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Energy, economy and exergy evaluations of the solutions for supplying domestic hot water from low-temperature district heating in Denmark

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Abstract

District heating in Denmark is going through the transition from 3rd generation (80/40 °C) to 4th generation (50-55 °C /25 °C) systems in preparation for district heating based completely on renewable fuels by 2035. However, concern about Legionella growth and reduced comfort with low-temperature domestic hot water supply may be discouraging the implementation of low-temperature district heating . Aimed at providing possible solutions, this study modelled various proposals for district heating systems with supply temperatures of 65 °C, 50 °C and 35 °C and for two different building topologies. Evaluation models were built to investigate the energy, economy and exergy performances of the proposed domestic hot water systems in various configurations. The configurations of the devised domestic hot water substations were optimized to fit well with both low and ultra-low-temperature district heating and to reduce the return temperature to district heating. The benefits of lower return temperatures were also analysed compared with the current district heating situation.

The evaluation results show that the decentralized substation system with instantaneous heat exchanger unit performed better under the 65 °C and 50 °C district heating scenarios, while the individual micro tank solution consumed less energy and cost less in the 35 °C district heating scenario.

Keywords

Low-temperature district heating, domestic hot water, Legionella, comfort, evaluation model, low return temperature

Highlights

- Provided domestic hot water configurations for low-temperature district heating.
- Various building typologies and district heating supply temperatures were included.
- Different scenarios were evaluated from the energy, economy and exergy aspects.
- The benefits of lower return temperature to district heating were investigated.

1. Introduction

District heating (DH) is of great importance for the sustainable energy system of the future. In the district heating system, the heat is generated at the heat plant and delivered to the substation by transmission network. In Denmark, most district heating substations are designed and dimensioned to the served buildings. But area substation and flat substation also exist for specific needs. Ultimately, the heat is supplied to the consumer by the distribution network. The schematic of the common conventional district heating system is shown in Fig. 1

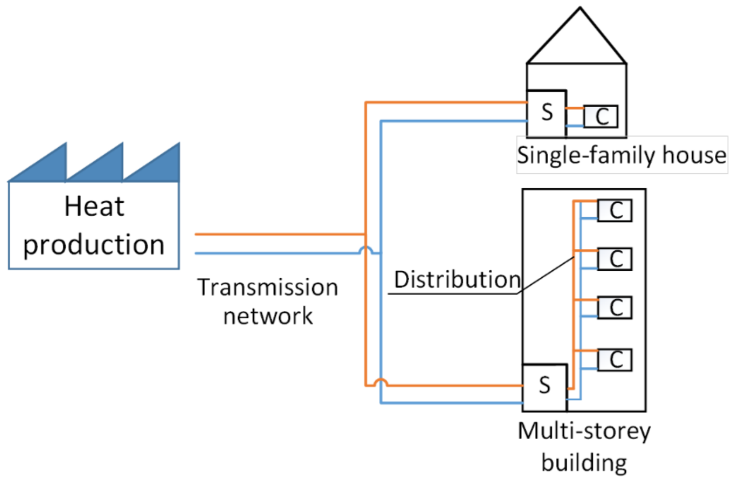


Fig. 1 Schematic of conventional district heating system

***S represents for substation, C represents for consumer**

In most European countries including Denmark, the heat supply convers the demand of both space heating and domestic hot water (DHW). To make the utmost use of industrial excess heat and renewable energy sources, as well as to improve the efficiency of the DH system, Danish district heating is undergoing the transition from the current 3rd generation district heating (80/40 °C) to 4th generation district heating (55/25 °C) without violating any comfort or hygiene requirements[1]. Moreover, the savings from a more efficient heating system can results in more significant benefits in the entire energy system by synergy effect with the electricity system, gas system and etc.[2]. For heat supply to energy-efficient buildings in low heat density areas, it will be even possible to apply the ultra-low-temperature district heating (ULTDH) with supply temperature at 35-45 °C to make the utmost use of the low-temperature excessive heat, and improve the efficiency of the heat pump as heat production.

The demand for domestic hot water (DHW), an important part of the total heat demand, will play a yet bigger role in the energy-efficient buildings of the future. Over the past 20 years, personal consumption of DHW has increased almost 50% [3], and, to prevent Legionella, the DH supply for DHW preparation is always operated at high temperatures. This leads to even larger energy consumption for DHW supply and more heat loss during transmission and distribution. Therefore, to improve the efficiency of the DH system, suitable solutions of supplying domestic hot water from low-temperature district heating are in need.

1.1 Comfort and hygiene requirements for domestic hot water supply

With careful design and operation, space heating can work properly at low DH supply temperature without supplementary heating. DHW production from LTDH, however, requires more attention, because of the hygiene and comfort requirements which can differ in different situations. According to the building regulations in Denmark, the temperature requirements for DHW comfort and hygiene vary depending on the size of the heating system. For systems with large DHW volumes, a high temperature regime is required to inhibit Legionella, while the temperature requirements for systems with no DHW storage or circulation are less strict. The specific comfort and hygiene requirements for DHW temperatures are summarized in the Table 1, in which both Danish and EU standards are taken into account [4].

Table 1 Temperatures required for hygiene and comfort in different building typologies

	Systems with no circulation or storage tank	**System with large DHW volume**

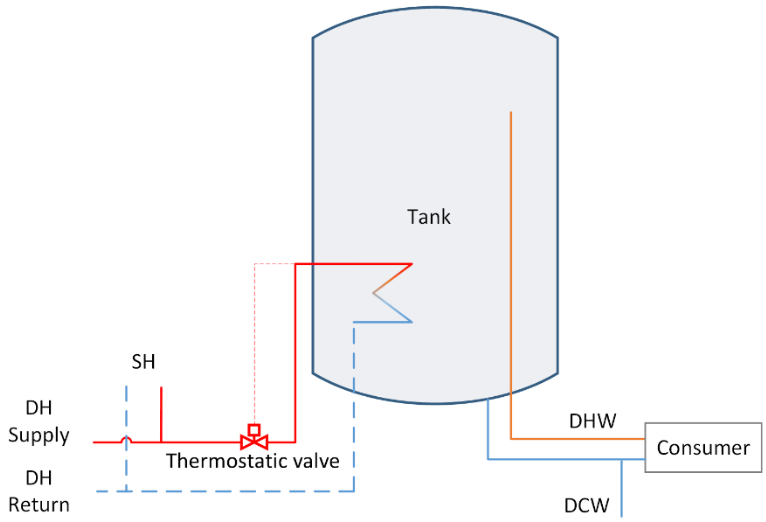
Requirements for Legionella prevention	-	Storage tank 60 °C, Circulation pipes > 50 °C
Requirements for comfort	45 °C for kitchen use, 40 °C for other uses, Waiting time < 10 s	45 °C for kitchen use, 40 °C for other uses Waiting time < 10 s

1.2 Existing DHW system configuration with medium-temperature district heating

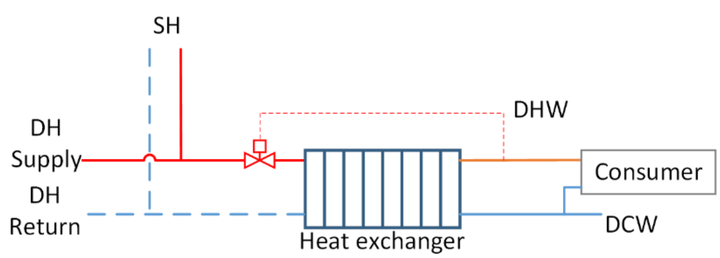
The conventional DHW system for medium-temperature district heating (MTDH) can be different in single-family houses and multi-storey buildings. Both building topologies can have small or large DHW volume depending on their substation configurations.

1.2.1 Conventional DHW configurations in single-family houses

Usually, DHW circulation is unnecessary for the single-family house to guarantee the acceptable (10s) waiting time, since the distribution pipe length from the substation to the tap is short. Currently, a storage tank or an instantaneous heat exchanger unit (IHEU) are most commonly used for DHW production in single-family house. The schematics of the DHW system configurations are shown in Fig. 2.



(a) DHW substation with a storage tank



(b) DHW substation with an instantaneous heat exchanger (IHEU)

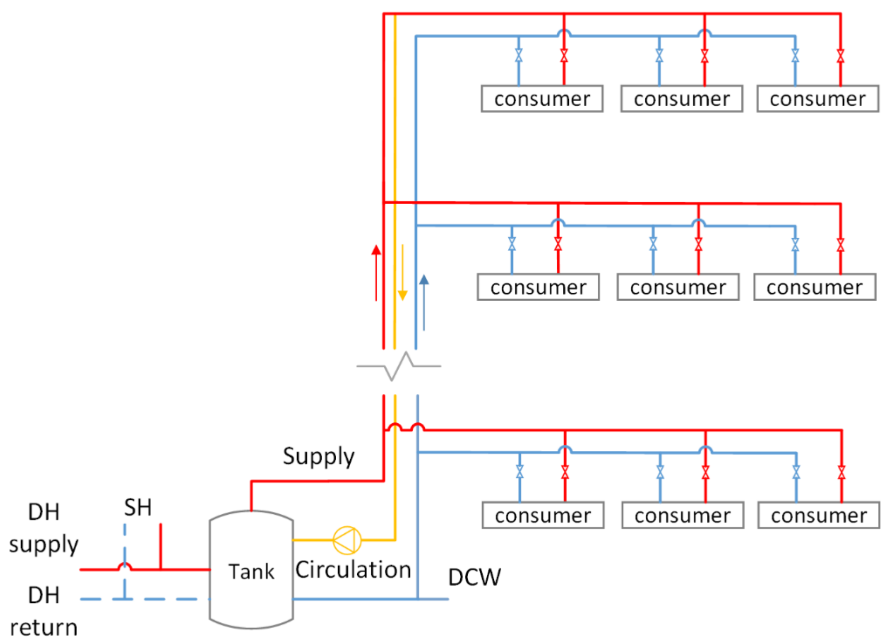
Fig. 2 Existing DHW configurations for single-family house

***SH represents for space heating**

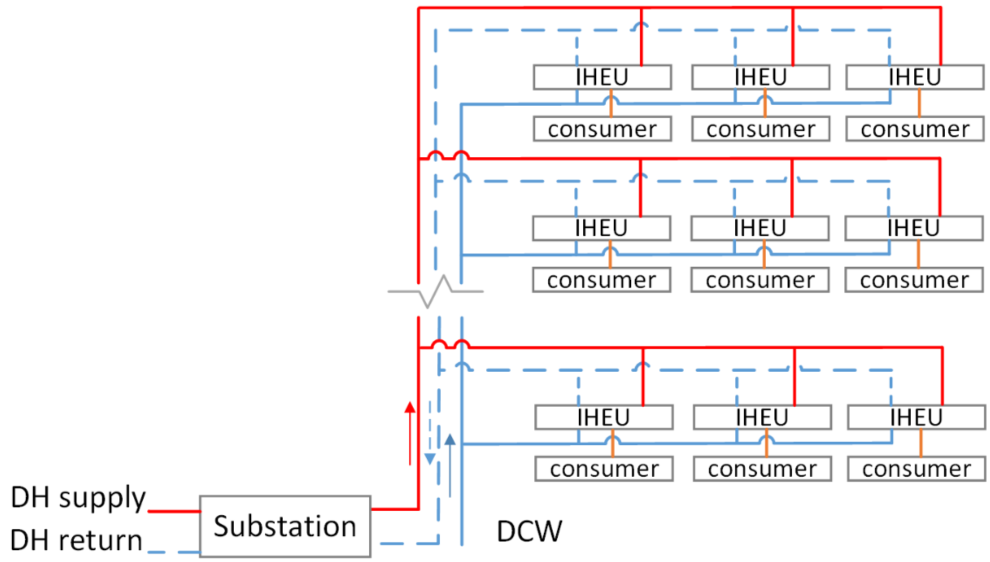
If the DHW is stored in a tank, the tank has to be maintained at no less than 60 °C to avoid the risk of Legionella. Where an IHEU is used, bypass flow is required to ensure the 10s waiting time for comfort reasons. These two existing methods can work properly with medium-temperature district heating without supplementary heating.

1.2.2 Conventional DHW configurations in multi-storey building

For multi-storey building, depending on whether the DHW is prepared in the central substation or locally, the configurations can be divided into mainly two types. The schematics are shown in Fig. 3.



(a) Centralized system with a storage tanks and circulation circuit



(b) Decentralized system with local heat exchanger (IHEU)

Fig. 3 Existing DHW configurations for multi-storey building

To take account of the overall DHW peak load and the comfort requirement, the DHW shown in Fig. 3 (a) requires a storage tank to shave the peak load and circulation pipes to ensure the 10s waiting time. The cold and hot water are mixed at the faucet to reach the desired temperature by the consumer. This study did not include systems only with a main heat exchanger and circulation in the analysis for multi-storey buildings because they are uncommon in Denmark. According to the standard for Legionella prevention [4], a centralized system with DHW circulation requires the tank to be maintained at 60 °C and the DHW circulation to be at least 50 °C. Consequently, the heat loss from such systems can be substantial. In Denmark, it has been found that the circulation system can waste up to 70% of the total energy delivered for DHW use [3]. Moreover, the high temperature regime for the circulation obstructs the implementation of LTDH/UTLDH. In comparison, DHW can be prepared locally by the individual heat exchanger as shown in Fig. 3. It is feasible to apply such a system with LTDH, but to ensure the 10s waiting time for comfort, bypass flow is always needed, which increases the return temperature to district heating.

1.3 DHW preparing technologies

There are some investigations of different technologies for DHW preparation. . Cholewa and et al. [5] test the performances of three different heating systems for multi-storey buildings: a system with centralized condensing gas boiler, a system with flat-based heat exchanger supplied by district heating, and a system with flat-based gas boiler. The results show that both the decentralized systems have higher annual efficiency than the centralised system. Thorsen [6] simulates the performance of flat-based heating unit system combined with district heating based on a Danish case. The energy saving of the flat-based heating unit system ranges from 2-4 kWh/m^2 annually compared with the conventional DHW circulation system and the system can be operated with lower supply temperature without Legionella problem. Tol and Svendsen [7] simulate the district heating network with different system layouts and substation configurations. They find that the substation with a storage tank can help to reduce the heat loss at the end of the branch network. Fernández-Seara and et al. [8] make experiment investigations for the performances of DHW production system with a storage tank under 4 control strategies. The result shows that the tank has better performance if the thermal stratification can be maintained. Chaturvedi and et al. [9] model a solar-assisted heat pump system for DHW production, and indicate that the life cycle cost of the solar-assisted heat pump system is better than the electric only system if the water is heated no higher than 70 °C. Brum and et al [10] model and compare three different heating systems for supplying space heating and domestic hot water to a 3-dwelling system. The ground source heat pump consumes the least electricity for cover the equivalent DHW demand, while the individual electric heater consumes the most. Bohm [11] makes large-scale investigation towards the DHW preparation and distribution system in Denmark, and indicates that the electric heat tracing cable can be used for maintaining the DHW temperature at the tap, which is helpful to guarantee the comfort and hygiene DHW supply from LTDH. However, the energy saving effect of the electric heat tracing system can be offset by the high primary energy factor of the electricity. Yang and et al. [12] make simulation of the electric heat tracing system for DHW supply to multi-storey building by LTDH. The heat loss can be saved up by 70% compared with the conventional heating system if the tracing cable is controlled corresponding to the DHW load pattern. Ghoubali and et al. [13] make a simulation study of simultaneous heating and cooling supply by heat pump, and find that the optimal seasonal coefficient of performance of the heat pump is obtained if the DHW is produced at the temperature 40-45 °C. Elmegaard and et al. [14] investigate 3 heat pump systems as well as a direct electric heating system for supplying heat with conventional district heating. The results show that the heat pump system using R134a with a storage tank on the DH side has better performance. Boait and et al [15] investigate five individual DHW systems, and find the instantaneous DHW production is more efficient than storage type. In addition, the insulation and smart control methods are of great importance to improve the efficiency for DHW system with a storage tank or a heat pump. Lu and Wu[16] have compared 8 different systems for covering the domestic energy demand. For DHW preparation, a system integrated an air conditioning unit and a heat pump has better economy and environment performance, since the heat pump can extract indoor heat for DHW production and provide cooling effect. However, most of the studies analyse DHW preparation methods in isolation. The DHW preparation methods combined with district heating are insufficiently studied. Moreover, the performances of the approaches vary depending on the specific applying situations. Therefore, suitable solutions for DHW preparation should be designed for LTDH and ULTDH, and broader comparison among different solutions needs to be made, so that the optimal solutions for specific scenarios can be determined.

1.4 Aim and scope

The aim of this study was to investigate optimal methods of supplying DHW from LTDH/ULTDH while taking the comfort and hygiene requirements into account. To be specific, it includes:

- Devise potential DHW configurations and operation methods to different scenarios
- Evaluate the energy, economy and exergy performance of the devised solutions
- Suggest the optimal solutions of DHW supply within the LTDH or ULTDH scenario

In this study, various DHW supply methods were analysed in the context of different generations of DH supply: medium-temperature district heating (65 °C), LTDH (50 °C) and ULTDH (35 °C). Different scenarios for the analysis were formed by combining different DH systems with different building typologies. The performances of each devised solution were calculated by the theoretical model ideally. Moreover, as an important factor for the system savings, the lowered return temperatures to district heating in the different scenarios and the resulting cost savings were also investigated. The results of this study can be helpful when planning for LTDH or even ULTDH in the future.

2. Material and Methods

To fit the LTDH/ULTDH scenarios better, innovative DHW configuration were proposed for different building typologies. Moreover, the operation methods corresponding to each DHW supply system were carefully designed to meet the comfort and hygiene requirements. The potential solutions that comprise the DHW configuration and operation are illustrated in this section, sorted by the different DH systems to applied with. Calculation models were built to evaluate the energy, economy, and exergy performances of the proposed DHW systems. The bases are the energy and exergy balance equations. The theories are explained in Section 2.3.

2.1 Solutions for DHW supply with low-temperature district heating (LTDH)

Three types of solutions were proposed for LTDH:

1) A central heat exchanger combined with a heat pump, which could be a solution for DHW supply with LTDH in multi-storey buildings where substantial renovations are not feasible.
2) An IHEU system with better-insulated distribution pipes and using bypass flow for bathroom floor heating, which can be applied with LTDH for both single-family

houses and multi-storey buildings. This would be best in new buildings or in existing buildings where deep renovation for the space heating and DHW system is possible.

3) Electric heat tracing combined with dynamic control. This could be applied in multi-storey buildings where the DHW circulation pipes can be replaced and in buildings that have special requirements for DHW hygiene, such as hospitals or nursing homes.

2.1.1 Central heat exchanger combined with heat pump

The central heat exchanger is used to replace the heat storage tank, which generates huge heat losses. In a typical multi-storey building with 6 floors and 3 apartments on each floor, the simultaneity factor is only 0.1. Therefore, the impact of the increased peak load to the network due to the removal of the storage tank is insignificant for large buildings. A schematic of this solution is shown in the following diagram:

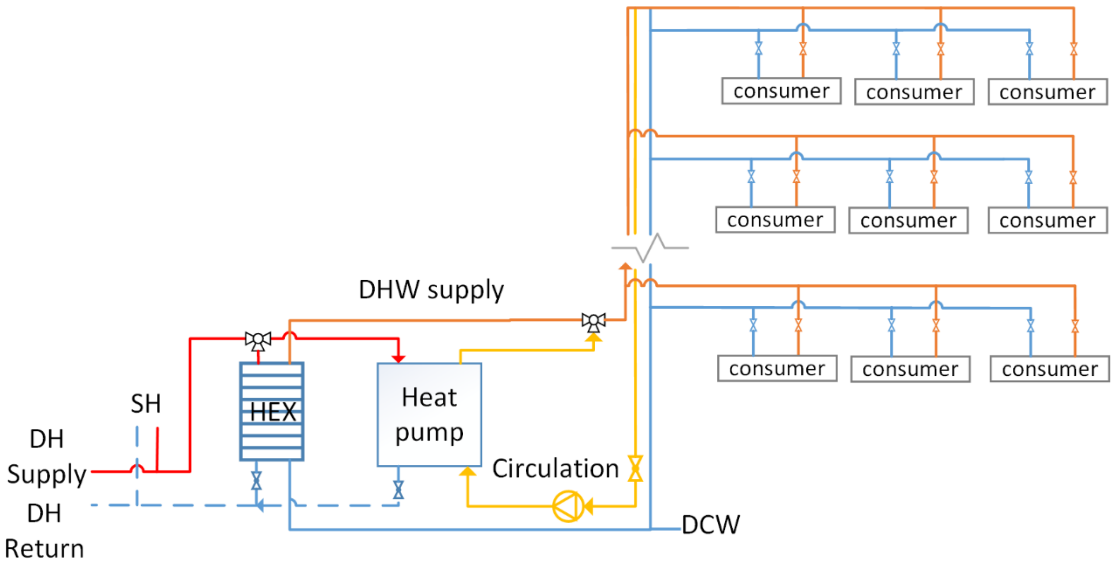


Fig. 4 Schematic of DHW preparation using a central heat exchanger combined with heat pump

When DHW is drawn off, the DH supply water will heat the DCW to no less than the comfort temperature. At other times, the heat pump is used to ensure a temperature of at least 50 °C for the DHW circulation and cover the generated heat loss. The heat source for the heat pump is the DH supply water. The return temperature at the outlet of the evaporator can be controlled by the thermostat. Since the circulation water only goes through the heat pump, the return temperature to district heating can be efficiently reduced without being influenced by the DHW circulation.

2.1.2 Improved decentralized system with instantaneous heat exchanger unit (IHEU)

The schematics are similar to those shown in Fig. 2 (b) and Fig. 3 (b), but the heat exchanger needs optimized design to improve the efficiency with low supply temperature, so that comfort temperature of DHW (45 °C) and low return temperature can be achieved. The DHW is prepared instantaneously through the IHEU, so the capacity of the unit needs to be sufficient to cover the peak load for DHW, which is 32.3 kW [17]. The conventional way of operating IHEUs requires a bypass to ensure the 10s waiting time. However, mixing the bypass flow with the DH return flow will increase the return temperature to district heating, which limits the efficiency of LTDH. One possible improvement might be to redirect the bypass flow to bathroom heating, so that the return temperature can be much reduced after heating the bathroom. According to the Danish building code, the air change rate in the bathroom is 15L/s [18]. To keep the tiled bathroom floor at a comfort temperature of 24-29 °C, 116 W space heating demand is required for each home for only heating the air flow through the bathroom from 20 °C to 26 °C. If the insulation of the supply pipe is adequate, the bathroom heating flow will be able to reach the end user with very limited temperature drop, and keep the supply pipe warm. As a result, the space heating demand may increase during the non-heating season, but cost savings will be available in the DH system due to the reduced return temperature to district heating. Moreover, the thermal comfort of the bathroom will be improved.

2.1.3 Electric heat tracing

Electric heat tracing uses electric tracing cable as supplementary heating for LTDH. The cable power is adjustable along with the difference between the set-point temperature and the temperature of the supply pipe, so that more precise temperature control can be achieved. The schematic of an electric heat tracing system is shown in the following diagram:

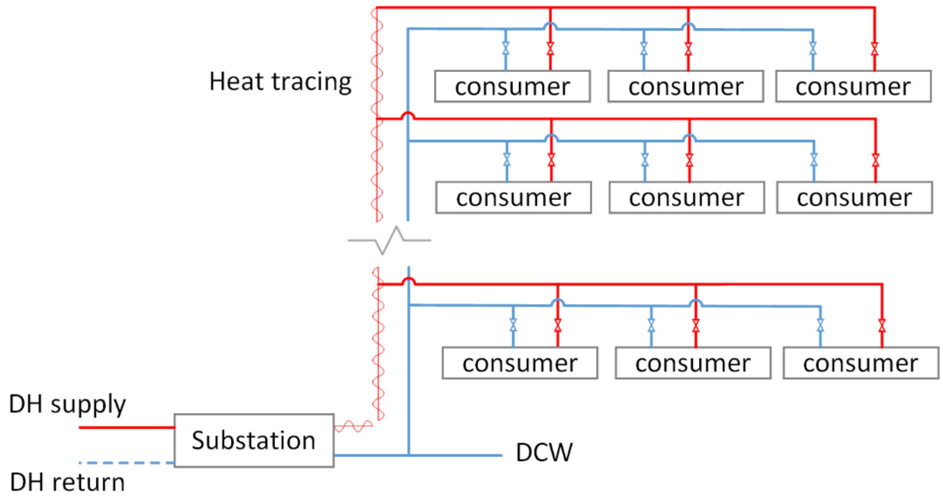


Fig. 5 Schematic of an electric heat tracing system

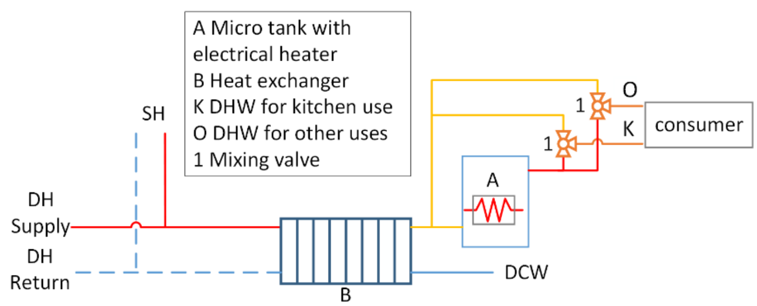
Since the supply line can be kept warm by the electric tracing cable, the storage tank and circulation pipe are unnecessary, saving much heat loss. Compared to the conventional system with DHW circulation, the electric heat tracing system can reduce the distribution heat loss by 50% [12]. The electricity consumption of the electric heat tracing system depends greatly on the control method. Smart control methods of the cable based on DH load profile plays a role in saving the power consumption.

2.2 Solutions for DHW supply with ultra-low-temperature district heating (ULTDH)

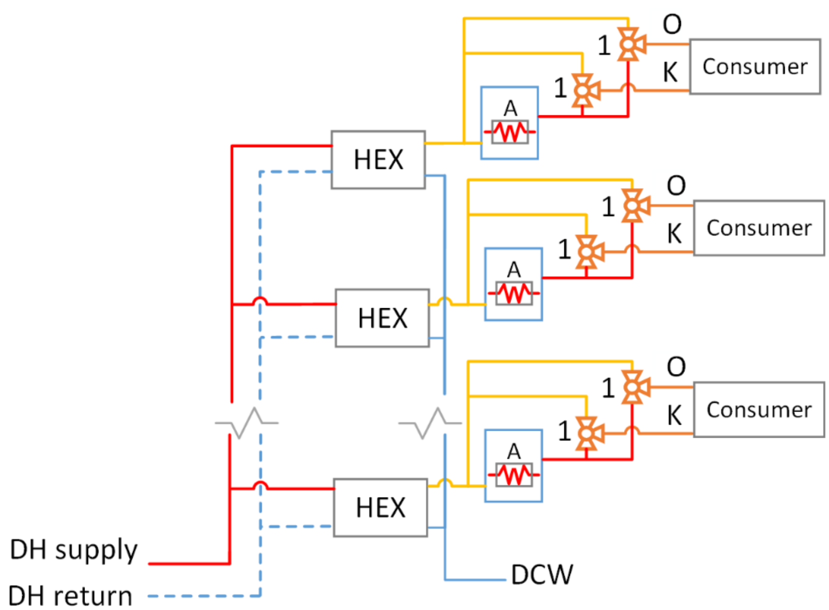
Since ULTDH is insufficient to heat DHW to the temperature required by the comfort or hygiene regulations, supplementary heating is needed. One solution is the IHEU combined with an electric micro tank, which can be easily installed in a new building or an existing building with IHEU. Another solution is the micro heat pump system, which is applicable for single-family houses.

2.2.1 Combination of IHEU and micro tank

The instantaneous electric heater can heat DHW to the required temperature instantaneously, but when the DH supply temperature is much lower than the comfort temperature (45 °C), the electricity peak load can be very high, which makes it difficult to install with the normal power supply. To address this problem, this study proposes the new concept of using a micro tank with immersion heater to shave the peak power load. A schematic of the micro tank solution is shown in the following diagram:



(a) Implementation for single-family house



(b) Implementation for multi-storey building

Fig. 6 Schematic of an electric micro tank system

The micro tank with an immersion electric heater is installed on the consumer side. The DHW is preheated by ULTDH through the heat exchanger. One stream of the preheated DHW is stored and further heated in the micro storage tank. To meet the requirement of Legionella prevention, the DHW in the tank is heated to 60 °C by the electric immersion heater. When DHW is drawn off, the DHW from the tank is mixed with the hot water preheated by the heat exchanger to achieve the comfort temperature. There are two thermostatic valves controlling the mixed temperature of DHW for kitchen use (45 °C) and for other uses (40 °C). Compared to the instantaneous electric heater, the micro tank solution can be designed to be compatible with the normal electricity supply. Moreover, since the micro tank can provide DHW immediately, no bypass is needed for the heat exchanger in this solution, so the average DH return temperature is also reduced. The micro tank system can be applied in both single-family houses and multi-storey buildings with instantaneous heat exchanger units.

2.2.2 Micro heat pump

A micro heat pump can be used as local booster for ULTDH with high thermodynamic efficiency. It can be applied in single-family houses. The schematic of a micro heat pump system is shown in Fig. 7.

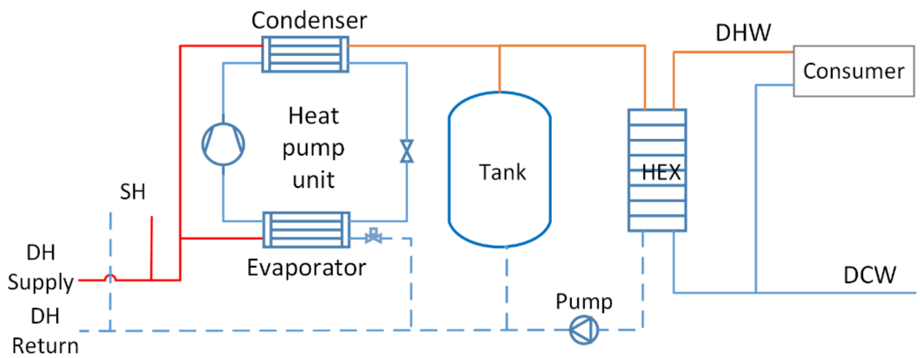


Fig. 7 Schematic of a micro heat pump system

The heat source of the heat pump is ULTDH supply water. The electricity is only used to lift the energy quality of the DH water. Compared to direct electric heating, therefore, the micro heat pump system consumes much less electricity than other supplementary heating devices to heat an equivalent amount of DHW. The storage tank helps to maintain stable operating conditions for the heat pump. Since the tank is installed on the primary side, the risk of Legionella is eliminated

2.3 Evaluation models for different scenarios

Three DH scenarios were defined as the background for the evaluation models: 1) medium-temperature district heating (MTDH) with a supply temperature of 65 °C, which ensures the comfort and hygiene of DHW supply without any supplementary heating. This scenario can be considered as the first step of the transition to 4th generation district heating. The conventional DHW system can be retained in this phase. 2) Low-temperature district heating (LTDH) with a supply temperature of 50 °C, which is sufficient to heat DHW to a comfortable temperature, but which will require certain solutions to prevent Legionella. 3) Ultra-low-temperature district heating (ULTDH) with a supply temperature of 35 °C, which is insufficient to meet either comfort or hygiene requirements.

Two building typologies were considered to build different scenarios: the single-family house and the multi-storey building. To formulate the reference DHW demand for the models, the single-family house in this study was assumed to have an overall floor area of 150 m^2, while the apartment in a multi-storey building was assumed to have an area of 90 m^2. The indoor DHW distribution systems of each building topology are assumed to be identical, therefore, they are excluded from the comparison for different scenarios. The multi-storey building was assumed to have six floors with three apartments on each floor, which is typical in Denmark. To make the analyses more comparable, the evaluation models were based on individual homes. This means that, for the multi-storey building, the evaluation results were specified for one apartment.

In accordance to the specific application conditions and operation methods, the performances of the DHW preparation method in each scenario are investigated by theoretical calculation models. The assumptions and basic equations for the energy, economy and exergy models are described separately.

2.3.1 Evaluation model for energy performance

The energy performance model evaluates the DH heat and electricity consumption for DHW preparation, also including heat loss from the equipment and distribution pipes inside the building. The relative DH heat and electricity consumption depend on the different DHW system configurations and corresponding operating temperatures. The operating temperature for each case was as described in previous sections.

The total energy consumption for DHW preparation, as one indicator of the energy performance of the DHW system investigated, can be calculated as:

$$Q_{tot} = Q_{dhw} + Q_{eq} + Q_p \qquad \text{(Eq.1)}$$

where

Q_{tot} is the total energy consumption [kWh],

Q_{dhw} is the DHW heat demand [kWh],

Q_{eq} is the heat loss from the equipment [kWh],

Q_p is the heat loss from the distribution pipe inside the building [kWh].

To make the cases of each building topologies comparable, all the DHW preparing methods were modelled to meet the same DHW demand, with a standardized volume ($250 L/m^2 \cdot yr$) of DHW [19, 20] produced at a comfortable temperature (45 °C), assuming that the required energy for DHW preparation can be much reduced due to the evolution of new technologies and efficient operation in the future. Considering the different operation modes, some systems may prepare DHW at a higher temperature due to the threat of Legionella, but the tap temperature can be adjusted to 45 °C ultimately by mixing with DCW.

The information of the storage tank was derived from standard products solutions. For the single-family house, the storage tank was 160 L with a heat loss rate of 60 W, while for the multi-storey building the tank was 1000L with a heat loss rate of 113 W. For the micro-tank system, the tank was assumed to be 60 L with a 2 kW immersion electric heater, so that combined with ULTDH, it would be able to cover the peak demand of one kitchen tapping and one shower happening at the same time (1.1 kWh) within a 20-minute interval [17]. The heat loss rate of the micro tank was calculated from the insulation standard [21] as 14W. The heat loss rate of the micro heat pump system was based on information from the manufacturer, and it consists of a heat loss rate of 60W for the tank and 40W for the compressor. With regard to the system with a central heat exchanger and heat pump, there was no auxiliary tank, so the equipment heat loss was assumed to be 40W for the compressor of the heat pump. The heat exchanger was assumed to be well insulated, so that the heat loss would be negligible compared to the energy needed for heating the DHW. For the multi-storey building, the equipment heat loss was assumed to be allotted to all the flats equally.

Heat loss from the distribution pipes inside the buildings was only taken into account for the multi-storey building. The distribution heat loss inside each apartment was not included in the model since it can be identical for all cases. For the systems with bypass or circulation, each flat was assumed to have 6 m of distribution pipe. For the electric heat tracing system, the distribution pipe only included 3 m supply pipe in the model. The pipe diameter of the riser was assumed to 40mm, while the diameter of the circulation pipe was assumed to 15mm. Advanced pipe insulation with polyurethane foam was selected for the model, the corresponding heat coefficients are 0.157 W/m·K and 0.094 W/m·K according to the existing product. The ambient temperature for calculating the heat loss was assumed to be 15 °C.

Typically, the DHW draw-off period only accounts for 1% of the day [22]. Therefore, the circulation or bypass was assumed to be operated continuously for the corresponding system, and the pipe temperature was approximated to circulation temperature or bypass temperature. For the micro tank solution that has no bypass operation, during the non-tapping period, the distribution pipe was assumed to be cooled down to the ambient temperature, and the pipe heat loss was negligible.

The heat loss from the pipe can be calculated as

$$Q_p = \sum L_i * q_i * (t_i - t_{amb}) * \tau \qquad \text{(Eq.2)}$$

where

L_i is the length of the supply/return/circulation pipe counted for one apartment [m],

q_i is the heat loss rate from the corresponding pipe [kW/m ·K],

t_i is the average temperature of the counted pipe [°C],

t_{amb} is the ambient temperature [°C],

τ is the time of the calculation period [h].

As an important performance parameter, the volume-based average return temperatures to district heating of the different scenarios were investigated. For the storage tank system with MTDH, the average return temperature to district heating was calculated based on the design return temperature in the product catalogue and the energy balance of the practical situation. For the IHEU system, the return temperature to district heating was calculated as the volume-averaged return temperature of the water-heating flow and the bypass flow for the MTDH scenario. The supply/return service pipe was assumed to be 5 m long, which connects the building to the DH transmission network. The set-point temperature of the bypass was assumed to be 45 °C to ensure the 10s waiting time required by the comfort standard [17, 20]. The flowrate of the bypass should be sufficient to provide 45 °C to the most remote consumer. For the LTDH scenario, the bypass of the IHEU was redirected to bathroom heating to reduce the return temperature to district heating. Thus, the volume-based average return temperature was calculated from the water-heating flow and the bathroom-heating flow. The return temperature of the bathroom-heating flow was assumed to be 25 °C with effective cooling. With effective heat exchanger, the water-heating flow at the outlet of the IHEU can be cooled down to 20 °C for MTDH and 18.8 °C for LTDH [19, 23]. The bypass flow and the bathroom-heating flow can be calculated as follows:

$$V_{bypass} = L_{bypass} * q_i * (t_i - t_{amb})/(\Delta t_{bypass} * 4200) * 3600 * 24 \qquad \text{(Eq.3)}$$

$$V_{bath} = q_{bath}/((t_{bs} - t_{br}) * 4200) * 3600 * 24 \qquad \text{(Eq.4)}$$

Where

V_{bypass} is the bypass flowrate on daily basis [L/day],

L_{bypass} is the pipe length including the service pipe and distribution pipe [m],

Δt_{bypass} is the temperature drop of the bypass flow along the supply line [°C],

V_{bath} is the bathroom heating flowrate on daily basis [L/day],

q_{bath} is the space heating demand of the bathroom (116W/apartment according to section 3.2) [W],

t_{bs} is the supply temperature to bathroom heating [°C],

t_{br} is the return temperature from bathroom heating [°C].

Therefore, the return temperature to district heating of the IHEU system can be calculated as:

$$\overline{t_{ret}} = (t_{de} * V_{wh} + t_b * V_b)/(V_{wh} + V_b) \qquad \text{(Eq.5)}$$

where

$\overline{t_{ret}}$ is the volume-averaged return temperature [°C],

t_{de} is the design return temperature of the IHEU [°C],

t_b is the temperature of the bypass flow (MTDH) or bathroom heating return flow (LTDH) [°C],

V_{wh} is the volume of the IHEU water heating flow on a daily basis [L/day],

V_b is the volume of the bypass (MTDH) or bathroom heating flow (LTDH) on a daily basis [L/day].

For the solutions with a heat pump, the design COP is 4.5 according to the existing product. The return temperature to district heating was calculated as the volume-averaged temperature of the return flow from the evaporator of the heat pump and the flow for DHW preparation. The ratio between the two volumes can be obtained from the energy balance of the heat pump, assuming the water-heating flow equals the DH flow to the heat pump condenser. For the micro tank solution and the electric heat tracing solution, the design return temperature from the heat exchanger catalogue was used.

The parameters for the energy evaluation model are shown in the Table 2 and Table 3 for the single-family house and the multi-storey building, respectively:

Table 2 Input parameters for the energy evaluation model for the single-family house

	Single family house				
	MTDH		LTDH	ULTDH	
	With tank	IHEU	IHEU	Micro tank	Micro heat pump
Energy sources	DH	DH	DH	DH & EL	DH & EL
T_dh_supply [°C]	65	65	50	35	35
T_dcw [°C]	10	10	10	10	10
V_dhw [L/m^2/year]	250	250	250	250	250
T_dhw [°C]	45	45	45	30	30
Set point T of the equipment [°C]	60	-	-	60	50
Equipment heat loss rate [W]	60W for tank	-	-	14W for micro tank	100W for heat pump

Table 3 Input parameters for the energy evaluation model for the multi-storey building

	Multi-storey building					
	MTDH		LTDH			ULTDH
	With tank and circulation	IHEU	Central HEX and HP	IHEU	El-tracing	Micro tank
Energy sources	DH	DH	DH & EL	DH	DH & EL	DH & EL
DH supply Temp. [°C]	65	65	50	50	50	35
DCW Temp. [°C]	10	10	10	10	10	10
Standardized volume of DHW [L/m^2/year]	250	250	250	250	250	250
DHW Temp. heated by DH [°C]	45	45	45	45	45	30
Set point T of the equipment [°C]	60	-	50	-	50	60
Equipment heat loss rate [W]	113 W for tank	-	40W for compressor	-	-	14 W for micro tank
Pipe heat loss coefficient [W/m·K]	Pipe_r: 0.157 Pipe_c: 0.094	0.157	Pipe_r: 0.157 Pipe_c: 0.094	0.157	0.157	0.157
Distribution pipe length per flat [m]	6	6	6	6	3	6

*** Pipe_r means the riser, Pipe_c means the circulation pipe.**

2.3.2 Evaluation model for economic performance

Economic performance depends on the investment cost, operation and maintenance (O&M) costs, and the energy cost. However, the investment cost and O&M costs are strongly dependent on the specific case, so only the DH heat and electricity costs were included in the economic model. The prices of DH heat and electricity were assumed to be 0.1 [24] and 0.25 [25] €/kWh, respectively.

$$C_{tot} = Q_{dh} * P_{dh} + Q_{el} * P_{el} \quad \text{(Eq.6)}$$

where

C_{tot} is the total energy cost [€],

Q_{dh}, Q_{el} are the consumptions for heat and electricity [kWh],

P_{dh}, P_{el} are the prices of district heating and electricity respectively [€/kWh].

In addition to the savings inside buildings, the benefits of low return temperatures to the DH system was also investigated for each scenario. According to Svend and Sven [22], the cost reduction from the low return temperature is estimated to be 0.16 EURO/MWh·°C. The cost reduction due to the low return temperature comparing to the conventional 80/40 °C DH scenario was therefore calculated.

$$E_s = \varepsilon \cdot Q_{sup} \cdot \Delta t \qquad \text{(Eq.7)}$$

Where,

E_s is the cost reduction for the DH system [EURO/year],

ε is the cost saving ratio, here is 0.16 [EURO/MWh·°C],

Q_{sup} is the total heat consumption for DHW supply [MWh/year],

Δt is the temperature difference between the calculated return temperature of the suggested solution and the conventional return temperature to DH, here the conventional return temperature is 40 [°C].

2.3.3 Evaluation model for exergy performance

To indicate the energy quality and the utilization efficiency of each DHW supply method, the exergy and exergy efficiency were calculated. The object systems for the exergy analysis in this study was confined to the DHW supply system in the building sector. The changes in kinetic and potential exergy were neglected [26], only physical exergy of the flow was considered. The reference pressure and temperature were assumed to be constant. The reference temperature was assumed to be 7.7 °C, which is the annual average ambient temperature in Denmark. The exergy efficiency of the DHW supply system was considered as the ratio of the exergy flow leaving the system to the exergy flow entering the system. The analysis methods described in reference [26] were used in this study. The exergy efficiency can be calculated as:

$$\eta_{ex} = Ex_{out}/Ex_{in} \quad \text{(Eq.8)}$$

$$Ex_{out} = Q_{dhw}(1 - \frac{T_0}{T_{dhw} - T_{dcw}} ln \frac{T_{dhw}}{T_{dcw}}) \quad \text{(Eq.9)}$$

$$Ex_{in} = Q_{dh}\left(1 - \frac{T_0}{T_{sup} - T_{ret}} ln \frac{T_{sup}}{T_{ret}}\right) + W_{el} \quad \text{(Eq.10)}$$

where

η_{ex} is the exergy efficiency of the DHW supply system [%],

Ex_{in}, Ex_{out} are the exergy flow entering and leaving the object system [kWh],

Q_{dhw} is the DHW heat demand [kWh],

T_0 is the temperature of the reference state [°C],

T_{dhw}, T_{dcw} are the temperatures of DHW and DCW, which were assumed to be 45 and 10 respectively [°C],

$\boldsymbol{T_{sup}}, \boldsymbol{T_{dcw}}$ are the supply and return temperatures of the district heating water [°C],

Q_{dh} is the supply heat from district heating [kWh],

W_{el} is the electricity consumption for DHW supply, which can be completely converted into useful work [kWh].

3. Results

3.1 Results of the energy performance evaluation

The results of the DHW- heating flow, the bypass flow and the bathroom-heating flow of the IHEU system are shown in Table 4.

Table 4 Daily water-heating flow, bypass flow and bathroom heating flow in the IHEU system

	Single-family house		**Multi-storey building**	
	IHEU with MTDH	IHEU with LTDH	IHEU with MTDH	IHEU with LTDH
Water-heating flow [L/day]	79.9	115.3	863	1244.7
Bypass flow [L/day]	32.3	(104.9)	148.6	(482.8)
Bathroom heating flow [L/day]	-	119.3	-	2147.6

*** The flow for the multi-storey building in the table is the overall value for the hypothetical building**

From the results, a single-family house supplied by MTDH required 19.4 L/day bypass flow to keep the set-point temperature of the bypass at 45 °C, while 140 L/day bypass flow was required for a 6-floor multi-storey building. The bypass flows of the LTDH scenario were calculated only for comparing with the bathroom heating flow, so that to verify the feasibility of using bathroom heating to keep the supply pipe warm.

Comparing the results in Table 4, the bathroom heating flows are larger than the required bypass flow, which indicates smaller temperature drop along the supply pipe. Therefore, the bypass function can be replaced by the bathroom heating flow. The flows in Table 4 were used to calculate the volume-averaged return temperature of the IHEU systems.

The average return temperatures to district heating of each system are shown in Table 5 and Table 6.

Table 5 Average return temperatures to district heating for single-family house systems

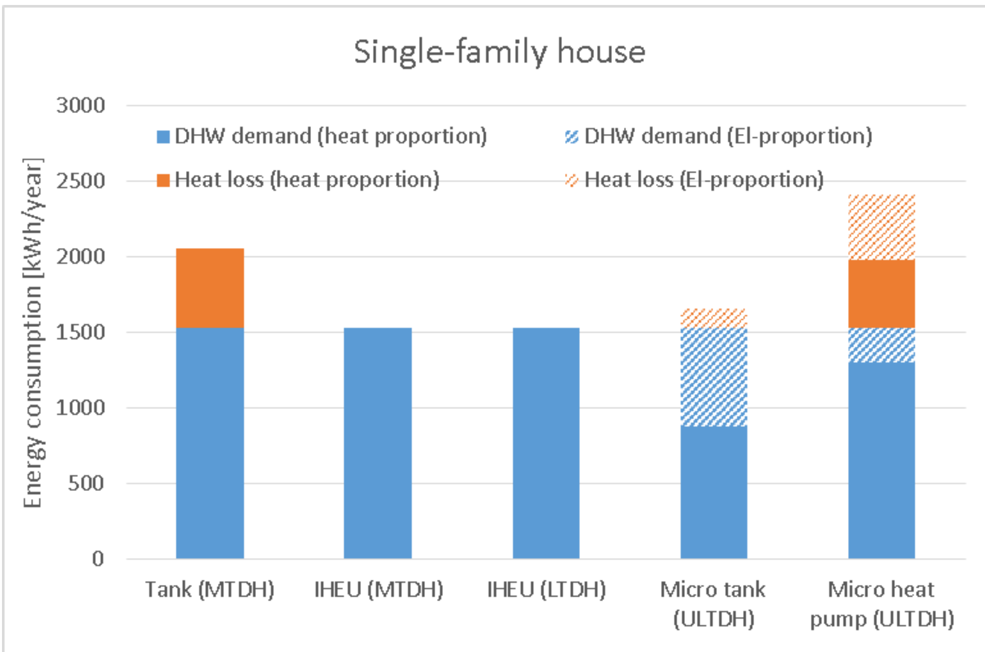
	Single family house				
	MTDH		LTDH	ULTDH	
	With tank	IHEU with bypass	IHEU with bathroom heating	Micro tank	Micro heat pump
Average return temperature [°C]	25	27	22	16	21

Table 6 Average return temperatures to district heating for multi-storey building systems

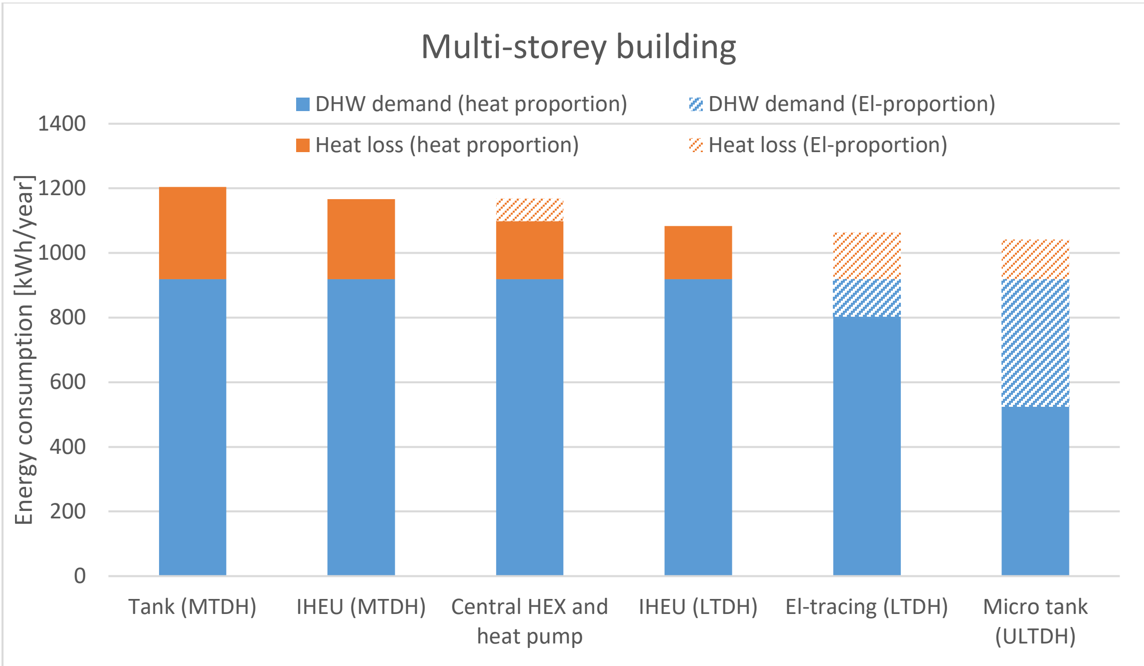
	Multi-storey building					
	MTDH		LTDH			ULTDH
	With tank and circulation	IHEU with bypass	Central HEX with heat pump	IHEU with bathroom heating	El-tracing	Micro tank
Average return temperature [°C]	28	24	20	23	19	16

For the IHEU system supplied with LTDH, if the bypass is retained, the calculated return temperatures to DH were 31 °C for single-family houses and 26 °C for multi-storey buildings based on the information in Table 4. However, as the bathroom heating is applied, the average return temperature can be reduced to 22 °C and 23 °C instead. The electric heat tracing and micro tank systems provided lower return temperatures to district heating since no bypass or hot water circulation was operated for those systems.

The energy performances of the investigated systems are shown in the Fig. 8.



(a)



(b)

Fig. 8 Energy consumption in the different scenarios for DHW supply [kWh/year]

From the results, the systems with MTDH supply are all able to provide DHW demand using just DH heat. The IHEU system requires less DH heat than the system with central storage tank. In the LTDH scenario, IHEU system and electric heat tracing system required less overall energy for DHW preparation. However, the electric heating tracing system requires more electricity for supplementary heating and covering the heat loss. Considering the different primary energy factors of heat and electricity, the IHEU method might be the best solution for the LTDH scenario, since it generated less heat loss than other methods and consumed no electricity. For the ULTDH scenario, the micro tank system had much less heat loss compared with the micro heat pump system.

3.2 Results of the economic performance evaluation

The results of the annual energy costs and savings from lower return temperatures in different scenarios can be found in Table 7 and Table 8.

Table 7 Evaluation of energy costs for single-family house systems

	Single family house				
	MTDH		LTDH	ULTDH	
	With tank	IHEU	IHEU	Micro tank	Micro heat pump
Heat cost [€/year]	206	153	153	88	174
Electricity cost [€/year]	0	0	0	195	166
Energy cost [€/year]	206	153	153	283	340
Savings for DH system [€/year]	4.9	3.2	4.4	3.4	5.3

Table 8 Evaluation of energy costs for multi-storey building

	Multi-storey building					
	MTDH		LTDH			ULTDH
	With tank and circulation	IHEU	Main HEX with heat pump	IHEU	El-tracing	Micro tank
Heat cost [€/year]	120	117	110	108	80	53
Electricity cost [€/year]	0	0	18	0	65	129
Energy cost [€/year]	120	117	128	108	145	182
Savings for DH system [€/year]	2.3	3.0	3.7	2.9	2.7	2.0

In the MTDH and LTDH scenarios, the energy cost of the IHEU system was less than the other systems. The main reason was that the instantaneous DHW production by the

IHEU eliminated the high temperature regime needed to meet the hygiene requirement, thereby reducing the heat loss from the system, and no supplementary heating was required. In a multi-storey building where substantial renovation is not feasible, the system with a central heat exchanger and a heat pump had lower energy costs. In the ULTDH scenario, where supplementary heating is necessary for DHW production, the energy cost is much higher due to the electricity consumption. Here, the micro tank system is more economical to apply than the micro heat pump system.

Since the saving potential from lower return temperatures for DH system is also affected by total DH heat required for DHW supply, a system that requires more energy for DHW production might have a large potential for savings. This means that the solutions with supplementary heating might have a smaller potential for savings because part of the energy supply is covered by electricity. Moreover, to investigate the total savings from lower return temperatures, the role played by space heating should be included, and the overall benefits would be more significant.

3.3 Results of the exergy performance evaluation

The exergy performances of different scenarios are shown in Table 9 and Table 10.

Table 9 Results of the exergy evaluation model for the single-family house

	Single-family house				
	MTDH		LTDH	ULTDH	
	With tank	IHEU	IHEU	Micro tank	Micro heat pump
Ex_in [kWh]	239	185	138	831	783
Ex_out [kWh]	99	99	99	99	99
Efficiency [%]	41.6%	54.3%	71.3%	12.0%	12.7%

Table 10 Results of the exergy evaluation model for the multi-storey building

	Multi-storey building					
	MTDH		LTDH			ULTDH
	With tank and circulation	IHEU	Main HEX with heat pump	IHEU	El-tracing	Micro tank
Ex_in [kWh]	145	136	166	101	328	548
Ex_out [kWh]	60	60	60	60	60	60
Efficiency [%]	41.1%	44.7%	35.8%	59.7%	18.1%	10.9%

For both MTDH and LTDH, the IHEU system has higher exergy efficiency. While the systems that require supplementary heating had lower exergy efficiency since extra electricity with high exergy quality was consumed.

4. Discussion

In Denmark, the DH system is currently going through the transition from MTDH to LTDH. The evaluation of the suitable substations corresponding to specific situations is of great importance if LTDH is to be realized. In general, the decentralized approaches for DHW supply performed better than the centralized approaches. In multi-storey buildings, the decentralized system helps to reduce the total DHW volume of each home, thereby eliminating the risk of Legionella. Moreover, the decentralized systems can produce the DHW instantaneously in each home, so that thermal storage or DHW circulation is unnecessary. As a result, the heat loss from the equipment can be much reduced.

Therefore, a decentralized IHEU system is a good solution for the realization of LTDH. However, the operation of a bypass weakens the performance of IHEU systems by increasing the return temperature to district heating. To reduce this negative impact, one solution is to supply bathroom heating all year round. This heating flow can help to keep the supply line warm, and ensure the 10s waiting time for comfort. To apply this alternative method, one thing that should be noted is that the flow for bathroom heating must be sufficient to maintain the set-point temperature for the most remote consumer. The space heating demand of the bathroom which determines the bathroom heating flow was calculated with a simplified method. However, for practical cases, more factors should be taken into account for the calculation, such as the heat transfer to the environment and neighbour rooms. Moreover, whether the benefits of the reduced return temperature can balance the extra investment or the increased space-heating demand in the bathroom requires detailed analysis in the specific case.

The economic evaluation in this study only included the energy cost. However, the full picture can be obtained only if the investment and the operation and maintenance costs are also included. The investment costs vary from case to case. The operation and maintenance costs are greatly affected by the cost of labour, which can also be different from case to case. Nevertheless, the results of this study can be helpful in the situation where the decision has to be made among candidate solutions with known investment prices. Policy makers can then derive the optimal solution by considering both factors together.

As one important factor, the LTDH can only be implemented if the return temperature to district heating can be cooled down sufficiently. Therefore, encouragement is given to the implementation of solutions with lower return temperatures. In Denmark, for example, for every 1 °C the return temperature is below 42.9 °C, the DH company can get 0.73 kr/GJ subsidy. In this study, the return temperature to district heating calculated were based on standard operation, but the heat exchangers were specially designed for LTDH, so the calculated return temperatures might be lower than in practice. The operation of the storage tank was assumed to be ideal, which also results in lower return temperature than in practice. However, with optimized design and operation, low return temperatures similar to those calculated can be achieved.

5. Conclusion

The concern of Legionella growth and less comfort of the DHW supply restricts the implementation of low-temperature district heating. This study analysed 11 different scenarios for DHW production with MTDH, LTDH and ULTDH for single-family house and multi-storey building. To meet the comfort and hygiene requirements, improvements or innovative design were made for the DHW supply method with LTDH and ULTDH. Energy, economy and exergy evaluation models were built to investigate the performances of the proposed systems. The potential benefit by lower return temperature was investigated. Recommended solutions to specific DH scenarios were derived based on the results of the evaluations.

For the MTDH scenario with supply temperature at 65 °C, the IHEU system has better energy performance compared to the system with a storage tank in both single-family houses and multi-storey buildings, since the instantaneous DHW preparation saves large amount of heat loss caused by the storage tank. For the LTDH scenario, by redirecting the bypass flow to floor heating in the bathroom, the return temperature of the IHEU system achieves significant reduction. Being applied in multi—storey buildings, the improved IHEU system requires the least primary energy for supplying the equivalent DHW demand. While the system with the central heat exchanger combined with a heat pump and the system with electric heating cables both require electricity for supplementary heating, which increase the overall primary energy consumption. As a result, the improved IHEU system also has better economy performance and higher exergy efficiency. For the ULTDH scenario, the micro tank solution proposed consumes less energy and is more economical than the micro heat pump solution, but has lower exergy efficiency.

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