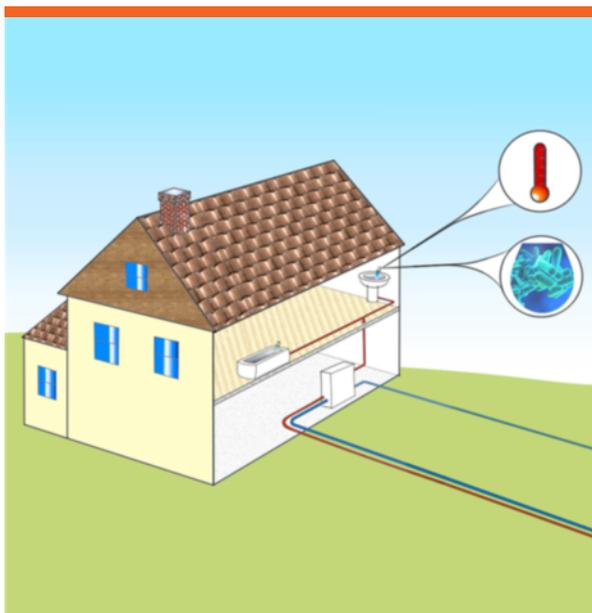


Supply of domestic hot Water at comfortable temperatures by low-temperature district heating without risk of Legionella



Xiaochen Yang

PhD Thesis

Department of Civil Engineering
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temperatures by low-temperature district heating
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11/03/2016

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Preface

This thesis is submitted as partial fulfilment of the requirements for a Doctorate of Philosophy at the Technical University of Denmark, Department of Civil Engineering.

The thesis is based on both theoretical work and field work on DHW preparation from low-temperature district heating with respect to the comfort and hygiene requirements. The results are also the accomplishment of the project “Supply of domestic hot water at comfort temperature without Legionella” of 4DH Research Centre.

I would like to thank my main supervisor Professor Svend Svendsen firstly, not only because of his guidance with foresight, but also his serious attitude towards research. His advice will no doubt be beneficial for me both in research and life. I also would like to give my thanks to my co supervisor Senior Researcher Hongwei Li, who gave me great help for both research and adaption to abroad life.

The study receives great support from the Strategic Research Centre for 4th Generation District Heating (4DH), which has received funding from the Innovation Fund Denmark. Therefore, I want to express my sincerest thanks to 4DH Research Centre, and all the academic and industrial partners.

I would like to give my earnest thanks to my friends and colleagues in the section of Building Physics and Services, everyone of you is so nice and warm-hearted. The special thanks go to Dorte Larsen (who will be Dorte Østergaard later), for her always kindly offering all kinds of help to me, and caring about me, and generously sharing her collection of chocolate with me. The special thanks also go to Dr. Maria Harrestrup and Dr. Kevin Smith, for their great support and willing to share their experience to me. Their encouragement and believe in me help me regain the confidence and pass through the tough times.

Thanks also extend to my Chinese friends in Denmark, for every heart-to-heart talk, for every memorable trip, for the company on every traditional Chinese festival, all of which made me less homesick.

Finally, I want to give my greatest thanks and also apologies to my parents in China. As the only child in my family, I feel regretful for not spending enough time with them, and not taking good care of them. But my parents are always caring about me and trying their best to support me. I really appreciate their respecting every decision I made, and always understanding me and trusting me. This thesis is dedicated to them!

Xiaochen Yang

Kgs. Lyngby, 1st March 2016

Abstract

In Denmark, about 25% of the primary energy is consumed for covering the heat demand in the buildings. To achieve a complete renewable energy system by 2050, which is the goal set by the Danish government, methods that are more efficient and economical for heat supply are urgently needed. Considering the overall energy efficiency and environment effect, the district heating (DH) is a cost-effective way of supplying heat to high heat density area. Currently, the DH system in most countries are still with supply and return temperature at 80/40 °C. The efficiency of the DH system can be improved by applying lower supply/return temperatures (55/25°C), which has been defined as the 4th generation district heating (4DH) or low-temperature district heating (LTDH). Compared to the current district heating, LTDH can give more access to the renewable energy sources (RES) with low heat quality, increase the recovered heat from industrial process and geothermal heat exchanging process, increase the heat recovery of flue gas condensation and increase the coefficient of performance (COP) of the heat pump if applied. Moreover, the low supply/return temperature in the network can also reduce the heat loss. To make utmost use of low-temperature energy sources, it can be beneficial to apply ultra-low-temperature district heating (ULTDH) in the future energy-efficient buildings, especially when heat pump is used for heat production. The supply temperature of ULTDH should be sufficient to ensure the comfort indoor temperature for space heating but lower than LTDH. Therefore, to meet the comfort and hygiene requirements for DHW supply, supplementary heating methods should be combined.

However, one obstacle to realize the LTDH/ULTDH is the concern of the violation of the comfort and hygiene requirements of DHW supply. According to the Danish standard, the supply for DHW should be able to reach 45 °C for the kitchen use and 40 °C for other uses for comfort. Regarding to the hygiene requirements, large DHW system with DHW storage tank and circulation has to use high temperature regime to get rid of Legionella. The storage tank should be able to reach 60 °C and the circulation should be operated no lower than 50°C. While the DHW system with small DHW volume has very low risk of Legionella. This study investigated available solutions for supplying DHW with LTDH or ULTDH meeting the comfort and hygiene requirements. Both the sterilization methods and optimized DHW system design methods are included. For the sterilization methods, we selected the most widely used treatments, and analyzed the feasibility of applying them in the LTDH scenario, the installation and operation difficulty, and the economy based on the review of substantial documents and relevant standards. In terms of the DHW system design methods, the optimal system configurations and operation methods were designed and evaluated with respect to the different DH scenarios and building typologies. Model studies were built to simulate the performances of the proposed systems under ideal situations. Some case studies were used as reference works to compare with the model results.

Considering the disinfection mechanism of different sterilization methods and the regulation for water quality in Denmark, the approaches of photocatalysis, UV light and filtration have good disinfection efficacy for Legionella if supplied by LTDH, and inject no additives into the water. Thus, they can be considered as feasible sterilization solutions.

In terms of the DHW system design methods, in addition to ensure the safe and hygiene DHW supply, the potential DHW systems should also be optimized for better energy and economy

performances. Therefore, targeting to different DH systems and building typologies, the optimal solutions can be different. This research investigated a variety of potential solutions by classifications.

For the LTDH scenario, the decentralized substation system is an optimal solution for buildings with new or deep-renovated DHW substations. The decentralized substation system eliminates the risk of Legionella by minimizing the total DHW volume in use. Large amount of the equipment heat loss can be saved by the local DHW preparation and the supplementary heating is unnecessary. As a result, the energy and exergy efficiency of the decentralized substation system are higher than other solutions, while the energy cost of decentralized substation system is the lowest. To fit the LTDH scenario better, two improved forms of the decentralized substation system were devised by replacing the bypass function, so that lower return temperature can be reached. One form is to replace the bypass by an in-line supply riser with a micro heat pump covering the generated heat loss and ensuring the acceptable waiting time for DHW. The improved decentralized substation system has the potential of saving 13% heat loss compared to the decentralized substation system with bypass. The other form is to redirect the bypass flow to the bathroom heating during the non-heating season. With well insulated supply pipe, the bathroom heating flow can substitute for the bypass function and be efficiently cooled down to room temperature by floor heating. The electric heat tracing system can 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. The electric heat tracing system guarantees the comfort and hygiene DHW supply by supplementary heating locally using electricity. Being improved by the smart control method which can response to the dynamic DHW load profile, the electric heat tracing system can save 50% energy for covering the heat loss compared with the conventional DHW circulation system.

In terms of ULTDH scenario, one solution is the instantaneous heat exchanger unit (IHEU) combined with a micro electric storage tank. The solution can be easily installed in a new building or an existing building with IHEU. The micro tank solution has less heat loss than the substations with normal heat storage. Moreover, the micro tank helps to reduce the peak load of the electric heater, and ensure the acceptable waiting time. Thereby, the bypass function of the heat exchanger can be replaced, which results in lower return temperature and less heat loss. Another solution for ULTDH is the micro heat pump system. Compared to the micro tank solution, the micro heat pump system requires more energy for equivalent DHW preparation, but less electricity. However, the heat loss of the heat pump unit should be taken into account when planning the system. The exergy efficiency of the two solutions are similar, but the micro tank solution has lower energy consumption and energy cost.

In summation, the decentralized substation system with instantaneous heat exchanger unit (IHEU) performed better under the medium-temperature district heating and low-temperature district heating scenarios, while the individual micro tank solution consumed less energy and cost less in the ultra-low-temperature district heating scenario.

Resumé

I Danmark anvendes omkring 25 % af primærenergiforbruget til at dække varmemeforbruget i bygninger. For at nå regeringens mål om at det danske energisystem skal være fuldt ud forsynet af fornybare energiresourcer i 2050, er der derfor hårdt brug for nye energieffektive og økonomiske metoder til at dække varmebehovet. Når der skal tages hensyn til den overordnede energieffektivitet og de miljømæssige påvirkninger, er fjernvarme en kosteffektiv måde at forsyne områder med en høj varmedensitet. På nuværende tidspunkt forsynes fjernvarmesystemerne i de fleste lande med frem- og returtemperaturer på henholdsvis 80 °C og 40 °C. Ved at sænke disse temperaturer kan effektiviteten i fjernvarmesystemerne forbedres betydeligt. Den næste generation af fjernvarmesystemer, også kaldet 4'nde generations fjernvarme, er derfor karakteriseret ved lavtemperaturfjernvarme, med frem- og returtemperaturer på henholdsvis 55 °C og 25 °C. Udover at varmetabet fra fjernvarmenettet mindskes betydeligt hvis temperaturerne sænkes, opnås der også en række fordele for energisystemet overordnet set. Hvis fjernvarmetemperaturerne sænkes, øges potentialet for at udnytte geotermisk varme og overskudsvarme fra industri, effektiviteten i røggaskondensering øges og varmeproduktion via solvarmeanlæg og varmepumper bliver mere effektivt. I nogle tilfælde kan fremløbstemperaturen sænkes yderligere, hvis en lavere temperatur er tilstrækkelig til at opretholde en god termisk komfort i bygningerne. Dette kan for eksempel være en fordel i områder med lavenergibygninger, hvor varmen produceres via en varmepumpe. Fjernvarme med så lav en fremløbstemperatur benævnes også ultra-lavtemperaturfjernvarme. Grundet den lave fremløbstemperatur, er der behov for at tilføre ekstra energi til brugsvandsopvarmning, for at imødegå kravene til komfort og hygiejne. Den ekstra energi tilføres eksempelvis via decentrale elektriske installationer.

En af barriererne for at realisere sænkningen af fjernvarmetemperaturerne, er bekymringen om at krav til komfort og hygiejne i varmtvandsanlæggene ikke kan overholdes. Ifølge Dansk Standard skal der kunne opnås en varmtvandstemperatur på 45 °C ved køkkenvaske og 40 °C ved andre tapsteder. For at nedsætte risikoen for Legionella er der samtidig krav til varmtvandstemperaturerne i brugsvandssystemer med lange rørstrækninger eller beholdertanke. I brugsvandstanke skal der kunne opretholdes en temperatur på 60 °C og brugsvandscirkulation skal foregå ved minimum 50 °C. Disse krav er ikke nødvendige i brugsvandssystemer med korte rørstrækninger og små vandvolumener, hvor der er meget lille risiko for problemer med Legionella, grundet vandets korte opholdstid.

Denne afhandling har undersøgt forskellige løsninger til hvordan der kan leveres varmt brugsvand i områder med lavtemperaturfjernvarme og ultra-lavtemperaturfjernvarme, uden at der går på kompromis med kravene til komfort og hygiejne. Undersøgelsen omfatter både steriliseringsmetoder og optimeret design af varmtvandssystemer. Vi analyserede muligheden for at anvende de mest almindeligt anvendte steriliseringsmetoder i forbindelse med lavtemperaturfjernvarme. Derudover evaluerede vi fordele og ulemper ved installation og drift af steriliseringsmetoderne, samt fastslog de økonomiske omkostninger ved at anvende de forskellige steriliseringsmetoder, på baggrund af en gennemgang af relevante dokumenter og standarder. Brugsvandssystemerne i typiske bygninger blev re-designet og driftsoptimeret, for at identificere optimale tekniske løsninger til levering af varmt brugsvand ved forskellige fjernvarmetemperaturer. Evalueringen af de forskellige brugsvandsløsninger blev foretaget på baggrund af case studier og beregningsmodeller, hvor den optimale drift blev simuleret.

Studierne viste at steriliseringsmetoder såsom fotokatalyse, UV lys og filtrering var effektive metoder til at fjerne Legionellabakterier fra varmtvandssystemer uden at brugsvandet skal tilføres tilsætningsstoffer. Disse kan derfor betragtes som velegnede steriliseringsmetoder, til brugsvandssystemer i områder med lavtemperaturfjernvarme.

I forbindelse med optimeringen af brugsvandssystemer i typiske bygninger, blev der lagt vægt på at identificere økonomiske og energieffektive metoder til at sikre god komfort og hygiejne i brugsvandsforsyningen. Den optimale brugsvandsløsning kan variere alt efter typen af bygning og forudsætningerne i det enkelte fjernvarmesystem. I denne afhandling undersøgte vi derfor en række forskellige designløsninger. Undersøgelserne viste, at en decentral varmeveksler er en optimal løsning til at levere varmt brugsvand i nye eller gennemrenoverede bygninger, som forsynes med lavtemperaturfjernvarme. Når der anvendes en decentral varmeveksler, er der ingen risiko for Legionella, fordi voluminet af varmt brugsvand er så småt. Varmeveksleren er samtidig energieffektiv, fordi den har et mindre varmetab end andre systemer og fordi der ikke er behov for at tilføre supplerende energi. Den decentrale veksler havde også de laveste omkostninger.

Vi undersøgte to forskellige designs med decentrale varmevekslere i etageejendomme. Formålet var, at evaluere hvordan omløbet i varmevekslerne kan optimeres, så den lavest mulige returtemperatur opnås. Det ene design var baseret på et rørsystem hvor cirkulationsrøret var ført inden i brugsvandsrøret og hvor en micro-varmepumpe dækkede varmetabet fra varmtvandsrørene, og sikrede at det varme vand kunne leveres indenfor en tilfredsstillende tidsperiode. Denne løsning mindskede varmetabet med 13 % i forhold til standardscenariet. I det andet design, blev omløbet fra brugsvandsveksleren anvendt til at opvarme badeværelsegulvet udenfor opvarmningsperioden. Denne løsning sikrede at returtemperaturen fra brugsvandscirkulationen var omkring stuetemperatur.

Det er muligt at anvende lavtemperaturfjernvarme til brugsvandsopvarmning i etageejendomme med brugsvandscirkulation, hvis cirkulationssystemet skiftes til et el-tracing system. I sådan et tilfælde anvendes der supplerende elektricitet for at garantere at brugsvandssystemet lever op til kravene om komfort og hygiejne. Hvis el-tracing systemet optimeres i forhold til forbrugsprofilen for varmt brugsvand, er det muligt at reducere varmetabet fra systemet med 50 %, i forhold til et typisk system med varmtvandscirkulation.

I områder med ultra-lavtemperaturfjernvarme kan varmeveksleren kombineres med en micro-varmtvandsbeholder, der er forsynet med en el-patron. Denne løsning kan anvendes både i nye og eksisterende bygninger. Micro-varmtvandsbeholderen har et mindre varmetab end en almindelig varmtvandsbeholder. Derudover sikrer varmtvandsbeholderen, at el-patronen ikke skal dække en stor spidsbelastning og at varmt vand kan leveres uden lange ventetider, selv hvis omløbet i varmeveksleren lukkes. Da omløbet i varmeveksleren kan lukkes, sikrer denne løsning en lav returtemperatur. En anden løsning, som kan anvendes til at levere varmt brugsvand i områder med ultra-lavtemperaturfjernvarme, er en micro-varmepumpe. Denne løsning har et større energiforbrug end micro-varmtvandsbeholderen, men den har til gengæld et mindre elforbrug. Når systemet designes, er det dog vigtigt at varmetabet fra micro-varmepumpen tages med i betragtning. Exergieeffektiviteten for de to løsninger er ens, men micro-varmtvandsbeholderen har lavest energiforbrug og energiomkostninger.

Overordnet set fandt vi, at decentrale varmevekslere var den bedste løsning til brugsvandsforsyning i områder med lavtemperaturfjernvarme. I områder med ultra-

lavtemperaturfjernvarme fandt vi, at micro-varmtvandsbeholdere var den løsning, som sikrede det laveste energiforbrug og var billigst.

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1. Introduction

1.1 Background

1.1.1 Energy frame of buildings and the DHW proportion

To achieve long-term sustainability, the European Union has set targets of a 20% reduction in greenhouse gas (GHG) emissions and energy consumption by 2020 compared with 1990 levels, 40% by 2030, and 80% by 2050 [1]. In Denmark, the goal is to transform the current energy system, which has just 28.5% of its energy consumption covered by renewable energy sources (RES) [2], into a completely fossil-free energy system by the year 2050 [3].

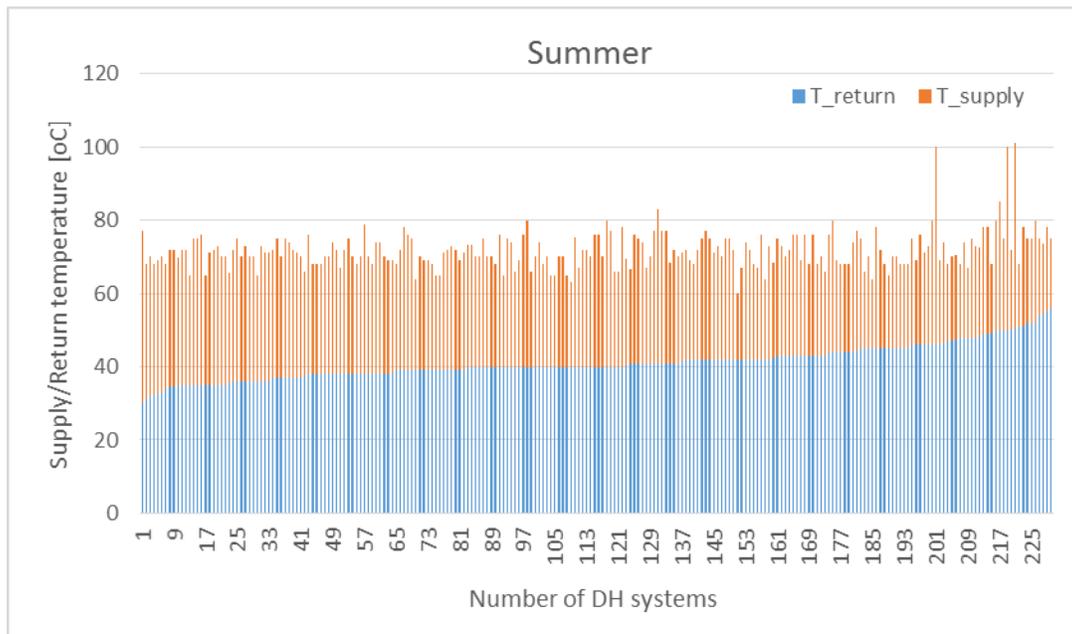
As society develops, the energy demand in the building sector plays an increasingly important role in the total energy consumption of the national energy system. In Europe, the energy consumption in buildings accounts for 40% of total energy supply [4]. Previous studies have shown the huge energy-saving potential in the building sector [5-8]. The EU's Energy Performance of Buildings Directive in 2010 requires all new buildings from 31st December 2020 to consume nearly zero energy [9]. According to the Danish Building Regulations 2010 [10], the total energy demand of the building sector needs to be reduced by more than 50% by 2020. Since the DHW demand will not go down, this means that the proportion of DHW demand in the total heating demand will increase from the current 29% to almost 50% in the future [11]. Cost-effective and energy-efficient measures for DHW preparation need attention as DHW becomes a more and more important part of the energy frame.

According to Danish energy statistics [12], about 25% of primary energy consumption was used for heat supply to buildings in 2009. The heating demand in buildings covers both space heating (SH) demand and domestic hot water (DHW) demand. Energy consumption for domestic hot water production constitutes a significant part of the total domestic energy usage. Information from the national energy statistics [12] shows that the energy consumed by an ordinary household is 200 PJ / year, of which electricity consumption accounts for 37 PJ / year, while heating consumption accounts for 163 PJ / year. The energy consumption for DHW is reported to take up 30% of the total heat consumption. While the energy demand regulated by the building code is decreasing gradually, the DHW consumption per capita has increased from 10 m³ per year to 15 m³ per year.

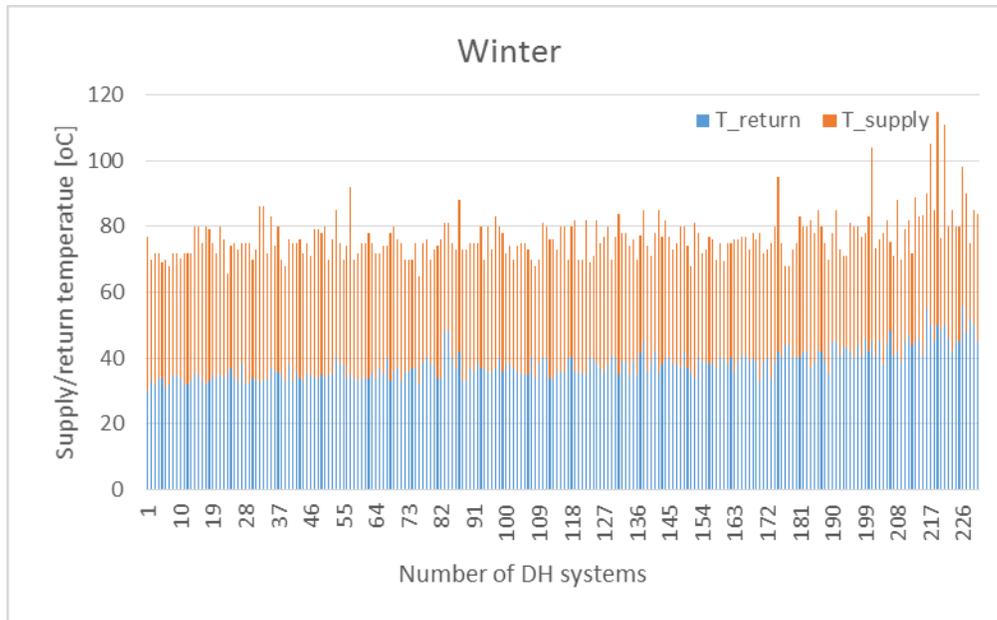
1.1.2 The transition to 4th Generation District Heating

Considering its overall energy efficiency and environmental effect, district heating (DH) is a cost-effective way of supplying heat to high heat density areas. Moreover, the heat source for DH is very flexible: it can use industrial excess heat, renewable energy, waste incineration etc. This means DH is of great importance for efforts to make the energy system 100% fossil-free.

By the year of 2010, 50% of the total heat demand in Denmark was supplied by DH. For the heat demand of residential buildings, the percentage was as high as 63% [5]. District heating is a cost-efficient way of supplying heat to consumers, especially in areas with high heat density. Currently, district heating is in transition from 3rd generation district heating to the 4th generation or low-temperature district heating (LTDH) [13]. The following diagrams show the supply and return temperatures of the current district heating system in Denmark in the heating and non-heating seasons.



(a) Supply/return temperatures of DH networks in Denmark in the summer of 2013/2014



(b) Supply/return temperatures of DH networks in Denmark in the winter of 2013/2014

Figure 1 Current supply and return temperatures of DH systems in Denmark [14]

The diagrams show that the average supply/return temperature of district heating system in Denmark is around 75/40 °C in summer and 80/35 °C in winter. However, the goal of LTDH is to reduce the supply temperature to 50-55 °C and the return temperature to around 25 °C [13]. With specially designed space heating systems, LTDH is sufficient to provide comfortable indoor temperatures. Compared with the 3rd generation district heating system, LTDH can give more access to renewable energy sources (RES) with low heat quality, increase the recovered heat from industrial processes and geothermal heat exchanging processes, and increase the coefficient of performance (COP) of heat pumps where applied. Moreover, the low return temperature can increase the heat recovery of flue gas condensation.

In addition to the actual heat demand, the total heat supply has to cover the heat loss during the heat transmission and distribution process. In addition to the heat loss from the DH grid, the conventional DHW system supplied by the current DH system can have heat losses as high as 70% of the heat supply inside the building [15]. Therefore, the reduction in heat loss due to low district heating temperatures can be very significant [16].

All this means that the transition to the 4th generation district heating will play a role in the improvement of the integrated heating system. The transition can be carried out step by step: 1) a medium-temperature district heating system (MTDH) with a supply temperature of 65 °C, which is sufficient to supply DHW that meets both the comfort and hygiene requirements without supplementary heating; 2) a low-temperature district heating system (LTDH) with a supply temperature of 50-55 °C, which is sufficient to heat DHW to a comfortable temperature, but will require that the total volume of DHW should be minimized to a small volume to prevent Legionella; and 3) an ultra-low-temperature district heating system (ULTDH), the supply temperature of which is insufficient for either comfort or hygiene requirements and will therefore require supplementary heating. Nevertheless, ULTDH can be a cost-effective way of supplying heat to energy-efficient buildings, and making the utmost use of low-temperature heat sources.

1.1.3 Conflicts between Legionella prevention and LTDH

Legionella are gram-negative bacteria that are common in both natural and man-made aquatic ecosystems, such as cooling towers, hot springs, domestic hot water systems, and also cold (potable) water systems [17-20]. Some species are reported as the etiological agents of Legionnaires' disease. Normally, Legionnaires' disease is acquired by inhaling the aerosol of contaminated water. Since 1976, several outbreaks of Legionnaires' disease have been diagnosed globally [21]. In 2013, 6012 cases were reported by 29 European countries with a fatality rate of about 10% [22]. In domestic hot water systems, which are strongly related to people's daily life, the contamination rate ranged from 6% to 32%, according to previous research [23-31]. The problem is considered to be even greater when the hot water is supplied by district heating (DH) [24, 27], because this is generally combined with a centralised water heating system with a central heat exchanger, which requires long distribution pipelines to the consumers. This creates favourable conditions for Legionella's multiplication [30, 32-34], which include: 1) water temperatures ranging from 25 °C to 45 °C; 2) long-term stagnancy; and 3) low levels of disinfectant residual and the presence of biofilm and sediments.

A high temperature regime is still the most widely-used method for preventing Legionella in hot water systems. In Denmark, for example, the standard regulates that the circulation pipe should be kept at no less than 50 °C, and the storage tank should be kept at 60 °C for buildings with large DHW volume [35]. However, if low-temperature district heating is implemented, it will be difficult for conventional systems with a circulation pipe and storage tank to meet the temperature requirements, due to the low-temperature supply and the temperature drop in the heat transmission process. Moreover, large systems are more likely to suffer from stagnancy. It is, therefore, crucial

to ensure that both comfort and health requirements will be met before LTDH is implemented.

1.2 Aim

The main target of this project is to demonstrate the feasibility of using LTDH/ULTDH to supply domestic hot water to different types of buildings at a comfort temperature of 40 - 45°C without the risk of Legionella. The optimal domestic hot water system with corresponding operation methods for specific scenarios will be recommended as the result of this study. Such a system will be able to fulfil the comfort and hygiene requirements, and at the same time lower current DH supply temperatures, which will reduce both the network heat loss and enhance the use of low-temperature renewable energy sources in district heating systems. Improvements in the existing DHW system or innovative design for a new system may be necessary to achieve this goal.

1.3 Scope

The scope of this thesis was limited to the feasibility and performance analysis of various solutions for DHW supply that meets the requirements for comfort and hygiene within the LTDH/ULTDH scenario. Sterilization methods and DHW system design methods are included. The focus is on the evaluations of each solution, and the possible improvement of the each solution for better energy and economy performances. The theoretical aspects of the sterilization mechanisms were introduced in general terms, but were not the subject of this study.

1.4 Hypothesis

The main hypothesis and sub-hypotheses are presented in this section.

1.4.1 Main hypothesis

The comfort and safe supply of domestic hot water can be achieved with low-temperature district heating if an appropriate solution is applied, which allows the development for the whole district heating system. In different situations, including the building typology, substation configuration, renovation depth, etc., the solutions can also vary. Their technical and economic feasibility can be identified by model-based comparison.

1.4.2 Sub-hypotheses

The main hypothesis is tested by the following 5 sub-hypotheses:

1st sub-hypothesis

In buildings with a large DHW volume due to a storage tank and DHW circulation, LTDH (50-55 °C) assisted by sterilization treatment can be a solution for the supply of DHW at a comfortable temperature without the risk of Legionella.

2nd sub-hypothesis

The combination of a central heat exchanger and local supplementary heating devices, such as electric heating and a heat pump, can be a solution which takes into account the comfort and hygiene requirements in large buildings with DHW circulation supplied by LTDH. The smart control method applied to the supplementary heating devices can optimize the energy consumption of DHW preparation and reduce operation costs.

3rd sub-hypothesis

A decentralized substation system can resolve the Legionella problem for LTDH without supplementary heating, which results in a substantial reduction of the overall heat consumption compared to conventional systems. It is possible to improve the system performance further by methods that eliminate the influence of the bypass on the average return temperature.

4th sub-hypothesis

It is possible to supply DHW based on ULTDH using supplementary electrical heating with an acceptable economic performance.

5th sub-hypothesis

It is possible to establish a set of safe and optimal solutions to supply DHW in all types of buildings with LTDH or ULTDH. The optimal solution can be derived by sophisticated evaluation models, and the benefits of lowering the DH temperatures can be also characterized.

1.4.3 Research questions

To examine the hypotheses, research questions were posed corresponding to each sub-hypothesis.

1st research question

What are the advantages and disadvantages of the sterilization methods for Legionella that are applicable in LTDH systems in Denmark?

2nd research question

Can the electric heat tracing system or the heat pump system combined with LTDH be beneficial in terms of energy and economy compared to a conventional system supplied by MTDH?

3rd research question

How much energy can be saved by a LTDH-supplied decentralized substation system compared with a conventional system? How much benefit can be obtained by replacing the bypass?

4th research question

What type of electrical supplementary heating can best fit the ULTDH scenario? How can we evaluate the performance of electrical heating methods with different configurations for DHW preparation?

5th research question

Can the existing DHW supply method be maintained for LTDH or ULTDH? If not, what improvements can be designed for the potential solutions, so that they are well-adapted to the LTDH/ULTDH scenario?

1.4.4 Tested sub-hypothesis in papers

All the sub-hypotheses were tested in articles. The papers are provided in the Appendix. Paper 1 includes the test for the 1st sub-hypothesis. Paper 2 contributes with the test of the 2nd sub-hypothesis. Paper 3 describes the test of the 3rd sub-hypothesis and part of the test of the 5th sub-hypothesis. Paper 4 describes the test of the 4th sub-hypothesis. Paper 5 describes the test of the 5th sub-hypothesis.

Paper 1

Xiaochen Yang, Hongwei Li, Svend Svendsen. “Alternative solutions for inhibiting Legionella in domestic hot water systems based on low-temperature district heating”, accepted by “*Building Services Engineering Research and Technology*”, DOI: 10.1177/0143624415613945

Paper 1 gives an overview of a number of alternative solutions for inhibiting Legionella divided into two categories: sterilization methods and alternative system design methods. The advantages and disadvantages of the solutions considered were documented, as well as their efficacy, the difficulty of their installation and operation, their action range, their cost, and so on. In addition, Paper 1 tested the 1st sub-hypothesis by investigating the feasibility of applying the solutions considered with LTDH by comparing with the respective regulations and standards.

Paper 2

Xiaochen Yang, Hongwei Li, Svend Svendsen. “Modelling and multi-scenario analysis for electric heat tracing system combined with low temperature district heating for domestic hot water supply”, accepted by “*Building Simulation*”, DOI: 10.1007/s12273-015-0261-4

Paper 2 describes dynamic models to simulate the performance of the electric heat tracing system. Multiple scenarios were set for the simulation, with regard to various control methods and various DHW load profiles. Comparison of the energy and economic performance of the electric heat tracing system with traditional DHW systems indicated the potential of applying electric heat tracing to an LTDH-supplied system. Thus, Paper 2 tested part of the 2nd sub-hypothesis.

Paper 3

Xiaochen Yang, Hongwei Li, Svend Svendsen. “Decentralized substations for low-temperature district heating with no Legionella risk and low return temperatures”, accepted by “*Energy*”, DOI: 10.1016/j.energy.2015.12.073

Paper 3 analysed the performance of a decentralized substation system with LTDH. The simulation results were compared with measurements from a practical application of a decentralized substation system supplied by conventional DH. In addition, an innovative concept of combining a micro heat pump and in-line circulation to replace the bypass was applied in the decentralized substation system. The performance of the developed decentralized substation system was compared with the conventional system and the normal decentralized substation system to explore its real potential with LTDH. This paper therefore tested the 3rd sub-hypothesis and demonstrated the feasibility of using a decentralized substation system to realize safe and comfortable DHW supply with LTDH. The implementation of the micro heat pump partially examined the 2nd sub-hypothesis. Moreover, the investigation of the improved decentralized substation system partially tested the 5th sub-hypothesis, in relation to the possible development of a system that could achieve lower return temperatures and their resulting benefits.

Paper 4

Xiaochen Yang, Hongwei Li, Svend Svendsen. “Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating”, *Energy*, 2016; 105:248-259, DOI: 10.1016/j.energy.2016.04.109

Paper 4 was based on real cases with ULTDH supply. Five substations with different system configurations were measured for the analyses. Moreover, an individual model was built for each substation to investigate the energy and economic performance under standard operation. The relative consumption of electricity was confirmed as an indicator of the performance of the ULTDH-supplied DHW system, which tested the 4th sub-hypothesis.

Paper 5

Xiaochen Yang, Hongwei Li, Svend Svendsen. “Energy, economy and exergy evaluations of the solutions for supplying domestic hot water from low-temperature district heating

in Denmark”, *Energy Conversion and Management*, 2016; 122 :142-152, DOI: 10.1016/j.enconman.2016.05.057

Paper 5 provided possible solutions for supplying DHW with LTDH/ULTDH that meet the comfort and hygiene requirements. Improvements and new designs were developed for the DHW substations in the LTDH and ULTDH scenarios. The system performances were investigated in terms of energy, economy and exergy. The optimal solution was obtained by integrating the evaluation results from all aspects. The proposals and analyses of the DHW substations considered for LTDH/ULTDH in Paper 5 helped test the 5th sub-hypothesis.

1.5 Structure of the thesis

This thesis consists of 7 main chapters. Chapter 1 is the introduction of the study. Chapter 2 introduces the state of the art related to the research topic. Chapter 3 presents the methods that test the hypotheses. Chapter 4 presents the results with regard to the main-hypothesis and sub-hypotheses. Chapter 5 is the discussion that shows the exceptions, implications, and applications of the results. Chapter 6 provides the conclusion on the main-hypothesis and sub-hypotheses. Chapter 7 indicates relevant research work that can be carried out in the future. The Appendices include the 5 research papers.

2. State of the art

This section documents the most relevant publications to this study, as well as the latest academic researches with respect to the investigated topic.

2.1 Sterilization methods for Legionella prevention for DHW

Based on different theories, sterilization methods for inhibiting Legionella can be divided into three kinds: thermal treatment, chemical treatment, and physical treatment.

Thermal treatment requires high temperature for the disinfection of Legionella. Previous studies[36, 37] have showed that *L. pneumophila* in vitro is killed rapidly by water temperatures >60 °C. Higher temperatures require less time to achieve the same log reduction (70 °C for 10 minutes, and 60 °C for 25 minutes)[37]. The efficacy of thermal treatment has been tested effective, if with proper and regular control. According to Krøjgaard et al.[23], a protocol of keeping the boiler at 70 °C for 24 hours (after hyperchlorination) and flushing all taps for 5 minutes reduced the concentration of Legionella and limited it below 10^2 CFU/L over a period of 7 months.

The chemical treatment can be sorted into chemical biocides method, ionization, UV light, and photocatalysis due to the different facts of disinfection. The chemical biocides are various. By injecting the chemical agent into the water, Legionella can be killed by disrupting the cellular processes. With precise residual control, biocides method can maintain continuous efficacy. For example, Experimental work by Muraca et al.[36] showed that chlorine with an average concentration of 4-6 mg/L can achieve 4-log reduction in 25 °C water after 3 hours. Walker et al.[38] observed that maintaining a chlorine dioxide concentration of 50-80 mg/l for 8 hours in the system tank and 1 hour at all outlets showed a good inhibiting efficacy for both planktonic and sessile Legionella. For continuous residual control, a level of 0.5 mg/L is effective in hot water systems[39]. Ionization works by using two different ionized metals in the water to disrupt the cell wall permeability of bacteria and cause the denaturing of proteins and subsequent cellular lysis[40, 41]. The most widely used electrodes are copper and silver. The effective dosages vary from 0.2-0.4 mg/L for copper and 0.02-0.04 mg/L for silver[42] mainly depending on the water quality. However, the use of biocide methods requires meticulous control to maintain effective concentrations without violating any local water quality requirements. For instance, in Denmark, the limits for Cu^{2+} and Ag^+ in the domestic water system are lower than the effective concentrations, which are 0.1 mg/L and 0.01mg/L respectively[43]. therefore, the ionization method cannot be applied in Denmark. Ultraviolet light adds no chemical agents into the water system. It kills bacteria by disrupting their DNA replication process with short-wavelength light (254 nm)[44]. Continuous UV disinfection at $30000 \mu\text{W}\cdot\text{s}/\text{cm}^2$ can achieve a 5-log reduction within 20 minutes[36]. Photocatalysis is a new water treatment technique for

hot water systems. The method used is to activate a solid catalyst such as titanium dioxide (TiO₂) using sunlight and produce oxidants to kill bacteria. The main oxidant generated by this reaction is the hydroxyl radical ($\cdot\text{OH}$), which is accompanied with superoxide anions ($\cdot\text{O}_2^-$) and hydrogen peroxide (H₂O₂). The wavelength of the ultraviolet light for photocatalysis should be no more than 385 nm (UV-A)[45]. Cheng et al.[45] used a 90-minute photocatalysis treatment with 1000mg/L of TiO₂ and 108 mW/cm² of UV light and achieved a 4.5-log reduction. Stenman et al. report[46] the achievement of a 5-log reduction in contaminated water with a flowrate of 10L/min using photocatalysis in a laboratory.

Physical treatment mainly refers to filtration, which prevent the microorganisms from getting into the protected site by using membrane filters[47-49]. The filter can be installed at the inlet of the water system or at the distal faucets. To maintain good efficacy, the filter has to be replaced regularly.

2.2 DHW system design for Legionella prevention based on DHW volume and temperature

Considering the conditions for the growth of Legionella described in Chapter 1.1.3, apart from the sterilization methods, a meticulously-designed DHW system can also achieve comfort and sanitary supply with LTDH. According to the Danish standard and directive for DHW system [35, 50], the comfort and hygiene requirements of DHW temperatures are different respecting to the size of the heating system. For large buildings with great DHW volume due to the implementation of storage tank and DHW circulation, high temperature regime is required to inhibit Legionella. While for system with small total volume, the requirement for DHW temperature due to the hygiene concern is less strict. In addition, the supply of DHW should also meet the comfort requirement according to the standard. The specific comfort and hygiene requirements for DHW temperature are summarized in the following table, with both Danish and EU standard were taken into account.

Table 1 Temperatures according to hygiene and comfort requirements for different building typologies

	Systems with no circulation or storage tank	System with large DHW volume
Requirement for Legionella prevention	-	Temp. of the tank 60 °C, Temp. of circulation >50 °C
Requirement 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

To realize LTDH/ULTDH without violating any DHW requirements, the system design method can be carried out in two ways:

- 1) Local temperature boosting
- 2) DHW volume minimization

Some previous researches have studied [51-65] the existing technologies for DHW preparation, which is possible to be renovated for the LTDH/ULTDH supply. The decentralized substation system can be applied with LTDH according to the theory of system division. By installing the decentralized substation unit in each apartment, the large building with great overall DHW volume can be divided into small-volume DHW system on apartment basis. Therefore, the risk of Legionella due to the stagnancy can be eliminated. According to the results of studies [51-54], the instantaneous heat exchanging unit (IHEU) system with district heating supply can save 10%-30% of heating energy compared to the centralized heating system with DHW circulation and is efficient to avoid the Legionella problem. Normally, to ensure the 10s waiting time for comfort, bypass is required for the decentralized substation system. However, the operation of bypass will result in high average return temperature, which restricts the efficiency of LTDH. Therefore, system improvement for eliminating bypass is needed.

Electric heat tracing is a solution based on the local temperature boosting theory. A case study in a Danish hospital used the electric heat tracing system to deal with the Legionella problem [58]. The operational cost of the electric heat tracing system was only half that of the previous system with DHW circulation. Bøhm [11] investigated the energy saving performance and return temperature of the electric heat tracing system, but the superiority was not evident. Since the electric heat tracing system requires electricity for supplementary heating, the smart control method corresponds to the practical DHW load profile plays a role in reducing the electricity consumption, which is insufficiently studied. However, the control method responding to the real DHW load profile is insufficiently studied, which is rather dynamic but plays a role in the electricity consumption of the cable.

The heat pump system is another application for local temperature boosting. The difference compared with the electrical supplementary heating is that the DH heat is still the main heat source for supplementary heating by the heat pump. The electricity is only used for lifting the energy quality of the heat source. Studies [55, 61-65] make either modelling study or case study of the performance of the heat pump for DHW preparation, by which the energy performance, economy performance, and the CO₂ emission of the heat pump system were investigated based on specific cases.

The electrical heating elements are widely used for domestic heating purpose. As the supplementary heating device, the only energy source of electric heating elements is electricity. It can be storage-type heaters or instantaneous-type heaters. Studies [55-57] investigated the performance of the electrical heating elements for DHW preparation, but considered it as the independent heating method for DHW production. However, if

combined with district heating, the operation of the electrical heating elements can be different, which requires serious consideration on the installation and optimization of the system.

3. Methods

Depending on different theories, the solutions of supplying DHW with LTDH without violating the comfort or hygiene requirements can be sorted into two categories: the sterilization method and the system optimization method. The research methods were different corresponding to their categories. The methods will be introduced in the following sections as:

- 1) For sterilization methods, the mechanism and characteristics were reviewed based on massive literature review. Conclusions were obtained by comparing the advantages and disadvantages, applying difficulty, investments and etc.
- 2) For system design methods, the proposals of the improved system or new-designed system were made for the target DH scenario (LTDH & ULTDH). Evaluation models were built to investigate the energy, economy and exergy performances of the proposed systems. The results were compared to the existing methods for DHW supply.

3.1 Evaluations of the sterilization system

The 1st sub-hypothesis was tested in this section. The evaluation of the sterilization system was based on summarizing the characteristics and mechanism of the treatments. There are many studies can be used as the disinfection methods for Legionella. Substantial laboratory studies or field studies were made to investigate those methods. However, to be used in the DHW system, the candidate treatments were limited to those stable and non-toxic treatment, which are allowed in national water treatment directive. Then the literature-based summarization was made mainly from the following activities:

- 1) Investigate the mechanism of the treatments, so that to confirm if the method works under the LTDH/ULTDH scenario. For example, the thermal treatment requires high temperature to inhibit Legionella, therefore it might not be suitable for LTDH/ULTDH scenario, unless supplementary heating is provided. In terms of the chemical treatments, they can be sorted into oxidizing agents and non-oxidizing agents. The oxidizing agents can still have log 5 disinfection efficacy if the water temperature between 45-50 °C, as the following diagram shows.

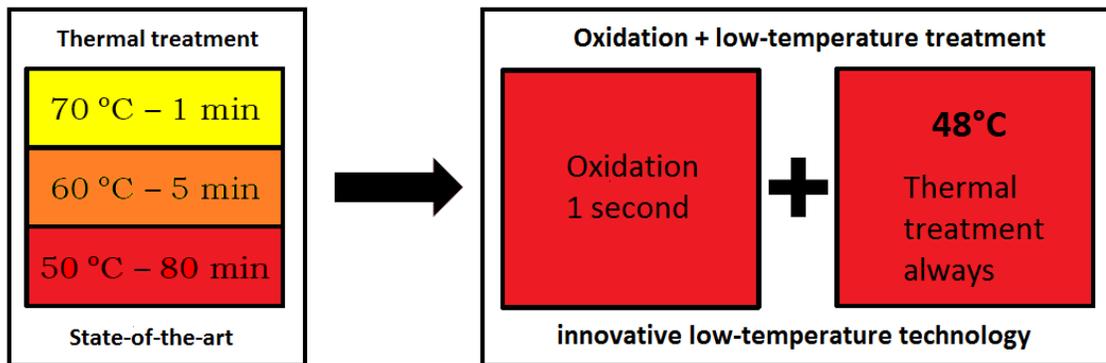


Figure 2 A comparison between the established disinfection technology and the new proposed disinfection technology. It combines oxidation with log 5 bacteria disinfection and depot disinfection with a hot water temperature of 48 ° C in large hot water system. Even at a temperature of 48 ° C, there is still disinfection efficacy[66]

- 2) Investigate the installation and operation difficulty as one evaluation factor. For example, for some chemical treatment, the residual concentration has to be controlled at certain level to maintain the effect. That no doubt will lead to more surveillance to the system, which might increase the labor cost.
- 3) Investigate the cost of each treatment. Depending on specific cases, the overall cost can include the investment, the labor cost, the operation and maintenance cost. Since the cost strongly depend on the specific producer, the local labor market and so on, the summarization can only provide preliminary overview of the relative economy of all the treatment investigated.

More detailed information about the mechanism, operation, advantages and disadvantages, and economy of each sterilization method and the comparisons can be found in Paper 1.

3.2 Description of the DHW substations for LTDH and ULTDH

If applied for LTDH or ULTDH scenario, the existing DHW system configurations that were reviewed in Section 2.2 have to be improved to ensure the comfort and hygiene requirements can be met. In addition, the systems should also be energy and economy feasible. The proposals of the DHW substations for LTDH and ULTDH are described in this section, which established the basis for the answers to the 2nd, 3rd and 4th sub-hypothesis.

3.2.1 DHW systems for LTDH

LTDH has the supply temperature at 50-55 °C at the heat plant. Considering some temperature drop during the heat transmission and distribution process, the temperature reaching the building inlet might around 50°C, which can be sufficient to heat DHW to comfort temperature. But to prevent Legionella for the DHW system, the

existing DHW system has to be changed. The following theories are the basis for the system redesign for LTDH scenario:

- 1) To limit the total DHW volume for each dwelling
- 2) To make supplementary heating locally

Based on those, three DHW systems were proposed with innovative configurations for the LTDH scenario in this section, which are introduced following the depth of the DHW system renovation in the following sections.

3.2.1.1 Central heat exchanger with heat pump

The central heat exchanger is used to replace the heat storage tank, which generates huge heat losses. The schematic is shown in the following diagram.

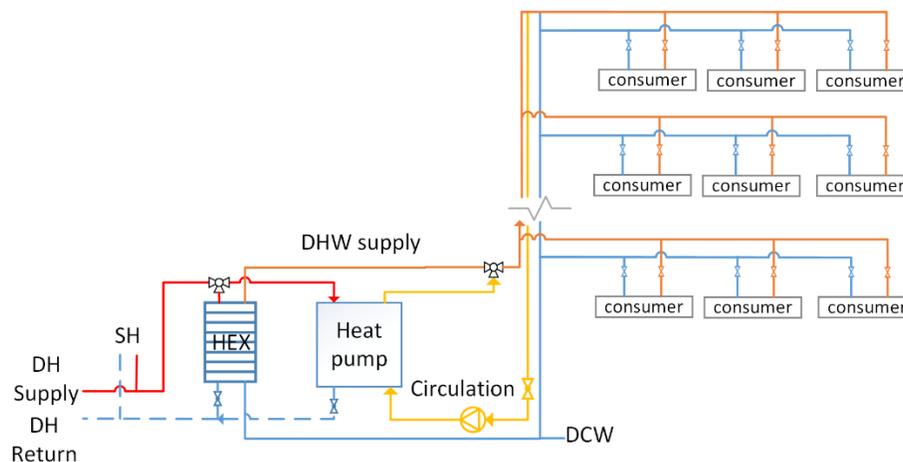


Figure 3 Schematic of the DHW system installing a central heat exchanger combined with heat pump

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.

3.2.1.2 Electric heat tracing

The electric heat tracing method is based on the theory of local supplementary heating. It can be a solution for LTDH supply to multi-storey buildings. The method is to use an electrical cable in thermal contact with the entire length of the external surface of the supply pipe, thereby heating up the supply pipe by electric power. The cable power is adjustable along with the difference between the set-point temperature and the temperature of the water preheated by DH, so that more precise temperature control

can be achieved. Thus no circulation pipe is necessary, saving both pump cost and space. The schematic is shown in the following diagram.

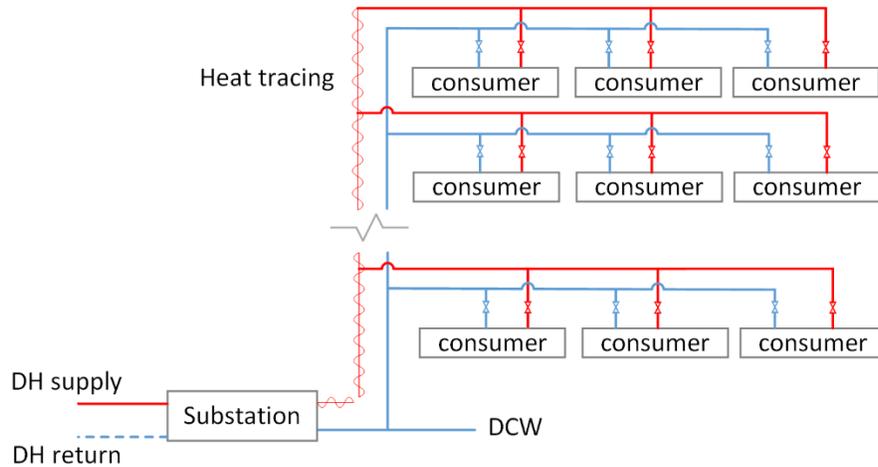


Figure 4 Schematic of electric heat tracing system

The DHW was preheated by the LTDH in the central substation. The electric heat tracing cable was used for supplementary heating and maintaining the temperature of DHW supply pipe according to the comfort and hygiene requirements.

The control methods of the electric tracing cable play an important role in the system energy performance. The current control method of electric tracing cable mainly refers to the self-regulation function correspond to the temperature. which reduces the heating current as the desired temperature is approached and delivers the appropriate amount of heat at every point along the pipe. Therefore, different cable segments could have different power rates. The on/off function can help maintain the cable at set point temperature. However, such control method cannot response to the various tapping pattern.

For multi-storey building, the tapping water has to be heated to 45°C for comfort, while during non-heating season, the supply pipe should be no less than 50 to prevent Legionella and ensure 10s waiting time. Since the user patterns can be various, the control of the tracing cable as supplementary heating method is better to follow the dynamic load profile to avoid unnecessary electricity consumption for heating.

Therefore, a smart control strategy was developed for the electric heat tracing system in this project. The smart control method aims at realizing a dynamic control for the tracing cable on floor basis. By installing temperature sensors and thermostats on each floor, the start and end of the DHW draw-off of each floor can be detected. If DHW tapping was detected on a certain floor, the tracing cable on that floor and below would be switched off, since the pipe is flushing with 45 °C DHW preheated by LTDH. If there is no DHW tapping on the certain floor or the floor above, the tracing cable would be

switched on to heat the supply pipe to 50 °C to avoid Legionella. To investigate the system performance with smart control method, a simulation study was made based on both standard DHW load profile and real load profile. The results were summarized in Paper2.

3.2.1.3 Individual heat exchanger unit (IHEU) with renovation for bypass

The individual heat exchanger unit (IHEU) system is an solution for LTDH in multi-storey building based on the volume limitation theory. Instead of using the centralized substation, a decentralized substation is installed for each apartment. The IHEU can provide space heating and DHW locally. As a result, the DHW volume for each apartment is much reduced, the storage tank and hot water circulation can be avoided. The schematics of the IHEU system for single-family houses and multi-storey buildings are shown in the following diagrams.

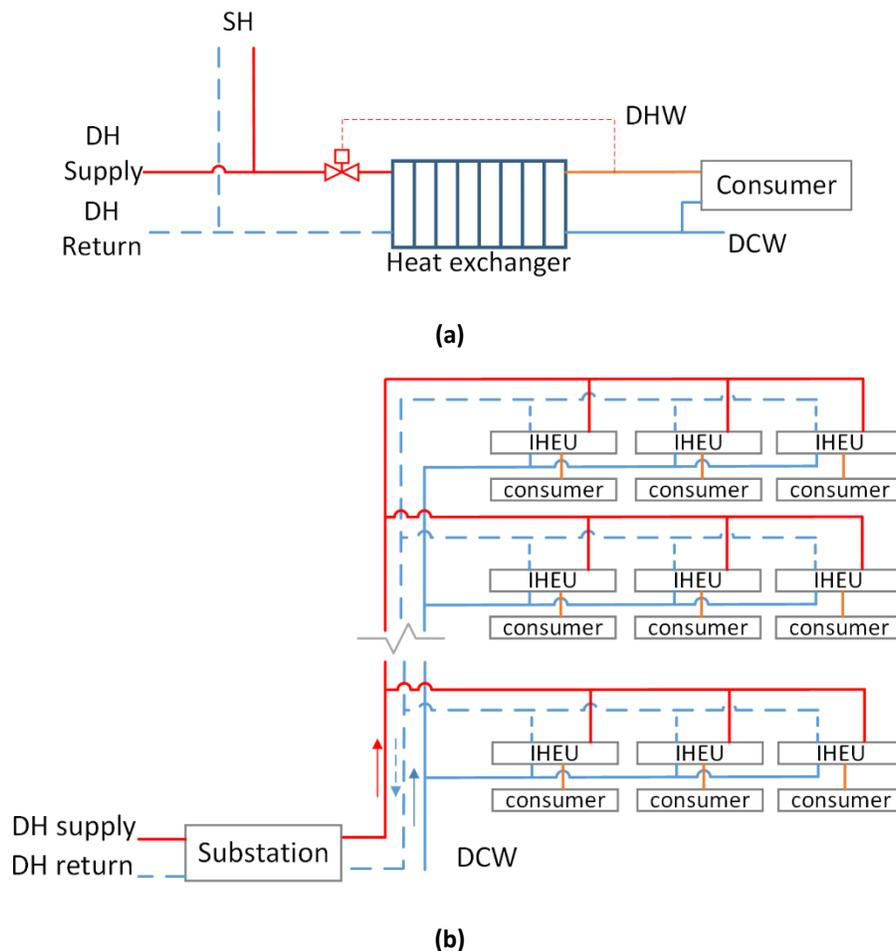


Figure 5 Schematic of decentralized system with IHEU

For the IHEU system, no supplementary heating is required, since the LTDH is able to heat DHW to comfort temperature. The DHW of each apartment is separated from the central DHW supply system. With no circulation and storage, the risk of Legionella is

also eliminated. To ensure the 10s waiting time, bypass is normally required for an IHEU system. However, the mix with bypass results in high return temperature, which reduces the energy efficiency in the DH grid and restricts the utilization of LTDH. To achieve lower return temperature for the IHEU system, possible improvements can be made in two ways: 1) applying an in-line supply pipe and using a heat pump to cover the circulation heat loss, as Figure 6 shown, 2) using better-insulated supply pipe and bathroom heating to replace the bypass.

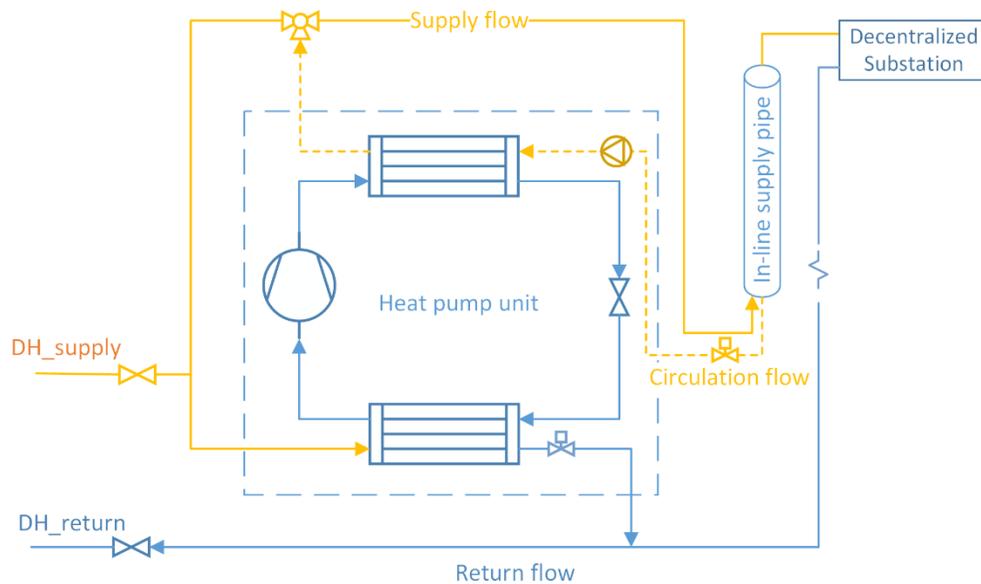


Figure 6 Improved IHEU system with a heat pump and in-line supply pipe

As shown in Figure 6, the in-line supply pipe includes the outer pipe for DH supply water and the inner pipe for the circulation water coming back to the substation. The idea is to use an in-line circulation to keep the supply line warm instead of using the bypass. The operation of the in-line supply pipe was assisted with a heat pump, which aims to cover the heat loss of the supply pipe and maintain the circulation temperature by heating up the circulation water. As a result, the return temperature can be much reduced by avoiding mixing with the bypass flow. Detailed analyses were made on the energy and economy performance of the improved IHEU system compared with the normal IHEU system and conventional circulation system in Paper 3.

In terms of the improvement of redirecting the bypass for bathroom heating, the idea is to keep the supply line warm by the bathroom heating flow. The return temperature can be reduced by efficient heat exchanging for bathroom heating, and the thermal comfort in the bathroom is also improved. No extra devices are required for this improvement, but the supply pipe has to be well insulated. So that the temperature drop caused by the heat distribution process can be covered by the bathroom heating

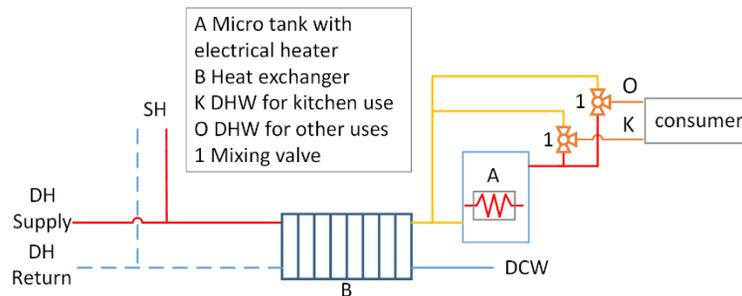
flow. The more concrete analyses about the energy, economy and exergy performance of the IHEU system with bathroom heating can be found in Paper 5.

3.2.2 DHW systems for ULTDH

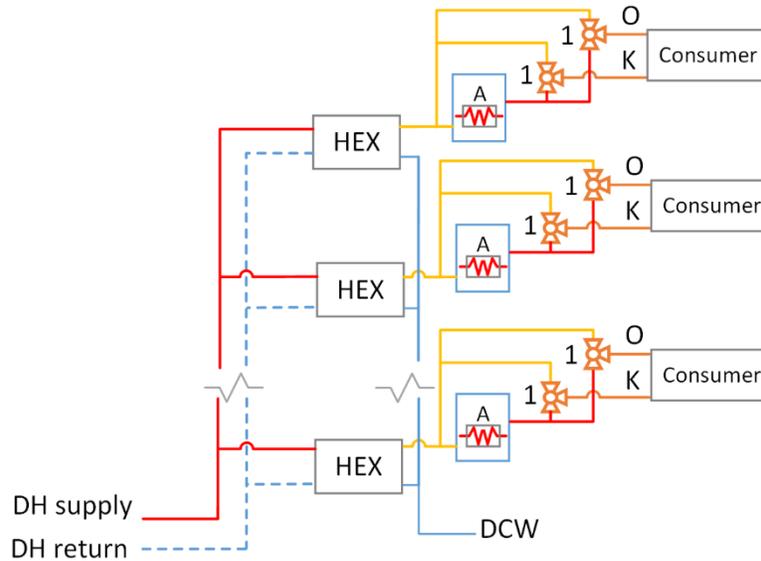
There is no confirmed definition of the supply temperature of ULTDH yet. However, the temperature should be lower than 50, which is the LTDH level. Considering the possible temperature drop during the heat transmission and distribution process, the ULTDH is insufficient to heat DHW to either comfort or sanitary temperature. Therefore, local supplementary heating devices are necessary. Two solutions were introduced in this section.

3.2.2.1 IHEU combined with electrical micro tank

The basis of this solution is the electrical supplementary heating. The electrical heater can heat DHW instantaneously, thereby saving large amount of heat loss generated by the heat storage and circulation. But one problem of applying the electrical heater is that if the DH supply temperature is much lower than the comfort temperature (45 °C), the electricity peak load of the instantaneous heater can be very high, which results in the difficulty of installation with the normal power supply. To address such problem, a new concept of using a micro tank to shave the peak power load of the instantaneous electric heater is proposed in this study. The schematics of the micro tank solution are shown in the following diagram.



(a) Micro tank solution implemented in single-family houses



(b) Micro tank solution implemented in multi-storey buildings

Figure 7 Schematics of electric micro tank system

The micro tank with immersion electrical heater is installed on the consumer side. The DHW is preheated by ULTDH through the heat exchanger. One stream of the preheated DHW is further heated to 60 °C by the electric immersion heater and stored in the micro storage tank to meet the requirement of Legionella prevention. When DHW draw-off occurs, the DHW from the tank is mixed with the hot water preheated by the heat exchanger to reach the comfort temperature. There are two thermostatic valves controlling the mixed temperature of DHW for kitchen use (45 °C) and other uses (40 °C). Such system has the benefit of lower return temperature since the bypass is unnecessary for maintaining the supply line warm. Moreover, the micro tank with small power rate is feasible to be implemented by the normal power supply. The reduced tank size also minimizes the heat loss.

3.2.2.2 Micro heat pump

Micro heat pump can be a solution of DHW supply for single-family house with ULTDH. It is based on the local supplementary heating theory. Unlike other supplementary approaches with electricity, DHW is not directly heated by electricity in the micro heat pump solution, the main heat source is still the ULTDH water. The schematic of micro heat pump is shown in the following diagram.

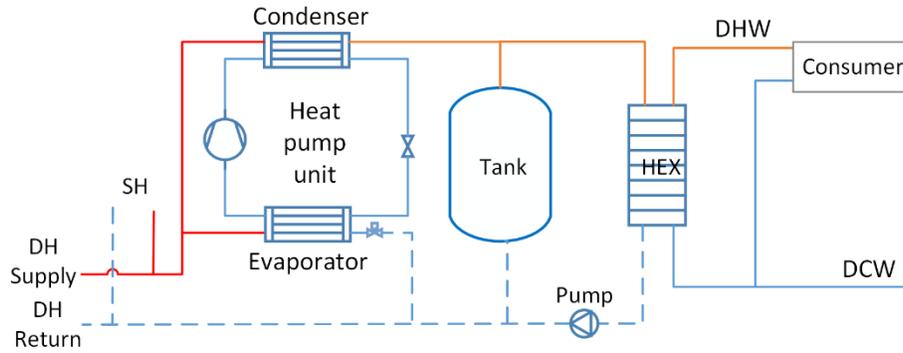


Figure 8 Schematic of micro heat pump system

As shown in the diagram, the ULTDH supply is divided into two streams, one of which is used as the heat source. The thermostat on the outlet of the evaporator can ensure efficient cooling for the return flow of the heat pump. Using the heat pump, the ULTDH supply can be heated to 50 °C and stored in the tank. Compared to direct electrical heating, the micro heat pump system consumes much less electricity to heat equivalent amount of DHW compared to electrical supplementary heating devices. The storage tank helps to maintain stable operation for the heat pump. Since the tank is installed on the primary side, the risk of Legionella is eliminated.

3.3 Theoretical basis for evaluation models of different DHW systems

To make recommendation of the optimal solution for the respecting DH condition, the performance of the proposed systems were evaluated from the energy, economy and exergy aspects by individual model, so that to investigate the 5th sub-hypothesis. The influence caused by different building topologies are taken into account. The following sections describe the general theories for setting up the models.

3.3.1 Energy evaluation model

The energy evaluation model mainly investigates the overall energy consumption of different solution systems for preparing DHW, including both the DH heat and energy for supplementary heating. In this study, the overall energy consumption constitutes of the DHW demand, the equipment heat loss and the heat loss of the distribution pipe inside the building. Since the system configurations are distinct from each other, to meet the comfort and hygiene requirements, the required overall energy for the whole DHW preparing process are different. The operation temperature for each case followed the system description 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:

$$Q_{tot} = Q_{dhw} + Q_{eq} + Q_p \quad (1)$$

where

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

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

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

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

The heat loss of the equipment can be found in the product catalogue.

The heat loss of the pipe can be calculated as

$$Q_p = \sum L_i * q_i * (t_i - t_{amb}) * \tau \quad (2)$$

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].

Considering the energy sources, the total energy consumption for DHW preparation can be calculated as:

$$Q_{tot} = Q_{dh} + Q_{el} \quad (3)$$

where

Q_{dh} is the heat from district heating for DHW production [kWh],

Q_{el} is the electricity consumption of the supplementary heating devices for DHW production [kWh].

The relative DH heat and electricity consumption can be calculated as:

$$\varepsilon_{dh} = Q_{dh}/Q_{dhw} \quad (4)$$

$$\varepsilon_{el} = Q_{el}/Q_{dhw} \quad (5)$$

where

ε_{dh} , ε_{el} are the relative use of DH heat and electricity.

More details of setting up the energy evaluation models for all investigated scenarios can be found in Paper 4 and Paper 5.

Because the primary factor of electricity is 2.5 times as much as that of the DH heat, with the same total energy consumption, the solution that has less electricity consumption has better energy performance. Therefore, the relative heat and electricity consumption are important factors for energy performance evaluation.

3.3.2 Economy evaluation model

The economy performance of the DHW supply methods mainly refers to the energy cost and the benefits for the DH system due to the low return temperature.

Due to different primary energy factor, the prices of DH and electricity are different. In this study, the price of DH and electricity were assumed to 0.8 DKK/kWh, and 2 DKK/kWh respectively. The overall energy expenses can be calculated as:

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

where

C_{tot} is the total energy cost [DKK],

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

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

With information of investment and maintenance, life circle assessment of the economy for specific substations can be made.

The levelized cost can be calculated as:

$$LC = \frac{(C_{inv} * CRF * n) + C_{O\&M} * n + P_{int} * Q_{dhw_y} * n}{Q_{dhw} * n} \quad (7)$$

where

LC is the levelized cost [DKK/kWh],

CRF is the capital recovery factor [%],

n is the life time [year],

C_{inv} is the investment cost, information from the local DH company [DKK/ unit],

$C_{O\&M}$ is the operation and maintenance cost [DKK/year],

Q_{dhw_y} is the annual DHW demand [kWh].

The capital recovery factor can be calculated as:

$$CRF = \frac{i * (1+i)^n}{(1+i)^n - 1} \quad (8)$$

where

i is the interest rate, in this study i was assumed to 6%.

More detailed analyses of the levelized cost of different DHW configurations can be found in “the 4th article”.

By optimized design and efficient operation, low return temperature can be reached by low-temperature district heating. The resulting benefits includes the savings in the heat production (improve the efficiency of the flue gas condensation), savings of the pump power, and savings of the pipe heat loss in the DH grid. According to a Swedish investigation to [10], the cost reduction caused by the low return temperature is estimated to 0.16 EURO/MWh · °C considering all the possible saving factors.

$$E_s = \varepsilon \cdot Q_{sup} \cdot \Delta t \quad (9)$$

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 reduction of the return temperature [°C].

In Denmark, the district heating company of Middelfart Fjernvarme estimated the saving coefficient caused by low return temperature, and proposed subsidy policy based on the result to encourage approaches of efficient cooling. It was stated that if the return temperature is below 42.9 °C, for every 1 °C reduction, the DH company can obtain 1% saving on the overall cost, which equals 0.73 DKK/GJ subsidy[67].

Paper 5 described more detailed economy-evaluation model of each DHW supply method investigated.

3.3.3 Exergy evaluation model

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

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \quad (10)$$

$$Ex_{out} = Q_{dhw} \left(1 - \frac{T_0}{T_{dhw} - T_{dcw}} \ln \frac{T_{dhw}}{T_{dcw}} \right) \quad (11)$$

$$Ex_{in} = Q_{dh} \left(1 - \frac{T_0}{T_{sup} - T_{ret}} \ln \frac{T_{sup}}{T_{ret}} \right) + W_{el} \quad (12)$$

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 45 and 10 respectively [°C],

T_{sup}, T_{ret} are the supply and return temperature of 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].

3.4 Comparisons of the different solutions

According to the theoretical models introduced in Section 3.3, the performances of the proposed DHW supply methods can be investigated. The performances of the proposed solutions with LTDH/ULTDH were evaluated by both specific and general comparisons to the conventional DHW supply methods with the 3rd generation DH. Thereby, the sub-hypothesis 2,3,5 can be tested. In addition, the case study of the ULTDH implementation in a Danish city was carried out to verify the estimation of the theoretical model and examine the sub-hypothesis 4.

3.4.1 Comparison 1 – Electric heat tracing system with LTDH and conventional circulation system with MTDH

Comparison 1 tests the 2nd sub-hypothesis. A smart control method was developed for the electric heat tracing system as described in Section 3.2.1.2. Compared with the normal control method, the smart control method is able to respond to the DHW load profile and adjust the cable power dynamically. The smart control method were developed in Matlab, the flowchart is shown as the following:

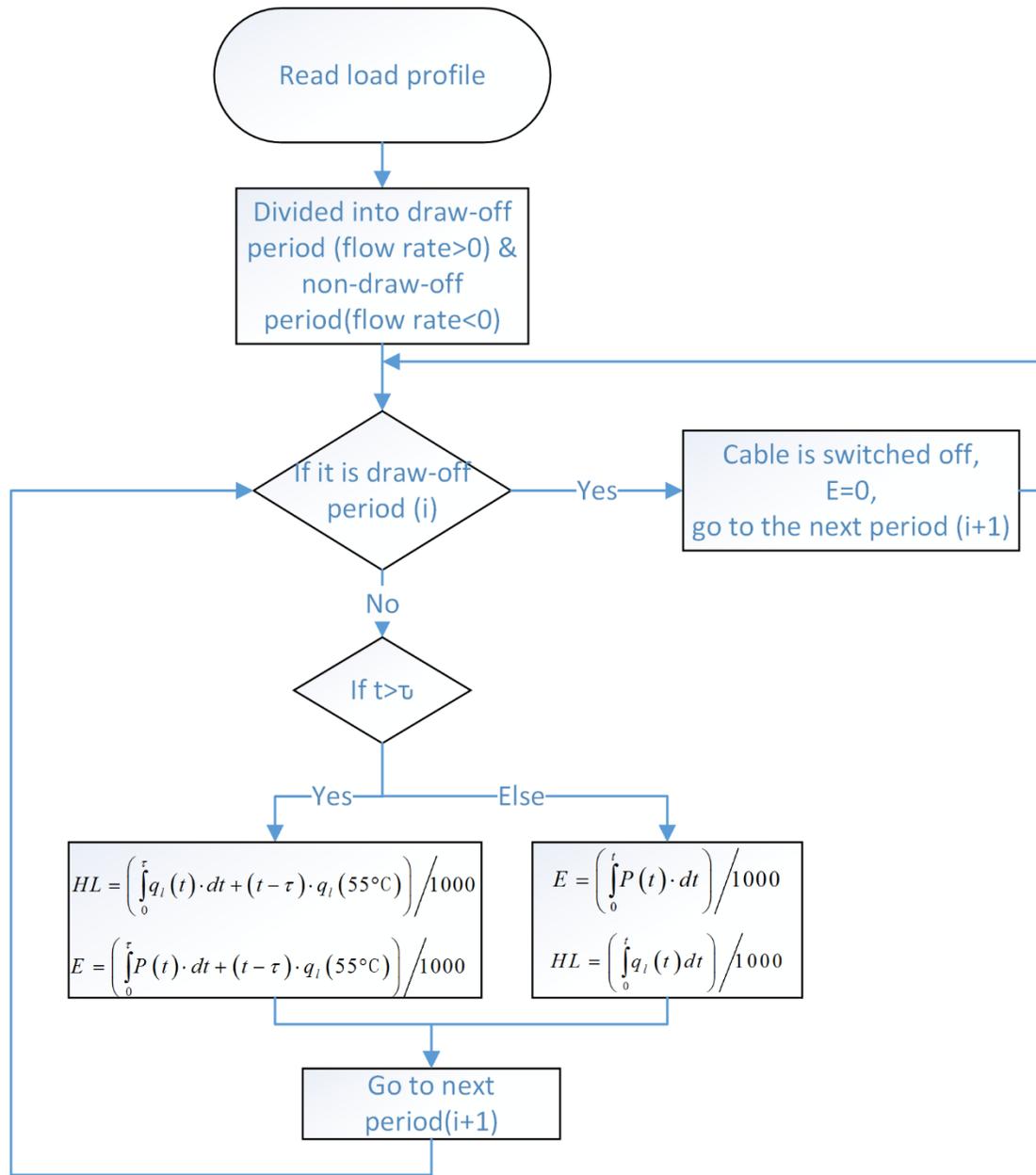


Figure 9 Logic for developing the smart control method in Matlab

The power rate of the cable was given by the real product catalogue, assuming the cable heats the DHW from 45 °C to 55 °C, the required time can be calculated as:

$$\tau = \int_{T_1}^{T_2} \frac{(C_p \cdot m) / 3600}{P(T) - q_l(T)} dT \quad (13)$$

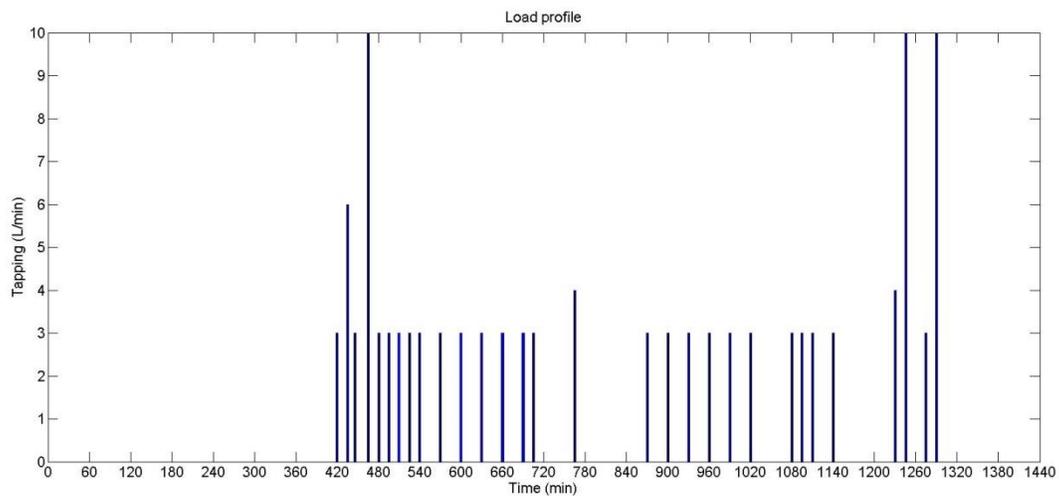
where

$P(T)$ is the cable power rate, which correlates to the temperature of the heated media [W],

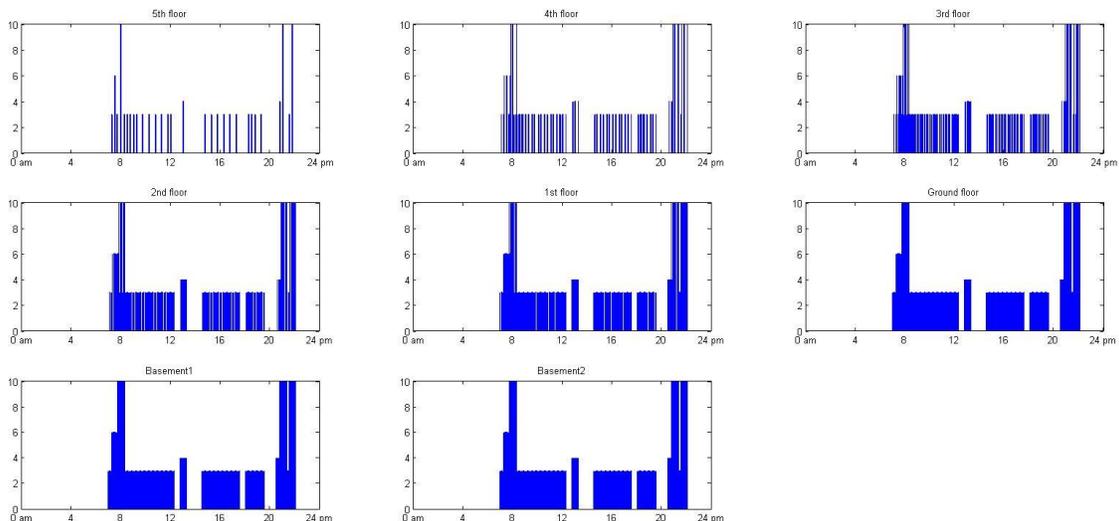
$q_l(T)$ is the heat loss rate of the supply pipe, which also correlates to the temperature of the heated media [W].

The interval length between two draw-offs determined the working time of the tracing cable. Depending on whether it was longer or shorter than the heat-up time, the electricity consumption and heat loss were calculated by different equations respectively.

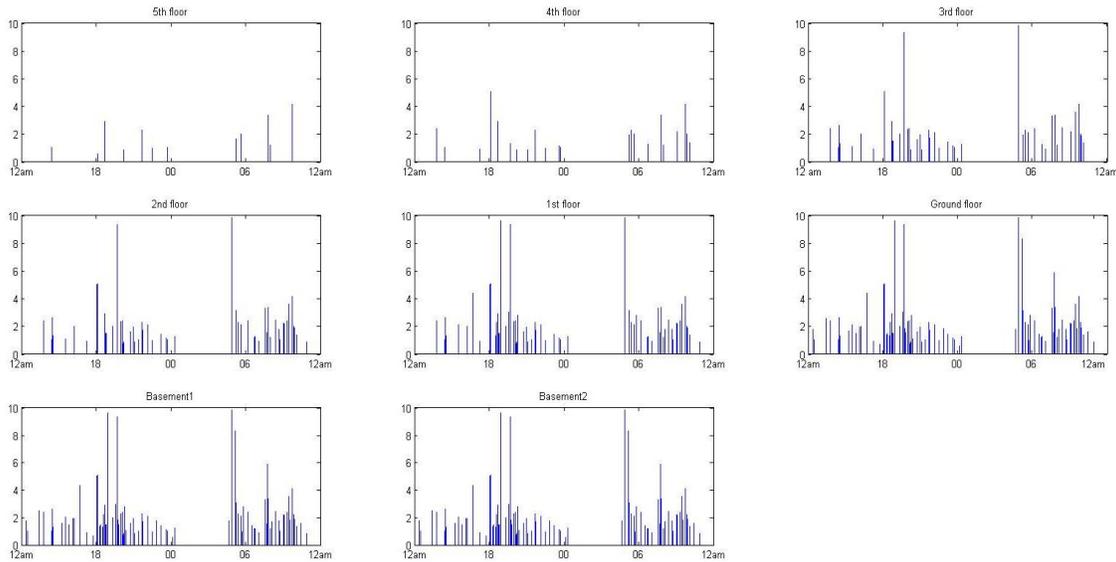
To test the impact of the DHW load profile on the energy performance of the electric heating tracing system, a case building that has 6 floors with two apartments on each floor was used for the analysis. Three types of DHW load profile were applied to the model. The three load profiles are shown in the following:



(1)



(2)



(3)

Figure 10 DHW load profiles for the models with time (hr) and flow rate (L/min)

Load profile 1 is the reference DWH load profile for European families [68], and it was assumed all apartments in the building followed the same DWH load profile, which was an extreme case. Load profile 2 based on profile 1, but distributed the standard load profile stochastically for different consumers to be more realistic. It was assumed that there was no overlapping on the starting points of the first tapping from different consumers. Load profile 3 is the measurement from a case building. Since the smart control method was assumed to be operated on every floor independently, Figure 10 shows the flow of the pipe segment on every floor. Thus, the performance of electric heat tracing system was investigated based on 3 different load profiles controlled by normal or smart method, which is 6 scenarios in total. To investigate the benefit of applying the electric heat tracing system with LTDH, the results were compared to the conventional in-line circulation system.

More detailed analyses can be found in Paper 2.

3.4.2 Comparison2 – Decentralized substation system with LTDH and conventional circulation system with MTDH

Comparison 2 aimed at testing the 3rd sub-hypothesis. Three scenarios were devised for the comparison. The conventional circulation system supplied by MTDH was used as the reference system for the comparison. The scenario of decentralized system supplied by LTDH (55°C) was built based on the information from a real case in Denmark. The 3rd scenario was a further development of scenario 2, which improved the return

temperature by using a central heat pump and in-line circulation (as described in Section 3.2.1.3).

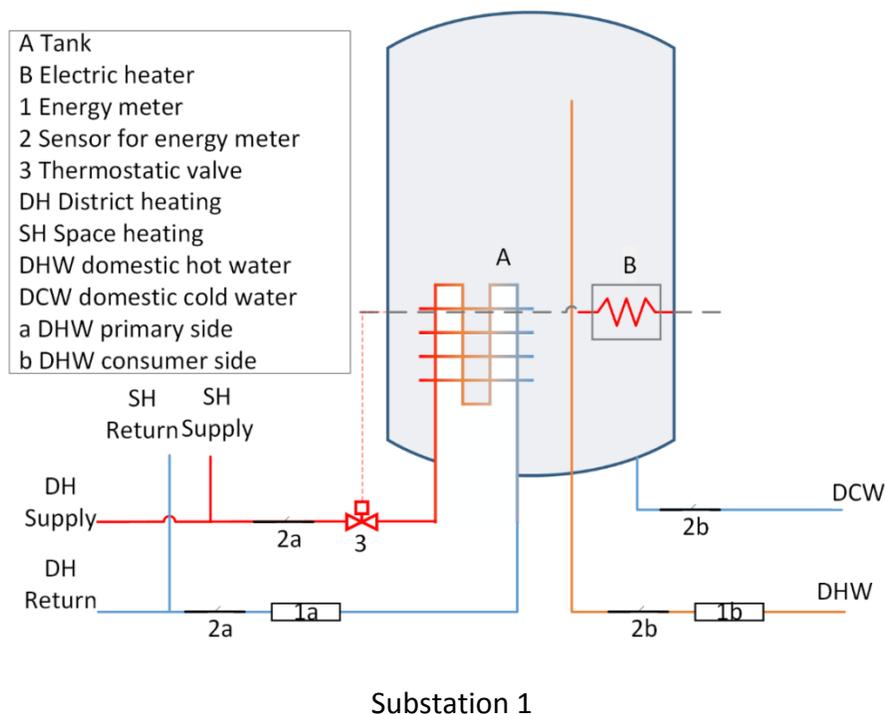
To form a fair comparison, the DHW heat demand was assumed to be the same for three scenarios. Thus, the analysis of the energy performance mainly refers to the distribution heat loss inside the building. The analysis was divided into heating season and non-heating season because of the different operation method of the IHEU system. It was assumed that the bypass is only required during the non-heating season, since the space heating flow is sufficient to keep the supply line warm. Accordingly, the heat pump is only operated in non-heating season in scenario 3.

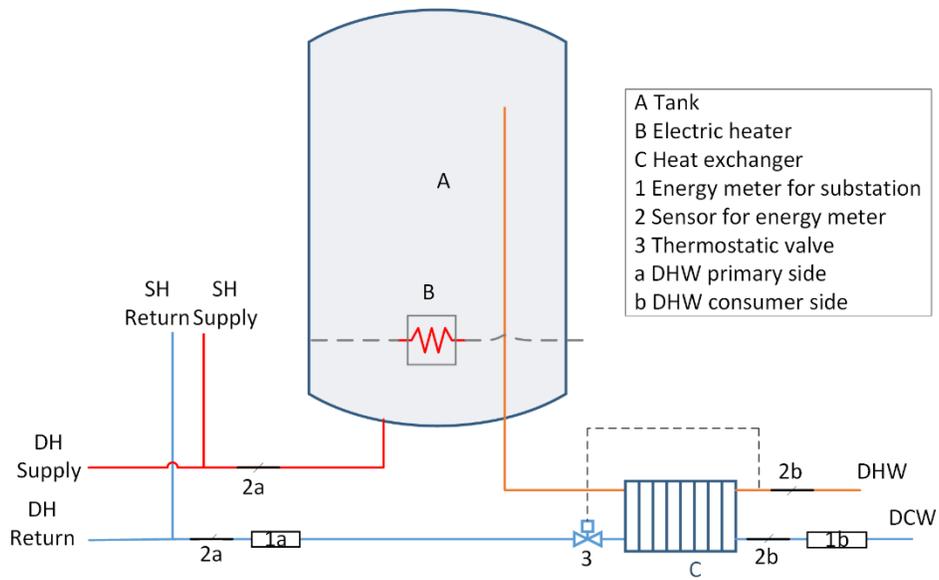
The distribution heat loss and the respecting cost of scenario 2 and scenario 3 were compared to scenario 1 (which is the conventional system with MTDH), so that the benefit of low-temperature supplied IHEU system and improved IHEU system can be featured step by step.

More detailed analyses can be found in Paper 3.

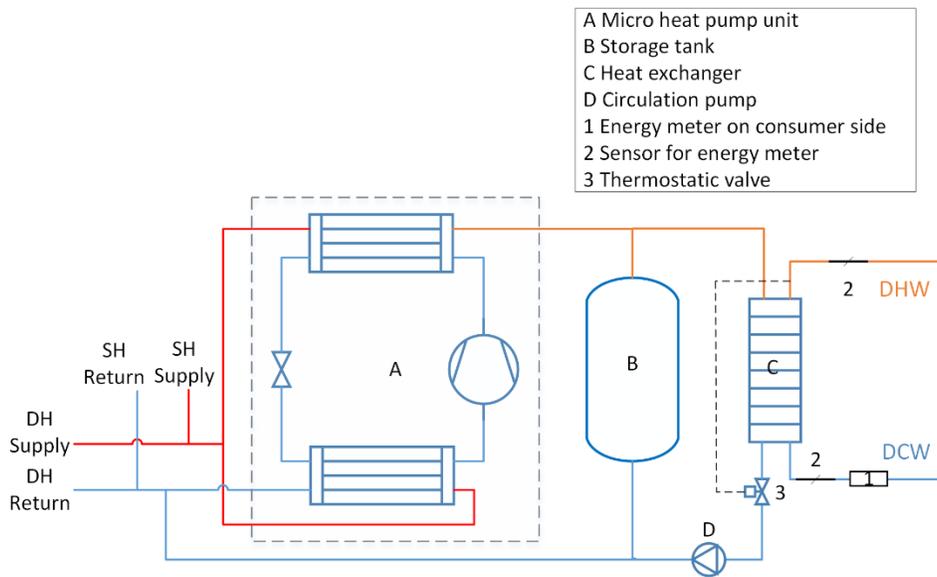
3.4.3 Case study of 5 single-family houses supplied from ULTDH

A case study that implemented ULTDH was carried out as the investigation of the energy and economy feasible DHW supply approaches for ULTDH, which helps to test the 4th sub-hypothesis. The practical measurements were performed in five case houses in the ULTDH supplied area. A local heat pump provided DH at 46 °C by using the industrial excess heat produced by a local pump factory. The substation layouts in the five case houses are shown as the following:

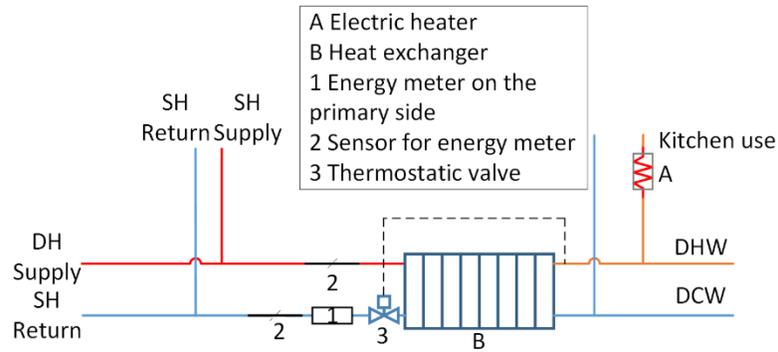




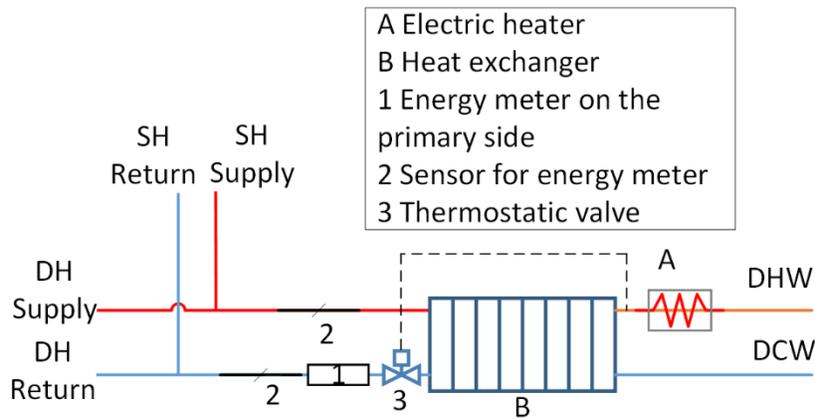
Substation 2



Substation 3



Substation 4



Substation 5

Figure 11 System configurations of the five measured substations

The measurements were operated for long term. But for the analysis of this study, the measurements of May 2015 were selected, and 6th May was selected as a typical day for investigating the daily variation in the temperatures.

Two sets of energy meters were installed for the measurements: the meters for heat consumption in the substations, and the meters for electricity consumption. The energy meters in the substations were set with a time step of 1.5 minutes, so that they would be able to detect DHW draw-off. The meters recorded data for instantaneous supply/return temperatures, instantaneous flowrate, accumulated heat consumption, and accumulated water volume. The meters for electricity consumption only measured the electricity for DHW production. The electricity measurement was recorded on a monthly basis.

In addition to the measurements, separated models were built for each substation under the standardized condition. The system performances of each substation for covering the same DHW demand without violating any comfort and hygiene requirements were investigated. It was assumed that all the pipes and heating devices

were dimensioned and insulated strictly in accordance with the standards, and that unnecessary heat loss from the heat exchanger and bypass flow could be avoided. To meet the DHW energy demand requirement for energy-efficient buildings in 2020[10], which is $13\text{kWh/m}^2 \cdot \text{yr}$, the DHW demand was assumed to be 2000 kWh/yr (approx. 170 kWh/month) for all the substations investigated to make a fair comparison.

The relative heat and electricity consumption under the standardized condition were calculated for each substation as an important indicator of system performance. The results were compared to the measurements to indicate whether error occurred in the operation process.

The levelized cost were calculated as introduced in section 3.3.2. The investment cost, operation and maintenance (O&M) cost, and energy cost were included. The investment cost includes the expenses of the equipment and the installation. The investment of the measured substations was obtained from the local DH company. The O&M cost was assumed to be 2% of the investment. The life time of all the heating units was assumed to 20 years. The method is well described in [57].

To verify the feasibility of applying the electrical heater (Substation 4 and Substation 5) with normal power supply, the power peak of substation 4 and substation 5 were calculated. Considering substation 4 and substation 5 have no storage tank and no DHW circulation, the electrical heater should be sufficient to heat DHW to comfort temperature ($45\text{ }^\circ\text{C}$ for kitchen use and $40\text{ }^\circ\text{C}$ for other uses) combined with ULTDH. The overall peak load of DHW was assumed to have kitchen tapping and shower at the same time, which is equivalent to 32.3 kW[50]. The electricity was used to heat DHW from $40\text{ }^\circ\text{C}$ to $45\text{ }^\circ\text{C}$. The electricity peak load of substation #4 and #5 can be calculated as:

$$E_4 = 4.2 * 0.1 * (t_{el} - t_m) \quad (14)$$

$$E_5 = E_s * \frac{(t_{el} - t_m)}{(t_{el} - t_{dcw})} \quad (15)$$

where

E_4 is the peak load of electricity in substation #4 [kW],

E_5 is the peak load of electricity in substation #5 [kW],

t_m is the DHW temperature after preheated by ULTDH [$^\circ\text{C}$],

t_{el} is the DHW temperature heated by the electrical heater [$^\circ\text{C}$],

0.1 is the DHW flowrate for kitchen use, which regulate by the standard[50] [L/s],

t_{dcw} is the temperature of the cold water, which was assumed to 10 [$^\circ\text{C}$],

E_s is the overall peak load in substation #5, which is 32.3 [kW].

3.4.4 Comparisons of DHW supply methods with MTDH, LTDH and ULTDH

A large-scale comparison was made for different DHW supply methods with MTDH, LTDH and ULTDH for covering the equivalent DHW demand. The aim is to specialize the optimal method for the specific situation. In addition, potential benefit of LTDH/ULTDH can be yielded by comparing with the MTDH scenario. The individual evaluation models were built for different DHW systems based on the theoretical basis (Section 3.3). However, certain adjustment was made by taking into account the specific situation of each investigated system. Three DH scenarios were defined as the background for the evaluation models: medium-temperature district heating (MTDH) with supply temperature at 65 °C at the building entrance, low-temperature district heating with supply temperature at 50 °C at the building entrance, and ultra-low temperature district heating with 35 °C at the building entrance.

The building typology was taken into account for the analyses: the single-family house and the multi-storey building. To make fair comparisons, all methods investigated were modelled as to cover the equivalent DHW demand. It was 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, so that the DHW can be produced at comfortable temperature (45 °C) with standardized volume (250L/m² · yr)[69]. The floor area for single-family house and multi-storey building were assumed to 150 m² and 90 m² according to the Danish Statistic Yearbook. The multi-storey building was assumed to have six floors with 3 apartments on each floor, and the riser length of each floor was assumed to be 3 m. Considering the different operation modes, some systems may prepare DHW at higher temperature due to the concern of Legionella, but the temperature at the faucet can be adjusted to 45 °C ultimately by mixing with DCW. In order to make more standardized analysis, the evaluation models were characterized on dwelling basis, which means for multi-storey building, the evaluation results were specified to one flat.

The investigated scenarios are shown in the following table:

Table 2 Proposed DHW supply approaches considering different DH supply and building typologies

Single family house					
MTDH		LTDH		ULTDH	
With tank	IHEU with bypass	IHEU with bathroom heating		Micro tank	Micro heat pump
Multi-storey building					
MTDH		LTDH			ULTDH
With tank and circulation	IHEU with bypass	Central HEX with heat pump	IHEU with bathroom heating	EI-tracing	Micro tank

For the details about how to set up evaluation models for each approach in Table 2, the procedure can be found in Paper 5.

4. Results

To test the main hypothesis that it is possible to supply DHW with low-temperature district heating meeting the comfort and hygiene requirements if appropriate solution is applied, this research was divided into five parts corresponding to the five sub-hypothesis. Both the theoretical work and field work were carried out for this research. The approval or rejection of the sub-hypothesis were determined according to the results of the investigations.

4.1 Evaluation of the sterilization methods

Based on the summarization of the substantial literature review, the properties of the available solutions are shown in the following table.

Table 3 Properties of the investigated sterilization methods

	Methods	Efficacy	Operation activity	Additive to water system	Investment Cost	Effective range	Feasibility & regulations
Thermal treatment	Heat flushing	Short	Temperature & operation time control	No	Low	systematic	No limits
	Ionization	Long term	Residual control	Yes	Medium	on-site	A+B
Chemical treatment	Chlorine	Long term	Residual control	Yes	Low	systematic	A
	Chlorine Dioxide	Short term	Residual control	Yes	Low	on-site	A
	Photocatalysis	Long term	Residual control	No	Medium	on-site	No limits
	Ultraviolet Light	Short term	-	No	Medium	on-site	No limits
Physical treatment	Filtration	Short term	-	No	High	on-site	No limits

* “-” represents for none specific control

* “A” the concentration of the agents must comply with local water quality regulations

* “B” not applicable in some countries

With respect to the limitation by low-temperature district heating and the regulation for water quality in Denmark, the approaches of photocatalysis, UV light and filtration can be feasible sterilization method to apply. The other factors shown in Table 3 should also be taken into account when making the decision for a specific case. For example, to apply photocatalysis or UV light, the installation location has to be carefully planned to ensure the utmost efficacy. The filtration has good efficacy, however, the extra cost for regular replacement has to be considered in the long run.

4.2 Performance of the smart-controlled electric heat tracing system with LTDH

The Matlab model simulated the work performance of the electric tracing cable with smart control method and normal control method, which is shown in the following diagram:

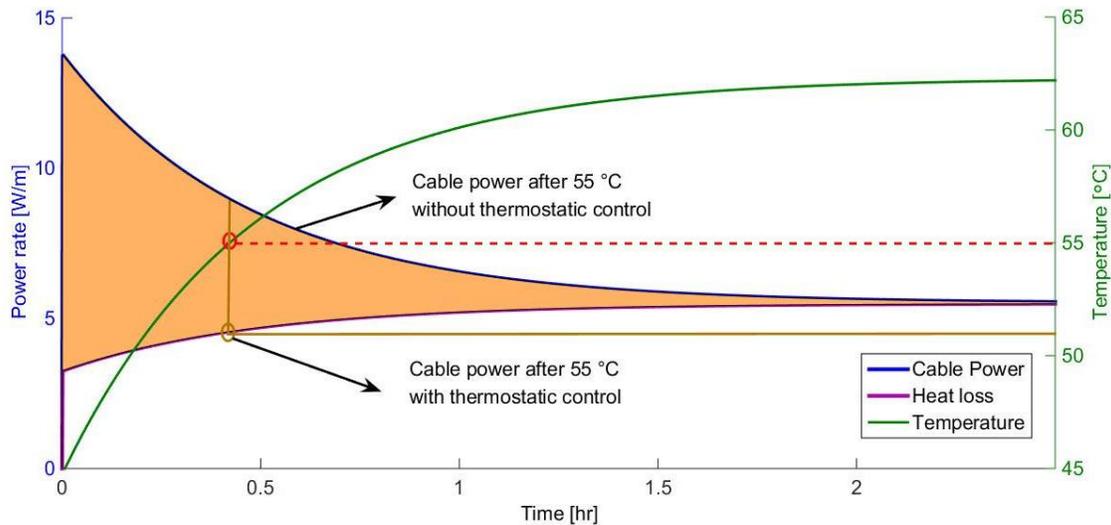


Figure 12 Dynamic working process of the tracing cable M for stainless steel plus on 5th floor with/without thermostatic control

With smart control method, the thermostat on each floor is able to reduce the cable power to only covering the heat loss independently after the set point temperature (55 °C in this case) is reached. In contrast, the normal control method only has one thermostat installed normally on the bottom floor, which can lead to overheating for other floors. The savings are quantified as the area between the blue curve and the brown line in the diagram (in relation with the time).

To test the impact of control methods and DHW load profiles, the authors built six scenarios with 3 different DHW load profiles and 2 control methods, the energy performances of the 6 scenarios are shown in the following table:

Table 4 Total electricity consumption and electricity for covering heat loss in different scenarios when applying electric heat tracing

	Load profile 1 [kWh/year]		Load profile 2 [kWh/year]		Real data [kWh/year]	
	Total electricity consumption	Heat loss	Total electricity consumption	Heat loss	Total electricity consumption	Heat loss
Smart control	8960	4551	4179	2650	8895	3780
Normal control	11286	5306	10467	3626	11294	4379

As shown in Table 4, compared with normal control, applying smart control saved 20.6%, 60.1%, and 21.2% on the total electricity consumption for the cases of Load profile1, Load profile 2, and the real data, respectively. The heat loss was also reduced by approximately 14-27%. That was because the smart control method helped avoid overheating of the pipes. Moreover, unnecessary power consumption was saved by switching off the heat tracing cable during draw-off periods.

Another thing should be noticed of is that among different load profiles, the total electricity consumptions under the normal control method were very similar. But with the smart control method, the load profiles played an important role in the total power consumption. The difference between the Load profile1 and Load profile2 under the smart control method was almost 50%. If the system has a high simultaneity factor, as in Load profile 1 in this case, the tracing cable has to heat up hot water for more intervals, which will undoubtedly lead to more power consumption. So the complex use of domestic hot water corresponds to the improvement of energy efficiency of the electric heat tracing system.

Comparison were made between the in-line circulation system and electric heat tracing system on the annual energy consumption for DHW distribution. The results are shown in the following diagram.

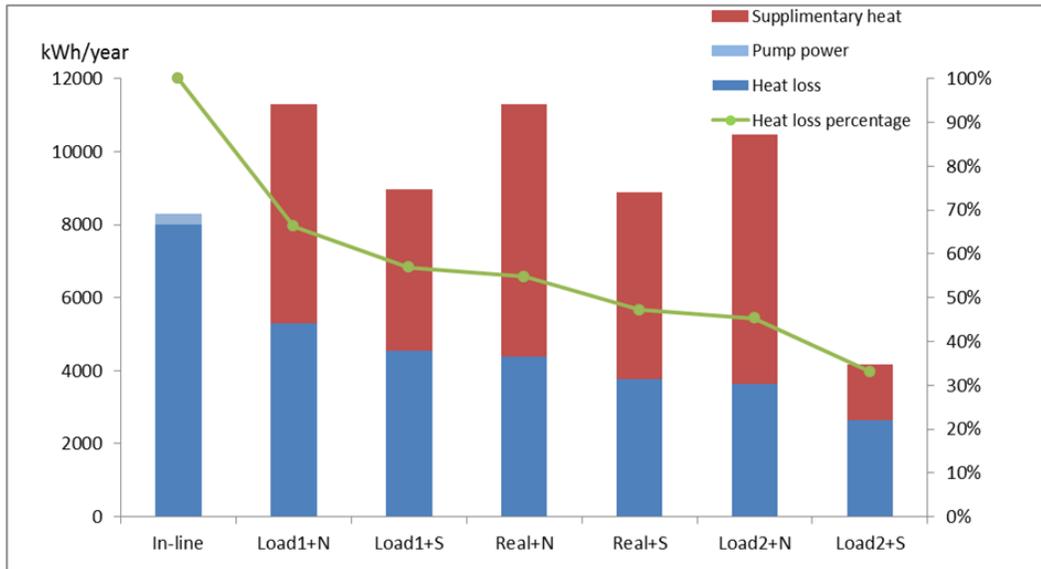


Figure 13 Comparison of annual energy consumption between circulation and electric heat tracing systems

***S- smart control, N- normal control**

According to the energy frame for the Danish dwellings[10], 46800kWh energy is allowed for DHW use in the case building annually. The heat loss of the in-line circulation system, which was approximately 8000 kWh per year, was greater than the heat loss in any of the electric heat tracing scenarios. Compared to the in-line circulation system, the heat loss reductions in the different electric heat tracing scenarios ranged from 34%-67%. However, for the electric heat tracing system, a large proportion of the overall electricity consumption was used as supplementary heating for DHW to avoid the problem of Legionella. But the district heating network only had to heat up hot water to 45 °C instead of 60 °C for the circulation system. Thereby, a large amount of heating energy can be saved from the district heating network. This means, it will be possible to make lower district heating price for the consumers, so that to compensate the extra expense by electricity. The break-even district heating price was calculated as 0.69 DKK/kWh.

The annual operation cost was also compared. With smart control method, the scenario with measured DHW load profile only spent 1000 DKK more on DHW distribution for the whole year based on the assumption that the prices of DH and electricity are 0.8 DKK/kWh and 2.0 DKK/kWh respectively.

4.3 Performance of the improved decentralized substation system with LTDH

Since the three DHW supply methods were assumed to cover the same DHW demand, and all the pipe heat loss inside the apartments were assumed to be identical, the distribution heat loss is of great importance for evaluating the energy performance of

investigated DHW supply methods with respecting DH systems. We built up models for simulating the heat loss of a devised scenario of IHEU supplied by LTDH. A case building with IHEU but supplied by MTDH was used to test the accuracy of the model. At first, the model was run with the identical input parameters as the real case. The results of the model and the measurement from the case building were compared. The deviation of the return temperature and the annual heat loss were within the acceptable margin. Afterwards, the supply temperature of the ideal model was adjusted to 55°C to simulate the system performance with LTDH supply. The distribution heat loss of the three scenarios are shown in the following table.

Table 5 Distribution heat loss for the three scenarios [kWh]

		Scenario 1		Scenario 2	Scenario 3
		Space heating loop	Domestic hot water loop		
Heating season	supply	1230	3952	2978	3233
	return	406	-	496	496
Non-heating season	supply	884	2852	2149	2333
	return	293	-	1714	358
Tank			840	-	-
Annual			10457	7337	6420
Heat loss savings			0%	30%	39%
Compared to Scenario 1					

Compared with the in-line circulation system, the IHEU system with LTDH can save 30% of the annual distribution heat loss and the improved IHEU system supplied by LTDH can save 39% distribution heat loss.

The resulting costs for DHW distribution were also calculated as the following:

Table 6 The cost of covering the distribution heat loss for the three scenarios

Costs	Scenario1	Scenario 2	Scenario3	
			Heat	Electricity
Cost of supply line	7807	4101	3987	700
Cost of return line	599	1768		683
Total annual cost caused by the distribution heat loss [DKK/yr]	8366	5869		5370

The improved IHEU system spent less money on the DHW distribution, even though it used electricity for covering the heat loss of the supply line. But by eliminating the bypass, the heat loss of the return line much reduced due to the lower return

temperature. In addition, lower return temperature also makes savings for the DH system.

4.4 Comparisons of 5 substations with ULTDH supply

All measured substations have supplementary heating devices. The measurements show that with well-operated supplementary heating devices, the ULTDH can supply DHW meeting both comfort and hygiene requirements. However, the energy and economy performances of the 5 substations are different because of their different configurations. The measurements of DH water usage, average supply/return temperatures are shown in the following table.

Table 7 Measurements of the accumulated volume of DH water on the primary side for DHW production and average supply/return temperatures in May

	#1	#2	#3	#4	#5
DH water consumption [m ³]	5.9	5.5	51.4	16.0	5.9
Average Supply Temperature [°C]	40.4	40.0	42.9	42.5	43.4
Average Return Temperature [°C]	27.9	27.4	40.0	39.6	37.2

From the table, substation #3 with a heat pump required significantly larger volume of DH water than the others, because extra volume of district heating water was used as the heat source for the heat pump. The high average return temperature in substation #3 might be explained by incorrect control of district heating water through the evaporator of the heat pump. In substations #4 and #5, the bypass flow to maintain acceptable waiting time mixed directly into the return line, which played a role in increasing the average return temperature.

In June 2015, substation #4 and #5 changed the heat exchanger with better performances but the same capacity. We performed supplementary measurements, and the return temperature of substation #4 and #5 obtained significant improvement after the renovation. The measurements after the renovation are shown in Table 8.

Table 8 Measurements after replacing the heat exchangers in substation #4 and #5 (in July)

	#1	#2	#3	#4	#5
Accumulated water volume delivered by DH [m ³]	3.7	3.9	46.4	1.4	0.8
Average Supply Temperature [°C]	38.3	42.9	41.3	40.8	41.5
Average Return Temperature [°C]	29.4	35.2	40.1	21.9	22.7

The heat and electricity supplied for DHW preparation are shown in Figure 14.

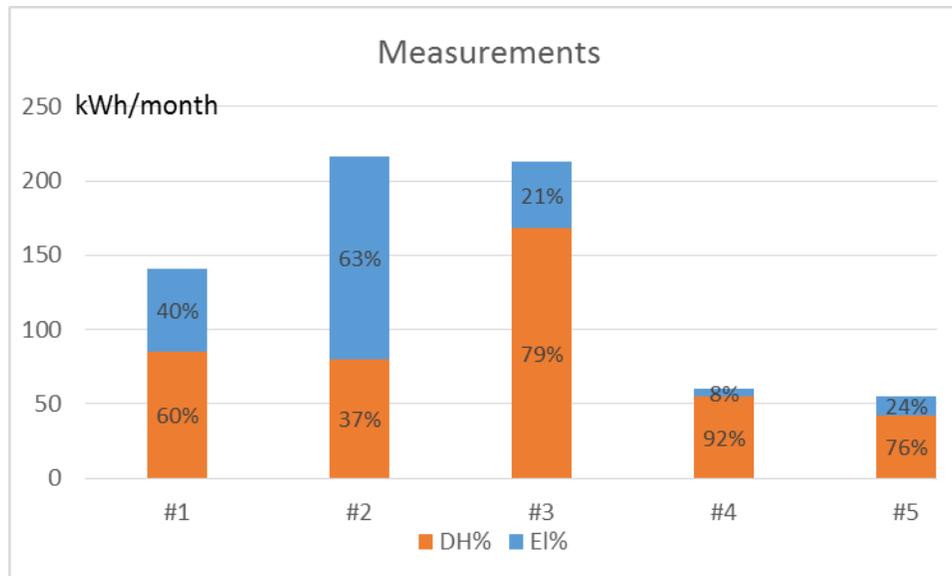


Figure 14 Measured heat and electricity delivered for DHW preparation in the five substations for May

From the measurements, the two substations with instantaneous electrical heater had used less energy for DHW preparation. The relative electricity consumption is also smaller than the other substations, which results in less annual energy costs.

We also built individual models to simulate the substation performance under the ideal conditions for covering the same DHW demand. The results are shown in the following diagram.

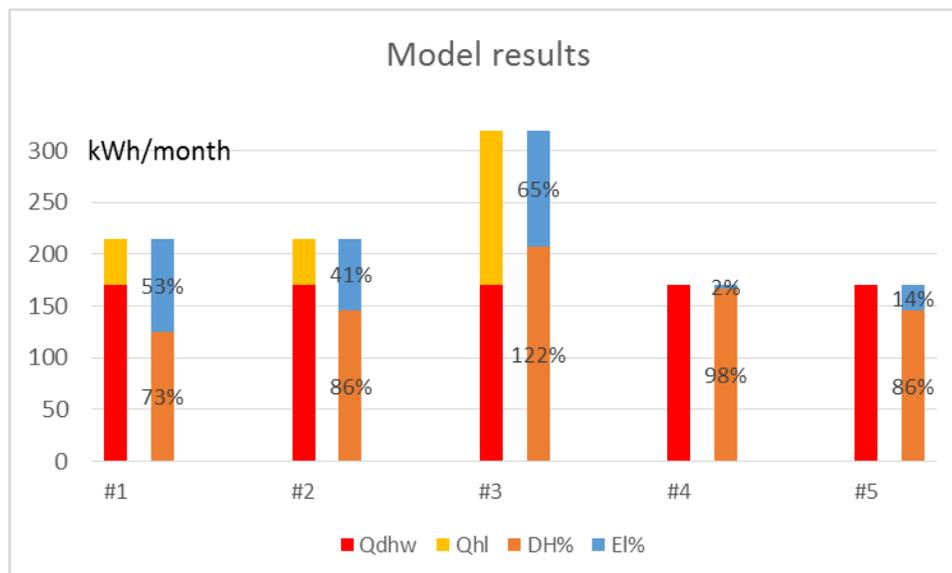


Figure 15 Model results of the energy delivered for DHW preparation in the five substations

All the substations were expected to use more heat from district heating than electricity for supplementary heating. The substations #4 and #5 with in-line electric heaters have

the much less relative electricity consumption compared to the relative heat consumption. That is mainly due to the instantaneous production of DHW at comfort temperature. While substation #3 with a heat pump had higher overall energy supply as well as the relative electricity consumption because a large proportion of energy was wasted covering the huge heat loss.

The model results can also be used as an indicator for operation fault in the substation. For example, by comparing the model results and measurements of substation #2, the correlation between the heat and electricity was totally opposite, which indicate that operation fault might occur in that substation. Based on analysis, we suppose the possible reason could be the wrong settings for the set-point temperature of the storage tank. In the following test, the set-point temperature of the tank was reduced by 5 °C. Consequently, the electricity consumption was 79.47 kWh according to the measurements in November, and 42% of the electricity was saved comparing with the measurements in May (136kWh).

The levelized costs for DHW preparation of the 5 substations are shown in the following table:

Table 9 Levelized costs for the 5 substations based on ideal operation

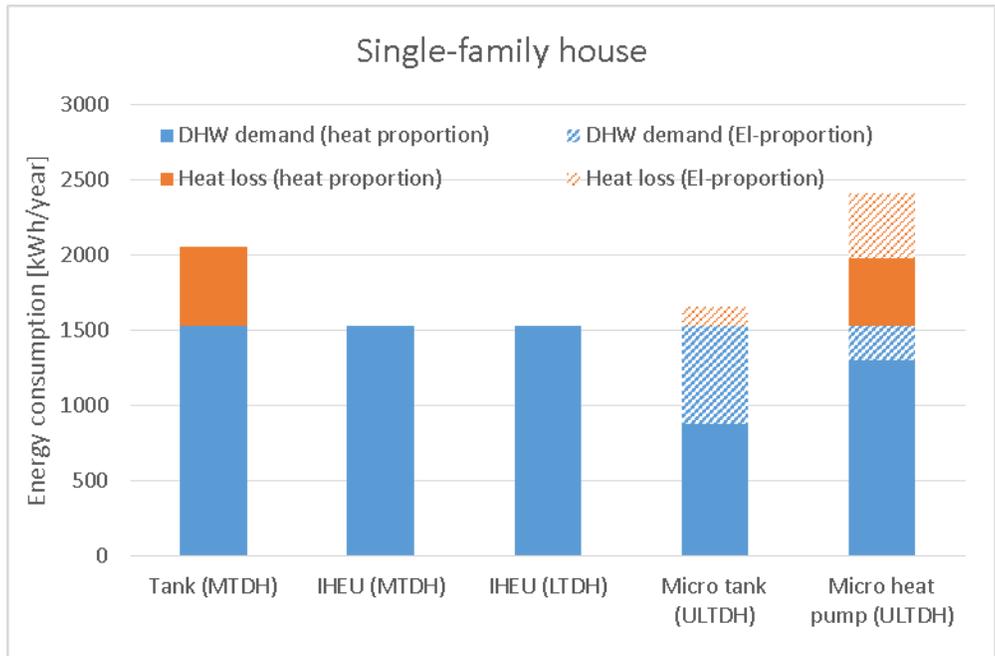
	#1	#2	#3	#4	#5
Investment [DKK/unit]	12000	15000	40000	11000	16000
n			20		
i			0.06		
CRF			0.087		
O&M Cost [DKK/unit]	240	300	800	220	320
Integrated energy price [DKK/kWh]	1.6	1.5	2.3	0.8	1
Annual DHW demand [kWh/year]			2000		
Levelized Cost [DKK/kWh]	2.2	2.3	4.4	1.4	1.9

From the results, the two substations with instantaneous electrical heaters had better economy performances than the other solutions, which proved the sub-hypothesis 4.

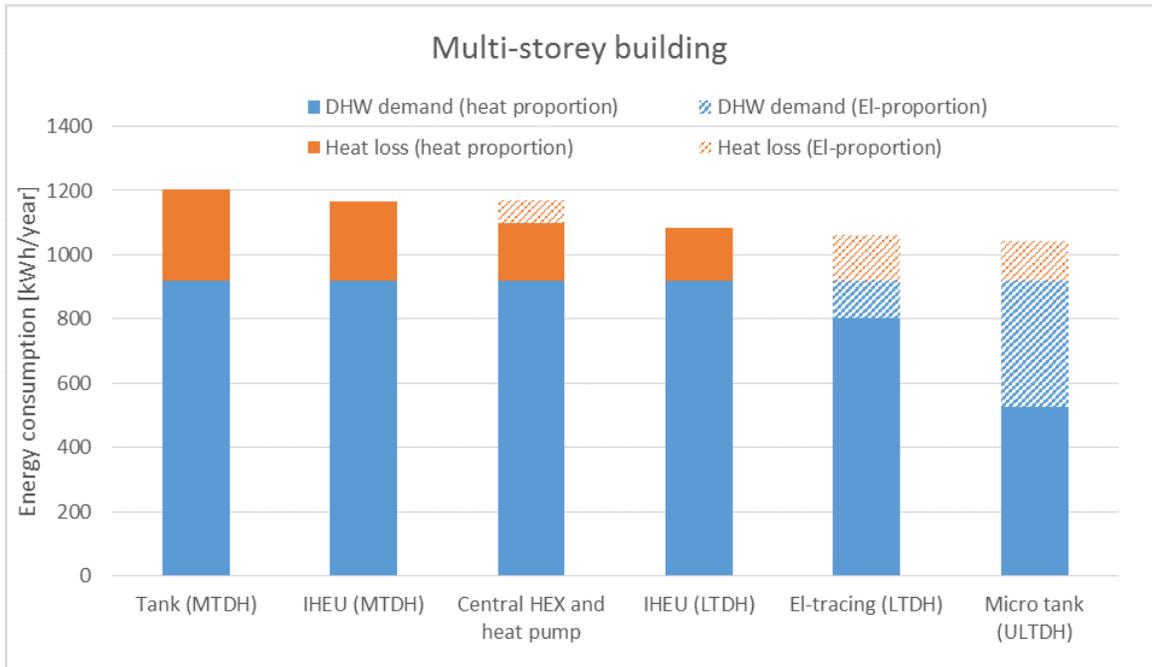
4.5 Energy, economy and exergy evaluations of DHW supply methods for different scenarios

The investigations of different DHW supply methods with different generations of DH aimed at confirming the optimal solutions for the LTDH or ULTDH scenario in the future, which examines the 5th sub-hypothesis. The investigation involved energy, economy, and exergy performances, and also took different building typologies into account.

The results of the energy performances can be seen in Figure 16:



(a)



(b)

Figure 16 Energy performances of different DHW supply methods corresponding to the applying scenarios

For single family houses, the IHEU system requires less energy for standardised DHW preparation within the MTDH and LTDH scenario. For the ULTDH, supplementary heating is required, the micro tank system requires less total energy than the micro heat pump solution, even though the electricity demand is a little higher.

For the multi-storey buildings, the IHEU system also has better performances in the MTDH and LTDH scenarios respectively, because it allows instantaneous DHW preparation and no electrical supplementary heating.

The volume-based average return temperature was also investigated since it is an important factor of the DH heat delivery. The average return temperatures of different DHW supply methods are show in the following tables.

Table 10 Average return temperature of systems in single-family house

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

Table 11 Average return temperature of systems in multi-storey building

Average return temperature [°C]	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
	28	24	20	23	19	16

To specialized the benefit of redirecting bypass to bathroom heating, the average return temperature of the IHEU configuration with bypass within the LTDH scenario was also calculated. The calculated return temperatures to DH were 31 °C for single-family houses and 26 °C for multi-storey buildings. Compared to the return temperature in Table 10 and Table 11, by redirecting the bypass to bathroom heating, the average return temperature of the IHEU system can be reduced efficiently, which also creates benefit for the DH grid.

The economy performances mainly included the energy cost. The results can be found in the following tables.

Table 12 Evaluation of energy cost for single-single family house

	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	282	341
Savings for DH system [€/year]	4.9	3.2	4.4	3.4	5.3

Table 13 Evaluation of energy cost 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	110	80	53
Electricity cost [€/year]	0	0	18	0	65	129
Energy cost [€/year]	120	117	128	110	145	182
Savings for DH system [€/year]	2.3	3.0	3.7	2.9	2.7	2.0

The exergy performance of the investigated DHW supply methods are shown in the following tables.

Table 14 Results of exergy evaluation model for 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 15 Results of exergy evaluation model 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

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%

From the results, the decentralized system performed better than the centralized system under the equivalent conditions. To be more specific, the IHEU system performs better than other solutions with the MTDH and LTDH supply. For the ULTDH scenario, electrical supplementary heating is necessary. The micro tank with electrical immersion heater can be a potential solution with flexibility.

5. Discussion

This research was aimed at providing proposals for supplying DHW by LTDH or ULTDH without violating any comfort or hygiene requirements. The solutions were to be feasible in terms of energy and economy, and applicable for different types of buildings. The whole investigation was carried out by testing the 5 sub-hypotheses. This section states the answers to the research questions as the main findings, and discusses their significance, the generalizations that can be made and the limitations that should be noted. Some potential theoretical and practical perspectives are also presented.

5.1 Investigation of sterilization methods to prevent Legionella in LTDH-supplied DHW systems

The related research question:

1st research question

What are the advantages and disadvantages of the sterilization methods for Legionella that are applicable in LTDH systems in Denmark?

Although many other papers have illustrated various sterilization methods for dealing with Legionella, not many have considered their use in combination with low-temperature district heating. Moreover, since the regulations on water quality might be different from one country to another, we need to confirm the applicability and efficacy of any disinfection method in the Danish LTDH scenario.

Therefore, only sterilization methods that are widely used in man-made aquatic systems were investigated in this research. Without the installation of local supplementary heating devices, the thermal disinfection method cannot be used with LTDH due to the low supply temperature. Chemical additives are widely used for water treatment in some countries, but the strict water regulations in Denmark [43] limit most additive agents into the residential water system. The photocatalysis method and UV light do not use chemical injection into the water, and they show good efficacy even with water temperatures below 50 °C, but their efficacy for water below 45 °C has not been proved. These two sterilization methods can be applied in buildings where renovation of the pipe system is impossible. The equipment for photocatalysis or UV light is usually installed at the inlet of the water system to prevent Legionella entering, and most of the DHW pipework can be retained. Filtration can also be used for LTDH-supplied systems, but the filter has to be replaced regularly due to its short life time, which may increase maintenance costs substantially. The filtration method is therefore more appropriate as an instant reaction if a trigger-concentration of Legionella occurs.

5.2 Investigations into particular DHW preparation methods with LTDH- 1) the electric heat tracing system

The electric heat tracing system is a solution for hygienic DHW supply with LTDH. It uses electricity to boost the DHW temperature locally. This allows DHW circulation to be eliminated, and the return temperature can be lowered. However, the primary energy factor of electricity is 2.5 times as much as that of district heating, so it is important to control the tracing cable in a smart way to make it more energy- and cost-efficient.

2nd research question

Can electric heat tracing and a heat pump system combined with LTDH be beneficial in terms of energy and economy compared to a conventional system supplied by MTDH?

The author developed a smart control method for the electric heat tracing system, which can react to the DHW load profile dynamically on a floor-by-floor basis. From the results, the electric heat tracing system with LTDH can save 34%-67% heat loss compared to the in-line circulation system with MTDH depending on the DHW load profile and control method applied. As supplementary heating for DHW to get rid of Legionella, the electric heat tracing system uses extra electricity and results in higher energy costs as well. However, savings can be made in the DH system due to the low supply/return temperatures. LTDH leads to less heat loss in the network, less pump work, more plant thermal efficiency from flue gas condensation, and so on. Whether the savings in the DH grid can compensate for the extra cost in the building sector due to the electricity usage for heat tracing is a prospective research direction for the future, but was not in the scope of this research.

5.3 Investigations into particular DHW preparation methods with LTDH - 2) the decentralized substation system

The decentralized substation (IHEU) system can ensure the hygiene for a LTDH-supplied DHW system by minimizing the total DHW volume in use instead of using a high temperature regime. This makes supplementary heating unnecessary. In fact, the decentralized substation with LTDH requires less DH heat for DHW preparation than the conventional circulation system with MTDH due to less heat loss, and may have lower operating costs. The calculation of the saving potential of such a decentralized substation system is therefore of great importance for planning the implementation of this method in LTDH.

3rd research question

How much energy can be saved by a LTDH-supplied decentralized substation system compared with a conventional system? How much benefit can be obtained by replacing the bypass?

The results show that the decentralized substation system supplied by LTDH with normal operation is able to save 30% of the heat loss from the DHW distribution process with the circulation system supplied by MTDH. With the improvement of replacing the bypass, the developed decentralized substation system supplied by LTDH can achieve a heat loss reduction of 39% compared to the circulation system supplied by MTDH. Since the decentralized substation system only requires DH heat for DHW preparation, the energy cost-saving ratio is the same as the energy saving ratio. However, the investment and maintenance costs were not included in this research, because they strongly depend on the specific situation. These aspects might be valuable to investigate in the future.

The investigation of the bypass impact shows that the operation of the bypass can increase the total heat loss by 10% and increase the return temperature as well. It is therefore important for the IHEU system to address this problem, thereby increasing the system's efficiency. And possible improvements are discussed in Paper 5 which answered the 5th research question.

5.4 Electric supplementary heating for DHW preparation with ULTDH

ULTDH is aimed at making the utmost use of the low-temperature heat sources available. It will be a cost-efficient way of supplying heat to low-energy buildings and improve the energy efficiency of the heat pump as the heat production approach. The supply temperature of ULTDH has not yet been clearly defined, but is to be lower than that of LTDH (50 °C). Supplementary heating will therefore be necessary for DHW preparation to meet the comfort and hygiene requirements. The 4th sub-hypothesis proposed a possible solution using electrical heater as supplementary heating for ULTDH.

4th research question

What type of electrical supplementary heating can best fit the ULTDH scenario? How can we evaluate the performance of electrical heating methods with different configurations for DHW preparation?

A case study was used for this investigation. Measurements were made in five ULTDH-supplied single-family houses with different supplementary heating methods. The storage-type electrical heater, the instantaneous electrical heater, and the heat pump were installed in the case substations as supplementary heating devices, and their energy and economic performances were analysed and compared. To eliminate the impact of the difference in DHW consumptions in different test houses, the relative use of DH heat and electricity were used instead to make a fair comparison. Moreover, simulation models were also built to evaluate the DH heat and electricity required to cover the equivalent DHW demand in ideal conditions. Both the measurements and the simulation results indicate that the instantaneous electrical heater requires less energy for DHW preparation and can achieve low return temperature. In terms of the levelized cost, the substation with instantaneous electric heater had less cost compared with the substation with heat storage, and the substation with a heat pump had the highest cost. That is because the instantaneous DHW production requires less supplementary electric heating. More comprehensive economic analysis should be carried out to investigate whether the extra cost by electricity consumption can be compensated by the benefits in the heat plant and network due to lower district heating temperatures.

The relative heat and electricity delivered can be used as an indicator of the energy performance of a substation with electrical supplementary heating. Comparison of the simulation value under the ideal situation and the measured value makes it possible to detect potential faults in the substation, such as inappropriate settings for the equipment and bad operations. In this case study, #2 substation showed a reversed relation between the relative heat consumption and relative electricity consumption in the measurement results compared to the simulated results. The fault might be caused by the overly high set-point temperature of the storage tank, which therefore heated a large amount of DH water to an unnecessarily high temperature. The fault was then addressed by reducing the set-point temperature of the tank by 5 °C, and the electricity consumption of #2 substation was reduced by 42% without violating any comfort or hygiene requirements.

5.5 Recommendation based on energy, economy and exergy evaluations

The different generations of district heating are characterized by their supply temperatures. This study looked at a number of DHW supply methods that can meet the comfort and hygiene requirements under the specific DH scenarios. To provide optimal solutions for the corresponding scenarios, it is necessary to evaluate the methods applied in the same scenarios.

5th research question

Can the existing DHW supply method be maintained for LTDH or ULTDH? If not, what improvements can be designed for the potential solutions, so that they are well-adapted to the LTDH/ULTDH scenario?

The current DHW supply methods were designed for use with a sufficient DH supply temperature for comfort and to inhibit Legionella. By definition however, LTDH and ULTDH require proper system configurations that guarantees DHW supply that meets the requirements for comfort and hygiene. Development and improvement of the system configuration were made, so that the new DHW substation can also have improved overall efficiency in the 4th generation scenarios.

Possible improvements for specific DHW supply methods were proposed in Paper 5 based on the detailed investigations for sub-hypotheses 2-4. The final investigation summarized all the previous work. The results showed that decentralized systems performed better than centralized systems under equivalent conditions. To be more specific, the IHEU system performs better than other solutions with both MTDH and LTDH supply. In the ULTDH scenario, the micro tank solution consumes less energy and is more economical. With the results of this study, the policy maker or the designer can reach a decision if LTDH or ULTDH is to be implemented with specific conditions. In particular cases, however, it may be necessary to take more detailed information on costs, local community restrictions, and installation difficulties into account, which might lead to different conclusions from the recommendations of this study.

6. Conclusion

This chapter provides a summary of the 5 sub-hypotheses and the results of the investigations. The conclusion of the main hypothesis rests on the evaluations of the sub-hypotheses. The evaluations are divided into three parts as follows.

6.1 The sterilization methods as a solution for hygienic DHW supply with LTDH

1st sub-hypothesis

In buildings with a large DHW volume due to a storage tank and DHW circulation, LTDH (50-55 °C) assisted by sterilization treatment can be a solution for the supply of DHW at a comfortable temperature without the risk of Legionella.

Evaluation:

The 1st sub-hypothesis is true. By investigating the disinfecting mechanisms, the conditions in which they are applied, and local regulatory restrictions for water systems, suitable sterilization methods were found that can keep an LTDH-supplied DHW system safe from Legionella.

The sterilization methods of photocatalysis and UV light can achieve 5-log disinfection efficacy on Legionella in LTDH-supplied DHW systems with no injection of chemical additives. Filtration methods can be used as an emergency action if the trigger-concentration (>100,000 CFU/L) of Legionella occurs.

6.2 Investigations targeted at particular DHW systems as solutions for comfort and sanitary DHW supply with LTDH

6.2.1 Solutions of local supplementary heating

2nd sub-hypothesis

The combination of a central heat exchanger and local supplementary heating devices, such as electric heating and a heat pump, can be a solution which takes into account the comfort and hygiene requirements in large buildings with DHW circulation supplied by LTDH. The smart control method applied to the supplementary heating devices can optimize the energy consumption of DHW preparation and reduce operation costs.

Evaluation:

The 2nd sub-hypothesis is partly true. Supplementary heating devices can heat DHW to the required temperature with respect to the comfort and hygiene requirements. With a real-time control method, the electric heat tracing systems can save a large amount of heat loss by avoiding the high temperature regime which is necessary to the conventional circulation system. However, the operating costs will need to be discussed in each specific situation due to the high energy-price of electricity.

An electric heat tracing system can replace the DHW circulation system. Compared to the circulation system, the electric heat tracing system can save the heat loss by 34%-67%, depending on the control methods and the DHW load profile. The lower return temperature with the electric heat tracing system can make potential savings in the DH network, which can compensate for the extra cost of the electric supplementary heating due to the high energy-price of electricity.

The DHW substation with an in-line supply pipe and a heat pump to cover the circulation heat loss is a potential solution for existing buildings where it is impossible to carry out a renovation of the circulation system. The heat pump also helps to reduce the high return temperature caused by the DHW circulation.

6.2.2 Decentralized substation system based on total DHW volume restriction

3rd sub-hypothesis

A decentralized substation system can resolve the Legionella problem for LTDH without supplementary heating, which results in a substantial reduction of the overall heat consumption compared to conventional systems. It is possible to improve the system performance further by methods that eliminate the influence of the bypass on the average return temperature.

Evaluation:

The 3rd sub-hypothesis is true. A decentralized substation system can divide the large DHW system into independent DHW loops, each with a small total volume and no circulation, thereby eliminating the risk of Legionella in the LTDH-supplied DHW system. Compared to the conventional system with DHW circulation, a large amount of heat loss can be saved in the DHW distribution inside the building due to the low operation temperature. It is technically and economically feasible to replace the bypass with a heat pump and in-line circulation, or a bathroom heating flow with a well-insulated supply pipe.

Taking into account the differences in system operation in heating and non-heating seasons, the low-temperature supplied decentralized substation system can save 30% distribution heat loss compared with the conventional system with DHW circulation. By applying heat-pump-assisted in-line circulation to replace the bypass, the heat loss savings can reach 39%, which results in lower operation costs even though extra electricity is used by the heat pump. Bathroom heating can be used to replace the bypass during the non-heating season and increase comfort for the consumer. However, the supply pipe has to be insulated carefully to minimize the pipe heat loss load.

6.3 Evaluations for different DHW preparation methods

6.3.1 DHW supply methods with ULTDH

4th sub-hypothesis

It is possible to supply DHW based on ULTDH using supplementary electrical heating with an acceptable economic performance.

Evaluation:

The 4th sub-hypothesis is true. Both measurements and model results showed that DHW supply in the case houses could meet the comfort and hygiene requirements with ULTDH supply combined with supplementary electrical heating devices. The levelized cost taking into account the investment, O&M cost, and the energy costs is acceptable.

The supplementary heating device of the instantaneous electrical heater had the better performance than the storage-type heater and the heat pump. Due to its instant preparation of DHW, the instantaneous electrical heater system saves a large amount of heat loss. The relative electricity consumption was minimized by heating DHW to the comfort temperature only when it was used. The levelized cost of the substation with the instantaneous electrical heater system is also much cheaper than the other substations.

6.3.2 Suitable DHW preparation methods for specific scenarios

5th sub-hypothesis

It is possible to establish a set of safe and optimal solutions to supply DHW in all types of buildings with LTDH or ULTDH. The optimal solution can be derived by sophisticated evaluation models, and the benefits of lowering the DH temperatures can be also characterized.

Evaluation:

The 5th sub-hypothesis is true. Suitable solutions of supplying DHW to different buildings by LTDH/ULTDH can be found with respect to the comfort and hygiene requirements. The theoretical basis can be either supplementary heating or DHW volume limitation. The evaluation model yielded preliminary results based on ideal operation.

For the MTDH and LTDH scenarios, the decentralized substation system demonstrated the best energy and economy performances. Replacing the bypass with bathroom heating flow, a low return temperature can be obtained without compromising on the 10s waiting time. For the ULTDH scenario, which requires supplementary heating, the micro tank with an electric immersion heater is the preferred solution due to its less energy consumption and flexibility.

6.4 Evaluation for the main hypothesis

The comfort and safe supply of domestic hot water can be achieved with low-temperature district heating if an appropriate solution is applied, which can be applied throughout the whole district heating system, In view of different situations, including building typology, substation configuration, renovation depth etc., the optimal solutions can also vary. Their technical and economic feasibility can be identified by model-based comparison.

Evaluation:

The evaluations of the sub-hypotheses show that the main hypothesis is true. Optimal solutions for the supply of domestic hot water that meets the comfort and hygiene requirements from LTDH or ULTDH can be recommended based on their energy and economic performances simulated by models that take into account possible system improvements and respect the local conditions.

7. Perspectives

This research provides proposals DHW supply methods that meet comfort and hygiene requirements based on LTDH or ULTDH, which is one of the key elements for realizing LTDH and achieving a completely renewable energy system in the future. For potential future work, the following suggestions could be considered.

7.1 Integral analysis with investigations of the LTDH grid

The target of this research was to explore solutions for supplying DHW based on LTDH/ULTDH that also meet the comfort and hygiene requirements. The research scope was therefore limited to the DHW supply system in the building sector. However, the main benefits of implementing LTDH are embodied in the heat production side and the transmission grid. One research interest in the future could be a full-scale investigation combining analyses of the heat production side, the transmission network, and the end user part, so that the full effect of applying LTDH can be confirmed.

7.2 Practical tests for the proposals of the devised DHW system

This research provided model-based evaluations for the investigated DHW systems. The feasibility of several possible solutions with innovative concepts has been demonstrated theoretically. However, real tests need to be planned to prove their practical performances. The modelled results can be used for fault detection and as a guide to better operation.

7.3 The role return temperature plays in the DH grid

The return temperature has been discussed here as an important factor that interacts with the DH grid on the basis of the ideal operation of the DHW system. However, in practice, the return temperature can be affected by dynamic heating load, the insulation level, the efficiency of the heat exchanger, the fluctuation of the supply temperature and so on. Comprehensive analysis on the impact of the return temperature therefore needs to be carried out using sophisticated models and validated in practical tests.

7.4 Development of the substation with local supplementary heating for ULTDH

Applying the energy-efficient building in the future, the heat demand on the consumer side might become less and less, which makes the DH transmission heat loss a more serious problem. Ultra-low temperature district heating can solve such problem, but it requires local supplementary heating in the substation. The results from the test for the 4th sub-hypothesis show that the instantaneous electric heating can be a good method. However, system optimization is needed on elimination of the bypass without compensation of the comfort, and also on how to reduce the peak power of the electric heater so that it can work with normal power supply.

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Appendix A – Paper 1

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Abstract

District heating is a cost-effective way of providing heat to high heat density areas. Low-temperature district heating (LTDH) is a promising way to make district heating more energy-efficient and adaptable to well-insulated buildings with low heating demand in the future. However, one concern is the multiplication of Legionella due to insufficient temperature elevation with low-temperature supply. The aim of this study was to find optimal solutions to this dilemma for specific situations. The solutions were of two types: alternative system designs and various methods of sterilization. The alternative design approach can eliminate the risk factors of Legionella by local temperature boosting and restricting system volume. Decentralized substations, micro heat pumps, electric heating elements and electric heat tracing are all investigated as alternative designs. With regard to sterilization methods, thermal treatment, ionization, chlorine, chlorine dioxide, ultraviolet light, photocatalysis and filtration are discussed as the most frequently used methods in hot water systems. The characteristics, efficacy and operation methods of LTDH using the solutions investigated are documented and compared. Finally, recommendations are given for their use in practice.

Practical application: The methods for inhibiting Legionella should fit into applicable situations according to their characteristics. This study aims to recommend optimum solutions for inhibiting Legionella in LTDH scenarios, and includes a comprehensive overview of their efficiency, installation, operation and costs, so as to give adequate information for selecting appropriate solutions. In addition to sterilization methods, alternative system design implemented with new technologies can also help prevent Legionella in hot water systems. They have the additional benefit of reducing the heat loss of the hot water system. The alternative design solutions both enrich our options for water sanitation and improve the energy efficiency of our energy systems.

Keywords

Legionella, domestic hot water, low-temperature district heating, alternative hot water system design, sterilization methods

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Introduction

Legionella are gram-negative bacteria that are common in both natural and man-made aquatic ecosystems, such as cooling towers, hot springs, domestic hot water (DHW) systems and also cold (potable) water systems.¹⁻⁴ Some species are reported as the etiological agents of Legionnaires' disease. Normally, Legionnaires' disease is acquired by inhaling the aerosol of the contaminated water. Since 1976, outbreaks of Legionnaires' disease have been diagnosed globally.⁵ In 2013, 6012 cases were reported by 29 European countries with a fatality rate of about 10%.⁶ In DHW systems, which are strongly related to people's daily life, the contamination rate ranged from 6% to 32%, according to previous research.⁷⁻¹⁵ The problem is considered to be even greater when the hot water is supplied by district heating (DH),^{8,11} because this is generally combined with a centralised water heating system with a central heat exchanger, which requires longer distribution pipelines to the consumers. This creates favourable conditions for Legionella's multiplication,^{14,16-18} which include: 1) water temperatures ranging from 25°C to 45°C, 2) long-term stagnancy and 3) low levels of disinfectant residual and the presence of biofilm and sediments.

Temperature control is still the most widely used method for preventing Legionella in hot water systems. In Denmark, for example, the standard regulates that the circulation pipe should be kept at 55°C all the time, and it should be possible to heat the storage tank up to 60°C on a regular basis.¹⁹ Some Scandinavian countries are currently planning to operate DH networks at lower temperatures (around 30–70°C)²⁰ to reduce fossil fuel consumption and improve energy efficiency. However, low-temperature district heating (LTDH) will make it more difficult to meet the temperature requirements for conventional systems with a circulation pipe and storage tank due to the low-temperature supply and the temperature drop in the heat transmission process. Moreover, large systems are more likely to suffer from stagnancy. It is, therefore, crucial to

ensure that both comfort and health requirements will be met before LTDH is implemented.

This paper investigates various options, which can be divided into two kinds: alternative designs for water supply systems and various sterilization treatments. Many other studies have discussed the effects of hydraulic components on preventing Legionella in hot water systems. For instance, field work studies on pipes and thermostatic shower mixer taps by van der Kooij et al.¹⁶ and van Hoof et al.²¹ have shown the effect of various materials on biofilm formation, which plays an important role in Legionella's growth. Copper pipes have been shown to perform better than PEX pipes, and systems with instantaneous heaters have been found to be less contaminated than those with storage tanks.⁸ Vertical tanks have been shown to be more vulnerable to Legionella than horizontal ones.²² The application of systematic design aimed at inhibiting bacteria in DHW has seldom been mentioned, but it can play a vital role in solving potential problems with the introduction of LTDH by replacing conventional hot water systems. Sterilization methods can be applied combined with alternative design for enhanced control, or as post-treatment if trigger-concentrations of Legionella occur due to an unexpected fault in the system. Although many other papers have illustrated various sterilization methods for dealing with Legionella, not many have considered their use in combination with LTDH. The main objective of this study is to provide feasible solutions that can both inhibit Legionella in DHW systems and fit into the LTDH scenario of the future.

Alternative designs for water supply systems

Since the insufficiently high temperatures and long-term stagnancy are the main risk factors for Legionella proliferation in hot water systems with DH, alternative designs are needed that can eliminate those factors. The basic concepts behind such designs are temperature boosting and volume limitation. Temperature boosting can be achieved using local supplementary heating devices. The volume limitation concept, in

accordance with the German Standard W551,²³ is that, if controlled properly, a system with a total volume (from hot water production to end use) of less than 3 L can eliminate the risk of Legionella. The advantages of alternative design are numerous. For instance, it does not affect water quality, involves no long-term monitoring or regular equipment replacement, and it can improve the system's comfort and energy efficiency at the same time.

Decentralised substation

This solution is to equip each home with an instantaneous heat exchanger for DHW and space heating (SH) production, instead of having just one heat exchanger in the substation for all the consumers.²⁴ This design uses the limited volume approach. The schematic is shown in Figure 1.

By installing a decentralized substation in each home, the volume of the DHW system is much reduced. Moreover, consumers can

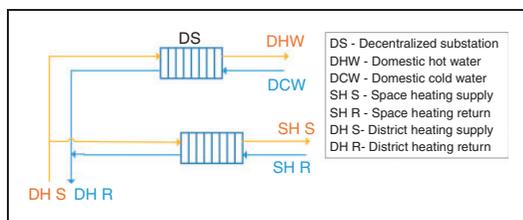


Figure 1. Schematic of decentralized substation system.

regulate the heat demand and set-point temperature of their own substation, so both control and operation are flexible.

With a decentralized substation system, hot water can be prepared locally, so there is no need to keep the circulation circle. A small bypass flow can ensure the consumers get hot water within an acceptable time. Moreover, the system energy efficiency is much improved. For a new 50-apartment building, the heat loss from decentralized substation systems for DHW production was only 30% of that from an electrical boiler, and only 40% of that from a centralized heating system. The annual cost was thereby reduced by 10–20%.²⁴

The operating temperature of decentralized substation system can be lower than the conventional system. However, so far, there is insufficient documentation about the lower limit for the operating temperature with regard to health safety, and more work needs to be done on this question.

Micro heat pump

A micro heat pump is an application for local temperature elevation. Since the LTDH cannot heat up DHW to a safe temperature, the micro heat pump can be used to boost the supply temperature using low-temperature energy sources. The energy source could be either the DH supply water itself or DH return water. Figure 2 and Figure 3 show schematic diagrams of the two types, respectively.

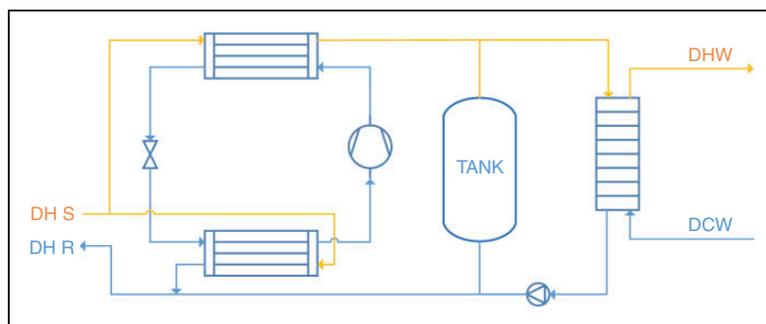


Figure 2. Heat pump application using DH supply water as heat source.

In Figure 2, DH supply water is divided into two streams. One flows through the evaporator of the heat pump system, which is used to boost the temperature of the other stream. In Figure 3, the heat source is the DH return water. In this scenario, the benefit is the cool-down effect of the DH return line, but the huge temperature difference between the DH supply and return water has a negative effect on the heat pump efficiency. In practice, to boost DH supply water from 40°C to 53°C, a system using DH supply water as the heat source might achieve a coefficient of performance (COP) of 5.3, while for a system using DH return water as the heat source could only achieve a COP of 3.5.²⁵ In both scenarios, the heat storage tanks are installed before the heat exchanger, so the contamination of the tank is not considered. The temperature boosting gives flexible and precise control. One disadvantage is that the heat pump consumes electricity as driving power, which decreases the energy efficiency of the system. But the energy saved in the network by implementing LTDH should be taken into account for a full picture.

Electric heating element

In contrast to a micro heat pump, an electric heating element uses electricity as a supplementary heat source. Its design and installation are much simpler than the heat pump solution. The electric heating element can be either integrated with storage tank or fitted separately. The

principles of this system are shown in the following diagrams.

The heating element can be used to boost the DH supply temperature (Figure 4) or heat up the DHW directly (Figure 5). Under the same conditions, both types have much lower COP and energy efficiency than the heat pump scenario, because the total supplementary heating energy is supplied by electricity. However, the separate heating element scenario has slightly higher

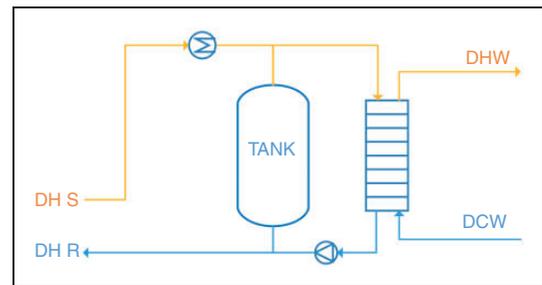


Figure 4. Separate electric heating element.

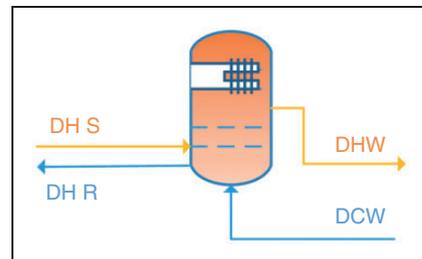


Figure 5. Integrated electric heating element.

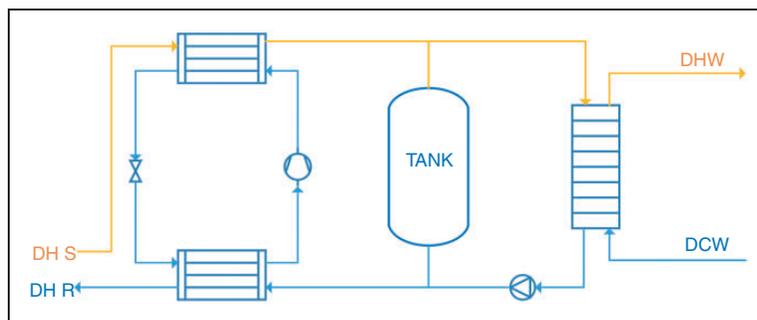


Figure 3. Heat pump application using DH return water as heat source.

energy efficiency than the integrated version.²⁵ Moreover, in the integrated scenario, DHW has to be stored in the storage tank, which increases the risk of Legionella multiplication.

Electric heat tracing

The electric heat tracing solution is another application of the temperature elevation approach. The electric tracing cable is wound around the DHW supply pipe. As a supplementary heating device for LTDH system, electric

heat tracing uses electricity to heat up the water when necessary.

As shown in Figure 6, since the DHW supply line is kept warm by the electric heat tracing system, there is no need for a circulation pipe or a heat storage tank, which reduces the risk of stagnancy in the system. Moreover, in multi-storey buildings with large hot water pipe works, the removal of the circulation pipe can reduce the overall heat loss by as much as 50% by removing the circulation pipe. Electric heat tracing is also very flexible. It can heat up either the whole supply line or part of it. To suppress the multiplication of Legionella, tracing cable can be used to maintain a safe temperature continuously, or for periodic thermal treatment.

The characteristics of each design are listed in Table 1. For the evaluation of the difficulty of the installation and operation, the complexity of installing the devices and setting up the control system are the main factors considered. The investment costs were compared by using the general prices of the devices in the market.

Sterilization methods

Sterilization methods for Legionella inactivation can be divided into three kinds: thermal treatment, chemical treatment and physical treatment. All sterilization treatments aim at inhibiting the growth of Legionella or keeping the bacteria separate from the users. Every method has its pros and cons. This study investigates only methods

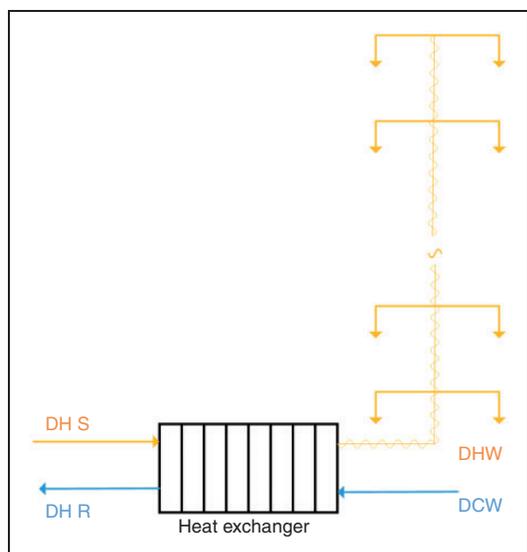


Figure 6. Schematic of electric heat tracing solution.

Table 1. Characteristics of each alternative solution.

Approach	Solution	Building type applicable in	Circulation required	Energy source for hot water	Installation & operation difficulty	Investment cost
Volume restriction	Decentralized substation	New	No	DH	Complicated	High
Local temperature elevation	Micro heat pump	Existing/new	Yes	DH + electricity	Medium	High
	Heating element	Existing/new	Yes	DH + electricity	Simple	Medium
	Electric heat tracing	Existing	No	DH + electricity	Simple	Low

that are applicable for DHW treatment. And more focus is put on methods that can be combined with alternative design as supplementary security for DHW with LTDH. In this way, even in the event of an unexpected temperature drop or stagnancy, the sterilization treatment can still protect the system.

Thermal treatment

Previous studies^{26,27} have showed that *Legionella pneumophila* in vitro is killed rapidly by water temperatures $>60^{\circ}\text{C}$. Higher temperatures require less time to achieve the same log reduction (70°C for 10 min, and 60°C for 25 min).²⁷ So, when DHW is supplied by LTDH, thermal treatment requires supplementary heating devices to achieve sufficient temperature elevation. When applying thermal disinfection, all the distal sites in the hot water system should be flushed with 60°C or higher temperature hot water for a certain period of time.^{28,29} According to Krøjgaard et al.,⁷ a protocol of keeping the boiler at 70°C for 24 h (after hyperchlorination) and flushing all taps for 5 min reduced the concentration of *Legionella* and limited it below 10^2 colony forming unit (CFU)/L over a period of seven months.

One benefit of thermal treatment is that it puts no additives into the water. This makes it the preferred solution in countries that have strict limits on water quality. Thermal treatment has good performance in transient use. Farhat et al. observed a 5-log reduction with a 30-min treatment.³⁰ The process is also easy to carry out. Nevertheless, insufficient temperature elevation or flushing time can result in failed sterilization.⁷ And temperature elevation and hot water flushing result in a loss of potential heating energy. Included among other disadvantages of thermal treatment are its limited efficacy on biofilm, its potential to enhance the thermal resistance of *Legionella*,^{30,31} the risk of scalding, etc.

The overall expense of thermal treatment includes the fuel cost for temperature boosting, the water flow used for flushing and the cost of labour, which constitutes the greatest part of the total cost. A 10-year study of a hospital building

in Modena, Italy reveals that it cost DKK 280 (EUR 37.5) per water point for two protocols (2 days $>60^{\circ}\text{C}$ at every distal) a year.³²

Chemical treatment

This section presents chemical treatments that are allowed for continuous use in a DHW system. However, the use of biocide methods requires meticulous control to maintain effective concentrations without violating any local water quality requirements.

Ionization. Ionization works by using two different ionized metals in the water to disrupt the cell wall permeability of bacteria and cause the denaturing of proteins and subsequent cellular lysis.^{28,33} The most widely used electrodes are copper and silver, which are extensively applied in recirculating hot water systems.³⁴ The effective dosages vary from 0.2 to 0.4 mg/L for copper and 0.02 to 0.04 mg/L for silver³⁵ mainly depending on the water quality. Liu et al. observed that 0.4 ppm Cu and 0.04 ppm Ag successfully reduced the *Legionella* positive rate from 65% to 0.8%.³⁶ However, the concentration of Cu^{2+} and Ag^{+} must comply with local requirements for water quality. The European standard limits the concentration of Cu^{2+} to 2 mg/L, while the limit for Ag^{+} is not defined. But EU member states can make stricter regulations locally. In Denmark, for instance, the limits for Cu^{2+} and Ag^{+} are lower than the effective concentrations, which are 0.1 mg/L and 0.01 mg/L, respectively.³⁷ So, this method cannot be used in Denmark.

To ensure a good reaction to the ionization process, the water should be clean. Campos et al.²⁸ suggest ionization should be applied under pH 7.6, since it is a pH sensitive method. Furthermore, higher temperatures accelerate the chemical process and are recommended when using ionization.³⁵

One of the benefits of copper/silver ionization is its long-term efficacy.^{38,39} Stout and Yu³⁸ report the successful control of *Legionella* using ionization in a five-year investigation in 16 hospitals. Another 70-month investigation

by Biurrun et al.⁴⁰ showed that the positive rates of *Legionella* were reduced to 0–10.3% with ionization treatment. Moreover, ionization can also perform well with intermittent use.⁴¹ This allows several systems to share the same generating equipment, which reduces investment costs. However, ionization is an on-site approach, and it has little effect on biofilm. Furthermore, concentrations of copper and silver that are too high will cause scaling accumulation and water discoloration.⁴²

The overall cost of ionization includes the initial investment and the maintenance cost. The initial investment varies a lot depending on the size of the water system, ranging between DKK 68,000 (EUR 9115) and DKK 240,000 (EUR 32,171), with an annual maintenance cost ranging between DKK 10,000 (EUR 1340) and DKK 27,000 (EUR 3619) for replacing electrodes.^{42,43}

Chlorine. Chlorine is one of the most widely used oxidizing agents in many kinds of water systems, including potable water systems in some countries. Normally, a residual level of 2–6 mg/L chlorine is required for continuous control of *Legionella*.⁴³ Experimental work by Muraca et al.²⁶ showed that chlorine with an average concentration of 4–6 mg/L can achieve 4-log reduction in 25°C water after 3 h. However, when *Legionella* bacteria are associated with host protozoa, a higher concentration of chlorine is required, for example, >4 mg/L for *Hartmannella vermiformis*⁴⁴ and >50 mg/L for *Acanthamoeba polyphage*.⁴⁵ Hyperchlorination (at least 2 h with 20 mg/L or 1 h with 50 mg/L) can be applied for cleaning purposes. However, the water system cannot be used until the chlorine concentration falls below the standard requirement.

Chlorine is a systematic disinfection method with good transient effect, and it can provide a residual concentration throughout the whole system. But chlorine has little effect on the persistence of *Legionella* in amoeba, and it is a highly corrosive chemical which will lead to pipe corrosion. To avoid this, protective coatings are required, which will increase costs. Moreover, chlorine residual has the potential to cause carcinogen disease to human beings.⁴⁵

The cost of chlorine includes the investment for necessary equipment and the expense for pipe work maintenance, protective coating and labour costs. Compared to the thermal treatment at the Italian hospital mentioned earlier,³² the average annual expense is slightly lower at DKK 228 (EUR 31) per water point.

Chlorine dioxide. Chlorine dioxide is another oxidizing agent widely used to treat potable water and other water systems in some countries. It kills the bacteria by disrupting their cellular processes.⁴⁶ As shock treatment, Walker et al.⁴⁷ observed that maintaining a chlorine dioxide concentration of 50–80 mg/L for 8 h in the system tank and 1 h at all outlets showed a good inhibiting efficacy for both planktonic and sessile *Legionella*. For continuous residual control, a level of 0.5 mg/L is effective in hot water systems.⁴⁸

Chlorine dioxide is more effective than free chlorine in most cases and bad odour can be avoided in potable water treatment. But one limitation with chlorine dioxide is its easy decomposition. Moreover, it is difficult to maintain a continuously effective residual concentration in water.

Chlorine dioxide is considered a cost-effective eradication method. The total cost includes investment and maintenance cost for precise injection and monitoring.

UV light. Ultraviolet light adds no chemical agents into the water system. It kills bacteria by disrupting their DNA replication process with short-wavelength light (254 nm).⁴⁹ Continuous UV disinfection at 30,000 $\mu\text{W s/cm}^2$ can achieve a 5-log reduction within 20 min.²⁶

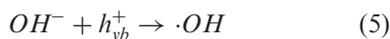
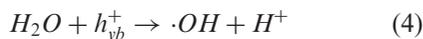
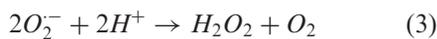
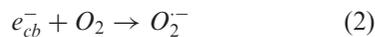
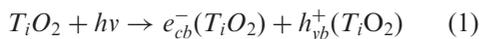
UV light has the advantages of good instant efficacy (5-log reduction within 1 h according to Muraca et al.²⁶), no chemical by-products, no damage to water quality or pipe work, and simple installation. But UV light provides no residual throughout the system, which limits its efficacy in large water systems and system colonized by biofilm. A study by Franzin et al.⁵⁰ showed that UV had better efficacy in central parts of a water system than in distal parts.

So, to maintain long-term efficacy, other treatments should be used in combination with UV.

The investment in UV lamps accounts for the largest part of the total expense. For a 500-bed hospital in the United States, where four large (260 gal/min) and two small (30 gal/min) units were installed, the cost was DKK 339,000 (EUR 45,442).⁴²

Photocatalysis. Photocatalysis is a new water treatment technique for hot water systems. The method used is to activate a solid catalyst such as titanium dioxide (TiO₂) using sunlight and produce oxidants to kill bacteria. The main oxidant generated by this reaction is the hydroxyl radical (\bullet OH), which is accompanied with superoxide anions (O₂⁻) and hydrogen peroxide (H₂O₂).

The main reaction process works in the following way:



The wavelength of the ultraviolet light for photocatalysis should be no more than 385 nm (UV-A).⁵¹ The disinfection contact time can vary for different kinds of microorganisms, such as viruses, bacteria, spores and protozoa. Photocatalysis has superior disinfection efficacy for bacteria that have strong chemical resistance. Cheng et al.⁵¹ used a 90-min photocatalysis treatment with 1000 mg/L of TiO₂ and 108 mW/cm² of UV light and achieved a 4.5-log reduction. Stenman et al.⁵² report the achievement of a 5-log reduction in contaminated water with a flow rate of 10 L/min using photocatalysis in a laboratory. According to equations (1) to (5),

photocatalysis is a stable treatment and produces no toxic residuals in the water system, so even countries that have strict policies on potable water quality are able to apply this method.

The main investment required for photocatalysis is the generation equipment. Compared to the investment, operation costs are small, since it only requires sunlight and a small amount of electricity.

Physical treatment. Physical treatment mainly refers to filtration, which prevent the microorganisms from getting into the protected site by using membrane filters.^{32,53,54} Filtration is very effective, but the short lifetime of the filter is one of its most important limitations. Operation costs of filtration are much higher than any other method, since the filter has to be replaced regularly. Another limitation is retrograde contamination. The filter can easily lose its efficacy by coming into contact with contaminated sources (such as splash water).

The cost is basically determined by the lifetime of the filter. Marchesi et al.³² report that the cost of filters for a single water point was DKK 6353 (EUR 852) annually due to their short lifetime (one month).

The characteristics of each sterilization method is shown and compared in Table 2.

The evaluation of the costs considered mainly the investment cost of the sterilization equipment.

Conclusion

Everyone who has the intention of promoting LTDH in the future needs to address the potential problem of Legionella proliferation in hot water systems due to insufficient temperature elevation in advance. This paper provides a broad overview of the options available in terms of both changes in design and sterilization treatments. The alternative design approach is based on two methods – temperature elevation and volume restriction. Considering the cost and difficulty of installation, decentralized substation systems are recommended for new buildings with a large hot water system and a diverse pattern of use. Micro heat pump systems can be

Table 2. Characteristics of different sterilization methods.

	Methods	Efficacy	Operation activity	Additive to water system	Investment cost	Effective range	Feasibility & regulation
Thermal treatment	Heat flushing	Short	Temperature & operation time control	No	Low	systematic	No limits
Chemical treatment	Ionization	Long term	Residual control	Yes	Medium	On-site	A + B
	Chlorine	Long term	Residual control	Yes	Low	Systematic	A
	Chlorine dioxide	Short term	Residual control	Yes	Low	On-site	A
	Photocatalysis	Long term	Residual control	No	Medium	On-site	No limits
	Ultraviolet light	Short term	-	No	Medium	On-site	No limits
Physical treatment	Filtration	Short term	-	No	High	On-site	No limits

“-” represents for none specific control; “A” the concentration of the agents must comply with local water quality regulations; “B” not applicable in some countries.

applied in both large systems and single family houses, but might be more appropriate in future low-energy buildings. Heating element and electric heat tracing systems are preferred when renovating water systems in existing buildings because they are cheap and easy to install. Sterilization treatment can be used as supplementary protection with alternative design or for post-treatment if trigger-concentration occur. Thermal treatment is a simple and non-additive method, but with LTDH, local heating devices will be required to achieve sufficient temperature elevation. If biocides are used, the concentrations need to be meticulously controlled to achieve the right efficacy without violating water quality regulations. UV and photocatalysis are best used in newly built water systems or uncontaminated systems, because of their on-site efficacy. Filtration is widely used in more places where the risks are higher (e.g. hospital water systems) for better protection, but the filters have to be replaced regularly.

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Appendix B – Paper 2

Yang, X.; Li, H.; Svendsen, S.

Modelling and multi-scenario analysis for electric heat tracing system combined with low temperature district heating for domestic hot water supply,

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Modelling and multi-scenario analysis for electric heat tracing system combined with low temperature district heating for domestic hot water supply

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Abstract

Low temperature district heating (LTDH) is a cost-efficient way of supplying space heating and domestic hot water (DHW) for buildings in urban areas. However, there is concern that the potential hygiene problems (Legionella) might occur if LTDH is implemented, especially for large buildings. In this study, electric heat tracing system was investigated as a solution to this dilemma. A model of electric heat tracing system for multi-storey buildings was built. Various pipe materials and insulation thicknesses as the parameters of the model were compared to make a comprehensive study. The performance of the electric heating tracing system with LTDH was simulated by taking the user pattern into account. A smart control method based on thermostatic and real-time control was developed, and compared with normal control method. The impact of user pattern was tested by applying standard, stochastic, and real load profiles to the model. The energy and economy performances of electric heat tracing system in different scenarios were simulated by Matlab. The results were compared to the conventional circulation system with the current generation district heating. The electric heat tracing system with LTDH showed good performance on heat loss saving, and it also gave benefits to district heating network by sharing part of the heating load.

Keywords

low temperature district heating, domestic hot water, electric heat tracing, user pattern profile, smart control modelling, Legionella prevention

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1 Introduction

1.1 Low temperature district heating

Energy consumption for heating accounts for a large proportion of the overall building energy consumption, especially in cold regions, like Scandinavia. One efficient way to supply heat to areas with high heat density is district heating (Reidhav and Werner 2008). Currently, 50% of residential buildings in Denmark are heated by district heating (Grontmij 2013), and it is planned to expand this to 70% by 2035 (Dyrelund 2010). It is important to make district heating more competitive and energy-efficient, so novel concepts should be implemented, such as the new low temperature district heating (LTDH, the 4th generation of district heating (Lund et al. 2014)).

Low temperature district heating has many advantages such as less heat loss in heat distribution networks, higher

utilization of renewable energy sources (such as solar and geothermal), higher power-to-heat ratio in the steam CHP plants, better recovery for waste heat from flue gas condensation, and easier maintenance. Currently, most European countries use 80 °C/40 °C as supply and return temperatures for district heating. However, the aim is to lower the supply/return temperatures to 55 °C and 25 °C respectively. As a result, the efficiency of both heat production and network can be improved significantly.

1.2 Prevention for Legionella in domestic hot water systems

One issue that prevents the application of LTDH is the concern of proliferation of Legionella in domestic hot water (DHW) system. The genus Legionella is a group of gram-negative bacteria that mainly exist in aquatic environments. People can become infected by inhaling an aerosol with a

List of symbols

ann	annually	Q_l	heat loss (Wh)
C_p	heat capacity of the water (J/(kg·K))	t	length of interval period (h)
D_1	inner pipe diameter (m)	T_{amb}	ambient temperature (°C)
D_2	outer pipe diameter (m)	T_{flow}	average temperature of the supply pipe (°C)
D_3	outer diameter of the insulation (m)	U_{pipe}	heat loss coefficient of the pipe (W/(m·K))
E	integral electricity consumption (kWh)	α_e	external heat transfer coefficient (W/(m ² ·K))
HL	integral heat loss (kWh)	α_i	internal heat transfer coefficient (W/(m ² ·K))
l_i	length of each pipe segment (m)	$\lambda_{insulation}$	thermal conductivity of the insulation (W/(m·K)), 0.037 W/(m·K) in this case
m	mass of water (kg)	λ_{pipe}	thermal conductivity of the pipe material (W/(m·K))
P	power rate of the electric cable (W)	τ	working time (h)
q_l	heat loss rate (W)		
$q_l(55^\circ\text{C})$	heat loss rate at 55 °C		
Q_h	energy for heating up DHW 45–55 °C (Wh)		

high concentration of Legionella if the domestic hot water system is contaminated. The most suitable proliferation temperature is in the range from 25 °C to 45 °C (van der Kooij et al. 2005). Long residence time (stagnancy) and a nutrition source (such as biofilm and sediments) also play important roles in the multiplication of Legionella (Ciesielski et al. 1984). Consequently, large hot water systems with low operating temperatures have a high risk of contamination. Many countries therefore have strict rules for domestic hot water temperatures. EU guidelines state that all water heaters should deliver water at a temperature of at least 60 °C, reaching taps at no less than 55 °C after 1 min of flushing (EWGLI group 2005). In Denmark, DHW temperature has to be maintained at 50 °C during normal use and no less than 45 °C at peak loads according to the comfort requirement in DS 439, while the CEN/TR standard 16355, which is for prevention of Legionella, recommends the hot water temperature should reach 55 °C in the whole system (DS 439 2009; DS/CEN/TR16355 2012).

Thus, a solution that can supply DHW with LTDH and without violating any comfort requirements or hygiene requirements is urgently needed.

1.3 Electric heat tracing

As mentioned above, low temperature district heating will be promoted in the future due to its prominent advantages. However, the temperature of domestic hot water cannot achieve the recommended 55 °C if the supply temperature from the district heating network is lower than that. Conventionally, to provide DHW to multi-storey buildings within an acceptable waiting time (10 s), DHW circulation is required. Therefore, to avoid Legionella, the DHW

circulation should be operated at 55 °C. However, a previous investigation in Denmark found that much of the energy was lost in the circulation process, which leads to the heating system having a very low efficiency (approx. 30%–77%) (Bøhm 2013). Another method is to use supplementary heating devices to keep domestic hot water supply at the required temperature. Electric heat tracing can be used for such concept.

The method is to use an electrical cable in thermal contact with the entire length of the external surface of the supply pipe, thereby heating up the supply pipe by electric power. Thus no circulation pipe is necessary, saving both pump cost and space. The overall heat loss is also reduced by removing the circulation pipe.

The application of electric heat tracing in industrial field has been well documented, such as process plants and offshore oil or gas equipment. However, the application to residential building has been insufficiently studied. Compared to industrial electric heat tracing systems, the control method required for residential buildings is complex, because the use of domestic hot water is not continuous and can vary due to different user patterns. One of the very few reported real case studies is an electric heat tracing system installed in Aalborg Hospital to deal with a Legionella problem. The operational cost of the new electric heat tracing system was only half that of the circulation system it replaced. The report states that the energy used by the electric heat tracing system could be further reduced by 30%–40% if real consumption pattern was taken into account (Olsen 2001).

This study set out to deal with the dilemma between low temperature district heating and the risk of Legionella, by developing a dynamically controlled model of an electric heat tracing system as an alternative solution for existing

multi-storey buildings, especially where deep renovation is difficult. The model took the complex use pattern of multi-residence building into account, which has not been studied before. The energy consumption and cost for DHW production with both normal control and smart control were compared with that of the conventional system with DHW circulation. The dynamic working characteristics of the cable were taken into consideration, so that the tracing cable was not just maintained at the set point temperature, but could respond instantly to every draw-off of the consumer, thereby achieving thermal comfort and effectively avoiding unnecessary heat loss at high temperatures. Three DHW load profiles from European directive, computer generation and a practical case were input to the model to investigate the impact of the user patter on the total heat consumption.

2 Methodology

2.1 Model building and system dimensioning

The theoretical building used in this study was defined as a typical Nordic building stock. It was a 6-storey building with three blocks (staircases). There were two apartments on each floor in each block, all with the same internal structure and floor area (100 m²). All three building blocks shared a central district heating substation in the basement, where the supply heat from the district heating network was transferred to the building's space heating and DHW loops. The air temperature was assumed to be 10 °C in the basement and 20 °C in the rest of the building. The height of each storey was 3 m, and the distance between staircases was 20 m.

2.2 System description

Simplified diagrams of a conventional system with in-line circulation and an electric heat tracing system are shown in Figs. 1(a) and (b) respectively.

For both the in-line circulation system and the electric heat tracing system, the space heating and DHW were supplied by district heating, but in separated loops. As the reference case, an "in-line circulation" system was designed as shown in Fig. 1(a). To provide hot water for domestic use, the domestic cold water is heated up in the central substation firstly, and then distributed to the consumers. To meet the comfort requirement, hot water circulation is necessary if there is no supplementary heating devices. In this study, the in-line circulation system is used for analysis, which has the circulation pipe going through the supply riser, thereby reducing the temperature drop for the circulation pipe. The external supply pipe was made of stainless steel, and the internal circulation pipe was made

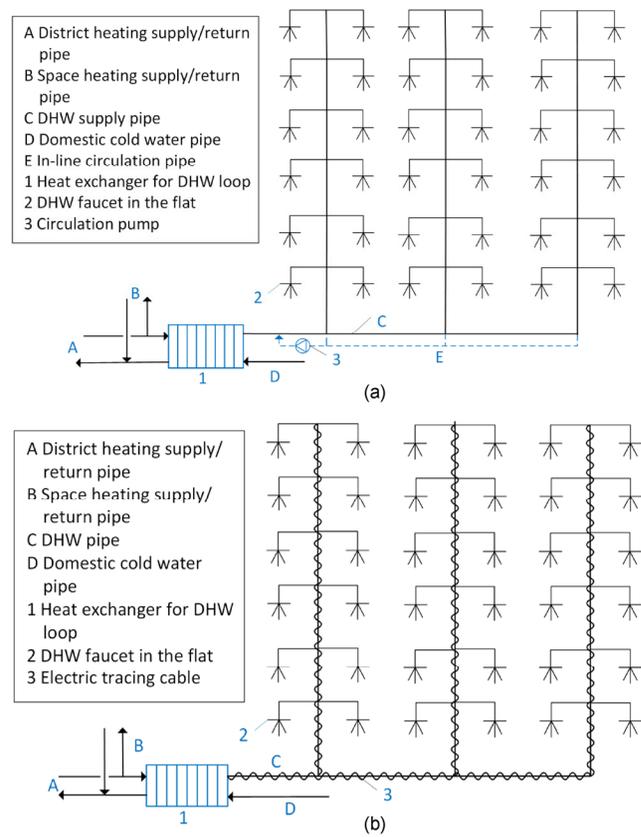


Fig. 1 Schematics of conventional system with (a) DHW circulation and (b) electric heat tracing system

of PEX. The pipe dimensions were selected by reference to existing product catalogue (Viega 2014).

For the electric heat tracing system, the schematic is shown in Fig. 1(b). The DHW was firstly heated up by the LTDH in the central substation. The electric heat tracing cable was used for supplementary heating and maintaining the temperature of DHW supply pipe. The control methods play an important role in the performance of the tracing cable. In this study, two control methods were applied in the dynamic model of electric heat tracing system. To provide a more comprehensive study, two common pipe materials (stainless steel and PEX) and two insulation classes (normal and plus) were selected. The specific pipe dimensions were found by reference (Geberit 2014; Uponor 2006). The insulation thickness was chosen in accordance with DS 452 and technical handbook (DS 452 2013; Rockwool 2014a, b) for corresponding situations.

2.3 Operating temperatures

The control temperatures in this study was chosen carefully in accordance with the standards for comfort and hygiene supply of DHW (DS 439 2009; DS/CEN/TR16355 2012). The system was designed to be able to supply 55 °C at any

point most of time, and no lower than 45 °C during a draw-off period. For the in-line circulation system, to ensure the whole system achieve 55 °C, the DHW was assumed to be produced around 60 °C. Therefore, the mean temperature of the in-line pipe (pipe-in-pipe) was assumed to be 57 °C, and was kept circulating all the time. For the electric heat tracing system, hot water was assumed to be heated to 45 °C by the district heating network, but the tracing cable had the capacity to heat up DHW from 45 °C to 55 °C. Thus, the temperature requirements for both systems were guaranteed.

2.4 Smart control for electric heat tracing system based on load profile

The electric heat tracing system was simulated under both normal control and smart control methods. The normal control method mainly refers to self-regulating function, which reduces the heating current as the desired temperature is approached and delivers the appropriate amount of heat at every point along the pipe. Therefore, different cable segments could have different power rates. The on/off function can help maintain the cable at the set point temperature. However, normal control method cannot response to the various tapping pattern. Therefore, this study developed a more sensitive and smart control method based on DHW load profiles. The on/off switch of the cable was not only controlled by the temperature set band, but also by each draw-off on the consumer side.

Figure 2 shows the typical load profile of European flats in a multi-storey building. The smart control system is able to detect the start and the end point of each draw-off from the temperature difference. Temperature sensors and thermostats were installed on each floor, so that, no matter which floor reached 55 °C, the cable segment was able to adjust

individually without affecting other floors. During the draw-off period, the tapping water can achieve 45 °C by the LTDH supply, the pipe segments from the basement to the tapping point is flushed with 45 °C hot water. Therefore, the cable segments from the basement to the tapping-point floor were switched off. At the end of the tapping, the cable is switched on to heat up the DHW through the interval between the draw-offs. So that the DHW temperature can be ensured to be no less than 45 °C, and the multiplication of Legionella is avoided. For non-tapping periods long enough to lift the temperature to 55 °C, the thermostat reduces the cable power rate to compensate only for the heat loss rate as soon as 55 °C is reached and maintains this temperature until the next draw-off. This means that the total power consumption of the cable is determined by the load profile. Draw-offs can be divided into four types, each with their own flow rates and tapping lengths as shown in Table 1, which is defined in DS 439 (DS 439 2009). Thereby, the tapping periods and non-tapping periods of a certain load profile can be calculated.

For the normal-control method in this study, the only temperature sensor was installed in the ground floor, which means that the cable power rate can be reduced to the heat loss rate only if the temperature of the ground floor reached 55 °C. The other parts of the cable were adjusted by the self-regulation function. Since the whole cable followed the pattern of the ground floor, some pipe segments could become overheated. To avoid scalding problems, thermostatic water mixers are required.

Three load profiles were applied in this study to investigate the influence on different control methods. Load profile 1 was based on the standard user pattern in Fig. 2. It was assumed to be an extreme scenario, in which all the consumers used hot water following the same hot water consumption pattern at the same time.

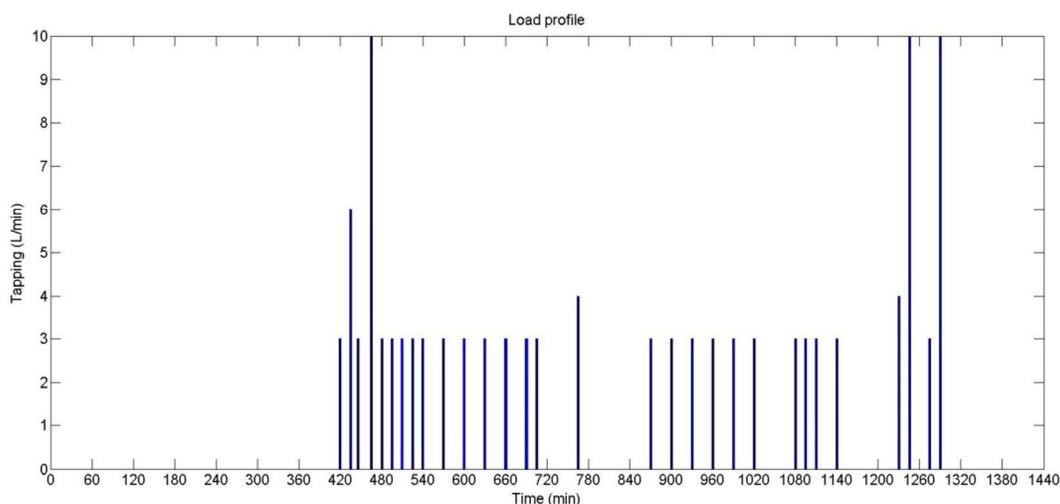


Fig. 2 Typical load profile of European flats from EU directive (Commission Delegated Regulation, European Commission 2013)

Table 1 Period length and flow rate of different types of draw-off

	Hand washing	Kitchen	Shower	Bathtub
Period (min)	3	2.5	5	10
Flow rate (L/min)	3	6	8.4	12

Load profile 2 was also based on the standard load profile. All the consumers followed the same pattern of using domestic hot water, but the start points of different flats were distributed along the timeline stochastically by the computer. Considering the diversity of DHW use in large

buildings, it was assumed that there was no overlap on the first draw-off between different apartments in the same building block. Figure 3 shows one day's domestic hot water use on each floor of one building block as generated by the computer.

Load profile 3 was based on practical load profile measured from a residential multi-storey building in Denmark. The data was collected for a one-day period from 12 am on the 28th to 12 am on the 29th August 2014, with a time step of approximately 0.5 hour. Figure 4 shows the measurements of the one-day draw-off profile.

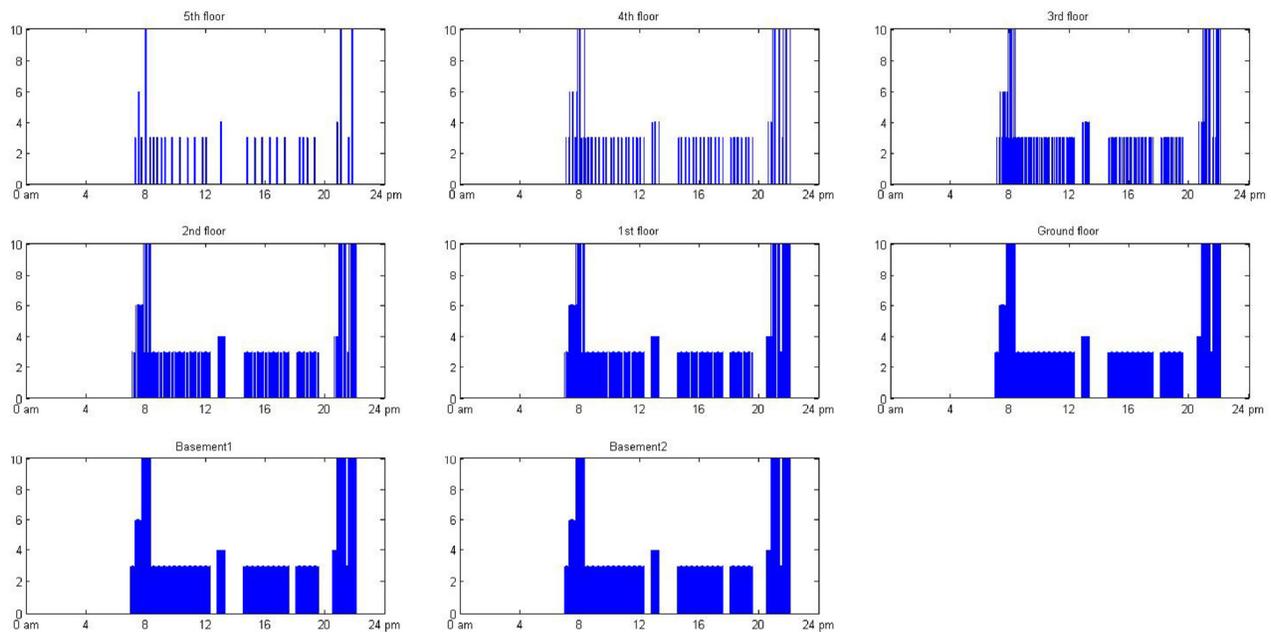


Fig. 3 Stochastically-distributed load profile with time (hr) and flow rate (L/min)

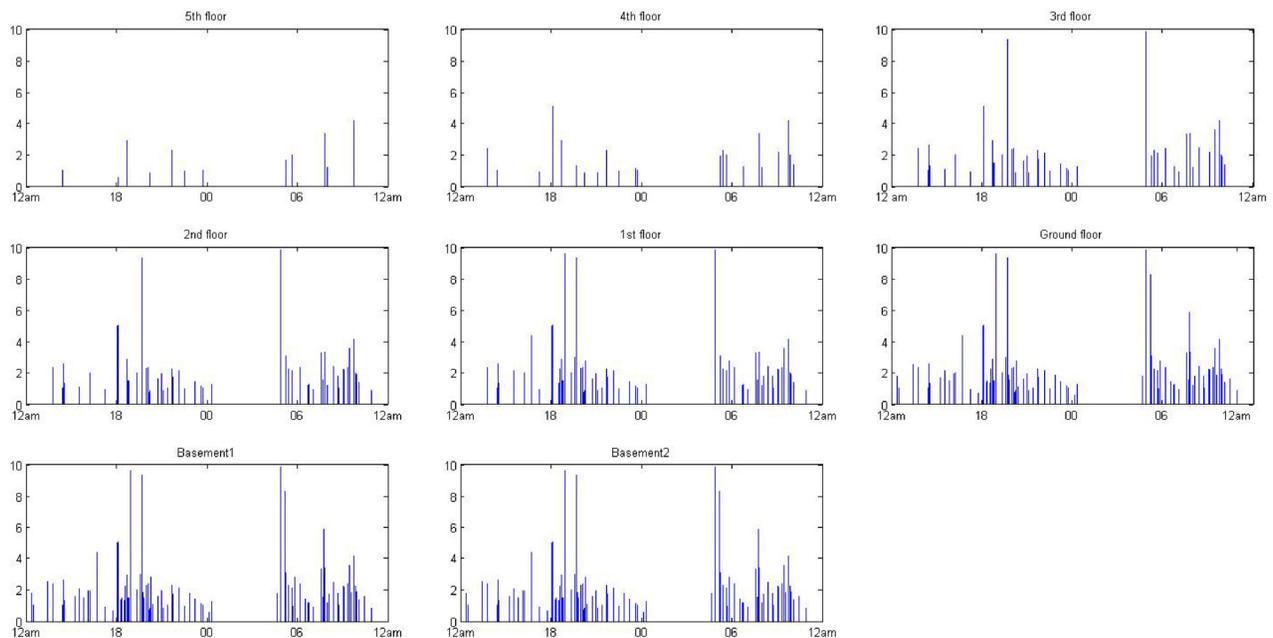


Fig. 4 Measured draw-off profile in a Danish multi-storey building with time (hr) and flow rate (L/min)

2.5 Computation for energy performance

2.5.1 Heat loss of pipe system

According to the heat transfer equation, the heat loss coefficient of the pipe can be calculated by Eq. (1)

$$U_{\text{pipe}} = \pi \cdot \left(\frac{1}{\alpha_1 \cdot D_1} + \frac{1}{2 \cdot \lambda_{\text{pipe}}} \cdot \ln\left(\frac{D_2}{D_1}\right) + \frac{1}{2 \cdot \lambda_{\text{insulation}}} \cdot \ln\left(\frac{D_3}{D_2}\right) + \frac{1}{\alpha_e \cdot D_3} \right)^{-1} \quad (1)$$

$$q_l = U_i \cdot l_i \cdot (T_{\text{flow}} - T_{\text{amb}}) \quad (2)$$

2.5.2 Power consumption for electric heat tracing

The energy conservation equation for electric tracing can be written as

$$P \cdot \tau = Q_h + Q_l \quad (3)$$

For self-regulating cables, the power consumption is proportional to the pipe temperature, which leads to reduced electricity consumption and more precise control. Two types of cable (R and M) were applied to the model. The correlation between the pipe temperature and cable power is linear between 10 °C and 60 °C, as shown in Fig. 5. Both cable power and heat loss are functions of temperature (T) and time (τ). Equation (3) can therefore be converted into a differential equation in terms of temperature and time,

$$P(T) \cdot d\tau = C_p \cdot m \cdot dT/3600 + q_l(T) \cdot d\tau \quad (4)$$

Since the required power rate varies with pipe size, the heat-up time for different pipe segments can be calculated by using Eq. (5):

$$\tau = \int_{T_1}^{T_2} \frac{(C_p \cdot m)/3600}{P(T) - q_l(T)} dT \quad (5)$$

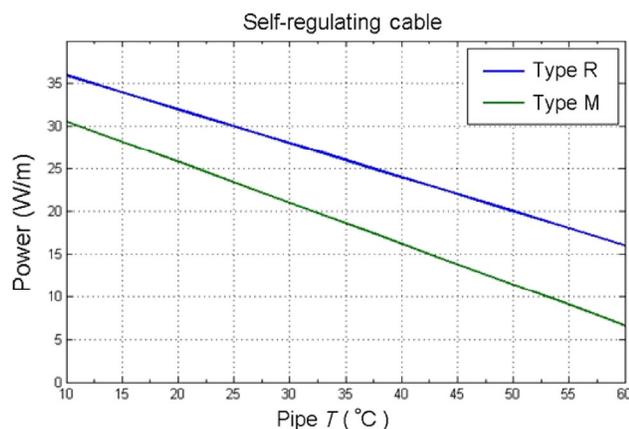


Fig. 5 Self-regulation function of the electric tracing cables

where, in this case study, $T_1=45$ °C, $T_2=55$ °C.

The correlation between cable power and time ($P(t)$), heat loss rate and time ($q_l(t)$) can also be obtained by regression method from Eqs. (4) and (5).

2.5.3 Simulation model

The smart control method was developed based on real-time control, which means the tracing cable can response to every variation of the hot water system. The model was proposed by Matlab dynamically. The schematic chart is shown in Fig. 6.

The interval length between two draw-offs determined the working time of the tracing cable. Depending on whether it was longer or shorter than the heat-up time, the electricity consumption and heat loss were calculated by different equations:

$$t > \tau \begin{cases} HL = \left(\int_0^{\tau} q_l(t) \cdot dt + (t - \tau) \cdot q_l(55^\circ\text{C}) \right) / 1000 & (6) \\ E = \left(\int_0^{\tau} P(t) \cdot dt + (t - \tau) \cdot q_l(55^\circ\text{C}) \right) / 1000 & (7) \end{cases}$$

$$t < \tau \begin{cases} E = \left(\int_0^t P(t) \cdot dt \right) / 1000 & (8) \\ HL = \left(\int_0^t q_l(t) \cdot dt \right) / 1000 & (9) \end{cases}$$

Thus, the performance of the heat tracing system can be simulated dynamically based on specific DHW load profile.

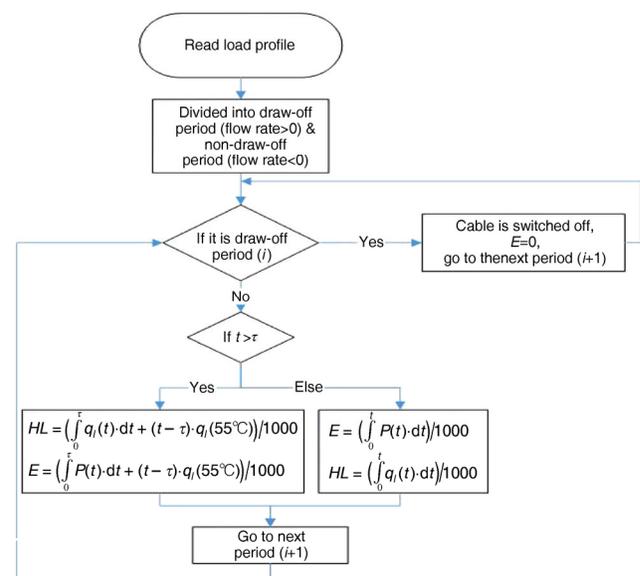


Fig. 6 Matlab model of electric tracing system with smart control

3 Results and discussion

3.1 Pipe dimensions of the case building

The system dimensions and insulations for different systems are shown in Table 2 and Table 3. The outer pipe diameter ranged from 35 mm × 1.5 mm to 54 mm × 2.0 mm for the in-line circulation system, while the circulation pipe diameter does not change with the exterior pipe for easier installation and maintenance.

For electric heat tracing, there were four different combinations: two pipe materials and two insulating levels. The heat loss rate of all four combinations was investigated in the following section.

3.2 Heat loss for different scenarios

For the in-line circulation system, the heat loss rate and

the total energy consumption for distributing DHW in the building was calculated, and the results are shown in Table 4.

For the electric heat tracing system, the calculation of heat loss was more complicated. The heat loss rate was not constant because the electric boosting process was dynamic depending on the random load profile. There was also a difference between smart control and normal control. However, the heat loss rate at 55 °C was calculated for the cable selection. The results are shown in Table 5.

The heat loss rate of all the investigated electric heat tracing systems was much less than that of the in-line circulation system, irrespective of the pipe materials used. That is due to the higher mean temperature of the pipe and the larger pipe diameter of the in-line circulation system. Moreover, because the circulation pipe was always at a high temperature, the heat losses of the circulation system sometimes even exceeded the net heating demand for DHW.

Table 2 Pipe dimensions and insulation of in-line circulation system

Segment	Apartments supplied	Exterior pipe dim. (mm)	Inline pipe dim. (mm)	Insulation thickness (mm)
Basement 1	12	42 × 1.5	14 × 2	30
Basement 2	24	54 × 2.0	14 × 2	40
Ground floor	12	42 × 1.5	14 × 2	30
1st floor	10	42 × 1.5	14 × 2	30
2nd floor	8	42 × 1.5	14 × 2	30
3rd floor	6	42 × 1.5	14 × 2	30
4th floor	4	42 × 1.5	14 × 2	30
5th floor	2	35 × 1.5	14 × 2	30

Table 3 Pipe dimension and insulation of electric heat tracing systems

Segment	PEX pipes			Stainless steel pipes		
	Pipe dim. (mm)	Insulation: normal (mm)	Insulation: plus (mm)	Pipe dim. (mm)	Insulation: normal (mm)	Insulation: plus (mm)
Basement 1	32 × 4.4	30	40	28 × 1.2	30	40
Basement 2	40 × 5.5	30	50	35 × 1.5	30	50
Ground floor	32 × 4.4	30	40	28 × 1.2	30	40
1st floor	32 × 4.4	30	40	28 × 1.2	30	40
2nd floor	28 × 4.0	30	40	22 × 1.2	20	40
3rd floor	28 × 4.0	30	40	22 × 1.2	20	40
4th floor	28 × 4.0	30	40	22 × 1.2	20	40
5th floor	22 × 3.0	20	40	18 × 1.0	20	40

Table 4 Heat loss of in-line circulation system

	Basement 1	Basement 2	Ground floor	1st floor	2nd floor	3rd floor	4th floor	5th floor
Heat loss rate (W/m)	11.2	11.2	8.8	8.8	8.8	8.8	8.8	7.9
Total heat loss (kWh/year)	8001		Pump power (kWh/year)			286		

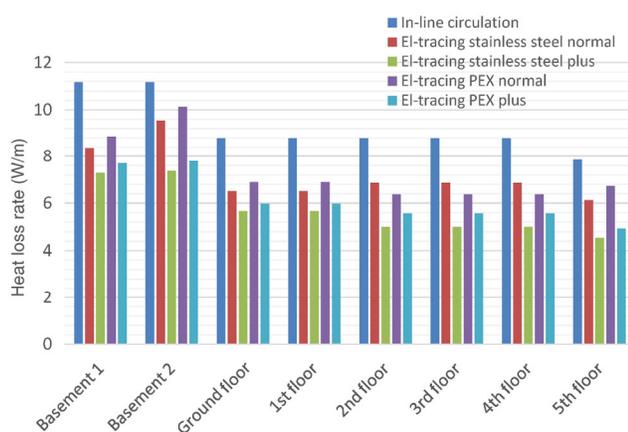
Table 5 Heat loss rate at 55 °C of electric heat tracing systems with different pipe materials and insulations

Segment	Heat loss rate at 55 °C (W/m)			
	Stainless steel Normal	Stainless steel Plus	PEX Normal	PEX Plus
Basement 1	8.37	7.29	8.87	7.70
Basement 2	9.54	7.37	10.14	7.79
Ground floor	6.51	5.67	6.90	5.99
1st floor	6.51	5.67	6.90	5.99
2nd floor	6.86	5.01	6.38	5.57
3rd floor	6.86	5.01	6.38	5.57
4th floor	6.86	5.01	6.38	5.57
5th floor	6.12	4.55	6.73	4.94

The floor-based comparison of the in-line circulation system and electric heat tracing system is shown in Fig. 7. The heat loss rate of the in-line circulation system is the highest for all pipe segments. For the electric heat tracing system, different materials and insulation thicknesses had impacts on the heat loss rate. As showed in Fig. 7, stainless steel pipes had better performances than PEX pipes with same insulations. Stainless steel pipe with plus insulation had the lowest heat loss. Increasing the insulation thickness by 30%–50% reduced the mean heat loss of stainless pipe by about 21%, while for the PEX pipe the reduction was about 16%. However, increasing the insulation thickness could also increase the investment cost. It is therefore of great importance to find the optimal insulation thickness, which takes both energy saving and economic performance into account.

3.3 Selection of the cable for the electric heat tracing system

The time required for heating up the DHW from 45 °C to 55 °C was calculated for both Cable R and Cable M.

**Fig. 7** Heat loss rates of the in-line circulation system and electric heating tracing systems on different floors

Suitable cable should have sufficient power to heat up the water within the required time. This means that the power rate should at least be higher than the heat loss rating at 55 °C. However, the cable power rate does not need to be much higher than the heat loss rate, considering the very high starting power rate and too frequent on-off switch of the cable caused by. The results are shown in Table 6 and Table 7.

As the results show, the time taken to heat up DHW from 45 °C to 55 °C using Cable R ranged from 12 minutes to around 1 hour, while for Cable M, it was not possible in all segments. That is because the rate of the heat loss at 55 °C was greater than the power rate of the cable at that temperature, which means that the temperature of DHW in this case cannot reach 55 °C. In this study, therefore, Cable R was chosen to heat up the pipes in the basements, and all the other pipe segments were heated by Cable M.

Table 6 Heat-up time for each pipe segment by Cable R

Segment	Time (h)			
	Stainless steel Normal	Stainless steel Plus	PEX Normal	PEX Plus
Basement 1	0.57	0.53	0.62	0.57
Basement 2	0.90	0.83	1.07	0.90
Ground floor	0.50	0.47	0.53	0.51
1st floor	0.50	0.47	0.53	0.51
2nd floor	0.31	0.28	0.39	0.37
3rd floor	0.31	0.28	0.39	0.37
4th floor	0.31	0.28	0.39	0.37
5th floor	0.20	0.20	0.25	0.22

Table 7 Heat-up time for each pipe segment by Cable M

Segment	Time (h)			
	Stainless steel Normal	Stainless steel Plus	PEX Normal	PEX Plus
Basement 1	2.56	1.72	4.29	2.03
Basement 2	—*	2.68	—*	3.27
Ground floor	1.38	1.18	1.57	1.30
1st floor	1.38	1.18	1.57	1.30
2nd floor	0.90	0.66	1.06	0.92
3rd floor	0.90	0.66	1.06	0.92
4th floor	0.90	0.66	1.06	0.92
5th floor	0.68	0.41	0.71	0.52

* The result by the model is infinitely great.

3.4 Simulation results for the electric heat tracing system based under different control methods

3.4.1 Dynamic working process of the electric tracing cable

Figure 8 shows the simulation results of how the tracing cable performed with/without thermostatic control. As shown

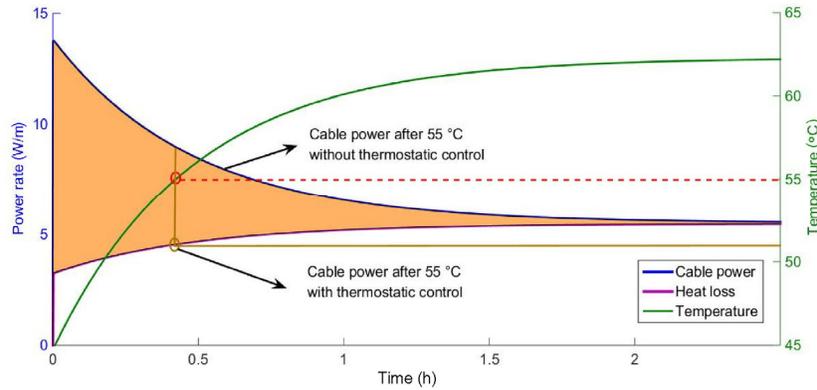


Fig. 8 Dynamic working process of the tracing Cable M for stainless steel plus on 5th floor with/without thermostatic control

in the picture, since the tracing cable had the self-regulating function, the power rate is not a constant value, but decreases with temperature. In contrast, the heat loss rate increases with time. As a result, the DHW temperature increases non-linearly with time and reaches its plateau when the power rate and the heat loss rate balance. The area between the cable power rate and heat loss rate is the energy consumption for heating up the DHW. In a conventional system with DHW circulation, this energy is provided by the district heating completely. However, by using electric tracing cable, the supply temperature of district heating can be reduced, and part of the heat from district heating network can be saved.

If normal control method was applied, it would be impossible for the cable above the ground floor to reduce the power to balance the heat loss rate when DHW reaches 55 °C, so the electricity consumption would be the whole area below the cable power curve. With smart control, the power can reduce to balance the heat loss rate as soon as 55 °C is reached. The power consumption after that is the area below the brown line (Fig. 8). As a result, overheating is avoided, saving both heat loss and heating energy.

3.4.2 Energy consumption of the electric heat tracing system in different scenarios

This analysis was made on the stainless steel plus system, the energy performance of the electric heat tracing system was analysed for 6 scenarios according to different load

profiles and control methods. The results of each scenario are listed in Table 8.

As shown in Table 8, compared with normal control, applying smart control saved 20.6%, 60.1%, and 21.2% on the total electricity consumption for the cases of Load profile 1, Load profile 2, and the real data, respectively. The heat loss was also reduced by approximately 14%–27%. That was because the smart control method helped avoid overheating of the pipes. Moreover, unnecessary power consumption was saved by switching off the heat tracing cable during draw-off periods. Thus, both cable power and heat loss were reduced. Additionally, the cable power was used not only to cover the heat loss, but also to heat up hot water locally. The real data scenarios used only 50% of the cable power for covering the heat loss, in both control methods.

Another thing that should be noticed of is that among different load profiles, the total electricity consumptions under the normal control method were very similar. But with the smart control method, the load profiles played an important role in the total power consumption. The difference between the Load profile 1 and Load profile 2 under the smart control method was almost 50%. If the system has a high simultaneity factor, as in Load profile 1 in this case, the tracing cable has to heat up hot water for more intervals, which will undoubtedly lead to more power consumption. So the complex use of domestic hot water corresponds to the improvement of energy efficiency of for the electric heat tracing system.

Table 8 Total electricity consumption and electricity for covering heat loss in different scenarios when applying electric heat tracing

	Load profile 1 (kWh/year)		Load profile 2 (kWh/year)		Real data (kWh/year)	
	Total electricity consumption	Heat loss	Total electricity consumption	Heat loss	Total electricity consumption	Heat loss
Smart control	8960	4551	4179	2650	8895	3780
Normal control	11286	5306	10467	3626	11294	4379

Note: The source of Load profiles 1 and 2 is described in Section 2.4.

3.4.3 Comparison between the in-line circulation system and the electric heat tracing system

The energy performances of all the different scenarios (as well as the in-line circulation system) are shown in Fig. 9. As shown in Fig. 9, the total energy consumption of the in-line circulation system consisted of two parts: the heat loss covered by district heating network and a small amount of electricity for pumping power. The heat loss of the in-line circulation system, which was approximately 8000 kWh per year, was greater than the heat loss in any of the electric heat tracing scenarios. Compared to the in-line circulation system, the heat loss reductions in the different electric heat tracing scenarios ranged from 34% to 67%. However, for the electric heat tracing system, a large proportion of the overall electricity consumption was used to heat up the DHW, which leads to higher overall energy consumption. Thus, only the scenario using Load profile 2 with smart control consumed less energy than the circulation system. According to the Danish Building Regulation (BR10 2010), the maximum amount of energy allowed for producing domestic hot water is 13 kWh/m². Thus, the allowable overall DHW heat consumption was 46 800 kWh/year for the analysed building. The extra electricity by the electric heat tracing system for heating up domestic hot water only accounted for 3%–15% of the standard value. But the district heating network only had to heat up hot water to 45 °C instead of 60 °C for the circulation system. Thereby, a large amount of heating energy can be saved from the district heating network.

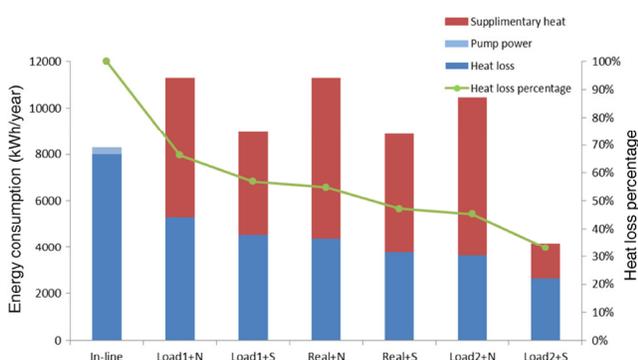


Fig. 9 Comparison of annual energy consumption between circulation and electric heat tracing systems (S: smart control, N: normal control)

The annual operation cost for distributing DHW from the substation to the consumers was calculated for each scenario. For the in-line circulation scenario, the power consumption of the circulation pump was also included. With regard to the primary energy factor, the prices for district heating and electricity are assumed to 0.8 DKK/kWh and 2 DKK/kWh, respectively. The economic performances of different scenarios are shown in Table 9.

The savings of district heating energy by using electric heat tracing were calculated by multiplying the supplementary heat by the district heating price (0.8 DKK/kWh ann). As shown in Table 9, almost half of the total costs of the electric heat tracing system were used to heat up the DHW. The costs for covering the heat loss were not significantly higher than that of the conventional system. Moreover, the district heating grid can save much energy because of the lower supply temperature. This means, it will be possible to make lower district heating price for the consumers, so that to compensate the extra expense by electricity. The break-even district heating price can be calculated by considering the total heat demand and electricity consumption. Take the “Real+S” scenario as an example, the overall heating demand according to the Danish Building Regulation is no more than 29.5 kWh/m² ann, while the annual electricity consumption is 8895 kWh for the whole building. To give an even overall expense to the consumer, the district heating price should be no higher than 0.69 DKK/kWh.

4 Conclusions

This paper presents scenario analyses of electric heat tracing system as an alternative solution for supplying DHW with LTDH. A dynamic model was built to simulate the performance of electric heat tracing system under different scenarios which were described by different control strategies and DHW load profiles. The effect of different pipe materials and insulations were also analysed. The results were compared to an in-line circulation system.

- The pipe material had only a very slight influence on the total energy use (less than 8%), but the use of better insulation (30%–50% thicker) made it possible to reduce power use by 10% and heat loss by 18%.
- Smart control method based on real-time and thermostatic control had a significant impact on the system performance

Table 9 Annual operation cost for distributing DHW (in DKK) of the different scenarios

	In-line	Load1+N	Load1+S	Real+N	Real+S	Load2+N	Load2+S
Total operation cost	6973	22572	17920	22588	17790	20933	8357
Heat loss cost	6401	10613	9103	8758	7559	7252	5300
Heating energy saving	—	4784	3527	5532	4092	5473	1223

of the electric heat tracing system. Compared to the normal control method, smart control was able to save more than 20% of the total electricity consumption.

- The load profile played an important role in the energy performance of the electric heat tracing system under smart control method. The difference between Load profile 1 (with a high simultaneity factor) and Load profile 2 (with a low simultaneity factor) was as much as 50%.
- Compared to the in-line circulation system, the electric heat tracing system saved 34%–67% of the loss. The energy for heating up the water locally accounted for almost 50% of the total energy consumption of the electric heat tracing system.
- The application of electric heat tracing system gives access to the implementation of LTDH. It is possible to compensate the extra cost caused by the cable power by lower district heating price, since the district heating grid can save much energy if LTDH is applied.

This study shows that both the comfort and safety requirements for DHW supply can be met by LTDH if combined with an electric tracing system. Electric tracing is thus a promising alternative method to realize LTDH when full renovation of the pipe network is not feasible or the space is very limited. Based on the results of this study, smart control is of great importance for energy conservation in electric tracing systems. Large multi-storey buildings with high variation in the DHW load are more appropriate to implement electric heat tracing system. In terms of the work in the future, the benefits caused by LTDH in the district heating network and heat production side should be investigated to give a more comprehensive overview.

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Appendix C – Paper 3

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Decentralized substations for low-temperature district heating with no Legionella risk, and low return temperatures

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 Heat pump

ABSTRACT

To improve energy efficiency and give more access to renewable energy sources, low-temperature district heating (LTDH) is a promising concept to be realized in the future. However, concern about Legionella proliferation restricts applying low-temperature district heating in conventional systems with domestic hot water (DHW) circulation. In this study, a system with decentralized substations was analysed as a solution to this problem. Furthermore, a modification for the decentralized substation system were proposed in order to reduce the average return temperature. Models of conventional system with medium-temperature district heating, decentralized substation system with LTDH, and innovative decentralized substation system with LTDH were built based on the information of a case building. The annual distribution heat loss and the operating costs of the three scenarios were calculated and compared. From the results, realizing LTDH by the decentralized substation unit, 30% of the annual distribution heat loss inside the building can be saved compared to a conventional system with medium-temperature district heating. Replacing the bypass pipe with an in-line supply pipe and a heat pump, the innovative decentralized substation system can reduce distribution heat loss by 39% compared to the conventional system and by 12% compared to the normal decentralized substation system with bypass.

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1. Introduction

District heating is an efficient method of supplying heat to consumers in many regions, especially in high heat density areas. Compared with other heating systems, district heating is flexible in using various forms of energy, such as surplus heat from industrial processes, geothermal energy, solar energy, and also residual resources, which might be used increasingly in the future. Therefore, district heating can play an important role in realizing a system of sustainable energy with 100% renewable energy supply [1].

After long-term development, the current temperature level of most district heating systems is often below 100 °C, but still high. To meet the lower heating demand of energy-efficient buildings in the future and give access to more low-temperature heat sources, the concept of 4th Generation District Heating [1] has been proposed, with the aim of developing a district heating system with lower supply temperature. A recent study investigated the feasibility of supplying space heating with low-temperature district

heating (LTDH) without compromising on comfort [2], which indicates that with extensive renovation and efficient heating equipment, LTDH supply is sufficient to provide an indoor temperature of 22 °C.

However, one obstacle to realizing LTDH is the conflict with hygiene requirements. Artificial aquatic systems are easily colonized with Legionella, which is the causative agent of Legionnaire's disease. Temperatures in water below 50 °C and stagnancy are considered the main factors that promote the growth of Legionella. The common solution is to use a high-temperature regime and domestic hot water circulation. Most countries require the district heating supply temperature to be at least 60 °C for large systems with circulation. Unfortunately, previous research has shown that the heat loss of a conventional system with domestic hot water circulation and a storage tank can be as much as 50% of all the energy delivered [3]. However, if the water volume can be limited, the proliferation of Legionella can be much restrained. According to the regulations of CEN/TR 16355 [4], a hot water system without a tank and circulation system has no need to be kept at a high temperature. So a system of decentralized substations can limit both the heat loss and the risk of Legionella. The domestic hot water can be produced in each apartment in a building using a compact flat-

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plate heat exchanger and distributed to the taps in the apartment with small-dimension pipes. In this way, the volume of the indoor domestic hot water system is so small that the risk of Legionella is eliminated without maintaining high temperatures.

Some articles have presented investigations of the benefits of applying the decentralized substation system, but with medium-temperature district heating. Breuer and Loose [5] point out that decentralized supply of domestic hot water can save approximately 30% of heating energy consumption comparing to the conventional circulation system, making it an economically efficient alternative method for DHW production. Cholewa and Siuta-Olcha [6] conducted a practical measurement for a 4-storey building with decentralized substations in Poland. By comparing the readouts of the heat provision and heat consumption (both space heating and DHW), they find the decentralized substation can achieve the efficiency of 67.1%, and motivate the consumer to reduce their heat consumption by 19.2%. In another article, Cholewa et al. [7] compare the measurements of a centralized heating system with gas boiler, a decentralized substations system with district heating, and a decentralized heating system with individual gas boiler for each dwelling. The decentralized substation system with district heating has 10.5% higher efficiency than the centralized system on annual average, but lower than the individual gas boiler system. However, more equipment for ventilation is required by the individual gas boiler system. Thorsen [8] provides a parametric study about the decentralized substation concept. According to the practical data, the investment of the decentralized substation system is on break-even level as the conventional system. And it can save 2–4 kWh/m²·yr energy without violating the comfort and hygiene requirements.

In this study, we explored the feasibility and benefit of realizing LTDH by applying the decentralized substation unit. In addition, we proposed and investigated an innovative decentralized substation system with an in-line supply pipe and a heat pump, which aims to further reducing the return temperature. Three models were built up to simulate the scenarios of the conventional system supplied by 3rd generation district heating, the decentralized substation system supplied by LTDH, and the innovative decentralized substation system supplied by LTDH respectively. The design information of the models was obtained from a case multi-storey building with decentralized substation system supplied by medium temperature district heating (70 °C). The model of decentralized substation system was compared with measurements of the case system to ensure accurate settings and parameter input, and is used to simulate the LTDH scenario by converting the supply temperature to 55 °C. The annual distribution heat loss, the resulting operation costs, the seasonal variation of the three scenarios, and the benefit of low return temperature were analysed and compared. The results provided by this study can be used to promote LTDH in the planning stage, and to improve the efficiency of the decentralized substation system.

2. Materials and methods

This section describes the methods for setting up the models that were made to investigate the energy performance of the heat distribution process. The distribution heat loss of three scenarios, as one crucial indicator of the efficiency for the heat distribution process, was simulated and compared. In this study, the distribution heat loss focused on is the heat loss from the building inlet to the apartment inlet. Distribution heat loss inside the apartments and in the network was not taken into account. In addition, the economic performances of different systems related to the heat distribution process were analysed and compared. The investment costs were not included in this study, since the price of the

equipment varies a lot among manufacturers. The benefit of a lower return temperature was also investigated from both energy and economy points of view. To make a common basis for the comparison, the conditions on the consumer side for three scenarios, such as heating demand, building insulation level, heating equipment, were all assumed to be the same.

2.1. Information of the case system

2.1.1. Building information

The case building is a six-floor residential building located in Denmark. The ground floor comprises two commercial stores. Each of the other floors has three apartments. The basement has a storage room and a technical room which only have space heating demand, while the rest of the basement is used for parking and is neither heated nor supplied with hot water.

The case building and the floor layout of the residential storeys are show in Fig. 1.

The apartment area is about 110 m². As shown in Fig. 1, each apartment has typical domestic hot water use with one kitchen, one shower head, and one hand basin. Floor heating in the bathroom is used all the year round for comfort. The building was constructed in 2006 and is well-insulated. The design space heating and domestic hot water demands are assumed to follow the Danish building code BR95 [9], which requires the total energy supply should be less than 70 kWh/m² per year plus 2200 kWh divided by the heated floor area.

2.1.2. Decentralized substation system in the case building

The reference heat distribution system in the case building is the decentralized substation heating system, which is not very common in multi-storey residential buildings in Denmark. However, to promote the utilization of LTDH, the local district heating company decided to apply decentralized substation systems in some new residential buildings. Each flat in the case building has its own decentralized substation installed in the cabinet inside. The substation is connected with the district heating service supply and return pipes installed as risers in the cabinet. There are three risers in the building. The substations of the three flats on the same floor are connected to different risers. The heat demand for both space heating and domestic hot water is supplied by the individual decentralized substations.

The type of substation unit used in the reference building is shown in Fig. 2.

Fig. 3 shows the installation and connection of the decentralized substation unit.

The thermostatic valve (2') of the domestic hot water heat exchanger also serves as a bypass to keep the supply line warm if necessary, so that an acceptable waiting time for domestic hot water can be guaranteed. Temperature and energy meters in the decentralized substation of each apartment record the accumulated heat consumption of the apartment. Normally, the time step of the meters was set to a daily or monthly basis. In this study, the meters were reset to save the data with a shorter time step (0.5 h) for a two-day test for more accurate measurements. At the building inlet, an energy meter is installed to measure the overall heat supplied to the building from the district heating network and the district heating supply and return temperatures. The distribution heat loss of the case building was calculated as the subtraction between the measured total heat supply by the district heating network and the total heat consumption of the consumers. It was compared to the simulation results by the model. The measured return temperature was also compared to the calculated return temperature of the decentralized substation model.

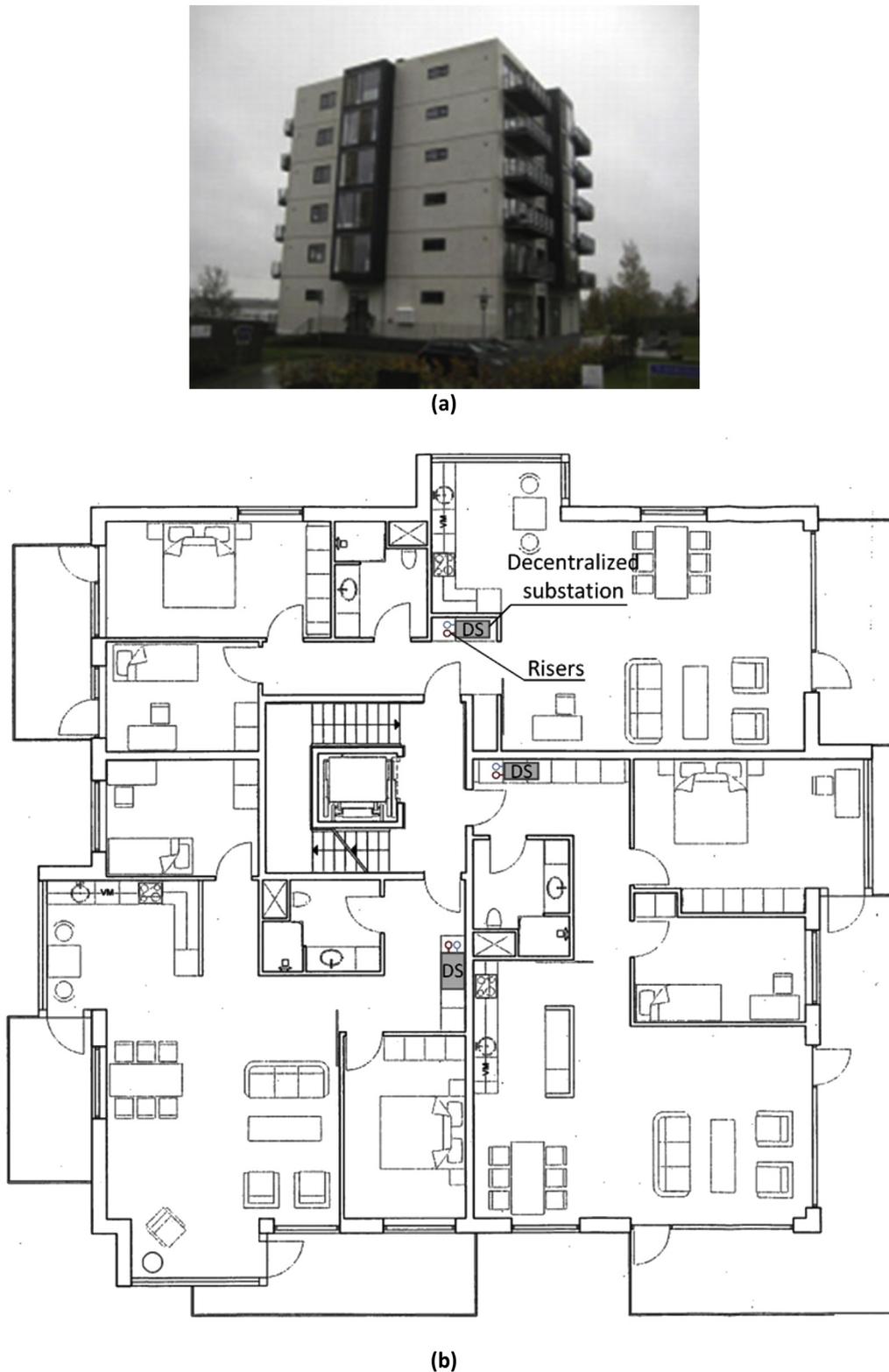


Fig. 1. The reference building (a) and the floor layout (b) of the residential storeys.

2.2. Distribution heat loss

The distribution heat loss is an important factor in evaluating the energy-efficiency of a heating system, because it directly affects the overall energy supplied by the district heating. In this study, the

distribution heat loss of the decentralized substation system includes the heat loss along the pipe, whereas in the conventional system with domestic hot water circulation, the heat loss of the storage tank also needs to be taken into account. The draw-off of domestic hot water can also affect the average return temperature,

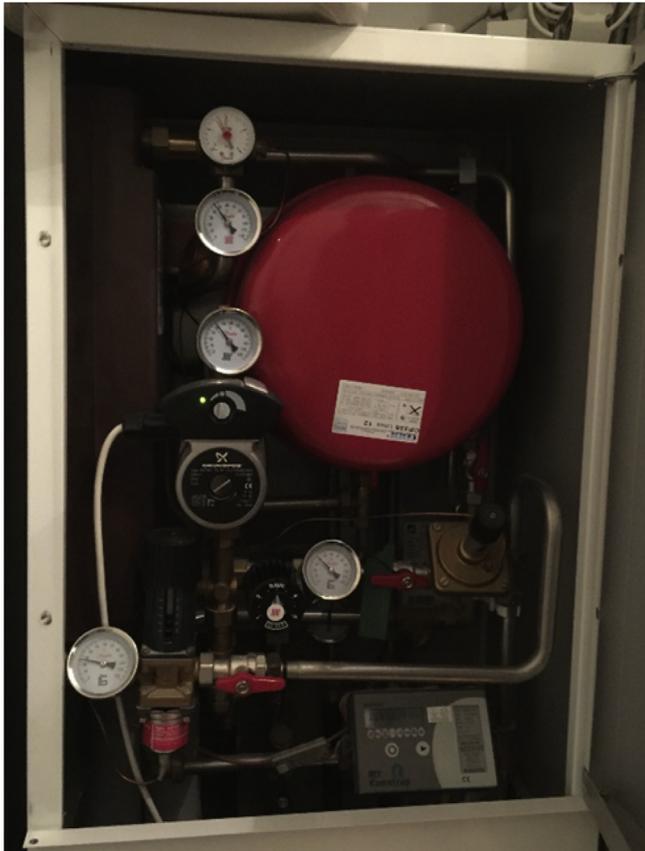


Fig. 2. Decentralized substation unit.

but since the draw-off happens only a few times a day and the draw-off periods are very short, the effect of domestic hot water draw-off on the average return temperature was ignored in this study.

The basic principles for calculating the distribution heat loss from the pipes are illustrated by the following equation:

$$Q_{HL} = \sum_1^i (\Phi_i \cdot l_i \cdot \Delta t_i \cdot \tau) / 1000 \quad (1)$$

where,

Q_{HL} is the overall heat loss including all the pipe segments, [kWh]

τ is the integration time, for the heating season and non-heating season separately, [hr]

Φ_i is the heat loss coefficient of the i th pipe segment, which depends on the pipe dimensions and insulation level, [W/m·°C]

l_i is the length of the i th pipe segment, [m]

Δt_i is the temperature difference between the individual pipe and the ambient, [°C].

The pipe dimensions and insulation levels for the models were determined in accordance with Danish standards and regulations. In this study, the average pipe temperatures for the heating season and the non-heating season were different because of different operation methods. These lead to different distribution heat loss. They are defined in the following section.

2.3. Investigations for the different scenarios

In this section, the three scenarios for comparison are described. They were all designed to fulfil the same heat demand as the case building. All three systems were assumed to be applied in energy-efficient buildings with floor heating, where the LTDH supply is sufficient to provide comfort indoor temperature. The pipe dimensions were determined carefully following the corresponding design guidelines, and insulated to Class 4 according to the standard [10,11]. Since all the risers were installed inside the cabinets in the flats, the surrounding ambient temperature for the distribution pipes was assumed to be 20 °C. The operation temperatures for each scenario were determined in accordance with Danish standards and regulations. To avoid Legionella, the temperature of the water in the circulation loop should be at minimum of 55 °C and the tank should be kept at 60 °C. In terms of the system without circulation and heat storage, the water temperature should be no less than 45 °C for comfort [4,10]. The heating season was defined as 1st October to 31st April in this study for seasonal analysis, which is applied for energy-efficient buildings in Denmark. The detailed assumptions and operations for the three models are illustrate in the following sections.

2.3.1. Scenario 1. Conventional system with domestic hot water circulation

Scenario 1 was built as the typical existing system for multi-family building with medium –temperature district heating. In

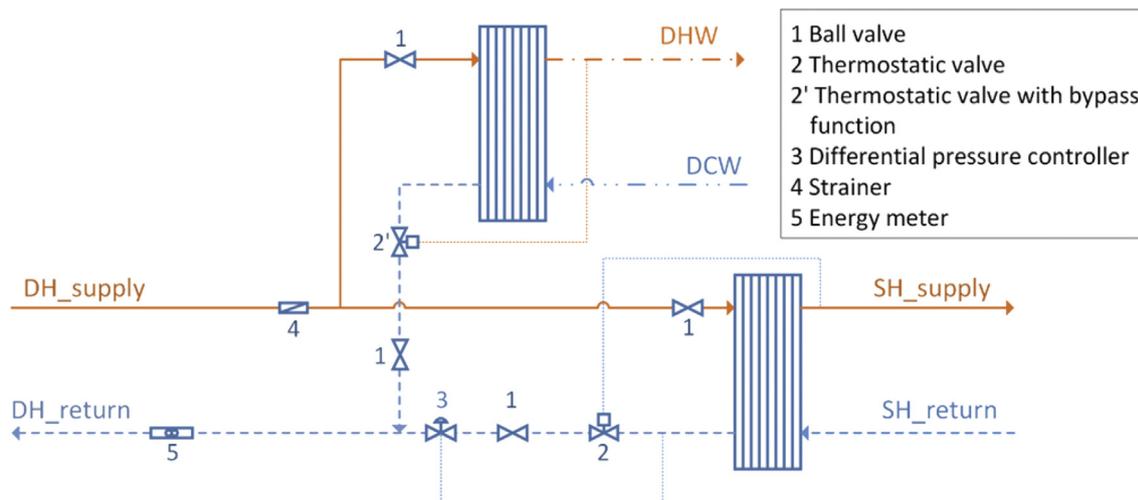


Fig. 3. Connection of decentralized substation unit.

such system, domestic hot water circulates at high temperature to avoid Legionella. Scenario 1 was used as reference case for the model comparison. A schematic of the conventional system is shown in Fig. 4.

The conventional heating system has separate loops for space heating and domestic hot water. Space heating is supplied directly by the district heating network. In the study, the floor heating in the bathroom was still maintained during the non-heating season to provide comfort. The temperature of the space heating supply can be adjusted by mixing the return flow into the supply flow. A 3-way valve was used to regulate a proper mixed temperature for space heating supply. For domestic hot water, an in-line supply pipe was utilized to achieve high efficiency circulation. As Fig. 4 shows, the supply water goes through the outer pipe and the recirculation water goes through the inner pipe. The in-line supply pipe was designed in accordance with the current product catalogue [12]. The pipe dimensions of the DHW loop range from 35 to 42 mm, while the diameters of the space heating loop range from 18 to 28 mm. The heat storage tank is used to provide sufficient hot water during peak load. The tank size was dimensioned by considering the domestic hot water peak load, the duration of the peak load, the storage temperature, and the simultaneity factor. The tank was insulated by Class5 according to the standard [11].

The temperature levels are also crucial inputs for the model. To fulfil the regulations for inhibiting Legionella in domestic hot water systems, the district heating supply temperature to the substation in Scenario 1 was assumed to be 70 °C throughout the year. However, the temperature levels for the space heating loop was assumed to be 35/25 °C to provide a comfortable floor surface temperature. In the domestic hot water loop, the temperature of the storage tank was assumed to be 60 °C in accordance with the hygiene standard [4].

The temperature at the outlet of the circulation pipe was assumed to be no less than 55 °C by thermostatic control.

2.3.2. Scenario 2. Decentralized substation system with LTDH

The model of the decentralized substation system was designed to have the same configuration as the case system. The schematic diagram of Scenario 2 is shown in Fig. 5.

With the decentralized substation unit, each apartment is decentralized from the centralized heating system. This means that the domestic hot water system inside each flat has a small volume with no circulation. The high-temperature regime to avoid Legionella is not necessary, which gives access to LTDH. According to the design guidelines, the diameter of the pipe line was dimensioned from 33.7 to 42 mm.

The district heating supply temperature was assumed to be 55 °C for the whole year, so that the supply temperature at the remote decentralized substation unit can be guaranteed to be no lower than 50 °C. The return temperature of the space heating was assumed to be 25 °C based on efficient cooling of floor heating. During the heating season, the space heating is operated all the time to provide comfort indoor temperature. According to the Danish standard [10], the overall tapping period is very limited during a day. So space heating flow dominated the mixed flow in the service pipes. Therefore, the effects of the bypass flow and the flow for domestic hot water were neglected. The return temperature of the service pipe was assumed to be the same as the return temperature of space heating.

During the non-heating season, the bathroom floor heating was maintained. Based on Danish Building Regulations 2010 [13], the mass flow for the bathroom floor heating should be sufficient to provide 26 °C for floor temperature, which was calculated as

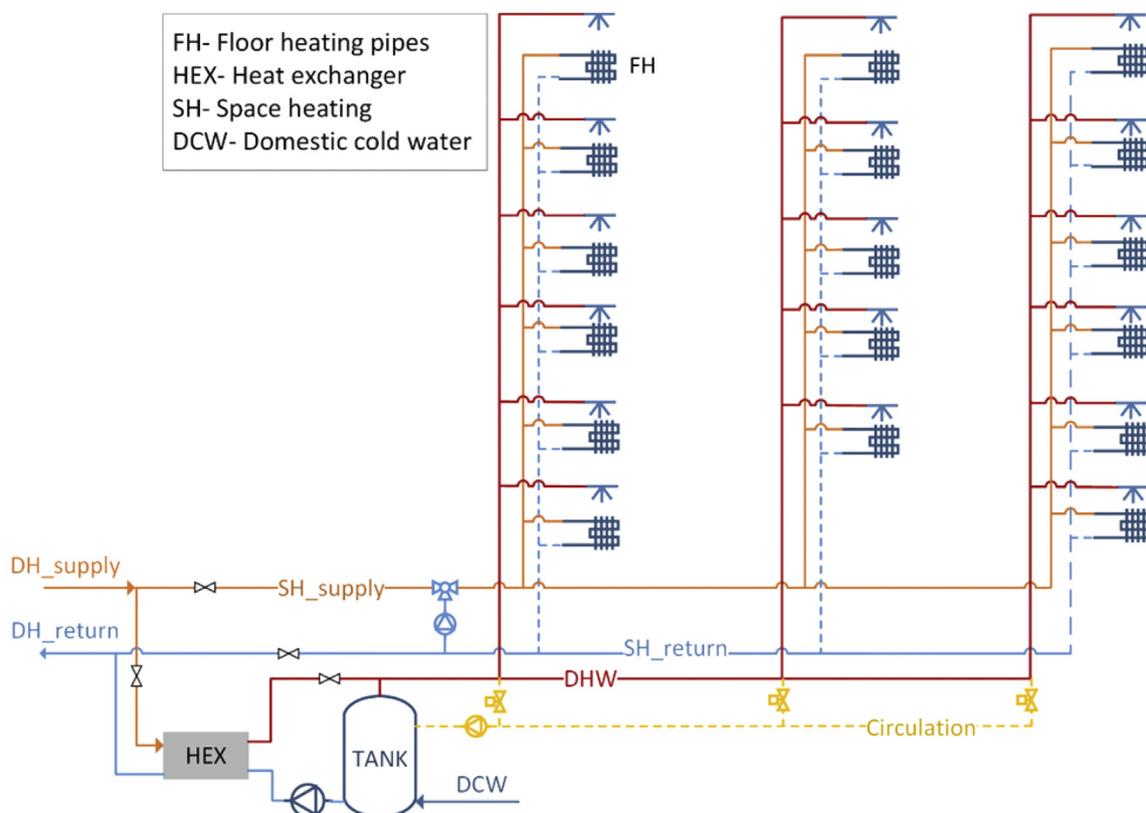


Fig. 4. Schematic of conventional heating system.

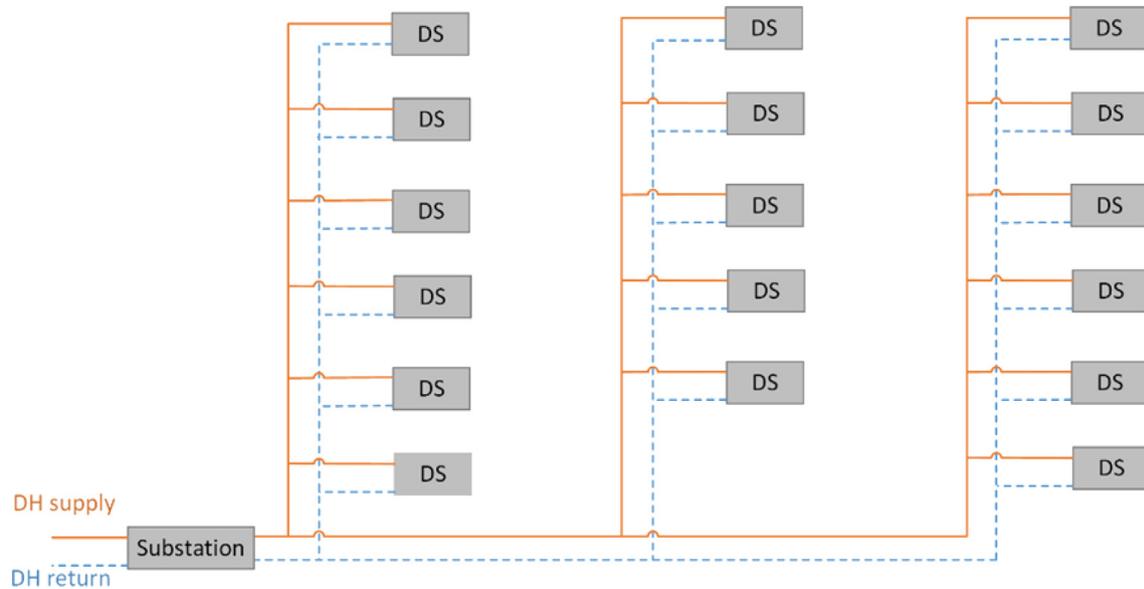


Fig. 5. Schematic of decentralized substation (DS) system.

19.9 kg/h for Scenario 2. The bypass flow should be sufficient to keep the set-point temperature no less than 50 °C, which was 62 kg/h. The effect of bypass should be taken into account. The return temperature of the service return pipe was calculated as the weighted average temperature considering both the bathroom heating flow and the bypass flow.

2.3.3. Scenario 3. Decentralized substation system with in-line supply pipe and heat pump

A decentralized substation system allows LTDH supply, but the mix with the bypass flow during the non-heating season results in high return temperatures and may restrict the use of LTDH. To reduce the return temperature for the decentralized substation system, an innovative concept was proposed. The idea is to use an in-line supply pipe to keep the supply line warm instead of using the bypass. The operation of the in-line supply pipe was assisted with a heat pump, which aims to cover the heat loss of the supply pipe and maintain the circulation temperature. As a result, the return temperature was expected to be lowered by avoiding mixing with the bypass flow. The dimension of the in-line supply pipe was larger than the supply pipe of Scenario 2, which ranged from 42 to 54 mm. The schematic of the new system is shown in Fig. 6.

To make sure the consumers can get domestic hot water at a comfort temperature, the temperature of the supply pipe was assumed to be no less than 50 °C. During the non-tapping period, the in-line circulation was operated to keep the supply pipe warm. The heat pump was used to transfer heat from the district heating supply to the in-line circulation to compensate for the temperature drop along the in-line supply pipe due to the distribution heat loss. The thermostatic control of the heat pump guaranteed the outlet temperatures of the evaporator to be 25 °C and the temperature of the in-line circulation no less than 50 °C. Ignoring the impact of domestic hot water draw-off, the heat pump was assumed to work full-time during the non-heating season. In this scenario, the return temperature of the service pipe was assumed to 25 °C without being mixed with the bypass.

2.3.4. Economic analysis

The costs of covering the distribution heat loss in the three scenarios were calculated and compared. Moreover, the benefit of

lower return temperature by applying Scenario 3 was obtained by summing up the cost reduction by the heat loss and savings for the district heating system compared to Scenario 2.

Since Scenario 3 used extra electricity for the heat pump, when calculating the costs of distribution heat loss, different energy prices were considered. For heat loss reduction, the extra cost of Scenario 3 included the heat pump power and the extra heat loss from the enlarged supply pipe. The savings included the reduction in the distribution heat loss of return pipe during the non-heating season. They were calculated as.

$$C_{sup} = C_{DH} + C_{el} \quad (2)$$

$$C_{el} = E_{el} \cdot P_{el} \quad (3)$$

$$E_{el} = Q_{sup} / COP \quad (4)$$

$$C_{DH} = P_{DH} \cdot (Q_{sup} - E_{el}) \quad (5)$$

$$C_{re} = P_{DH} \cdot Q_{re} \quad (6)$$

where,

C_{sup} is the overall cost of covering the heat loss of the supply line, [DKK]

C_{el} is the cost of electricity for the heat pump, [DKK]

C_{DH} is the cost of covering the heat loss by district heating, [DKK]

E_{el} is the electricity used by the heat pump, [kWh]

P_{el} is the price for electricity, [DKK/kWh]

Q_{sup} is the overall heat loss of the in-line supply pipe, [kWh]

COP is the coefficient of performance of the heat pump, the design COP in this case was assumed to 4,

P_{DH} is the price for district heating, [DKK/kWh]

C_{re} is the cost of covering the heat loss of the return line, [DKK]

Q_{re} is the heat loss of the return line, [kWh]

The low return temperature can also give benefits for the heat production side, including the decreased pumping power and the option of switching to low-temperature heat sources. According to an investigation in Sweden [14], the estimation of the cost reduction from low return temperature is 1.5 SEK/MWh·°C. Converting

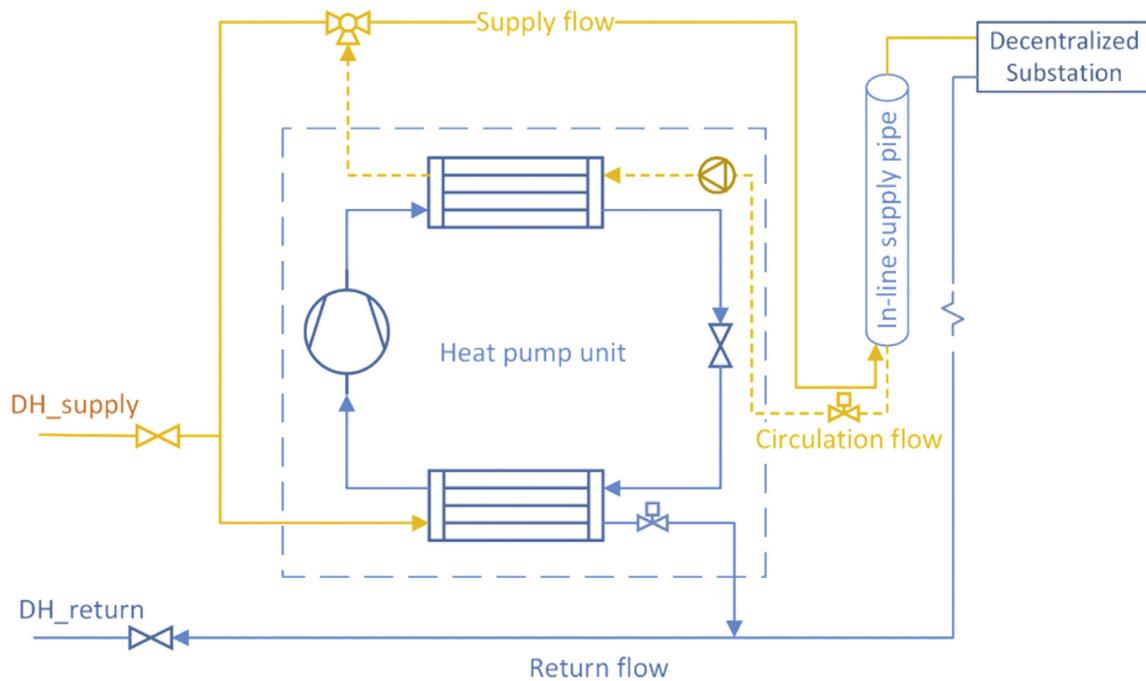


Fig. 6. Decentralized substation system combined with heat pump and in-line supply pipe.

to this case, the cost saving ratio was assumed to 1.8 DKK/MWh·°C considering the different heat prices between Sweden and Denmark.

Thus, the saving by lower return temperatures is:

$$S = R \cdot Q_S \cdot \Delta t_{re} \quad (7)$$

where,

S is the cost reduction on the heat production side, [DKK]

R is the cost-saving ratio, here 1.8 [DKK/MWh·°C]

Q_S is the overall heat supplied to the building when the return temperature is reduced by heat pump, in this study in the non-heating season, [kWh]

Δt_{re} is the reduction in return temperature, [°C]

The technical parameters for the calculation are shown in Table 1.

3. Results

3.1. Measurements and simulation results for the case heating system

To test the average return temperature during the non-heating season, the two-day test was performed on 28th August - 29th August, 2014. The simulated result of the weighted average return temperature was 43.9 °C by the model. The deviation between the measurements and the calculation result is shown in Fig. 7.

Table 1

The technical parameters for the economy analysis.

Features	Abbreviation	Value
Price of electricity [DKK/kWh]	P_{el}	2
Price of district heating [DKK/kWh]	P_{DH}	0.8
Heat pump COP	COP	4
Cost-saving ratio of low return temperature [DKK/MWh·°C]	R	1.8

The measured return temperatures fluctuate around the calculated value. The average deviation is 2.44 °C ($\chi = -0.39$). Several data points have obvious negative deviations. That is mainly caused by peak load of domestic hot water. During the tapping period, the return temperature of domestic hot water is lower than the bypass temperature, which made the average return temperature lower than the estimation. The drops match the load profile of domestic hot water in the case building and are also consistent with our assumption that tapping occurred for very limited lengths of time during the test period. The effect on the average return temperature is negligible.

By inputting the measured instantaneous temperature into the model, it was possible to calculate the heat loss rates of the supply line and return line of the decentralized substation system, as well as the accumulated heat loss. The measured distribution heat loss was compared with the simulated values. The results are shown in Fig. 8 (a) and (b) respectively.

In Fig. 8, the blue area represents the heat loss rate of the supply line, and the red area above represents the heat loss rate of the

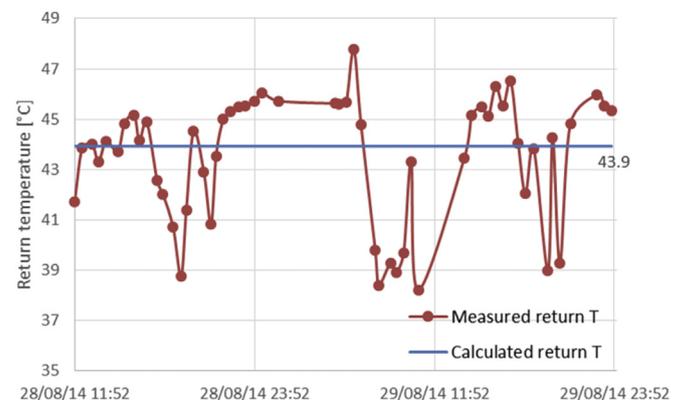


Fig. 7. Deviation between the measured return temperature and calculated return temperature.

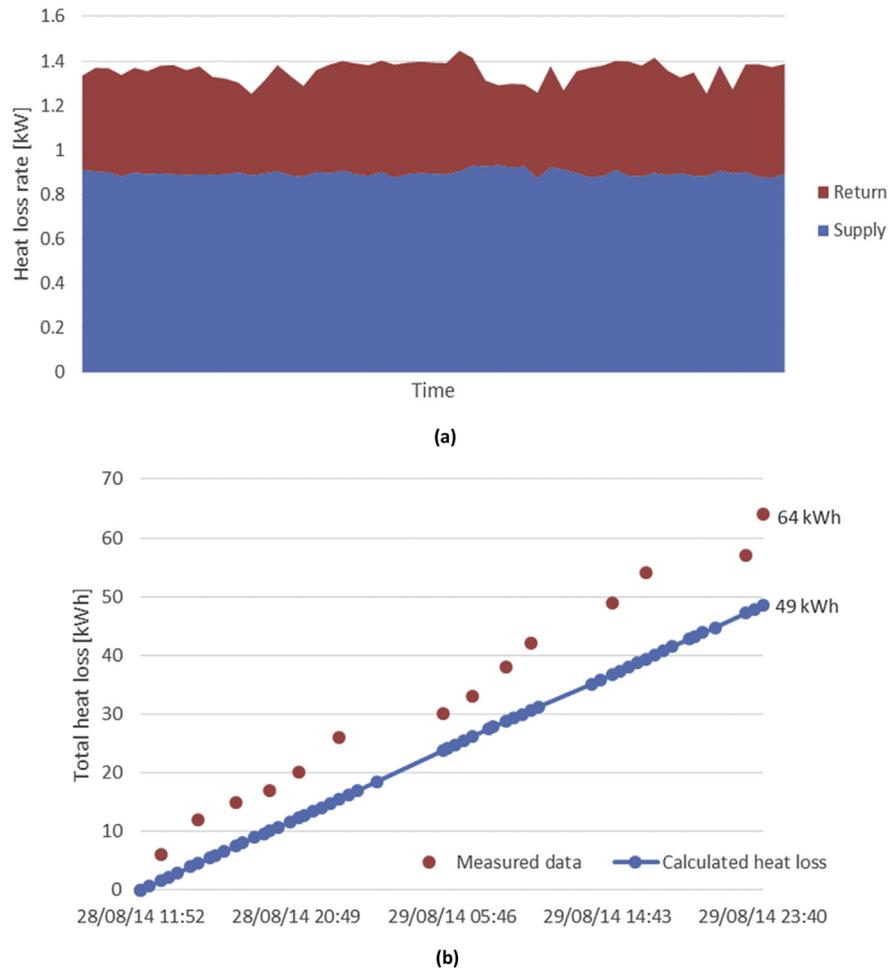


Fig. 8. Simulation results of the heat loss rate (a) and accumulated heat loss (b).

return line. The heat loss rate of the supply line is stable, while the return line has more fluctuations. That is the result of the tapping load. According to the measurements, the accumulated heat loss at the end of the test period achieved 64 kWh, while the simulated result was 49 kWh. The deviation of 23% can be explained by the fact that the model was built based on ideal conditions, which did not include the effects of thermal bridges, such as pipe junctions or contact with the surrounding walls in reality. However, it is possible to eliminate the extra heat loss in the future by more precise system design and construction. For the following scenario analysis, all three models were built under ideal conditions to make fair comparisons.

3.2. Distribution heat loss of the three scenarios

All three scenarios were modelled with the input parameters defined in the previous section. The input temperature of the ideal model was changed to simulate the system performance with LTDH supply. Separate results are given for the heating and non-heating seasons, as shown in Table 2.

The conventional system has the largest distribution heat loss, followed by decentralized substation system with LTDH, while the decentralized substation system with LTDH and the in-line supply pipe and heat pump has the lowest distribution heat loss of all the scenarios.

Compared with Scenario 1, Scenario 2 can save 30% of the annual distribution heat loss and Scenario 3 can save 39%. The

domestic hot water loop of Scenario 1 requires high temperature regime and circulation to inhibit Legionella. Furthermore, the extra pipe work with separate space heating loops and domestic hot water loops also results in large heat loss.

3.3. Distribution costs of the three scenarios

The costs of covering the distribution heat loss for the three scenarios were calculated to evaluate the economics of the heat distribution process. The annual costs for the supply line and return line were calculated separately. The results are shown in Table 3.

Table 2
Distribution heat loss for the three scenarios [kWh].

		Scenario 1		Scenario 2	Scenario 3
		Space heating loop	Domestic hot water loop		
Heating season	supply	1230	3952	2978	3233
	return	406	–	496	496
Non-heating season	supply	884	2852	2149	2333
	return	293	–	1714	358
Tank			840	–	–
Annual			10,457	7337	6420
Heat loss savings					
Compared to Scenario 1			0%	30%	39%

Table 3

The cost of covering the distribution heat loss for the three scenarios.

Costs	Scenario 1	Scenario 2	Scenario 3	
Cost of supply line	7807	4101	Heat 3987	Electricity 700
Cost of return line	599	1768	683	
Total annual cost caused by the distribution heat loss [DKK/yr]	8366	5869	5370	

The conventional system has the highest cost for covering the distribution heat loss. Because of the cost of electricity consumed by the heat pump and the larger pipe dimensions of the in-line supply pipe, Scenario 3 incurs 586 DKK more on covering the distribution heat loss of the supply line than Scenario 2. However, the lower return temperature of Scenario 3 during the non-heating season leads to 1084 DKK cost reduction of the return line compared to Scenario 2. Moreover, supplying the same heat demand as the case building, Scenario 3 can save 577 DKK for district heating system compared with Scenario 2. Therefore, comparing the total economy of the low return temperature, Scenario 3 can save 18% on the operation cost compared to Scenario 2. In practice, the COP of the heat pump depends on the actual inlet/outlet temperatures, a more realistic value might be around 3.5. The actual electricity consumed by the heat pump could be more than the design case, which can lead to less cost reduction. But, the cost-saving ratio of 1.8 DKK/MWh·°C is an average value; if the heat source is strongly temperature-dependent, the cost-saving ratio could be higher, which means more savings for the district heating system.

4. Discussion

4.1. Energy-saving effect of the decentralized substation system

To fulfil hygiene and comfort requirements, the most common approach to supply heat to multi-storey buildings is domestic hot water circulation with a high-temperature regime. However, this approach leads to unnecessary distribution heat loss and reduces the energy efficiency of the entire system.

Scenario 2 and Scenario 3 implemented decentralized substation units. In contrast to the centralized heating system, the

decentralized substation system can balance the conflict between the hygiene requirements and energy efficiency. Domestic hot water circulation at high temperature is no longer necessary to inhibit Legionella in the decentralized substation system. For energy-efficient buildings in the future, LTDH supply with efficient space-heating devices will be sufficient to provide comfort indoor temperatures for consumers. This makes the system of decentralized substations a promising solution for the realization of LTDH in multi-storey buildings. The benefits include not only savings in distribution heat loss, but also access to more low-quality energy sources that might have lower energy prices. Moreover, the decentralized substation system without storage tanks and circulation pipes has simpler layout than the conventional system. However, in view of the investment costs, the decentralized substation system is best applied in new constructions. During the transition period, the decentralized substation system with medium-temperature district heating can be considered as preparation for realizing LTDH.

4.2. Seasonal variation

The heating demand varies in different seasons. To adapt to the decreased heating demand in the summer, the supply temperature of district heating normally is reduced. However, the decreased heating demand means the district heating return flow cannot have efficient cooling, which leads to high return temperature. Fig. 9 shows the measurements of supply/return temperature in the case building for a whole year.

The return temperature to district heating shows different trend from the district heating supply temperature. The return temperature reaches a small peak during the non-heating season. Besides the inefficient cooling, the mix of bypass flow also contributes to the temperature increase of the return flow. And that undoubtedly leads to higher heat loss.

According to the model calculation, Fig. 10 shows the comparison of the seasonal heat loss of the three scenarios of the return line.

The three scenarios have similar distribution heat loss of the return lines in the heating season. However, during the non-heating season, Scenario 2 shows a significantly higher distribution heat loss on the return line than the other two scenarios. In the case building with decentralized substation system, the annual heat loss percentage was approximately 10% of the total heat

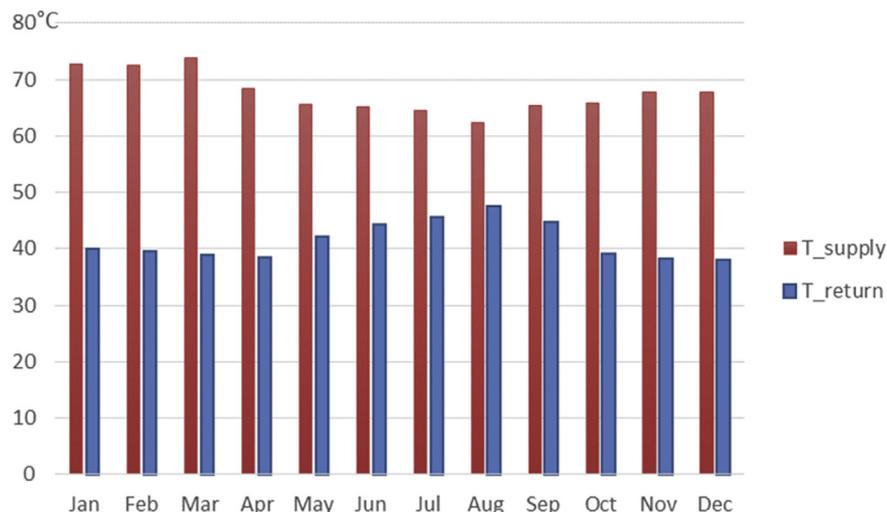


Fig. 9. Measured supply and return temperatures in the case building.

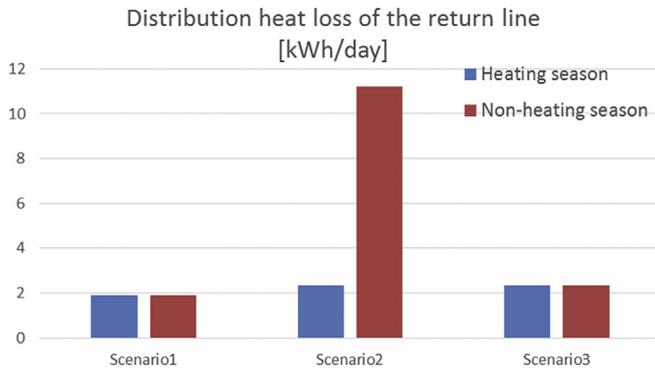


Fig. 10. Seasonal variation of the distribution heat loss of the return pipelines.

delivered, while the percentage in summer was almost 30%. The high return temperature during the non-heating season plays a role in the high heat loss. As the application to realize LTDH in the future, such high return temperature will no doubt restrict the overall energy efficiency of the decentralized substation system. Therefore, methods should be considered to reduce the average return temperature of the decentralized substation system without violating the comfort requirement.

4.3. Reducing the return temperature for LTDH

A high return temperature is a long-term problem that restricts the efficiency of the distribution process. Moreover, the return temperature can deeply affect the heat production process too, depending on the type of heat source used. For example, if the district heating is supplied by excess heat from industrial processes, lower return temperatures help increase the heat recovery efficiency of the excess heat source or the efficiency of the turbine. And lower return temperatures make it more feasible and promising to apply low supply temperatures. As a result, more heat sources with low energy quality can be applied, and fossil fuels can be replaced as the backup heat source for peak loads.

One benefit of using the decentralized substation system is that such systems can use LTDH without risk of Legionella. However, the use of the high-temperature bypass flow restricts the lower limit of the return temperature. In Scenario 2, the bathroom heating during the non-heating season helps reduce the average return temperature to some extent, but it is not sufficient enough to replace the bypass flow completely. In Scenario 3, lower return temperature was obtained by using a combination of in-line supply pipe and heat pump to replace the bypass function. According to the results of this study, even though the supply pipe has larger dimensions and extra electricity is consumed for the heat pump, Scenario 3 still has the lowest cost for covering the distribution heat loss. Moreover, the low return temperature also gives benefits to the heat production side and the district heating network. However, the exact economic benefits of the low return temperature can only be evaluated for specific cases with concrete information on the heat source type, the pipework of the network, the investment in applied devices, etc.

5. Conclusion

This study investigated the energy and economy performances of the decentralized substation system with LTDH supply. Models of conventional system with medium temperature district heating, decentralized substation system with LTDH, and innovative

decentralized substation system with LTDH supply were built to make scenario analysis. The results obtained by comparing the three systems can be summarized as follows:

- The decentralized substation system can be operated with LTDH (55 °C) without risk of Legionella. It is a promising solution for energy-efficient buildings with a large domestic hot water heating system.
- Although the space-heating loops of the conventional system were designed to be operated efficiently with floor heating, the extra pipelines with separate space heating and domestic hot water loops, as well as the high-temperature regime to prevent Legionella still lead to high overall distribution heat loss.
- The decentralized substation system with LTDH can save 30% of the annual distribution heat loss compared to the conventional system.
- Replacing the bypass function with an in-line supply pipe and a heat pump can help to reduce the return temperature of the decentralized substation system. As a result, the annual distribution heat loss decreased by 12%. Also by considering the potential savings for the district heating system, the innovation decentralized substation system can help to save 577DKK by the operation in non-heating season.

Finally, this study provides the basis for a future full-scale analysis of a decentralized substation system with improved lower return temperatures.

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Appendix D – Paper 4

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Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating,

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Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating



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ABSTRACT

This study investigated the performances of five different substation configurations in single-family houses supplied with ULTDH (ultra-low-temperature district heating). The temperature at the heat plant is 46 °C and around 40 °C at the substations. To avoid the proliferation of Legionella in the DHW (domestic hot water) and assure the comfortable temperature, all substations were installed with supplementary heating devices. Detailed measurements were taken in the substations, including the electricity demand of the supplementary heating devices. To compare the energy and economic performance of the substations, separate models were built based on standard assumptions. The relative heat and electricity delivered for preparing DHW were calculated. The results showed that substations with storage tanks and heat pumps have high relative electricity demand, which leads to higher integrated costs considering both heat and electricity for DHW preparation. The substations with in-line electric heaters have low relative electricity usage because very little heat is lost due to the instantaneous DHW preparation. Accordingly, the substations with in-line electric heaters would have the lowest energy cost for DHW preparation. To achieve optimal design and operation for the ULTDH substation, the electricity peak loads of the in-line electric heaters were analysed according to different DHW-heating strategies.

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1. Introduction

1.1. Temperatures of DH (district heating) and DHW (domestic hot water)

District heating is a cost-efficient way of supplying heat to consumers, especially in regions with high heat density. After decades of development, district heating is now transiting from medium-temperature district heating to LTDH (low-temperature district heating). From a macroscopic point of view, low-temperature levels bring many benefits to a district heating system. Low-temperature district heating system is an integrated part of the future sustainable energy systems, which aims at better utilizing the renewable energy sources, such as the geothermal energy, solar thermal energy, or industrial excessive heat, waste incineration and etc., and phasing out the fossil fuels. With developed technologies and operation methods, low-temperature district heating system is able to achieve low distribution heat losses

by integrating with heat storage. To achieve low supply temperature without changing the DH system dimension and weaken the DH system efficiency, more efficient cooling is required to reduce the return temperature. The more efficient cooling of the DH flow can be achieved by better operation of the heating system, well designed and controlled radiators for space heating, more effective heat exchangers for DHW and etc. One benefits by the low distribution temperatures is the savings of the heat loss in the district heating grid [1]. Moreover, Low return temperatures can increase heat recovery through flue gas condensation. According to the definition of 4th generation district heating [2], LTDH can achieve supply and return temperatures of 50 °C/20 °C without violating comfort and hygiene requirements.

The aim of applying ULTDH (ultra-low-temperature district heating) is to make the utmost use of available low-temperature heat sources and to achieve both energy savings and economic feasibility when supplying heat to consumers. The supply temperature of ULTDH is lower than that of LTDH (50 °C), but has not yet been clearly defined. To meet comfort and hygiene requirements, ULTDH can be used in combination with local supplementary heating devices. However, it is better to have sufficient ULTDH supply temperature for space heating to provide a

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Nomenclature	
c	Specific heat capacity of water [kJ/kg °C]
CRF	Capital recovery factor [%]
C_{inv}	Investment cost, [DKK/unit]
$C_{O\&M}$	Operation and maintenance cost [DKK/year]
E	DHW peak load in the substation [kW]
E_s	DHW peak load from the standard [kW]
i	Interest rate [%]
LC	Levelized cost [DKK/kWh]
\dot{m}	Flowrate of the water [kg/s]
n	Life time [year]
P_{dh}	Price of DH heat [DKK/kWh]
P_{el}	Price of electricity, [DKK/kWh]
P_{int}	Integrated energy price considering the DH and electricity [DKK/kWh]
q	Transient energy flow [kW]
Q_{dh}	Heat from district heating for DHW preparation [kWh]
Q_{dhw}	The increased energy content of the DHW [kWh]
Q_{dhw-y}	Annual DHW demand [kWh]
Q_{el}	Electricity demand of the supplementary heating devices for DHW preparation [kWh]
Q_{hl}	Heat loss of the DHW preparation process [kWh]
Q_{input}	Total energy input to the substation [kWh]
Q_{output}	Total energy output from the substation [kWh]
t_{dcw}	Temperature of the domestic cold water [°C]
t_{dh-s}	Supply temperature of DH [°C]
t_{dh-r}	Return temperature of DH [°C]
t_{el}	DHW temperature heated by electricity [°C]
t_{in}	Inlet temperature of the water flow [°C]
t_m	DHW temperature preheated by district heating [°C]
t_{out}	Outlet temperature of the water flow [°C]
<i>Greek</i>	
ε_{dh}	Relative heat demand for DHW preparation [%]
ε_{el}	Relative electricity demand for DHW preparation [%]
φ_k	Volume percentage of DHW for kitchen use [%]
<i>Abbreviations</i>	
COP	Coefficient of performance
DCW	Domestic cold water
DH	District heating
DHW	Domestic hot water
LTDH	Low-temperature district heating
ULTDH	Ultra-low-temperature district heating
<i>Numbers</i>	
1–5	Substation #1–5

comfortable indoor temperature, so that extra investment costs for space heating can be avoided. With efficient operation and space-heating devices, a supply temperature above 40 °C is sufficient to provide comfortable room temperatures during the heating season. In terms of supply temperature for DHW, auxiliary heating devices are needed to reach 45 °C for kitchen use and 40 °C for other uses based on the requirement for comfort [3].

1.2. Concern about Legionella in the DHW system

Prevention of Legionella in DHW systems plays a very important role in the design and operation for DH substations. Several previous studies [4–6] have indicated that favourable conditions for Legionella's proliferation are: 1) water temperatures ranging from 25 to 45 °C, and 2) long-term stagnancy. The problem of Legionella in DHW systems clearly needs to be addressed in advance of the realization of LTDH and ULTDH. One approach could be to add local supplementary heating devices, so that the temperature of DHW can be boosted. Another method is to limit the total volume of DHW in use and heat the DHW locally and instantaneously, thereby reducing the risk of stagnancy as much as possible. The operation requirements of DHW installations depend on their layouts. For example, in Denmark the standard [7] for Legionella prevention requires that no point in a DHW system with circulation should have a water temperature lower than 50 °C, and it should be possible to heat the water in the tank up to 60 °C. But if the DHW system has no circulation and or water storage, there are no requirements for the temperature beyond those for comfort.

1.3. The performances of different substations

Different substations have different layouts and operation modes, which have great influence on the efficiency of DHW preparation and distribution. Bøhm [8] measured DHW systems in 13 apartments and 2 institutes in Denmark, and found that circulation systems have very low efficiency. By removing the circulation

pipe and adding electric heat tracing to the supply pipe, he found that both the district heating return temperature and the pipe heat loss could be reduced. Cholewa et al. [9], made experimental measurements and found that residential thermal stations have better annual average efficiency than centralized heating systems when supplying both space heating and DHW. Boait et al. [10] report test results for five different DHW heating systems with five heating appliances in the UK. They found that instantaneous preparation of hot water is much more efficient than systems with storage tanks, as well as more effective in preventing Legionella. A simulation study made by Basciotti et al. [11], compared different types of substations with LTDH supply. Their results indicate that the instantaneous preparation of DHW at 50 °C using a heat pump results in lower district heating return temperatures, while a system with an air source heat pump as auxiliary heater and storing hot water at 60 °C has the lowest primary energy demand. In addition to the selection of appropriate substations for specific cases, fault detection also plays a role in ensuring the correct operation and good performance of the substation. In Gadd and Werner's work [12], the frequency of annual temperature difference faults in substations is more than 6%, and they are difficult to detect and eliminate because of the irregular heat demand pattern and intensive labour cost. This means it is of great importance to have a reference indicator that can evaluate the operation and performance of the substation, thereby improving efficiency on both the consumer side and the supply side.

1.4. The scope of this study

Very little research has been done on the performance of substations with ULTDH. The aim of this study is to provide comprehensive analysis based on both empirical data and models of various substations with ULTDH supply. We made detailed measurements in five single-family houses with ULTDH supply. Since the five houses all have different supplementary heating devices for DHW preparation, we built five models to simulate the DHW

preparation process according to the standard conditions. The relative heat and electricity demands meeting an equivalent DHW heat demand were modelled for the different substations. The results can be used to suggest well-performing substations for ULTDH and, in comparison with the measurements, to indicate possible faults in the substation. The integrated energy costs of DHW preparation were calculated as the combined cost of heat and electricity, which show the economy of substations with different layouts. To achieve optimal dimension of the substation supplied by ULTDH scenario, the electricity peak loads of the supplementary heating devices were analysed. It is hoped that such analysis can provide adequate information for substation selection and operation within the ULTDH scenario.

2. Description of the substations and the measurements

Five single-family houses supplied by ULTDH were selected for the measurements. The case houses are located in Jutland, Denmark, and have different substation layouts. The heat source is industrial excess heat from a local pump factory, and the heat was recovered by a heat pump for district heating use. The district heating supply temperature at the heat plant is controlled at 46 °C except that if the outdoor temperature falls below 5 °C, the district heating supply temperature is increased by 1 °C for every 1 °C decrease in the outdoor temperature below 5 °C, so that the consumers can get enough heat during extremely cold weather. Due to heat loss along the transmission process, however, the district heating supply temperature at the substations is around 40 °C.

Since the ULTDH supply temperature is lower than the required temperature for comfort and sanitation, all the case houses have supplementary heating devices installed. The layouts of the five substations and the energy meter locations are illustrated in the schematic diagrams in Figs. 1–5.

In substation #1, the DHW is stored in the storage tank and used directly. The DHW is preheated by the district heating and further heated by the immersion heater. To meet the hygiene requirement of avoiding Legionella [7], the temperature of the tank has to be maintained at 60 °C. However, the actual temperature of the immersion heater in the tank was set to 50 °C in substation #1. Energy meters were installed on both the DHW primary side and consumer side.

The layout difference between substations #1 and #2 is that substation #2 has a heat exchanger after the storage tank, and the district heating water is stored in the tank. The DHW can be heated instantaneously by the heat exchanger, which reduces the risk of Legionella. The set-point temperature of the immersion heater in substation #2 was 55 °C to assure the DHW could achieve

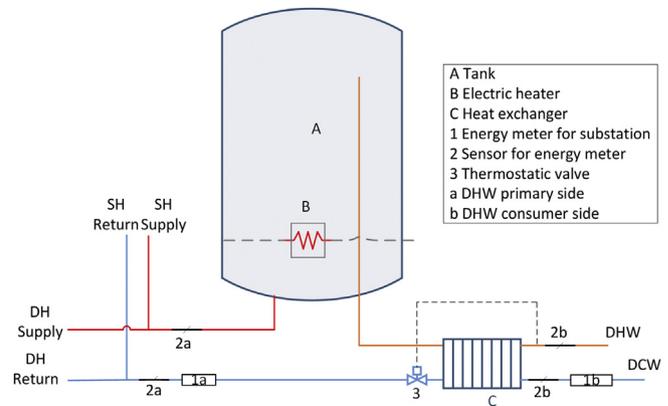


Fig. 2. Substation #2.

45–50 °C. Energy meters were installed on both the DHW primary side and consumer side.

For substation #3, a micro heat pump and a storage tank are installed before the heat exchanger. Such application has been tested and proved to have a good exergy performance for heat supply [13]. One stream of the district heating supply is used as the heat source for the heat pump. The set-point temperature of the tank was 55 °C. The tank is discharged when DHW draw-off occurs. Since the DHW is separated from the storage tank by the heat exchanger, the risk of Legionella is also eliminated. The energy meter was installed only on the consumer side.

In substation #4, the DHW is preheated by district heating through a heat exchanger. The temperature could be comfortable for taking a shower, but considering the requirement for hotter DHW for washing purposes in the kitchen, an instantaneous electric heater is installed on the DHW pipe to the kitchen taps. The heater has an electronic controller inside it, which regulates the power rate according to the inlet temperature and flowrate, so that to maintain a constant outlet temperature (set-point temperature) of DHW. The heater boosted the water temperature to 55 °C in the case substation even though 45 °C would be sufficient for the comfort requirements. The hot water temperature is adjusted by mixing cold water at the tap. The performance on the DHW primary side was measured.

Substation #5 has the same layout as substation #4, except that an electric heater was used to heat up the total DHW flow. The energy meter was installed on the DHW primary side.

The basic information on substations is summarized in Table 1.

3. Methods

3.1. Set-up for the measurements

Two sets of energy meters were installed for the measurements: the energy meter in the substations for district heating, and the meter for electricity. The energy meters for district heating were set with a time step of 1.5 min, so that they would be able to detect DHW draw-off. The meters recorded data for instantaneous supply/return temperatures, instantaneous flow rate, accumulated heat supplied by district heating, and accumulated water volume. The meters for electricity only measured the electricity for DHW preparation use. The electricity measurement was recorded on a monthly basis.

The measurements for May 2015 were selected for the analysis of this study, and the date of 6th May was selected as a typical day for investigating the daily variation in the temperatures. Additionally, the transient energy flow of DH or DHW during the day

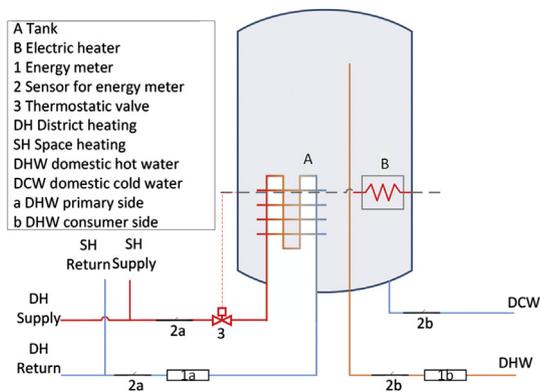


Fig. 1. Substation #1.

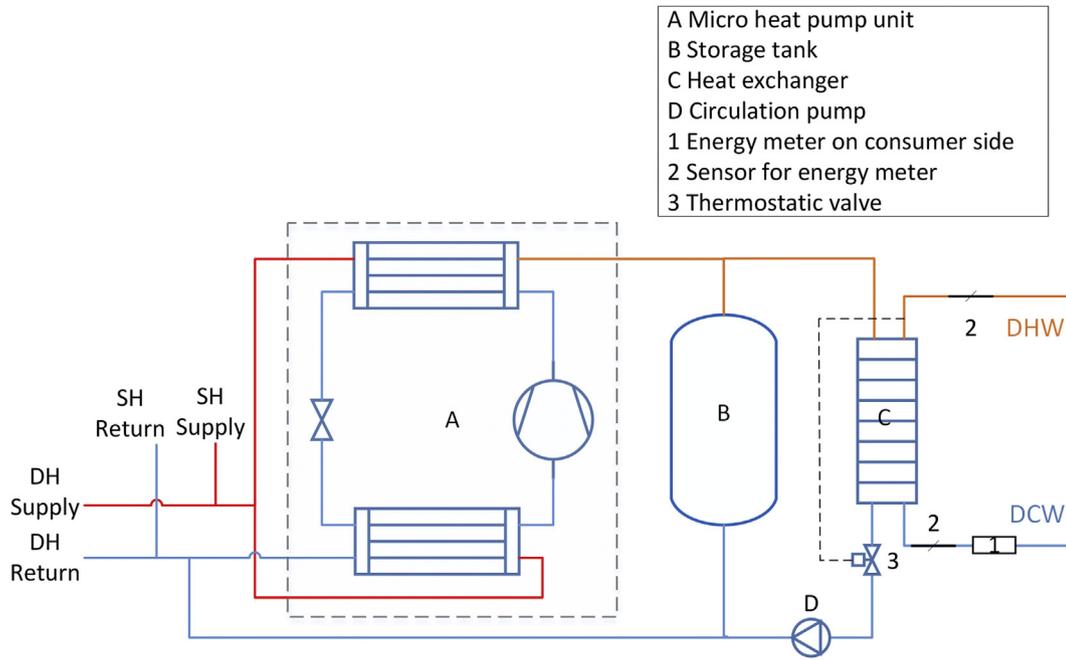


Fig. 3. Substation #3.

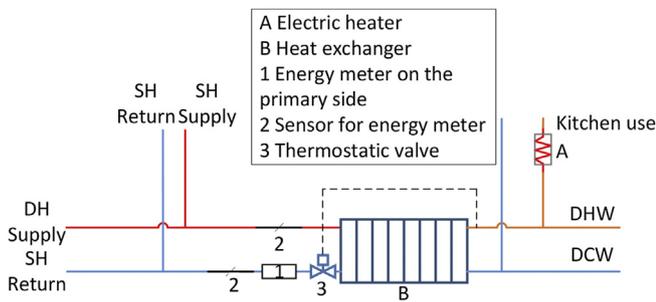


Fig. 4. Substation #4.

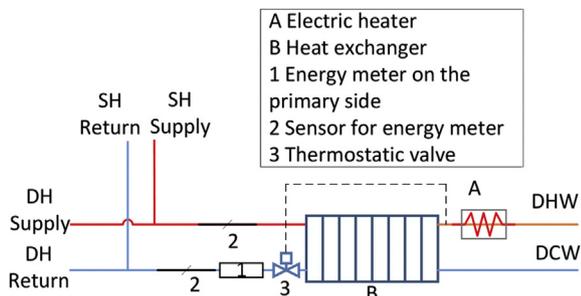


Fig. 5. Substation #5.

was calculated based on the measurements, in accordance with the following equation:

$$q = c \cdot \dot{m} \cdot |t_{in} - t_{out}| \quad (1)$$

where

q is the transient energy flow [kW],
 c is the specific heat capacity of water [kJ/kg·°C],

\dot{m} is the flowrate of the water [kg/s],
 t_{in} is the inlet temperature of the water flow, (DH supply temperature or DCW (domestic cold water) temperature) [°C],
 t_{out} is the outlet temperature of the water flow, (DH return temperature or DHW temperature) [°C].

The monthly measurement of the heat and electricity delivered to the substation were used to indicate the actual proportion of heat and electricity in the overall energy supply. The measurements were also used to calculate the average supply and return temperatures over the month. To eliminate the impact of the period without DHW preparation, the average supply temperature in the substation was approximated to the average DH supply temperature at the inlet of the case substation, which was measured by the local district heating company. The monthly average return temperature for DHW preparation was calculated by using the monthly accumulated heat delivered, the average supply temperature and the accumulated volume of the DH water for DHW preparation.

3.2. Model of relative heat and electricity delivered for DHW preparation

The different ways of producing DHW in the five substations resulted in different relative demands of heat from district heating and electricity. To evaluate the performances of the five substations for equivalent DHW preparation, a separate model was built in excel for each substation. The monthly relative heat and electricity delivered for DHW preparation were compared.

The basis of the models is the balance of the energy flow in and out of each DHW substation under the ideal condition. The total energy input to the substation for DHW preparation includes the heat from district heating and electricity for the supplementary heating devices. It can be calculated as:

$$Q_{input} = Q_{dh} + Q_{el} \quad (2)$$

where

Table 1
Practical information on the five measured substations.

House	Elements in the substation					Operation information	
	Storage tank			Heat exchanger for DHW	Separate electric heater	Micro heat pump	
Stored fluid	Size	Heater					
1	DHW	160 L	3 kW electric heater	Coil in the tank	–	–	The DHW is stored in the tank. The immersion heater can heat up the DHW to 50 °C.
2	DH water	160 L	3 kW electric heater	Plate heat exchanger between the tank and DHW system	–	–	The DH water is heated up to 55 °C in the tank, and DHW was heated instantaneously by the separate heat exchanger.
3	DH water	160 L	–	Plate heat exchanger between the tank and DHW system	–	Design COP 4.5 Max power 250 W	Charging temperature of the tank is 55 °C
4	–	–	–	Plate heat exchanger between the DH supply and DHW system	11 kW in-line heater only for kitchen use	–	Set-point temperature of the in-line heater is 55 °C
5	–	–	–	Plate heat exchanger between the DH supply and DHW system	18 kW in-line heater for all DHW use	–	Set-point temperature of the in-line heater is 55 °C

Q_{input} is the total energy input to the substation [kWh],
 Q_{dh} is the heat from district heating for DHW preparation [kWh],
 Q_{el} is the electricity demand of the supplementary heating devices for DHW preparation [kWh].

The total energy output from the substation is the increased energy content of the DHW and the heat loss. It can be calculated as:

$$Q_{output} = Q_{dhw} + Q_{hl} \quad (3)$$

where

Q_{output} is the total energy output from the substation [kWh],
 Q_{dhw} is the increased energy content of the DHW [kWh],
 Q_{hl} is the heat loss of the DHW preparation process [kWh].

The relative supply of heat and electricity compared to the DHW demand can be calculated as:

$$\varepsilon_{dh} = Q_{dh}/Q_{dhw} \quad (4)$$

$$\varepsilon_{el} = Q_{el}/Q_{dhw} \quad (5)$$

3.2.1. The individual models for relative energy supply

To calculate the relative heat and electricity demands of each substation with its distinct layout, a separate model was built for each substation. It was assumed that all the pipes and heating devices were dimensioned and insulated strictly in accordance with the standards, and that unnecessary heat loss from the heat exchanger and bypass flow could be avoided. To meet the DHW energy demand requirement for energy-efficient buildings in 2020 [14], which is 13 kWh/m² yr, the DHW demand was assumed to be 2000 kWh/yr (approx. 170 kWh/month) for all the substations investigated to make a fair comparison. The individual models are described in the following paragraphs:

3.2.1.1. Substation #1. The energy inputs of heat and electricity included the proportion for heating up the DHW and the proportion for covering heat loss. The heat from district heating heated the DHW from 10 °C to 40 °C, while the electric immersion heater in the tank further heated the DHW to 60 °C as the requirement for Legionella prevention. The tank in substation #1 has the heat loss rate of 60 W (information from the manufacturer). The heat loss

was assumed to be evenly covered by DH heat and electricity since the heat exchanger and immersion heater are installed at the same height. The relative supply of heat and electricity compared to the DHW demand can be calculated as:

$$\varepsilon_{dh}^1 = \frac{Q_{dhw} * (t_m^1 - t_{dcw}) / (t_{el}^1 - t_{dcw}) + \frac{1}{2} * Q_{hl}^1}{Q_{dhw}} \quad (6)$$

$$\varepsilon_{el}^1 = \frac{Q_{dhw} * (t_{el}^1 - t_m^1) / (t_{el}^1 - t_{dcw}) + \frac{1}{2} * Q_{hl}^1}{Q_{dhw}} \quad (7)$$

where

Q_{dhw} is the DHW heat demand, 170 [kWh/month],
 Q_{hl}^1 is the heat loss from the tank, [kWh],
 t_{el}^1 is the DHW temperature heated by the tank [°C],
 t_m^1 is the DHW temperature heated by district heating [°C],
 t_{dcw} is the temperature of the domestic cold water (DCW) [°C]

3.2.1.2. Substation #2. Assuming the temperature difference of the heat exchanger is 5 °C, to prepare DHW at 45 °C based on the standard, the district heating supply water at 45 °C was heated to 50 °C by the electric heater in the tank. After exchanging heat with 10 °C DCW, the DH water was supposed to be cooled down to 15 °C. The efficiency of the heat exchanger was assumed to be 100%. The relative demands of heat and electricity were proportional to the temperature differences of the district heating supply water. The design heat loss rate of the tank was 60 W (information from the manufacturer), and the heat loss of the tank was covered solely by electricity. The relative supply of heat and electricity compared to the DHW demand can be calculated as:

$$\varepsilon_{dh}^2 = \frac{Q_{dhw} * (t_{dh-s}^2 - t_{dh-r}^2) / (t_{el}^2 - t_{dh-r}^2)}{Q_{dhw}} \quad (8)$$

$$\varepsilon_{el}^2 = \frac{Q_{dhw} * (t_{el}^2 - t_{dh-s}^2) / (t_{el}^2 - t_{dh-r}^2) + Q_{hl}^2}{Q_{dhw}} \quad (9)$$

where

Q_{dhw} is the DHW heat demand, 170 [kWh/month],
 Q_{hl}^2 is the heat loss from the tank, [kWh],
 t_{dh-r}^2 is the temperature of the DH water heated by the tank [°C],
 t_{dh-s}^2 is the supply temperature of ULTDH [°C],
 t_{el}^2 is the return temperature of ULTDH [°C],

3.2.1.3. Substation #3. The district heating supply water at 45 °C was heated by the heat pump to 50 °C and stored in the tank. The tank was discharged when DHW draw-off occurred. The heat exchanger was assumed to be well insulated, so that the heat loss of the heat exchanger was considered negligible. The return temperature to the district heating was assumed to be 15 °C. The heat source of the heat pump is the district heating supply water. The electricity was used to boost the temperature of the DH supply water. This means that the coefficients of relative heat and electricity demands were affected by the COP (coefficient of performance) of the heat pump. The design COP of the heat pump was 4.5 (information from the manufacturer, also for the overall heat loss rate of the heat pump). The heat loss of the heat pump unit included the heat loss from the tank (60 W) and heat loss from the compressor (140 W). The heat loss of the tank was assumed to be covered by electricity and DH heat in the same ratio as the corresponding relative demand. The heat loss of the compressor was covered solely by electricity. Consequently, the coefficient of relative heat and electricity demands of the substation with a heat pump were calculated using the following equations:

$$\begin{aligned} \varepsilon_{dh}^3 &= \frac{Q_{dh-o}^3 + Q_{hp-s}^3 + Q_{hl-dh}^3}{Q_{dhw}} \\ &= \frac{(t_{dh-s}^3 - t_{dh-r}^3) + \left(1 - \frac{1}{COP}\right) * (t_{el}^3 - t_{dh-s}^3)}{(t_{el}^3 - t_{dh-r}^3)} * \left(1 + \frac{Q_{hl-tank}^3}{Q_{dhw}}\right) \end{aligned} \quad (10)$$

$$\varepsilon_{el}^3 = \frac{Q_{el}^3 + Q_{hl-el}^3}{Q_{dhw}} = \frac{(t_{el}^3 - t_{dh-s}^3) / COP}{(t_{el}^3 - t_{dh-r}^3)} * \left(1 + \frac{Q_{hl-tank}^3}{Q_{dhw}}\right) + \frac{Q_{hl-com}^3}{Q_{dhw}} \quad (11)$$

where

- Q_{dh-o}^3 is the heat supplied by district heating for DHW preparation with its original temperature [kWh],
- Q_{hp-s}^3 is the DH heat used as the heat source for the heat pump [kWh],
- Q_{hl-dh}^3 is the heat loss covered by the DH heat [kWh],
- $Q_{hl-tank}^3$ is the heat loss of the tank [kWh],
- Q_{el}^3 is the electricity used to drive the heat pump [kWh],
- Q_{hl-el}^3 is the heat loss covered by the electricity [kWh],
- Q_{hl-com}^3 is the heat loss of the compressor [kWh].

3.2.1.4. Substation #4. The DHW is heated by the district heating from 10 °C to 40 °C. In this substation, since DHW for kitchen use requires no lower than 45 °C, while other uses only require 40 °C [3], the set point temperature of the in-line electric heater was assumed to 45 °C. The kitchen-use of DHW accounts for 12.6% of the total volume of DHW demand [3]. The heat exchanger was assumed to be well-insulated. Since the DHW was heated instantaneously by the electric heater, the heat losses of the heater and the heat exchanger were neglected compared to the overall energy for heating DHW. The relative use of heat and electricity were calculated by the following equations:

$$\varepsilon_{dh}^4 = \frac{Q_{dhw} * (t_m^4 - t_{dcw}) / ((t_m^4 - t_{dcw}) + \varphi_k * (t_{el}^4 - t_m^4))}{Q_{dhw}} \quad (12)$$

$$\varepsilon_{el}^4 = \frac{Q_{dhw} * (t_{el}^4 - t_m^4) * \varphi_k / ((t_m^4 - t_{dcw}) + \varphi_k * (t_{el}^4 - t_m^4))}{Q_{dhw}} \quad (13)$$

where

φ_k is the percentage of the total volume of DHW that is for kitchen use [%].

3.2.1.5. Substation #5. Substation #5 had the same DHW preparation process as substation #4, except that all DHW was heated to 45 °C by the instantaneous electric heater. This leads to the calculation equations being:

$$\varepsilon_{dh}^5 = \frac{Q_{dhw} * (t_m^5 - t_{dcw}) / ((t_m^5 - t_{dcw}) + (t_{el}^5 - t_m^5))}{Q_{dhw}} \quad (14)$$

$$\varepsilon_{el}^5 = \frac{Q_{dhw} * (t_{el}^5 - t_m^5) / ((t_m^5 - t_{dcw}) + (t_{el}^5 - t_m^5))}{Q_{dhw}} \quad (15)$$

Information on the individual models is summarized in Table 2:

3.2.2. Levelized costs for DHW preparation

To compare the economic performances of the five substations, the integrated cost of energy delivered for unit DHW preparation was calculated based on the results of the individual models:

$$P_{int} = P_{dh} * \varepsilon_{dh} + P_{el} * \varepsilon_{el} \quad (16)$$

Where

- P_{int} is the integrated energy price considering the DH and electricity [DKK/kWh],
- P_{dh} is the price of DH heat, which was assumed to 0.8 [DKK/kWh],
- P_{el} is the price of electricity, which was assumed to 2 [DKK/kWh].

The levelized cost were calculated considering the investment cost, operation and maintenance (O&M) cost, and energy cost. The investment cost includes the expenses of the equipment and the installation. The investment of the measured substations was obtained from the local DH company. The O&M cost was assumed to be 2% of the investment. The life time of all the heating units was assumed to 20 years.

The method for calculating the levelized cost is well described in Refs. [15], adapting to the specific cases in this study, the levelized cost of different DHW supply methods can be calculated as:

Table 2
Design parameters for the ideal models.

Substation no.	#1	#2	#3	#4	#5
Supply temperature on the primary side [°C]			45		
Return temperature on the primary side [°C]			15		
Temperature of DCW [°C]			10		
Set point temperature of the heating device [°C]	60	50	50	45	45
Heat loss rate [W]	60	60	200	-	-
DHW heat demand [kWh/yr]			2000		

“-”Substations #4 and #5 heat DHW instantaneously, and the heat exchanger is assumed to be well insulated, so the heat loss is ignored.

$$LC = \frac{(C_{inv} * CRF * n) + C_{O\&M} * n + P_{int} * Q_{dhw-y} * n}{Q_{dhw} * n} \quad (17)$$

where

LC is the levelized cost [DKK/kWh],
 CRF is the capital recovery factor [%],
 n is the life time [year],
 C_{inv} is the investment cost, information from the local DH company [DKK/unit],
 $C_{O\&M}$ is the operation and maintenance cost [DKK/year],
 Q_{dhw-y} is the annual DHW demand [kWh].

The capital recovery factor can be calculated as:

$$CRF = \frac{i * (1 + i)^n}{(1 + i)^n - 1} \quad (18)$$

where

i is the interest rate, in this study i was assumed to 6%.

3.3. Peak load of electricity for DHW preparation

In substations #1, #2 and #3, a heat storage tank is installed either on the DHW primary side or on the consumer side, which can help to shave the peak load of electricity for DHW preparation. Therefore the power of the electric heater in those substations has no significant fluctuation. But, in substations #4 and #5, DHW is heated instantaneously. The peak loads of the in-line electric heaters need to be considered to secure the sufficient DHW supply. The temperature difference of the heat exchanger was assumed to be 5 °C. For substation #4, the ULTDH supply temperature was assumed to 45 °C, so that the DHW other than the kitchen use was able to reach the temperature of 40 °C [3]. The DHW flow for the kitchen use was heated by the in-line heater to 45 °C, of which the flow rate was assumed to 0.1 L/s in accordance with the standard [3]. For substation #5, the supply temperature was assumed to be the same at 45 °C. The overall peak load of DHW was assumed to have kitchen tapping and shower at the same time, which is equivalent to 32.3 kW [3]. The electricity was used to heat DHW from 40 °C to 45 °C. The electricity peak load of substation #4 and #5 can be calculated as:

$$E_4 = 4.2 * 0.1 * (t_{el}^4 - t_m^4) \quad (19)$$

$$E_5 = E_s * \frac{(t_m^5 - t_{dcw}^5)}{(t_m^5 - t_{dcw}^5)} \quad (20)$$

where

E_4 is the peak load of electricity in substation #4 [kW],
 E_5 is the peak load of electricity in substation #5 [kW],
 E_s is the overall peak load in substation #5, which is 32.3 [kW],

4. Results

4.1. Measurements of five substations

4.1.1. Temperature variations in the five substations based on measurements

The daily variations of the supply/return temperatures on the DHW primary side and the DHW/DCW temperatures are shown in

Fig. 6, which are based on the measurements on the typical day (6th May) for each of the substations.

The energy meters used for the measurements has the approved accuracy of $\pm(0.15 + 2/\Delta\Theta)\%$. For most of the measurements, the temperature difference was larger than 2 °C, which resulted in the maximum error as $\pm 1.15\%$. From the diagrams (a)–(c), substations #1–3 all functioned to heat up the DHW to the set point temperature (50–55 °C). The variations in temperature of DHW and DCW corresponded to the DHW draw-off pattern. In substation #2, no measurements of the substation return temperature are shown in the diagram since the sensor that measures the return temperature did not work. From the results shown, the fluctuations in the supply/return temperatures are consistent with the corresponding energy flow. Substations #1, #4 and #5, which have results for the energy flow on the primary side, show some very small flows that appear from time to time, in addition to the obvious energy flow for producing DHW. These small volumes presumably keep the heat exchanger warm, thereby ensuring the comfort requirement of 10 s waiting time. That could explain the high return temperature during the night time in substation #4. However, such flows without exchanging heat with DHW can result in a high average return temperature, which would have a negative effect on the overall efficiency. For substation #2 and #3, the energy flow on the consumer side represents the DHW draw-offs. When DHW draw off occurs, the temperature of DCW decreases from room temperature to 10 °C, while the DHW temperature increases from room temperature to approx. 55 °C.

4.1.2. Measurements for monthly DHW preparation

The total energy delivered for DHW preparations in the 5 substations are shown in Fig. 7. The relative uses of the DH heat and electricity are indicated in different colours (in the web version).

The accumulated volume of district heating water and the average supply/return temperatures in the substations for May are shown in Table 3.

Since the practical DHW demands varied among the five substations, the delivered electricity and heat to different substations are not comparable. Therefore, the relative demands of heat and electricity were calculated to eliminate the impact of the different DHW demand. With the exception of substation #2, all the other substations had smaller relative electricity demand than heat demand for DHW preparation. From Table 3, substation #3 with a heat pump required significantly larger volume of DH water than the others, because extra volume of district heating water was used as the heat source for the heat pump. The high average return temperature in substation #3 might be explained by incorrect control of district heating water through the evaporator of the heat pump. In substations #4 and #5, the bypass flow to maintain acceptable waiting time mixed directly into the return line, which played a role in increasing the average return temperature.

4.1.3. Supplementary measurements after the renovations of the substations

In June 2015, system renovations were made for substations #4 and #5. In substation #5, both the heat exchanger and the electric heater have been replaced by new products but with the same capacity for better performance. The installation of substation #4 has been changed to be the same as substation #5. As a result, the electric heater in substation #4 heats DHW for all purposes. Supplementary measurements were performed, and the accumulated volume of district heating water and the average supply/return temperatures in the substations for July are shown in Table 4.

Compared to the results in May, the average return temperature of substations #4 and #5 achieved significant reduction. One possible reason could be the new heat exchanger reduced or

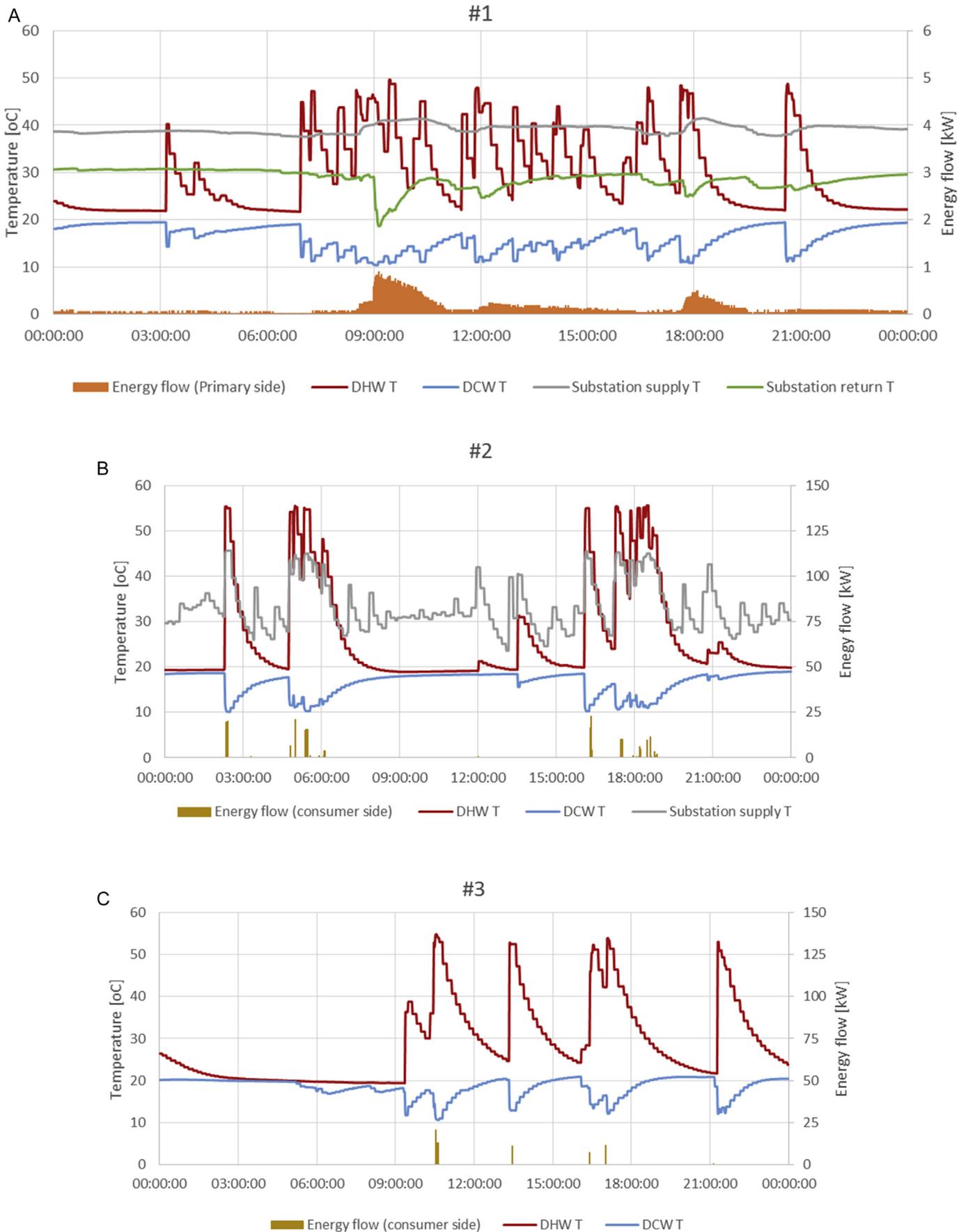


Fig. 6. Daily variation in the measured temperatures on 6th May 2015, diagrams (a)–(e) correspond to the substation #1–#5.

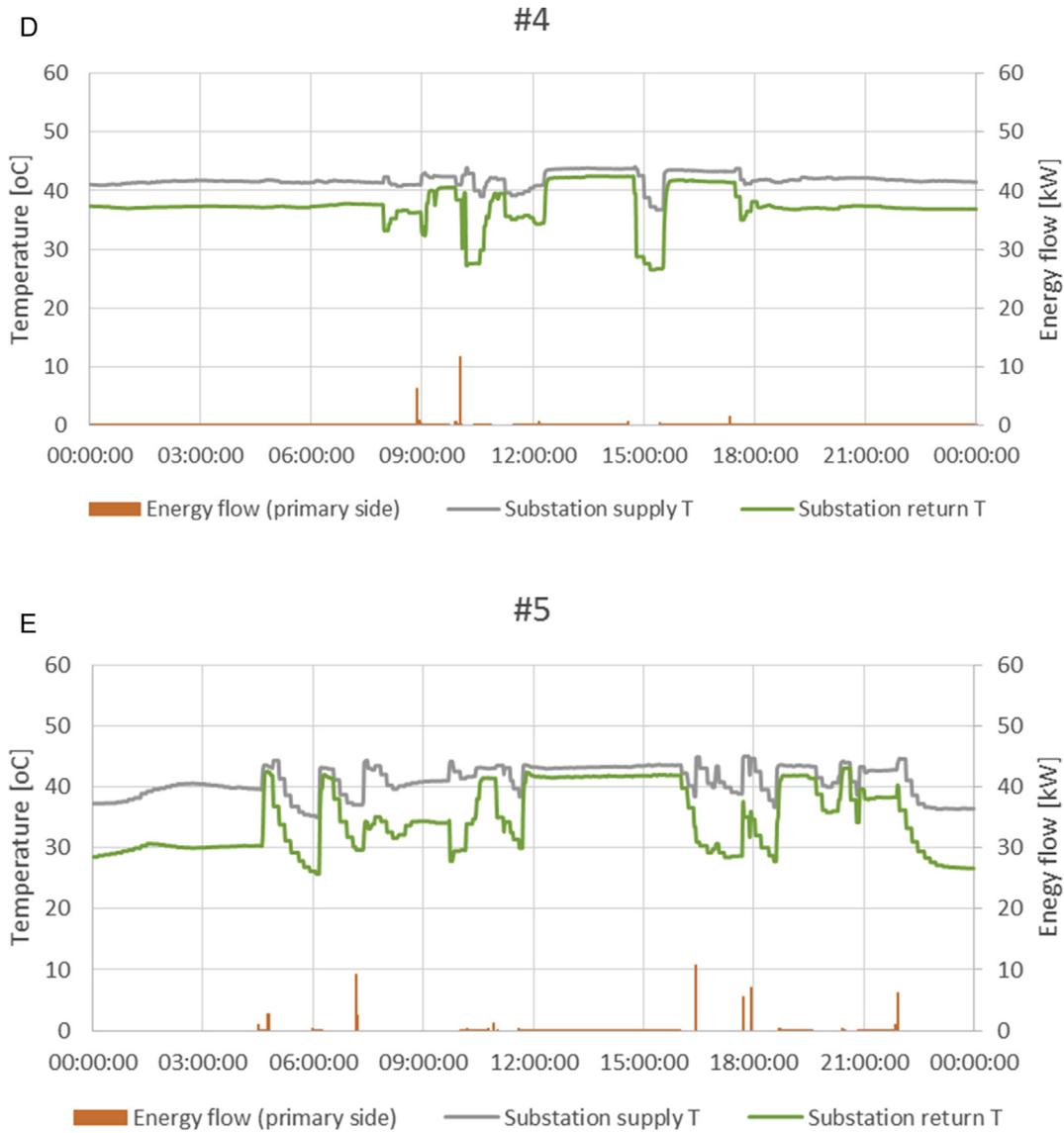


Fig. 6. (continued).

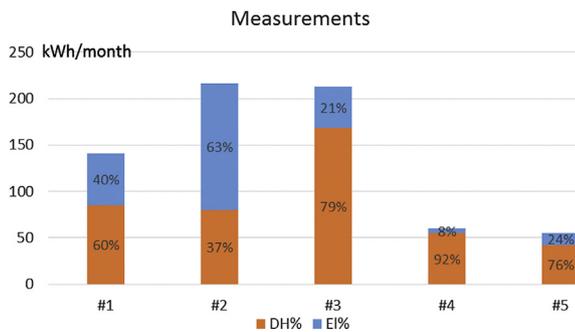


Fig. 7. Measured heat and electricity delivered for DHW preparation in the five substations for May.

eliminated the bypass flow. As a result, the DH water delivered to the substations also much reduced. Since the electric heater has enough heating capacity, it is unnecessary to use the bypass to ensure the acceptable waiting time for DHW. Accordingly, the average return temperature on the primary side can be lowered by avoiding mixing with the bypass flow.

4.2. Energy and economy performances of the case substations by models

4.2.1. Relative heat and electricity demands for DHW preparation by models

The model results for the monthly DHW load including the DHW demand and heat loss are shown in Fig. 8. The relative heat and electricity demand compared to the DHW demand are also illustrated in percentage.

From Fig. 8, all the substations were expected to use more heat from district heating than electricity for supplementary heating. The substations #4 and #5 with in-line electric heaters have the much less relative electricity demand compared to the relative heat demand. That is mainly due to the instantaneous preparation of DHW at comfort temperature, which avoided the heat loss of heat storage equipment and unnecessary supplementary heating for DHW. While substation #3 with a heat pump had higher overall energy demand as well as the relative electricity demand because a large proportion of energy was wasted covering the huge heat loss.

The actual heat and electricity delivered for DHW preparation can be different due to the different DHW demands of the

Table 3

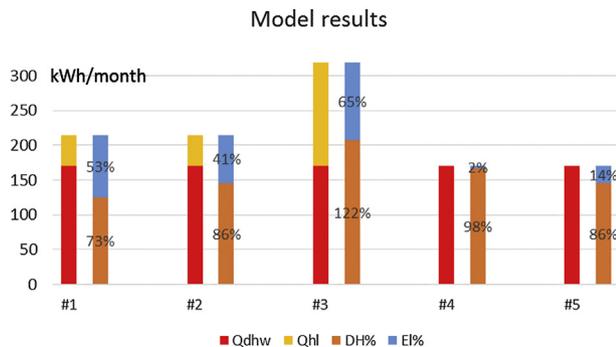
Measurements of the accumulated volume of DH water on the primary side for DHW preparation and average supply/return temperatures (in May).

	#1	#2	#3	#4	#5
Accumulated water volume delivered by DH [m ³]	5.9	5.5	51.4	16.0	5.9
Average supply temperature [°C]	40.4	40.0	42.9	42.5	43.4
Average return temperature [°C]	27.9	27.4	40.0	39.6	37.2

Table 4

Supplementary measurements after replacing the heat exchangers in substation #4 and #5 (in July).

	#1	#2	#3	#4	#5
Accumulated water volume delivered by DH [m ³]	3.7	3.9	46.4	1.4	0.8
Average supply temperature [°C]	38.3	42.9	41.3	40.8	41.5
Average return temperature [°C]	29.4	35.2	40.1	21.9	22.7

**Fig. 8.** Model results of the energy delivered for DHW preparation in the five substations.

consumers. However, the relative DH heat and electricity demands eliminate the effects of the different DHW demand, and are comparable. The simulation results of relative heat and electricity indicate the energy performances of different substations under ideal situations. It can be used as indicator of the faults in the substation by analysing the difference with the measurements. Comparing Figs. 8 and 7, the trends of the simulation results and the measurements are similar for most substations. The substations #4 and #5 still required much less electricity than heat. Substation #4 had the least relative electricity demand. The relative electricity demands in substation #1 with a storage tank and substation #3 with a heat pump were slightly larger for the model results than the measurements. However, in substation #2, the relative electricity demand of the measurement was reversed to the model result. That might be caused by the fault settings in the substation, where the set point temperature of the tank was higher than necessary. As the fault was found out, the set point temperature of the storage tank in substation #2 was lowered by 5 °C–50 °C since November 2015. Consequently, the electricity delivery in

November was reduced to 79.5 kWh. Compared to the electricity load in May (136 kWh/month from Fig. 7), the savings was as much as 42%. According to both the model results and the measurements, substation #4 with an in-line heater in the kitchen makes the optimal uses of energy, which also fulfils the comfort and hygiene requirements. In addition, it should be noticed that the heat loss from the equipment is an important factor that can significantly reduce the overall energy efficiency of the substation, which makes instantaneous preparation of DHW the preferred option.

4.2.2. Levelized costs for DHW preparation in 5 substations

Considering the investment, O&M cost and the integrated energy price, the levelized costs for the 5 substations preparing DHW under the ideal conditions are shown in Table 5.

The reference expense for unit DHW preparation is 0.8 DKK/kWh with the current 3rd generation district heating where supplementary heating is not considered. Except for substation #4, all the substations had significantly higher integrated energy costs than the reference. Due to less heat loss, substations #4 and #5, which have instantaneous electric heaters, can save the integrated energy cost for DHW preparation by 33–50% compared to the substations with storage tanks, and 57%–65% compared to the substation with the micro heat pump. Regarding to the investment cost, substation #3 with the micro heat pump had the highest investment, while substation #4 with a 11 kW instantaneous heat exchanger had the lowest investment cost. As a result, the levelized cost of substation #4 is the lowest among the 5 substations, which is 1.4 DKK/kWh. In practice, the unit cost of DHW preparation might be higher than the ideal calculation because of the extra heat loss and bypass flow, but the real unit cost can approach the ideal cost by applying optimized insulation and efficient operation. In addition, the more comprehensive economic analysis should include the benefits in the heat plant and network due to lower district heating temperatures, which might compensate the extra heat loss.

Table 5

Levelized costs for the 5 substations based on ideal operation.

	#1	#2	#3	#4	#5
Investment [DKK/unit]	12,000	15,000	40,000	11,000	16,000
n			20		
i			0.06		
CRF			0.087		
O&M Cost [DKK/unit]	240	300	800	220	320
Integrated energy price [DKK/kWh]	1.6	1.5	2.3	0.8	1
Annual DHW demand [kWh/year]			2000		
Levelized Cost [DKK/kWh]	2.2	2.3	4.4	1.4	1.9

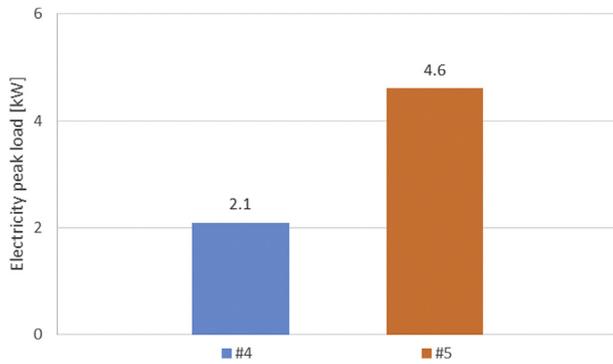


Fig. 9. Electricity peak loads of substations #4 and #5.

4.3. Peak load of electricity for the DHW preparation

The peak loads of the in-line heaters were calculated in accordance with the standard requirements. The electricity peak loads of substations #4 and #5 are shown in Fig. 9.

For substation #4, to assure the temperature of DHW other than kitchen use can achieve 40 °C as required by the standard, the supply temperature was assumed to be 45 °C. By only covering the DHW demand for the kitchen use, the electricity peak load of the in-line heater is 2.1 kW. For substation #5, by heating the whole DHW flow to 45 °C, the peak load of substation #5 is 4.6 kW. Unlike substation #4, since the in-line heater of substation #5 can heat up all DHW uses, there is no restriction for the ULTDH supply temperature. That means, substation #5 is more flexible to use if the supply temperature of ULTDH is lower than 45 °C. However, improvements are required to adapt substation #5 with normal power supply.

5. Discussion

5.1. Relative energy demand as an indicator of faults in the substation

The relative energy demands of DH heat and electricity were calculated under ideal situation in this study, which did not take into account possible faults that might occur in practice. However, the results can be used for fault-detection in substations by comparing with the actual relative energy demand based on the measurements. For example, in substation #2, the relation between the heat and electricity delivered in practice was reversed compared with the result from the model. That indicated a fault in the substation, which might be caused by overly high set-point temperature of the tank and supplementary heating for the bypass flow. The fault was then addressed by reducing the set-point temperature of the tank by 5 °C, which reduced the electricity demand by 42%. Further improvement can be made on eliminating the bypass function of the heat exchanger with supplementary heating devices, which can help to improve substation efficiency further. Therefore, the relative heat and electricity demand can be an important indicator for the substations.

5.2. Integration of heat and electricity for system design

Unlike 3rd generation district heating, when ULTDH is used, supplementary heating is necessary to guarantee comfort and hygiene supply of DHW. This means that, both the heat and electricity are the energy sources for the ULTDH supplied DHW substations. This may result in higher demand of overall primary energy for

DHW preparation and higher energy cost. However, potential benefits can be obtained due to the improved energy efficiency in the transmission network or in the heat production side if a heat pump is applied. Moreover, the performance of the ULTDH-supplied substations can be improved by avoiding the unnecessary heat loss from the heat storage, which also helps to reduce the overall heating load and enhance the economy. From substation #4, the electricity peak load was reduced by covering part of the DHW demand, which makes this solution to be easily applied in normal dwellings. In substation #5, the in-line heater was used to heat up all DHW flow. This type of solution could be better applied when the supply temperature of ULTDH is below 45 °C, and all DHW uses are assured not fall below the required temperatures. However, the difficulty of combining it with normal power supply should be addressed first.

From the macroscopic view, it is almost impossible to operate the heating system without influencing other energy systems in any future smart energy system. In the future, the electricity grid, the heat grid, and the gas grid will need to be integrated together. To achieve more flexibility for the integrated operation of electricity grid and heat grid, the dynamic demand and peak load, as well as the synergies between the grids requires full consideration [16]. Scenario analyses will be needed to optimize the smart system to achieve 100% fossil-free energy sources.

It should be mentioned that, when performing the long-term measurements in the case substations, the controllability of the tests were limited by the practical situations. For instance, the settings of the equipment were mostly kept at constant values to prepare DHW at comfort temperature to the consumers and avoid the risk of Legionella. The parameters were not changed unless the faults in the substations occurred. Moreover, due to the different DHW demands, it is difficult to carry out controlled tests between the case substations. To address this problem, we used relative heat and electricity load in this study, so that to make the measurements from different substations comparable.

6. Conclusion

In this study, detailed measurements and investigations were carried on in five substations that supply DHW with ULTDH. All five substations have supplementary heating devices. According to the measurements, the combination of ULTDH and supplementary heating devices was proved sufficient to supply DHW that can meet the comfort and hygiene requirements. To compare the energy and economic performances of the substations investigated, separate models were made for each substation. The relative heat and electricity delivered for DHW preparation were simulated under ideal conditions. The simulation results can be used as an indicator of faults in the substation by comparing them with the measurements. To compare the economy of unit DHW preparation by different substation configurations, levelized costs of the case substations were investigated taking into account the investment, the O&M cost, and the fuel cost.

Comparing the measurements and model results of the five substations, substation #4 and #5 with an in-line heater as supplementary heating device had better energy and economy performances than the other substations. The substation with heat storage required more energy to cover the heat loss and higher set-point temperature for supplementary heating, which resulted in lower energy efficiency. By improving the operation for the heat exchanger, the substation with an in-line electrical heater can also reach low return temperature. The levelized cost of the substation with an in-line electrical heater to supply unit DHW demand was also much cheaper than other substations within the same life time period. Finally, as better solutions for preparing DHW with ULTDH,

the electricity peak loads of substations with in-line heaters were analysed. The in-line heater for covering only part of the DHW demand (kitchen use) had the electricity peak load of 2.1 kW, which can be applied with normal power supply. While the in-line heater that in charge of the whole DHW demand had higher peak load, which requires further improvement to be applied with normal power supply.

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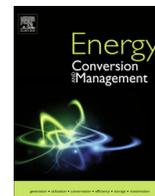
Appendix E – Paper 5

Yang, X.; Li, H.; Svendsen, S.

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

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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 optimised 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.

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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.

In most European countries including Denmark, the heat supply covers 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 result in more significant

benefits in the entire energy system by synergy effect with the electricity system, gas system, 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

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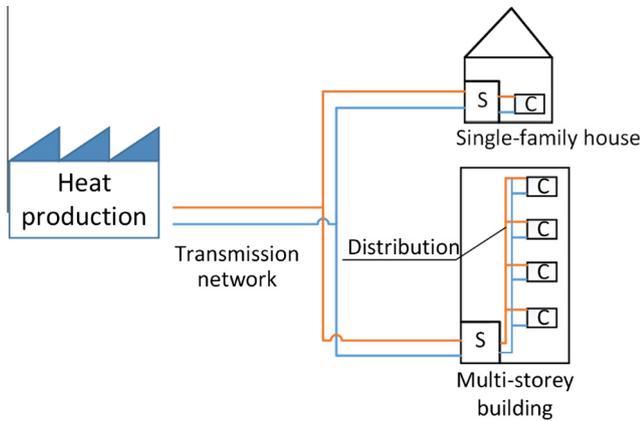


Fig. 1. Schematic of conventional district heating system. [^]S represents for substation, C represents for consumer.

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 summarised in the Table 1, in which both Danish and EU standards are taken into account [4].

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.

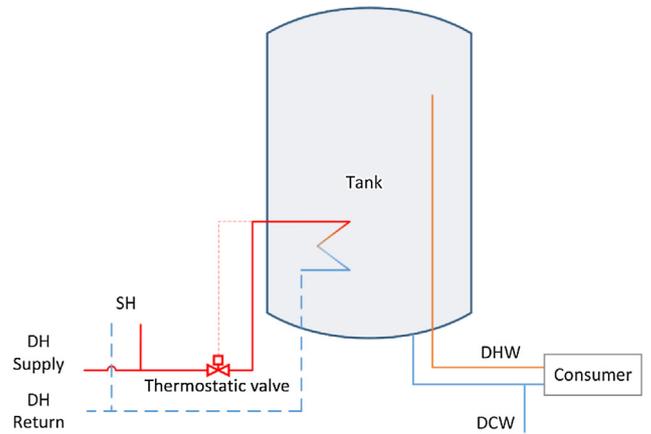
1.2.1. Conventional DHW configurations in single-family houses

Usually, DHW circulation is unnecessary for the single-family house to guarantee the acceptable (10 s) 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.

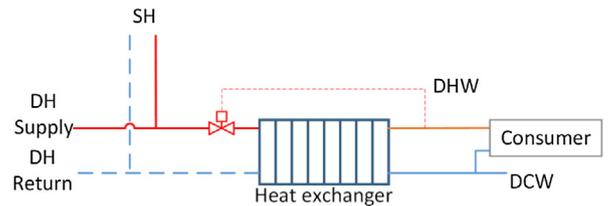
If the DHW is stored in a tank, the tank has to be maintained at no less than 60 °C to avoid the risk of Legionella. Where an IHEU is used, bypass flow is required to ensure the 10 s waiting time for comfort reasons. These two existing methods can work properly with medium-temperature district heating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

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



(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.

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.

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 10 s 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 10 s 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 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

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 Fig. 4:

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 Figs. 2(b) and 3(b), but the heat exchanger needs optimised 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 10 s 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 15 L/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 Fig. 5:

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 Fig. 6:

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.

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 m², while the apartment in a multi-storey building was assumed to have an area of 90 m². 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 energy 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:

$$Q_{tot} = Q_{dhw} + Q_{eq} + Q_p \quad (1)$$

where

Q_{tot} is the total energy consumption (kW h),

Q_{dhw} is the DHW heat demand (kW h),

Q_{eq} is the heat loss from the equipment (kW h),

Q_p is the heat loss from the distribution pipe inside the building (kW h).

To make the cases of each building topologies comparable, all the DHW preparing methods were modelled to meet the same DHW demand, with a standardised volume (250 L/m² 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 1000 L 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 kW h) within a 20-min interval [17]. The heat loss rate of the micro tank was calculated from the insulation standard [21] as 14 W. The heat loss rate of the micro heat pump system was based on information

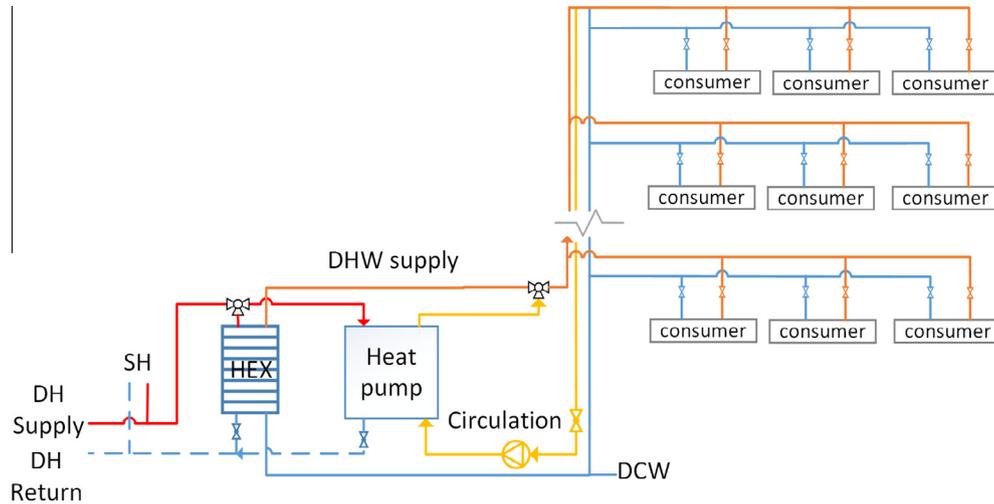


Fig. 4. Schematic of DHW preparation using a central heat exchanger combined with heat pump.

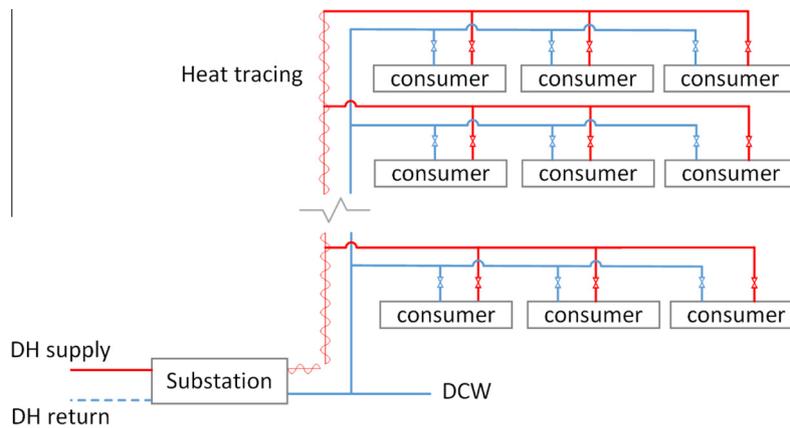


Fig. 5. Schematic of an electric heat tracing system.

from the manufacturer, and it consists of a heat loss rate of 60 W for the tank and 40 W 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 40 W 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 be 40 mm, while the diameter of the circulation pipe was assumed to be 15 mm. 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

$$Q_p = \sum L_i * q_i * (t_i - t_{amb}) * \tau \quad (2)$$

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

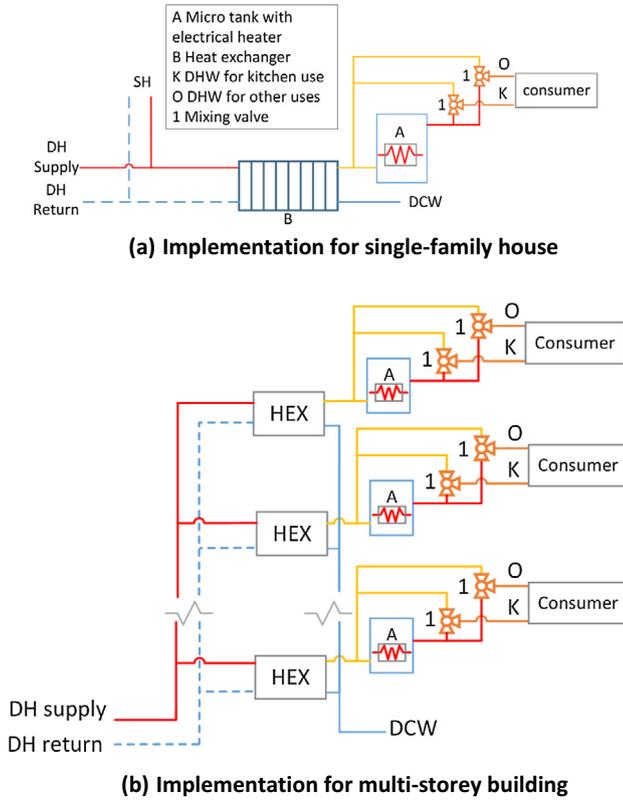


Fig. 6. Schematic of an electric micro tank system.

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 10 s 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:

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

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

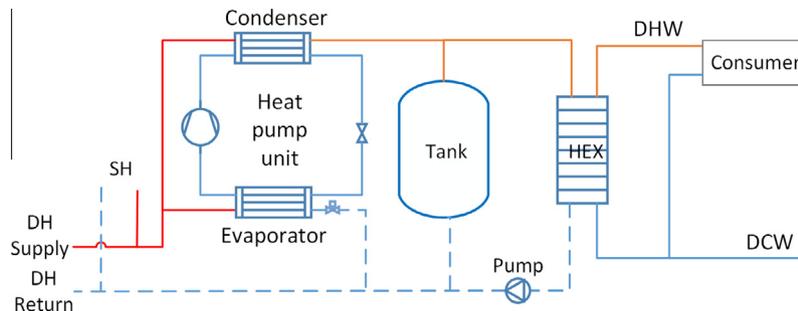


Fig. 7. Schematic of a micro heat pump system.

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 (116 W/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:

$$\bar{t}_{ret} = (t_{de} * V_{wh} + t_b * V_b) / (V_{wh} + V_b) \quad (5)$$

where

\bar{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 Tables 2 and 3 for the single-family house and the multi-storey building, respectively.

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.

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)	60 W for tank	–	–	14 W for micro tank	100 W for heat pump

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

where

C_{tot} is the total energy cost (€),

Q_{dh}, Q_{el} are the consumptions for heat and electricity (kW h),

P_{dh}, P_{el} are the prices of district heating and electricity respectively (€/kW h).

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/MW h °C. The cost reduction due to the low return temperature comparing to the conventional 80/40 °C DH scenario was therefore calculated.

$$E_s = \varepsilon \cdot Q_{sup} \cdot \Delta t \quad (7)$$

where

E_s is the cost reduction for the DH system (EURO/year),

ε is the cost saving ratio, here is 0.16 (EURO/MW h °C),

Q_{sup} is the total heat consumption for DHW supply (MW h/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 utilisation 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:

$$\eta_{ex} = EX_{out}/EX_{in} \quad (8)$$

$$EX_{out} = Q_{dhw} \left(1 - \frac{T_0}{T_{dhw} - T_{dcw}} \ln \frac{T_{dhw}}{T_{dcw}} \right) \quad (9)$$

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

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 (kW h),

Q_{dhw} is the DHW heat demand (kW h),

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),

T_{sup}, T_{dcw} are the supply and return temperatures of the district heating water (°C),

Q_{dh} is the supply heat from district heating (kW h),

W_{el} is the electricity consumption for DHW supply, which can be completely converted into useful work (kW h).

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.

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

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
Standardised 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	–	40 W 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.

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.

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 Tables 5 and 6.

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.

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 Tables 7 and 8.

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

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

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 Tables 9 and 10.

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 realised. 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 realisation 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 10 s 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.

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

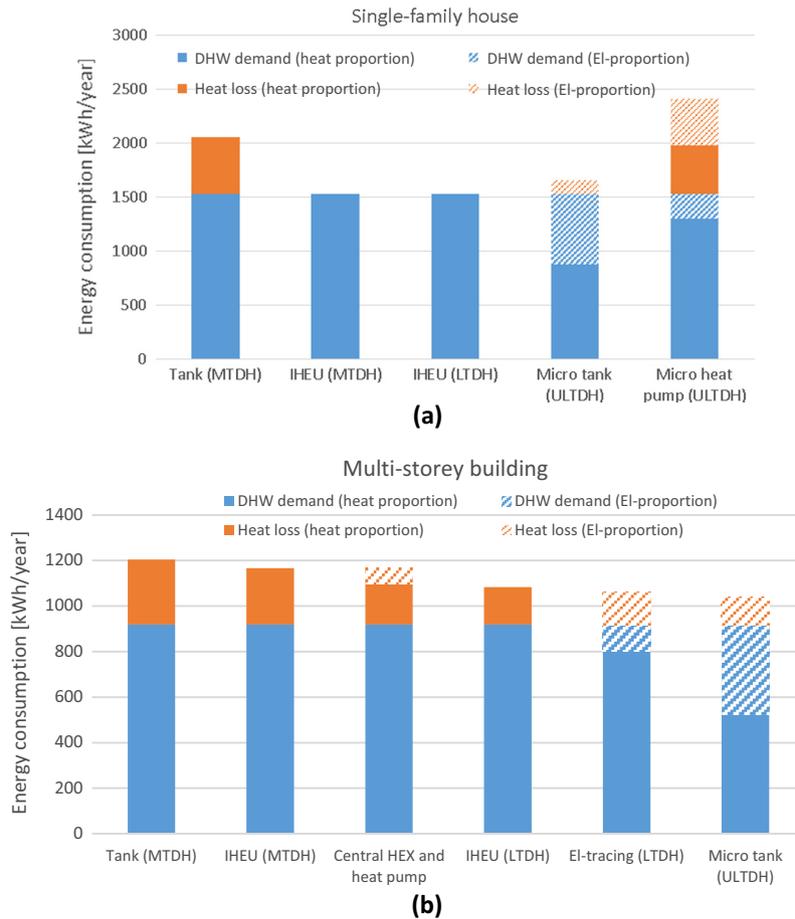


Fig. 8. Energy consumption in the different scenarios for DHW supply (kW h/year).

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

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

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

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 (kW h)	239	185	138	831	783
Ex_out (kW h)	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 (kW h)	145	136	166	101	328	548
Ex_out (kW h)	60	60	60	60	60	60
Efficiency (%)	41.1%	44.7%	35.8%	59.7%	18.1%	10.9%

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 optimised 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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Based on the background of implementing low-temperature district heating in Denmark in the near future, this study aims at providing cost-efficient solutions that meet comfort and hygiene requirements for domestic hot water preparation. System performances of different configurations were analysed with respect to different district heating scenarios and building topologies. Both simulation work and case studies were included to draw the final conclusion. The optimal solutions for domestic hot water preparation were provided to specified scenarios.

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