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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 ultra-low-temperature district heating (ULTDH). The temperature at the heat plant is 46 °C and around 40 °C at the substations. To avoid the proliferation of *Legionella* in the domestic hot water (DHW) 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.

Keywords

Ultra-low-temperature district heating; domestic hot water; Legionella; electric heating; return temperature; peak load

Highlights

- Five different substations supplied with ultra-low-temperature district heating were measured
- The relative heat and electricity delivered for DHW preparation were modelled for different substations
- The levelized cost of the five substations in respect of DHW preparation was calculated
- The feasibility of applying instantaneous electric heater with normal power supply was tested

Nomenclature

c	Specific heat capacity of water [kJ/kg · °C]	t_{dcw}	Temperature of the domestic cold water [°C]
CRF	Capital recovery factor [%]	t_{dh_s}	Supply temperature of DH [°C]
C_{inv}	Investment cost, [DKK/ unit]	t_{dh_r}	Return temperature of DH [°C]
$C_{O\&M}$	Operation and maintenance cost [DKK/year]	t_{el}	DHW temperature heated by electricity [°C]
E	DHW peak load in the substation [kW]	t_{in}	Inlet temperature of the water flow [°C]
E_s	DHW peak load from the standard [kW]	t_m	DHW temperature preheated by district heating [°C]

i	Interest rate [%]	t_{out}	Outlet temperature of the water flow [°C]
LC	Levelized cost [DKK/kWh]	<i>Greek</i>	
$\dot{m}$	Flowrate of the water [kg/s]	ε_{dh}	Relative heat demand for DHW preparation [%]
n	Life time [year]	ε_{el}	Relative electricity demand for DHW preparation [%]
P_{dh}	Price of DH heat [DKK/kWh]	φ_k	Volume percentage of DHW for kitchen use [%]
P_{el}	Price of electricity, [DKK/kWh]	<i>Abbreviations</i>	
P_{int}	Integrated energy price considering the DH and electricity [DKK/kWh]	COP	Coefficient of performance
q	Transient energy flow [kW]	DCW	Domestic cold water
Q_{dh}	Heat from district heating for DHW preparation [kWh]	DH	District heating
Q_{dhw}	The increased energy content of the DHW [kWh]	DHW	Domestic hot water
$Q_{dhw,y}$	Annual DHW demand [kWh]	LTDH	Low-temperature district heating
Q_{el}	Electricity demand of the supplementary heating devices for DHW preparation [kWh]	ULTDH	Ultra-low-temperature district heating
Q_{hl}	Heat loss of the DHW preparation process [kWh]	<i>Numbers</i>	
Q_{input}	Total energy input to the substation [kWh]	1-5	Substation #1-5
Q_{output}	Total energy output from the substation [kWh]		

1. Introduction

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

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 low-temperature district heating (LTDH). 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 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 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 25-45 °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 Fig. 1, Fig. 2, Fig. 3, Fig. 4 and Fig. 5.

Fig. 1 Substation #1

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.

Fig. 2 Substation #2

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

Fig. 3 Substation #3

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.

Fig. 4 Substation #4

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.

Fig. 5 Substation #5

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.

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	160L	3kW 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	160L	3kW 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	160L	-	Plate heat exchanger between the tank and DHW system	-	Design COP 4.5 Max power 250W	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

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

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

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 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

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 $13 \text{ kWh/m}^2 \cdot \text{yr}$, 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 individual models are described in the following paragraphs:

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:

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

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

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]

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_{el}^2 is the temperature of the DH water heated by the tank [°C],

$t_{dh_s}^2$ is the supply temperature of ULTDH [°C],

$t_{dh_r}^2$ is the return temperature of ULTDH [°C],

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 coefficient of performance (COP) 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 (60W) and heat loss from the compressor (140W). 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:

$$\varepsilon_{dh}^3 = \frac{Q_{dh_o}^3 + Q_{hp_s}^3 + Q_{hl_dh}^3}{Q_{dhw}} = \frac{(t_{dh_s}^3 - t_{dh_r}^3) + \left(1 - \frac{1}{COP}\right) * (t_{el}^3 - t_{dh_s}^3)}{(t_{el}^3 - t_{dh_r}^3)} * \left(1 + \frac{Q_{hl_tank}^3}{Q_{dhw}}\right) \quad (10)$$

$$\varepsilon_{el}^3 = \frac{Q_{el}^3 + Q_{hl_el}^3}{Q_{dhw}} = \frac{(t_{el}^3 - t_{dh_s}^3) / COP}{(t_{el}^3 - t_{dh_r}^3)} * \left(1 + \frac{Q_{hl_tank}^3}{Q_{dhw}}\right) + \frac{Q_{hl_com}^3}{Q_{dhw}} \quad (11)$$

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].

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 [%].

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 the following table:

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.

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 [15], adapting to the specific cases in this study, the levelized cost of different DHW supply methods can be calculated as:

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

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 0.1L/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:

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

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

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

(a)

(b)

(c)

(d)

(e)

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

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 10s 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.

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

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

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

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.

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

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 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.

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

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 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 Fig. 8 and Fig. 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 to 50 °C since November 2015. Consequently, the electricity delivery in November was reduced to 79.5 kWh. Compared to the electricity load in May (136kWh/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.

Table 5 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

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 11kW 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.

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.

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

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 4.6kW. 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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