first by the heat exchanger and then by the heat pump. The DH flow is divided into the individual \dot{m}_1 in the heat exchanger for the hot-water production, \dot{m}_2 in the heat exchanger, and then the heat pump responsible for the circulation loop.

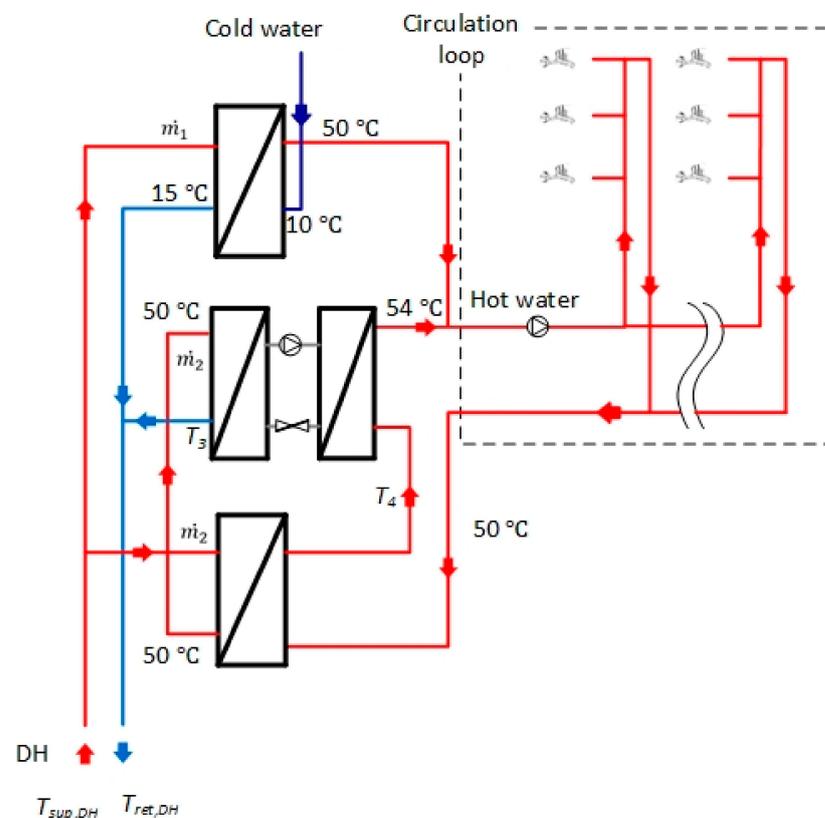


Figure 6. A DHW system with a heat exchanger for DHW production and a micro-booster heat pump plus another heat exchanger for the circulation loop. The circulation flow is heated first by the heat exchanger.

The assumption in this configuration is that the return temperature from the heat exchanger to the heat pump can be considered very close or similar to the return temperature of the circulation flow. This is because the circulation loss is relatively small and the \dot{m}_2 flow in the primary side is significantly lower than the circulation flow on the secondary side of the heat exchanger.

The heat delivered to the heat exchanger responsible for the hot-water production can also be described by Equation (9). The return temperature T_3 is a parameter set by the control of the flow \dot{m}_2 through the heat pump. T_3 was set again to 41 °C with a COP of 6, according to the performance data of an existing heat pump on the market with a heat source at 40 °C and DHW temperature at 10–53.5 °C [37].

The energy delivered to the heat pump (P_{HP}) is expressed by Equation (21), taking into account the expression of the heat out of the heat pump (P_{out}) to the heat into the heat pump (P_{in}) as a function of the COP of the heat pump from Equations (18)–(20):

$$COP = \frac{P_{out}}{P_{el}} \quad (18)$$

$$P_{out} = P_{in} + P_{el} \quad (19)$$

$$\frac{P_{out}}{P_{in}} = \frac{COP \cdot P_{el}}{P_{out} - P_{el}} = \frac{COP}{P_{out}/P_{el} - 1} = \frac{COP}{COP - 1} \quad (20)$$

$$P_{HP} = \dot{m}_2 C_{water} (50 - T_3) \frac{COP}{COP - 1} \quad (21)$$

According to the energy balance of the heat pump and the heat exchanger:

$$\frac{(50 - T_3) \frac{COP}{COP - 1}}{T_{sup,DH} - 50} = \frac{54 - T_4}{T_4 - 50} \leftrightarrow T_4 = \frac{55 + 50 \left(\frac{(50 - T_3) \frac{COP}{COP - 1}}{T_{sup,DH} - 50} \right)}{1 + \frac{(50 - T_3) \frac{COP}{COP - 1}}{T_{sup,DH} - 50}} \quad (22)$$

The total heat delivered to the circulation loop (P_{cir}) is expressed as:

$$P_{cir} = \dot{m}_2 C_{water} (T_{sup,DH} - 50) + \dot{m}_2 C_{water} (50 - T_3) \frac{COP}{COP - 1} \quad (23)$$

The ratio P_{cir}/P_{use} from Equations (9) and (23) can be expressed as:

$$\frac{P_{cir}}{P_{use}} = \frac{\dot{m}_2}{\dot{m}_1} \cdot \frac{T_{sup,DH} - 50 + (50 - T_3) \frac{COP}{COP - 1}}{T_{sup,DH} - 15} \quad (24)$$

As a result, the ratio \dot{m}_2/\dot{m}_1 can be expressed as a function of the ratio P_{cir}/P_{use} , $T_{sup,DH}$, T_3 , and COP. The DH return temperature can be calculated from the mixing of the return flows \dot{m}_1 and \dot{m}_2 .

$$T_{ret,DH} = \frac{\dot{m}_1 \cdot 15 + \dot{m}_2 T_3}{\dot{m}_1 + \dot{m}_2} \quad (25)$$

The energy out of the heat pump equals the ratio of the temperature difference across the heat pump to the temperature difference of the circulation loop times the energy delivered to the circulation loop, as in Equation (26):

$$P_{el} \cdot COP = P_{cir} \frac{54 - T_4}{54 - 50} \quad (26)$$

From Equation (26), the ratio P_{el}/P_{use} can be expressed as:

$$\frac{P_{el}}{P_{use}} = \frac{P_{cir}}{P_{use}} \frac{1}{COP} \frac{54 - T_4}{54 - 50} \quad (27)$$

2.4.3. DHW System with a Secondary Heat Exchanger after the Micro-Booster Heat Pump in the Circulation Loop

This is a variation of the previous configuration where the return flow from the circulation loop is heated first by the heat pump and then by the heat exchanger, as illustrated in Figure 7. The DH flow is divided again into the individual \dot{m}_1 in the first heat exchanger for the hot-water production, \dot{m}_2 in the heat exchanger, and then the heat pump responsible for the circulation loop.

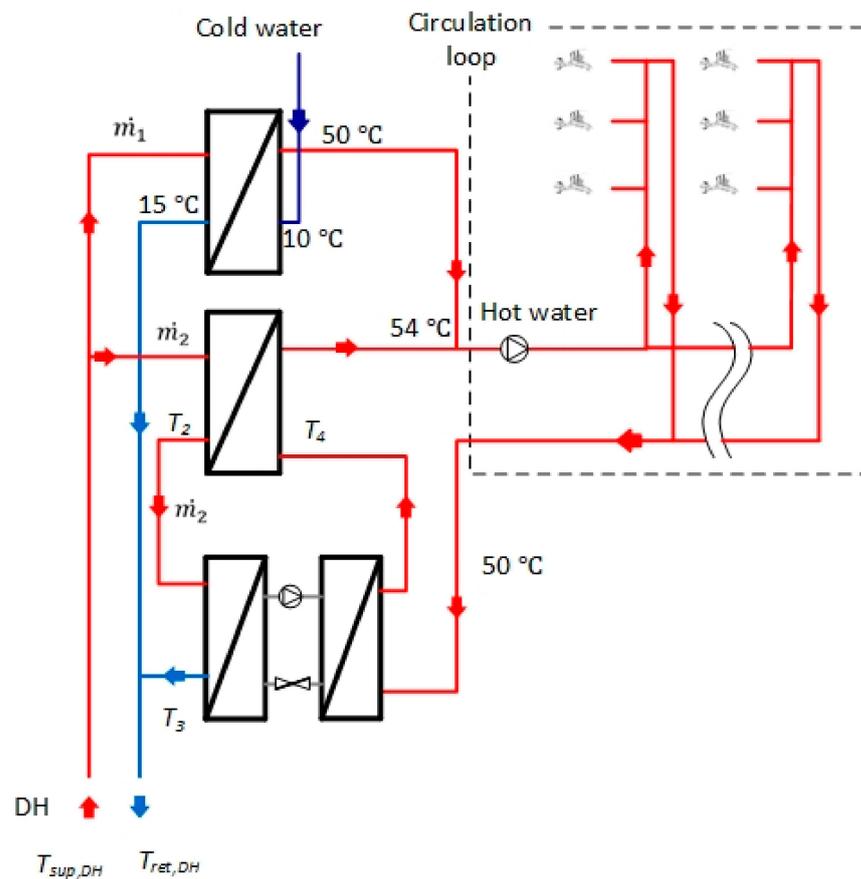


Figure 7. A DHW system with a heat exchanger for DHW production and a micro-booster heat pump, plus another heat exchanger for the circulation loop. The circulation flow is heated first by the heat pump.

Similar to the previous case, it is assumed that the primary return temperature from the second heat exchanger is close or similar to the return temperature of the circulation flow ($T_2 = T_4$), due to the relatively small circulation loss and because the primary flow (\dot{m}_2) is significantly lower than the circulation flow on the secondary side of the heat exchanger.

Equations (9) and (18)–(20) also apply in this configuration. The return temperature T_3 is a parameter set by the control of the heat pump. T_3 was set again to 41 °C with a COP of 6, according to the performance data of an existing heat pump on the market with a heat source at 40 °C and DHW temperature at 10–53.5 °C [37].

The energy delivered from the heat pump (P_{HP}) to the circulation loop is expressed as:

$$P_{HP} = \dot{m}_2 C_{water} (T_2 - T_3) \frac{COP}{COP - 1} \quad (28)$$

The energy balance of the heat pump and the heat exchanger of the circulation loop, similar to the previous case and taking into account the assumption $T_2 = T_4$, is expressed according to Equation (29):

$$\frac{(T_2 - T_3) \frac{COP}{COP-1}}{T_{sup,DH} - T_2} = \frac{T_4 - 50}{54 - T_4} \leftrightarrow \frac{(T_4 - T_3) \frac{COP}{COP-1}}{T_{sup,DH} - T_4} = \frac{T_4 - 50}{54 - T_4} \quad (29)$$

Solving Equation (29) with respect to T_4 :

$$\left(1 - \frac{COP}{COP-1}\right) T_4^2 + \left(\frac{COP}{COP-1} \cdot 54 + \frac{COP}{COP-1} T_3 - T_{sup,DH} - 50\right) T_4 - \frac{COP}{COP-1} T_3 \cdot 54 + T_{sup,DH} \cdot 50 = 0 \quad (30)$$

Equation (30) is a polynomial equation of second grade. As a result, the solution(s) are ($T_4 > 0$):

$$T_4 = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (31)$$

where:

$$a = 1 - \frac{COP}{COP-1}, \quad b = \frac{COP}{COP-1} \cdot 54 + \frac{COP}{COP-1} T_3 - T_{sup,DH} - 50, \quad c = -\frac{COP}{COP-1} T_3 \cdot 54 + T_{sup,DH} \cdot 50 \quad (32)$$

The values for COP , $T_{sup,DH}$ and T_3 are considered parameters in this mathematical model. Besides T_4 , T_2 can also be calculated ($T_2 = T_4$). The total heat delivered to the circulation loop (P_{cir}) is expressed as:

$$P_{cir} = \dot{m}_2 C_{water} (T_{sup,DH} - T_2) + \dot{m}_2 C_{water} (T_2 - T_3) \frac{COP}{COP-1} \quad (33)$$

The ratio P_{cir}/P_{use} from Equations (9) and (26) can be expressed as:

$$\frac{P_{cir}}{P_{use}} = \frac{\dot{m}_2}{\dot{m}_1} \cdot \frac{T_{sup,DH} - T_2 + (T_2 - T_3) \frac{COP}{COP-1}}{T_{sup,DH} - 15} \quad (34)$$

As a result, the ratio \dot{m}_2/\dot{m}_1 can be expressed as a function of the ratio P_{cir}/P_{use} , $T_{sup,DH}$, T_3 , T_2 , and COP . The DH return temperature can be calculated from the mixing of the return flows, \dot{m}_1 and \dot{m}_2 , according to Equation (25). Similar to Equation (27), the ratio P_{el}/P_{use} can be expressed as:

$$\frac{P_{el}}{P_{use}} = \frac{P_{cir}}{P_{use}} \frac{1}{COP} \frac{T_4 - 50}{54 - 50} \quad (35)$$

2.5. Combining the DHW System with a Low-Temperature Space Heating System

The DH flow used for heating the DHW circulation loop with a separate heat exchanger, as presented in Section 2.3, can be cooled in a low-temperature space heating system, as shown in Figure 8. The principle of this additional solution is that the DH return flow at a high temperature that delivers heat to the circulation loop is redirected to the heat exchanger for space heating. Then, the overall DH return temperature is limited only by the return temperature from the space heating system. As a result, this solution is relevant for heating systems with a low-temperature operation of approximately 50 °C supply and 30 °C return temperature of the primary side of the heat exchanger. This requires a small adjustment in the DHW system but without additional operating costs.

This solution can also be used as an addition to the DHW configuration with a storage tank if a separate heat exchanger for heating the circulation loop is established, according to Figure 9. The storage tank will then be used only for preparing the DHW for use.

This solution is relevant for DHW systems with a low DH supply temperature and high circulation losses that result in a high return temperature from the circulation loop.

The ratio of the energy delivered to the circulation loop to the energy delivered to the space heating system (P_{cir}/P_{SH}) is equal to the cooling of the m_2 flow at the circulation loop to the cooling of the same flow at the space heating system, according to Equation (36):

$$\frac{P_{cir}}{P_{SH}} = \frac{T_{sup,DH} - 50}{50 - 35} \quad (36)$$

As a result, the potential for cooling the DH flow from the DHW circulation loop is defined by the ratio P_{cir}/P_{SH} as a function of the DH supply temperature. High DH supply temperature results in a smaller DH flow from the DHW circulation loop, which can be cooled in the space heating system even for a relatively small heat demand.

Combining the DHW system with a low-temperature space heating system may also be added to the configurations with a micro-booster heat pump. Here, it will reduce the district heating flow and make it possible to combine it with a space heating system throughout the whole heating season. However, this gives only a marginal extra period, and it was therefore not investigated further.

3. Results

3.1. DHW System with Storage Tank with Internal Heat Exchanger

Figure 10 presents the critical values of the ratio P_{cir}/P_{use} for each $T_{sup,DH}$ that results in a $T_{ret,DH}$ of 15 °C and a T_1 of 51 °C, according to Equation (8). Figure 11 presents all the possible combinations of DH supply and return temperature regarding the operation of the two heat exchangers that represent the operation of the DHW tank for different ratios of P_{cir}/P_{use} .

Critical ratio of P_{cir}/P_{use} for the DHW system with storage tank

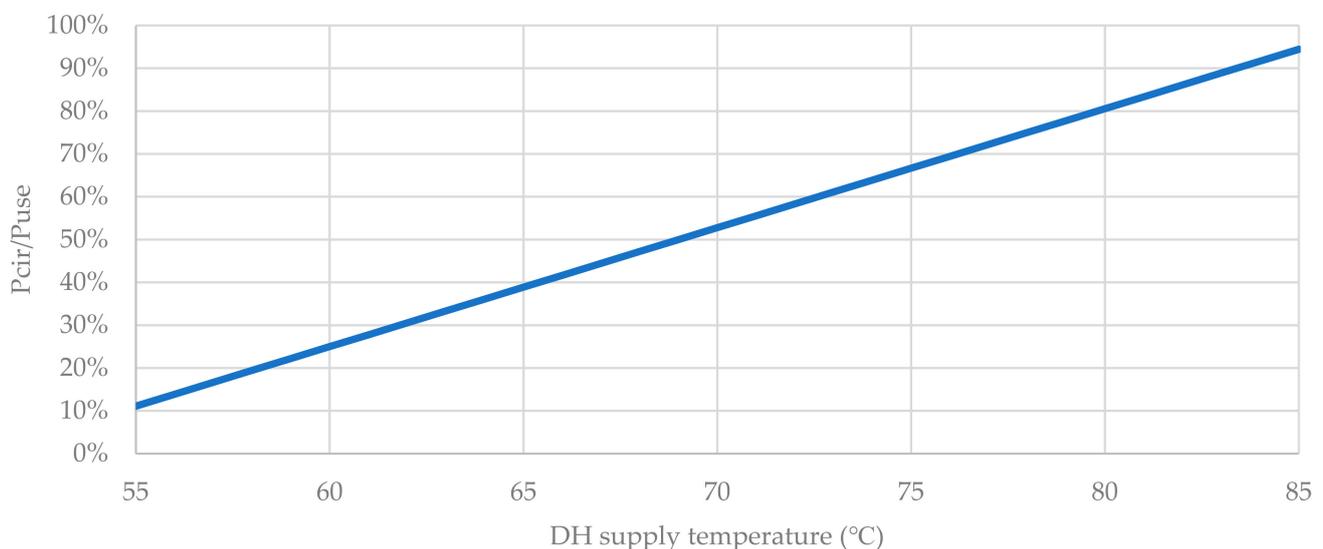


Figure 10. The critical values of the ratio P_{cir}/P_{use} for each $T_{sup,DH}$ that results in a $T_{ret,DH}$ of 15 °C and a T_1 of 51 °C, according to Equation (8).

According to Figure 11, the influence of the circulation heat loss on the actual use of hot water affects the potential combinations of DH supply and return temperature. The general trend implies that, for a higher DH supply temperature, a low DH return temperature can be achieved. However, to achieve both a low DH supply and return temperature, the heat loss in the circulation loop should be minimized.

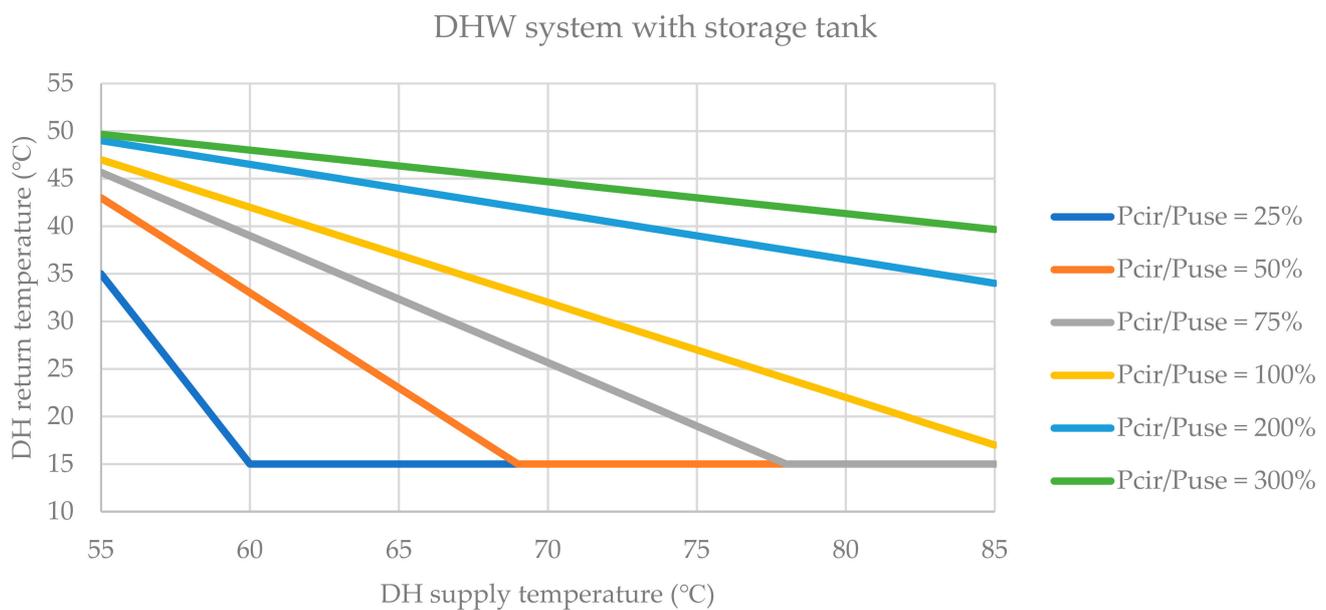


Figure 11. Combinations of operating temperatures for the DHW system with a storage tank for different ratios of circulation heat loss in the actual use of hot water.

Test Results of DHW Tank with a Heating Power Limitation Functionality and a Safety Function for Peak Loads

In Figure 12, the demonstration of the heating power limitation functionality, without the additional safety functionality under the EnergyLab Nordhavn project [34] during 31 December 2018, showed that during days with high demand, such as New Year's Eve, the temperature of the tank drops below the acceptable temperature for comfort. The limited charging power of the tank, defined by the heating power limitation functionality and the high heat demand during the afternoon, resulted in a significant temperature drop in the tank. This temperature drop was below the acceptable temperature of 45 °C for comfort, reaching even 30 °C at 16:00. This temperature drop was noticeable by the person responsible for the operation of the DHW system. To avoid complaints from the end users, he manually deactivated the heating power limitation function to allow the tank to be charged with a higher power than 30 kW and increase the temperature of the tank to acceptable levels within a short period. This resulted in an increase in the heating power above 70 kW. On the specific day of the year, the increase in the peak power to such a level is not beneficial for the overall district heating system. As a result, there is a necessity for implementing a novel safety functionality that would allow the heating power of the tank to increase when the temperature drop of the tank is reduced due to the high heat demands.

The new safety functionality to prevent the problem presented in Figure 12 was developed and applied to the thermostatic ECL controller during 2020. In Figure 13, the demonstration of the heating power limitation functionality, including the new safety functionality during 31 December 2020, showed that the temperature of the tank during the period of high heat demand (13:00–19:00) did not drop below the critical level of 45 °C. The reason was that the safety functionality switched off the heating power limitation at 13:30 when the DHW temperature dropped to 45 °C. At 15:30, when the temperature of the tank reached 55 °C, the safety functionality switched on the heating power limitation functionality. Under the operation of the heating power limitation, the heating power was always below 25 kW by securing the return temperature below 30 °C.

DHW tank operation at 31st of December 2018

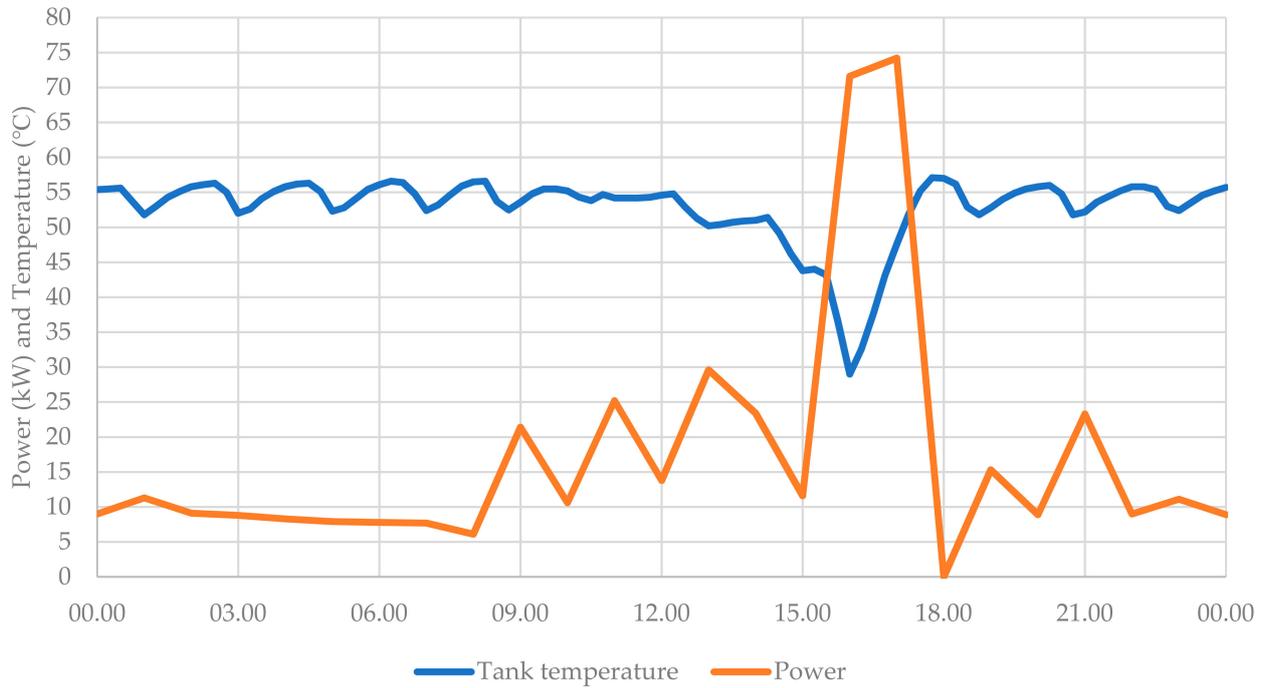


Figure 12. The operation of the DHW tank with a capacity limitation functionality without a safety mechanism on New Year’s Eve of 2018, under the Nordhavn Project.

DHW tank operation at 31st of December 2020

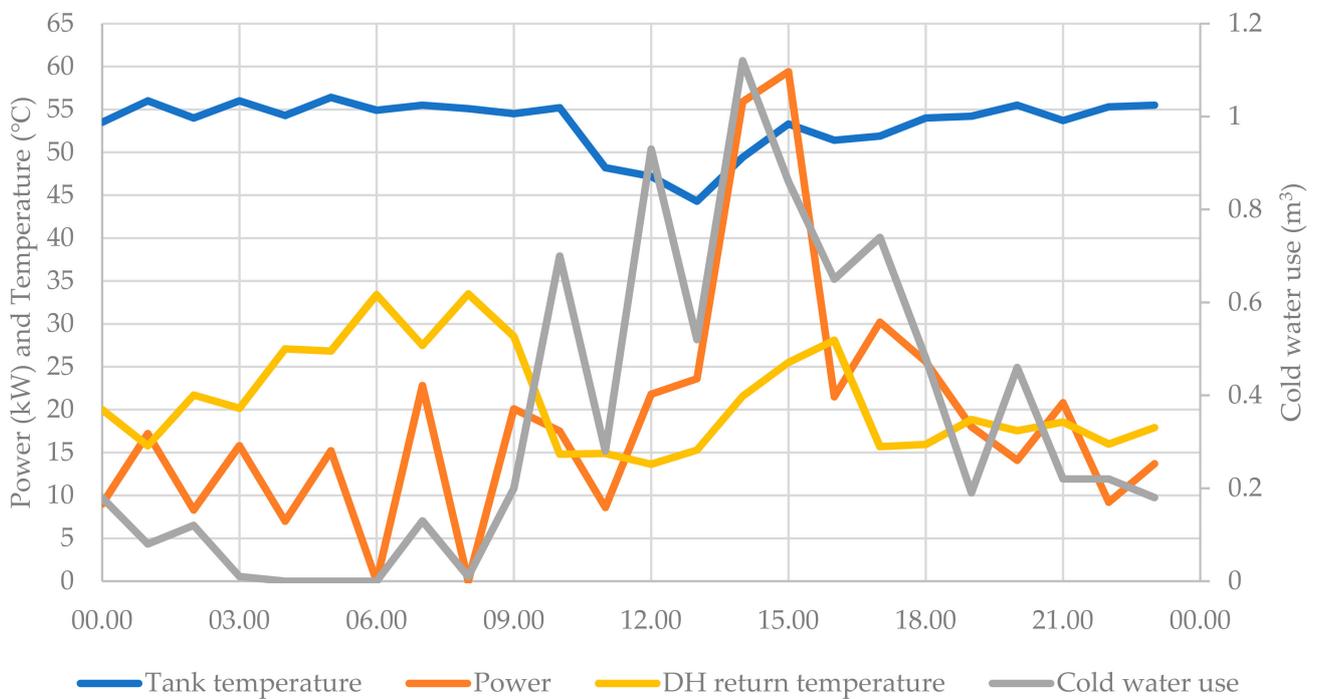


Figure 13. The operation of the DHW tank with a capacity limitation functionality and a safety mechanism on New Year’s Eve of 2020, under the Nordhavn Project.

3.2. DHW System with Individual Heat Exchangers

Figure 14 presents the possible combinations of DH supply and return temperature for the DHW configuration with separate heat exchangers for hot-water production and for the circulation loop for different ratios of P_{cir}/P_{use} . In this configuration, lower return temperatures can be achieved for higher DH supply temperatures. The minimizing of the circulation loss is important to achieve the lowest return temperature possible. By reducing the DH supply temperature, the DH return temperature is increased to achieve only a 5 °C cooling of the primary flow of the system.

DHW system with individual heat exchangers

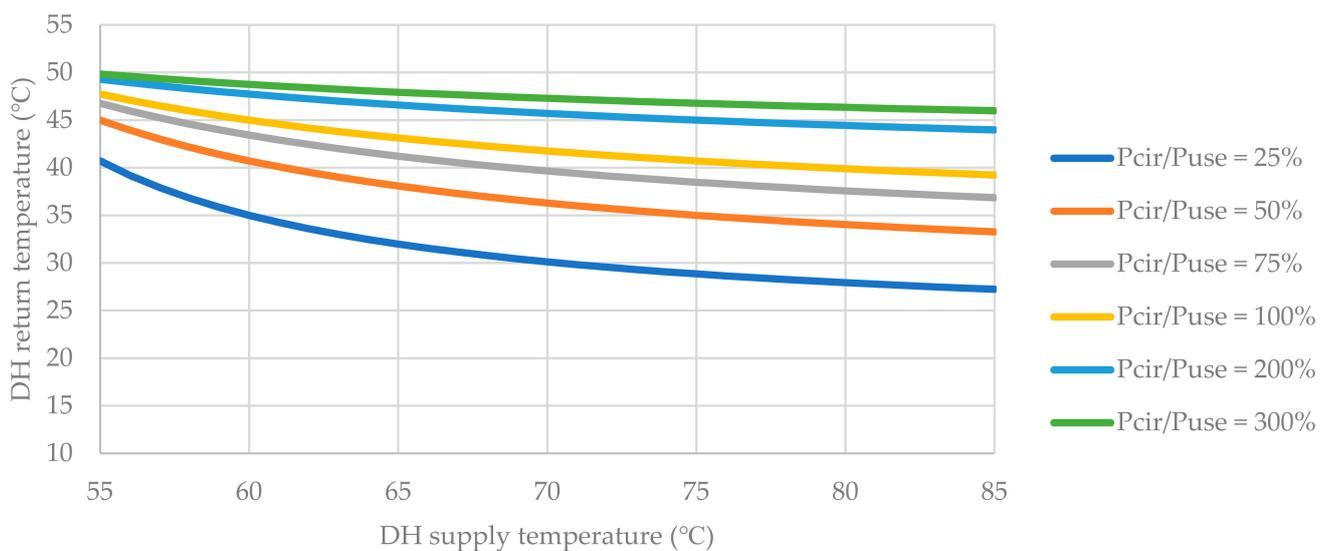


Figure 14. Potential for achieving low-temperature operation in a DHW system with separate heat exchangers for hot-water production and the circulation loop.

3.3. DHW System with Micro-Booster Heat Pump

For the DHW configurations with micro-booster heat pumps, to maintain the temperature of the circulation loop, either alone or in combination with heat exchangers, the return temperature from the circulation loop can be set to control the flow to the heat pump. Then, the DH return temperature from the DHW system depends on the ratio between the energy delivered to the circulation loop and the energy used for the hot-water production.

Figure 15 presents the possible combinations of DH supply and return temperature for the DHW configuration with only a micro-booster heat pump to deliver the required heat to the circulation loop for different ratios of P_{cir}/P_{use} .

Figures 16 and 17 present the possible combinations of DH supply and return temperature for the DHW configuration with a micro-booster heat pump along with a secondary heat exchanger to deliver the required heat to the circulation loop for different ratios of P_{cir}/P_{use} . Figure 16 refers to the configuration where the circulation flow is heated first by the heat exchanger, while Figure 17 refers to the configuration where the circulation flow is heated first by the heat pump.

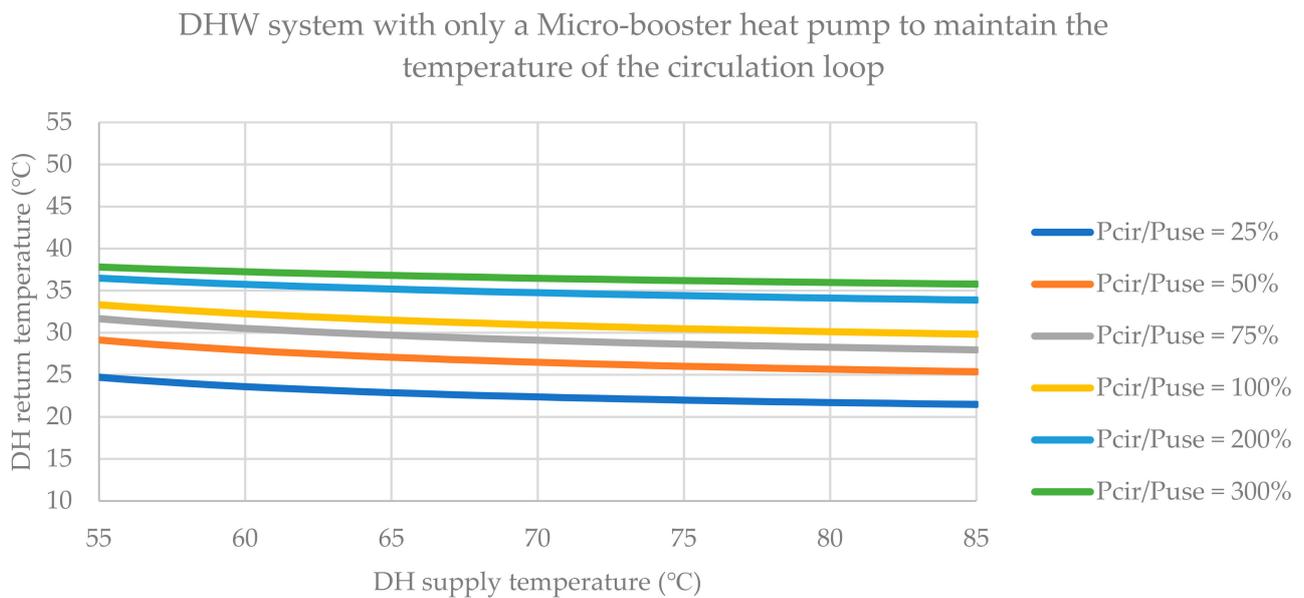


Figure 15. Potential for achieving low-temperature operation in a DHW system with only a micro-booster heat pump to deliver the required heat to the circulation loop.

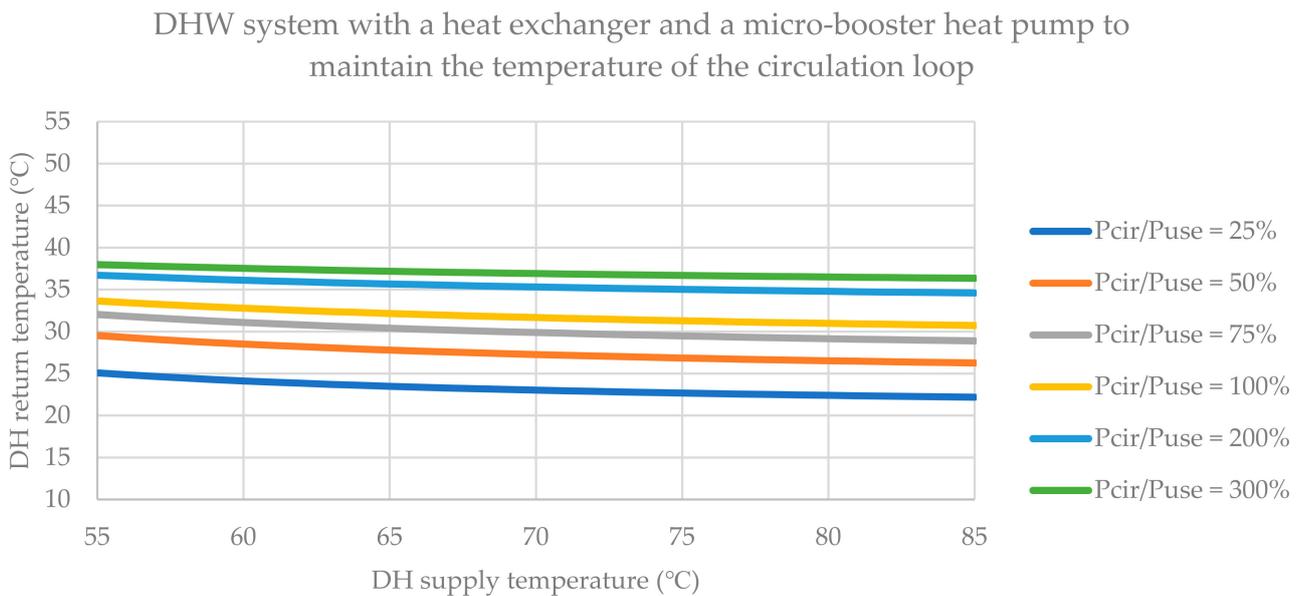


Figure 16. Potential for achieving low-temperature operation in a DHW system with a heat exchanger and a micro-booster heat pump to deliver the required heat to the circulation loop. The circulation flow is heated first by a heat exchanger.

The use of a micro-booster heat pump to supply the required energy to the circulation loop results in a low DH return temperature below 40 °C, even with high circulation losses. When the circulation losses are minimized, the DH return temperature from the DHW system can be below 25 °C for a DH supply temperature close to 55–60 °C. All the different variations of using the micro-booster heat pump result in similar return temperatures. As a result, the use of a micro-booster heat pump to deliver the required energy to the DHW circulation loop has the potential to secure the low-temperature operation of the DHW system.

DHW system with a micro-booster heat pump and a heat exchanger to maintain the temperature of the circulation loop

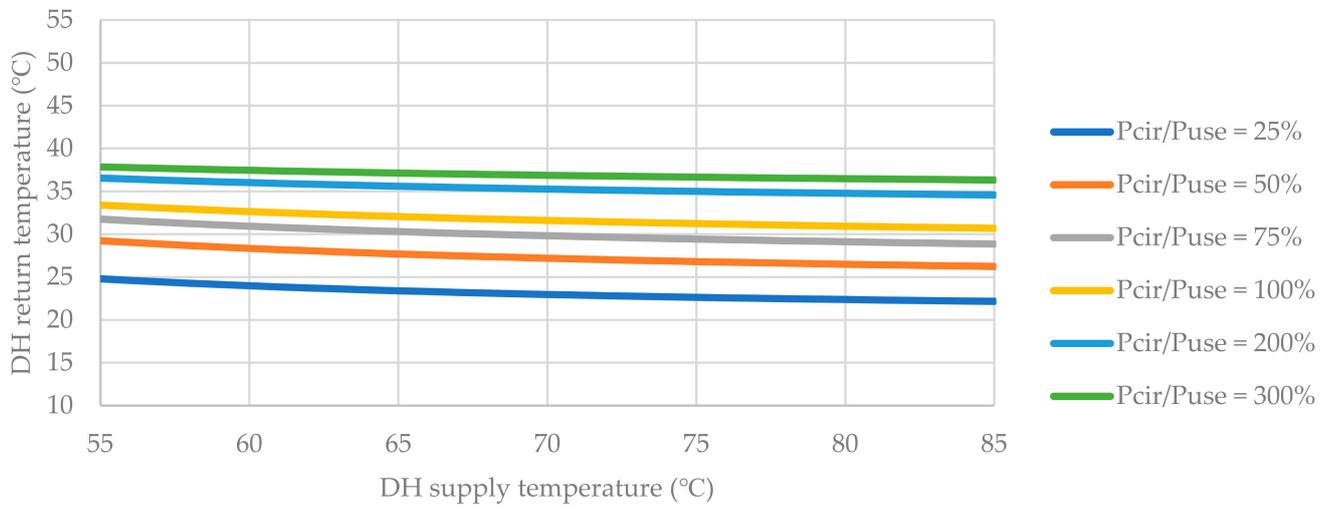


Figure 17. Potential for achieving low-temperature operation in a DHW system with a micro-booster heat pump and a heat exchanger to deliver the required heat to the circulation loop. The circulation flow was heated first by the micro-booster heat pump.

In Figure 18, the ratio of electrical power delivered to the heat pump to the total heat delivered to the circulation loop (P_{el}/P_{cir}) is presented for different supply temperatures and for $P_{cir}/P_{use} = 100\%$. For different ratios of P_{cir}/P_{use} , the comparison between the three different configurations results in curves with the same trend between them. According to Figure 18, the configuration with the heat exchanger before the micro-booster heat pump results in the smallest ratio of P_{el}/P_{cir} for a lower DH supply temperature.

P_{el}/P_{use} for each of the three different variations with heat pump in the circulation loop

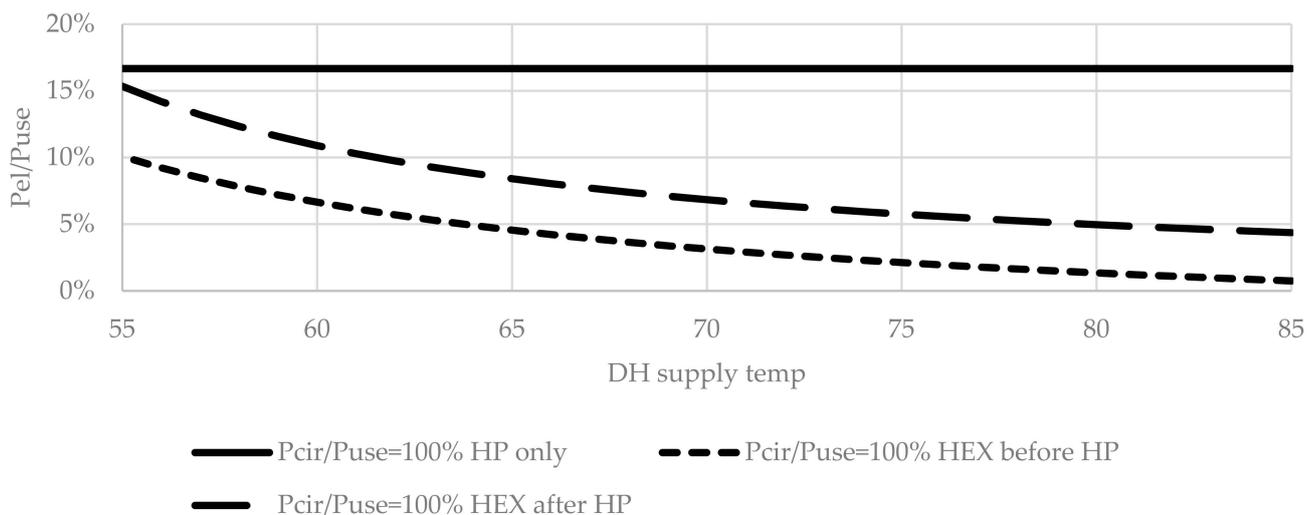


Figure 18. The ratio of electrical power delivered to the heat pump to the total heat delivered to the circulation loop (P_{el}/P_{cir}) for $P_{cir}/P_{use} = 100\%$ for all three configurations with a heat pump.

3.4. Combining the DHW System with Low-Temperature Space Heating System

Figure 19 presents the potential for cooling the DH return flow from the heat exchanger of the circulation loop to the space heating system, defined by the ratio P_{cir}/P_{SH} for each DH supply temperature, as calculated by Equation (36). According to the results for DH temperatures below 65 °C, the ratio is below one. This means that the flow from the circulation loop to the space heating system is large. In order to cool this flow through the space heating system, the space heating demand should be bigger than the circulation loss. On the other hand, for higher DH supply temperatures, the DH flow from the circulation loop to the space heating system is small, which results in a requirement for a small space heating demand in order to cool this flow.

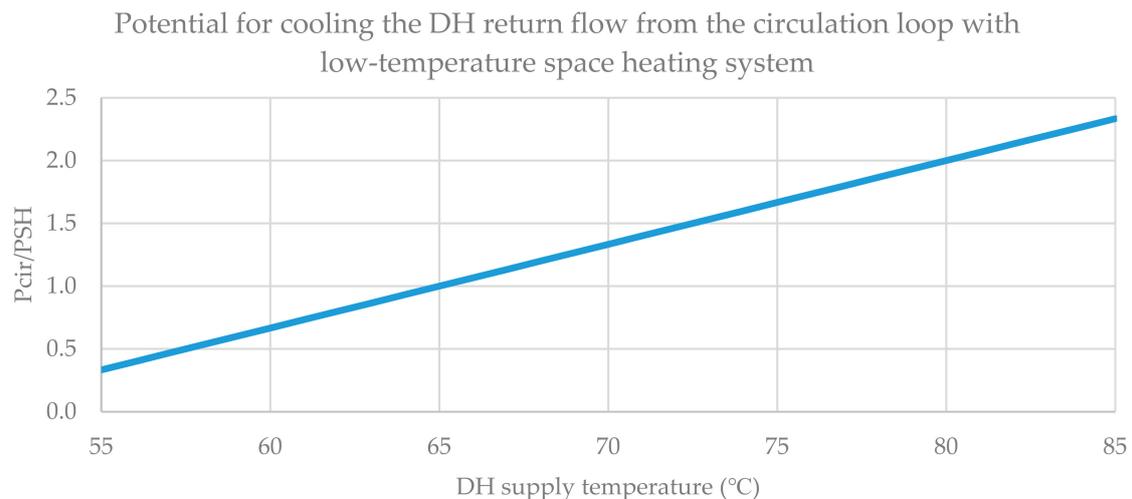


Figure 19. The ratio of P_{cir}/P_{SH} for different DH supply temperatures for cooling the return flow from the circulation loop to the low-temperature space heating system.

For example, for a typical DHW circulation loss of 3 kW, the minimum space heating demand required in order to cool the redirected flow from the DHW circulation loop is in accordance with Figure 20.

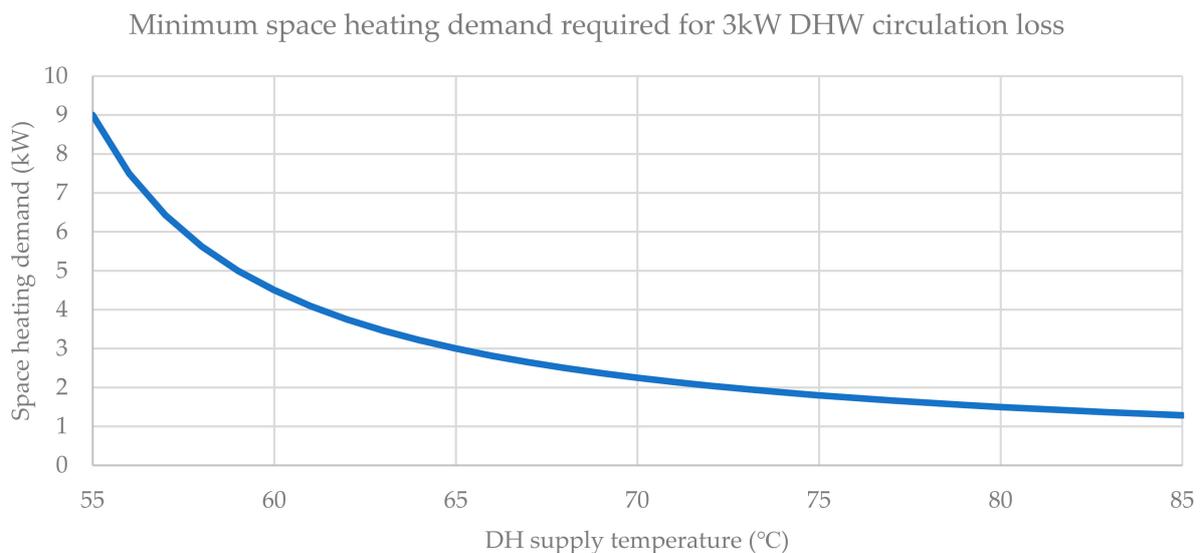


Figure 20. The minimum space heating demand required in order to cool the flow from the DHW circulation loop for a typical circulation loss of 3 kW.

4. Discussion

From Figures 11 and 14–17, the influence of the circulation loss on the DH return temperature from the DHW system can be identified. As a result, minimizing the circulation loss is a key requirement in order to achieve the minimum DH return temperature regardless of the DHW configuration used, especially for low DH supply temperatures.

According to Figures 12 and 13, the test of the heating power limitation functionality with the safety functionality in a typical DHW system with a storage tank, designed according to Danish standards and guidelines, was successful. The results show that a district heating return temperature below 30 °C can be achieved all year with a minimum heating power of the tank. Moreover, the thermal comfort of the DHW system can be secured even in periods of high heat demand. The test of this solution to a typical DHW system with a storage tank shows that this solution may be widely used in any typical DHW system with a storage tank and similar characteristics, such as a high district heating supply temperature and moderate circulation heat loss. This solution can be implemented in the DHW system by adjusting the typical ECL controller of the system.

According to Figure 14, the use of a heat exchanger to compensate for circulation loss results in a high return temperature. The addition of a micro-booster heat pump after the heat exchanger, as illustrated in Figure 6, can reduce the DH return temperature even for low DH supply temperatures, according to Figure 16. However, additional electrical energy is required for the operation of the heat pump. According to the results presented in Figure 18, when the circulation flow is heated first by the heat exchanger and then by the heat pump, this results in the minimum electrical energy required compared to the other variations for the position of the pump. The use of the heat pump in addition to the heat exchanger was not investigated from the economic perspective in this article to identify the feasibility of this configuration within the overall DH system. However, the reduction in the return temperature achieved with the use of a heat pump could be a strong incentive to implement it in actual systems under a low DH supply temperature.

According to Figure 20, the minimum required space heating demand to cool the redirected flow from a typical DHW system with a 3 kW circulation loss to the space heating system is 9 kW for a DH supply temperature of 55 °C. This is a small space heating demand for a multi-family apartment building that typically has a much greater heat demand during the heating season. As a result, the flow from the DHW system to the space heating system can be cooled according to the return temperature of the space heating system for the whole period of the heating season. For higher space heating demands than 9 kW, the temperature and energy content of the redirected DHW flow to the heat exchanger of the space heating system are not sufficient to meet the demand. In that case, the additional DH flow should be mixed with the redirected flow to secure the temperature and energy requirements, according to Figure 8. The cooling of the redirected flow and the additional DH flow would be as low as the return temperature from the space heating system. To make sure that this solution can work sufficiently throughout the whole year, a control valve has to be placed on the supply pipe that connects the heat exchanger of the space heating system with the DH network before the mixing point with the redirected flow from the circulation loop. As a result, the redirected flow will always be able to run through the heat exchanger of the space heating system, and, in case additional flow is required, the control valve will be adjusted accordingly. This makes it very simple to make use of the redirected flow from the DHW system without any additional control system.

Finally, all the assumptions described in Section 2.1 were made to be able to simplify the calculations and in order to compare the different configurations with the same base. Of course, some of the assumptions taken into account may not apply in several actual DHW systems. In this case, of course, the return temperatures that can be achieved in real tests may not be as low as the ones presented in the results. However, the potential of the solutions presented to achieve the low-temperature operation of the DHW systems, compared to the current operation, cannot be overlooked.

5. Conclusions

This article shows an overview of different concepts for reducing the return temperature from DHW systems with a circulation loop. The main result is the recommendation of three solutions depending on combinations of the following three criteria: district heating supply temperature, relative circulation heat loss due to the use of hot water, and the existence of a low-temperature space heating system.

For typical DHW systems with a storage tank, high DH supply temperature, and moderate circulation heat losses, the solution based on heating power limitation with a safety functionality may secure the required DHW temperature at all times, resulting in the limited heating power of the tank, extended reheating periods, and a DH return temperature of below 30 °C. This solution has no extra cost, and only a small adjustment in the control system of the tank is required.

For DHW systems with relatively high circulation heat losses and relatively low DH supply temperatures, it is not possible to achieve a low DH return temperature from the DHW system. However, if the building has a low-temperature space heating system, the solution based on redirecting the return flow from the DHW system to the space heating system can cool the flow to the level of the space heating return temperature. The return flow from the DHW system can be cooled by the space heating system during most of the heating season. This solution requires a small cost related to the additional pipe sections.

For DHW systems in buildings without low-temperature space heating systems and with low DH supply temperatures (down to 55 °C) or relatively high circulation losses, the solution based on the use of a micro-booster heat pump in addition to a heat exchanger for compensating the circulation loss can result in an optimal low return temperature. The competitiveness of this solution needs to be investigated from the economic perspective due to the additional electrical energy required for the operation of the micro-booster heat pump.

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