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

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10

11 **Abstract**

12 District heating in Denmark is going through the transition from 3<sup>rd</sup> generation  
13 (80/40 °C) to 4<sup>th</sup> generation (50-55 °C /25 °C) systems in preparation for district heating  
14 based completely on renewable fuels by 2035. However, concern about Legionella  
15 growth and reduced comfort with low-temperature domestic hot water supply may be  
16 discouraging the implementation of low-temperature district heating . Aimed at  
17 providing possible solutions, this study modelled various proposals for district heating  
18 systems with supply temperatures of 65 °C, 50 °C and 35 °C and for two different  
19 building topologies. Evaluation models were built to investigate the energy, economy  
20 and exergy performances of the proposed domestic hot water systems in various  
21 configurations. The configurations of the devised domestic hot water substations were  
22 optimized to fit well with both low and ultra-low-temperature district heating and to  
23 reduce the return temperature to district heating. The benefits of lower return  
24 temperatures were also analysed compared with the current district heating situation.

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

## 29 Keywords

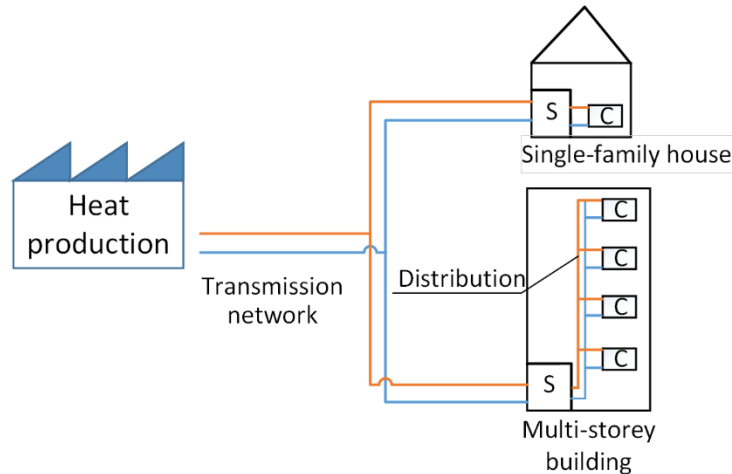
30 Low-temperature district heating, domestic hot water, Legionella, comfort, evaluation  
31 model, low return temperature

## 32 Highlights

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

## 37 1. Introduction

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



45

46

**Fig. 1 Schematic of conventional district heating system**

47

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

48

49 In most European countries including Denmark, the heat supply covers the demand of  
 50 both space heating and domestic hot water (DHW). To make the utmost use of  
 51 industrial excess heat and renewable energy sources, as well as to improve the  
 52 efficiency of the DH system, Danish district heating is undergoing the transition from the  
 53 current 3<sup>rd</sup> generation district heating (80/40 °C) to 4<sup>th</sup> generation district heating  
 54 (55/25 °C) without violating any comfort or hygiene requirements[1]. Moreover, the  
 55 savings from a more efficient heating system can results in more significant benefits in  
 56 the entire energy system by synergy effect with the electricity system, gas system and  
 57 etc.[2]. For heat supply to energy-efficient buildings in low heat density areas, it will be  
 58 even possible to apply the ultra-low-temperature district heating (ULTDH) with supply  
 59 temperature at 35-45 °C to make the utmost use of the low-temperature excessive heat,  
 60 and improve the efficiency of the heat pump as heat production.

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

69 1.1 Comfort and hygiene requirements for domestic hot water supply

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

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

	<b>Systems with no circulation or storage tank</b>	<b>System with large DHW volume</b>
--	--	---

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

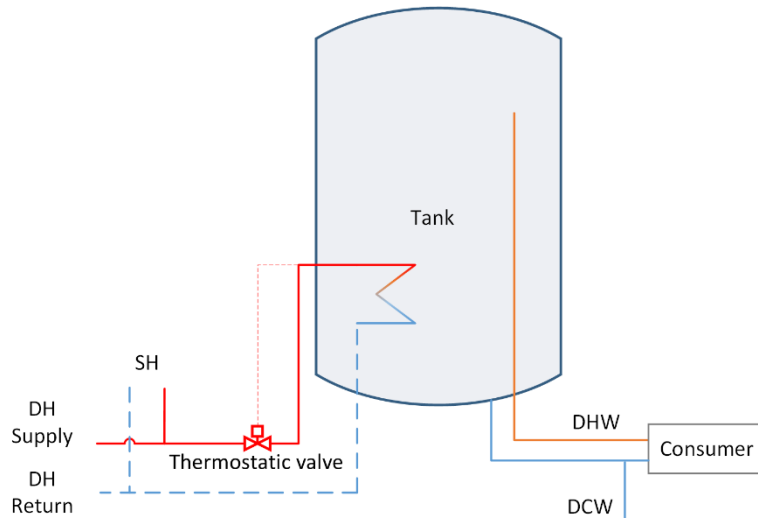
81

82 1.2 Existing DHW system configuration with medium-temperature district heating

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

86 1.2.1 Conventional DHW configurations in single-family houses

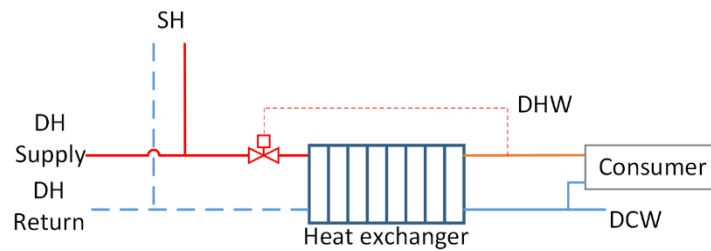
87 Usually, DHW circulation is unnecessary for the single-family house to guarantee the  
88 acceptable (10s) waiting time, since the distribution pipe length from the substation to  
89 the tap is short. Currently, a storage tank or an instantaneous heat exchanger unit  
90 (IHEU) are most commonly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



92

93

**(a) DHW substation with a storage tank**



94

95

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

**Fig. 2 Existing DHW configurations for single-family house**

**\*SH represents for space heating**

96

97

98

99 If the DHW is stored in a tank, the tank has to be maintained at no less than 60 °C to

100 avoid the risk of Legionella. Where an IHEU is used, bypass flow is required to ensure

101 the 10s waiting time for comfort reasons. These two existing methods can work

102 properly with medium-temperature district heating without supplementary heating.

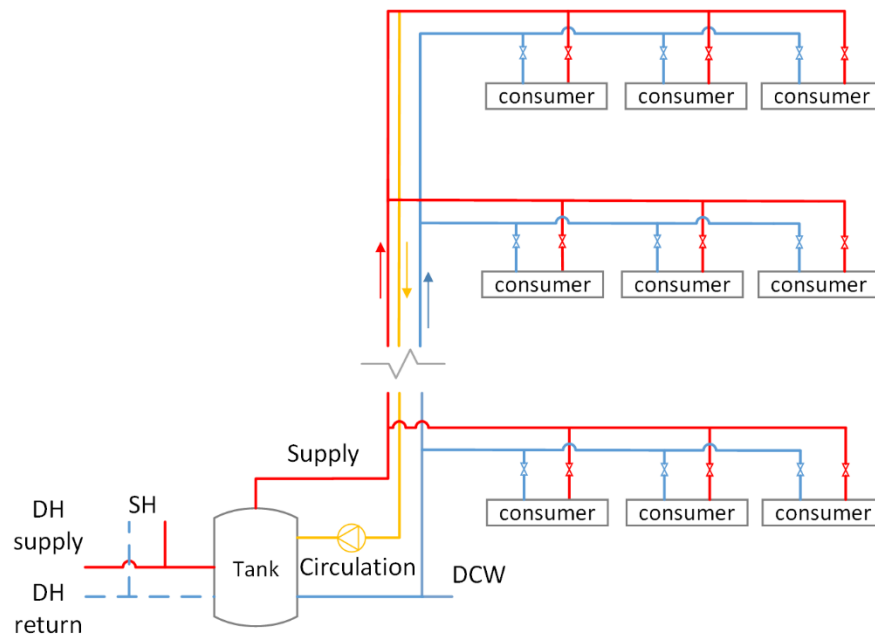
103 1.2.2 Conventional DHW configurations in multi-storey building

104 For multi-storey building, depending on whether the DHW is prepared in the central

105 substation or locally, the configurations can be divided into mainly two types. The

106 schematics are shown in Fig. 3.

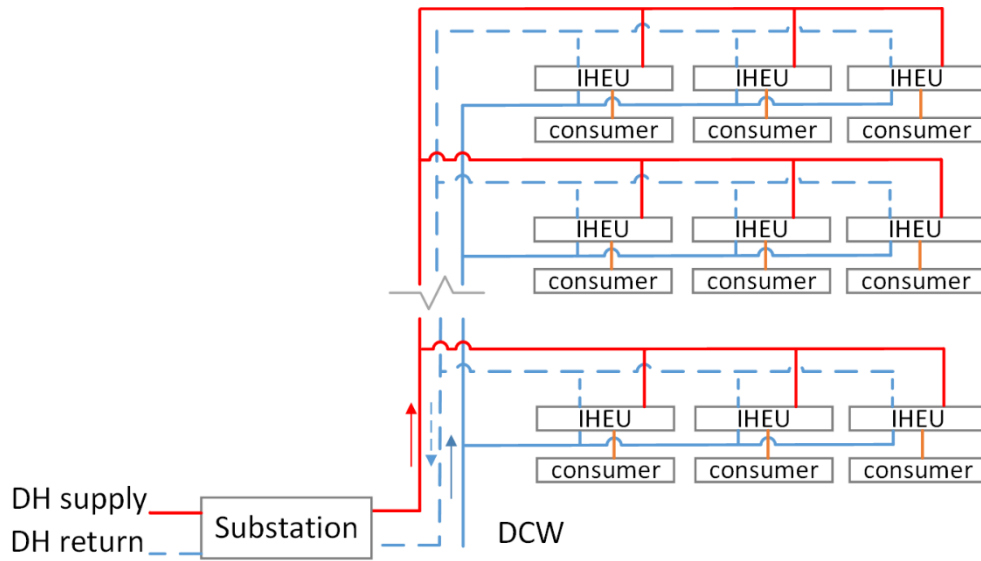
107



108

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





110

111

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

112

**Fig. 3 Existing DHW configurations for multi-storey building**

113

To take account of the overall DHW peak load and the comfort requirement, the DHW

114

shown in Fig. 3 (a) requires a storage tank to shave the peak load and circulation pipes

115

to ensure the 10s waiting time. The cold and hot water are mixed at the faucet to reach

116

the desired temperature by the consumer. This study did not include systems only with

117

a main heat exchanger and circulation in the analysis for multi-storey buildings because

118

they are uncommon in Denmark. According to the standard for Legionella prevention

119

[4], a centralized system with DHW circulation requires the tank to be maintained at

120

60 °C and the DHW circulation to be at least 50 °C. Consequently, the heat loss from

121

such systems can be substantial. In Denmark, it has been found that the circulation

122

system can waste up to 70% of the total energy delivered for DHW use [3]. Moreover,

123

the high temperature regime for the circulation obstructs the implementation of

124

LTDH/UTLDH. In comparison, DHW can be prepared locally by the individual heat

125

exchanger as shown in Fig. 3. It is feasible to apply such a system with LTDH, but to

126 ensure the 10s waiting time for comfort, bypass flow is always needed, which increases  
127 the return temperature to district heating.

### 128 1.3 DHW preparing technologies

129 There are some investigations of different technologies for DHW preparation. . Cholewa  
130 and et al. [5] test the performances of three different heating systems for multi-storey  
131 buildings: a system with centralized condensing gas boiler, a system with flat-based heat  
132 exchanger supplied by district heating, and a system with flat-based gas boiler. The  
133 results show that both the decentralized systems have higher annual efficiency than the  
134 centralised system. Thorsen [6] simulates the performance of flat-based heating unit  
135 system combined with district heating based on a Danish case. The energy saving of the  
136 flat-based heating unit system ranges from 2-4 kWh/m<sup>2</sup> annually compared with the  
137 conventional DHW circulation system and the system can be operated with lower supply  
138 temperature without Legionella problem. Tol and Svendsen [7] simulate the district  
139 heating network with different system layouts and substation configurations. They find  
140 that the substation with a storage tank can help to reduce the heat loss at the end of  
141 the branch network. Fernández-Seara and et al. [8] make experiment investigations for  
142 the performances of DHW production system with a storage tank under 4 control  
143 strategies. The result shows that the tank has better performance if the thermal  
144 stratification can be maintained. Chaturvedi and et al. [9] model a solar-assisted heat  
145 pump system for DHW production, and indicate that the life cycle cost of the solar-  
146 assisted heat pump system is better than the electric only system if the water is heated  
147 no higher than 70 °C. Brum and et al [10] model and compare three different heating

148 systems for supplying space heating and domestic hot water to a 3-dwelling system. The  
149 ground source heat pump consumes the least electricity for cover the equivalent DHW  
150 demand, while the individual electric heater consumes the most. Bohm [11] makes  
151 large-scale investigation towards the DHW preparation and distribution system in  
152 Denmark, and indicates that the electric heat tracing cable can be used for maintaining  
153 the DHW temperature at the tap, which is helpful to guarantee the comfort and hygiene  
154 DHW supply from LTDH. However, the energy saving effect of the electric heat tracing  
155 system can be offset by the high primary energy factor of the electricity. Yang and et al.  
156 [12] make simulation of the electric heat tracing system for DHW supply to multi-storey  
157 building by LTDH. The heat loss can be saved up by 70% compared with the  
158 conventional heating system if the tracing cable is controlled corresponding to the DHW  
159 load pattern. Ghouali and et al. [13] make a simulation study of simultaneous heating  
160 and cooling supply by heat pump, and find that the optimal seasonal coefficient of  
161 performance of the heat pump is obtained if the DHW is produced at the temperature  
162 40-45 °C. Elmegaard and et al. [14] investigate 3 heat pump systems as well as a direct  
163 electric heating system for supplying heat with conventional district heating. The results  
164 show that the heat pump system using R134a with a storage tank on the DH side has  
165 better performance. Boait and et al [15] investigate five individual DHW systems, and  
166 find the instantaneous DHW production is more efficient than storage type. In addition,  
167 the insulation and smart control methods are of great importance to improve the  
168 efficiency for DHW system with a storage tank or a heat pump. Lu and Wu[16] have  
169 compared 8 different systems for covering the domestic energy demand. For DHW

170 preparation, a system integrated an air conditioning unit and a heat pump has better  
171 economy and environment performance, since the heat pump can extract indoor heat  
172 for DHW production and provide cooling effect. However, most of the studies analyse  
173 DHW preparation methods in isolation. The DHW preparation methods combined with  
174 district heating are insufficiently studied. Moreover, the performances of the  
175 approaches vary depending on the specific applying situations. Therefore, suitable  
176 solutions for DHW preparation should be designed for LTDH and ULTDH, and broader  
177 comparison among different solutions needs to be made, so that the optimal solutions  
178 for specific scenarios can be determined.

#### 179 1.4 Aim and scope

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

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

186 In this study, various DHW supply methods were analysed in the context of different  
187 generations of DH supply: medium-temperature district heating (65 °C), LTDH (50 °C)  
188 and ULTDH (35 °C). Different scenarios for the analysis were formed by combining  
189 different DH systems with different building typologies. The performances of each  
190 devised solution were calculated by the theoretical model ideally. Moreover, as an

191 important factor for the system savings, the lowered return temperatures to district  
192 heating in the different scenarios and the resulting cost savings were also investigated.  
193 The results of this study can be helpful when planning for LTDH or even ULTDH in the  
194 future.

## 195 2. Material and Methods

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

### 204 2.1 Solutions for DHW supply with low-temperature district heating (LTDH)

205 Three types of solutions were proposed for LTDH:

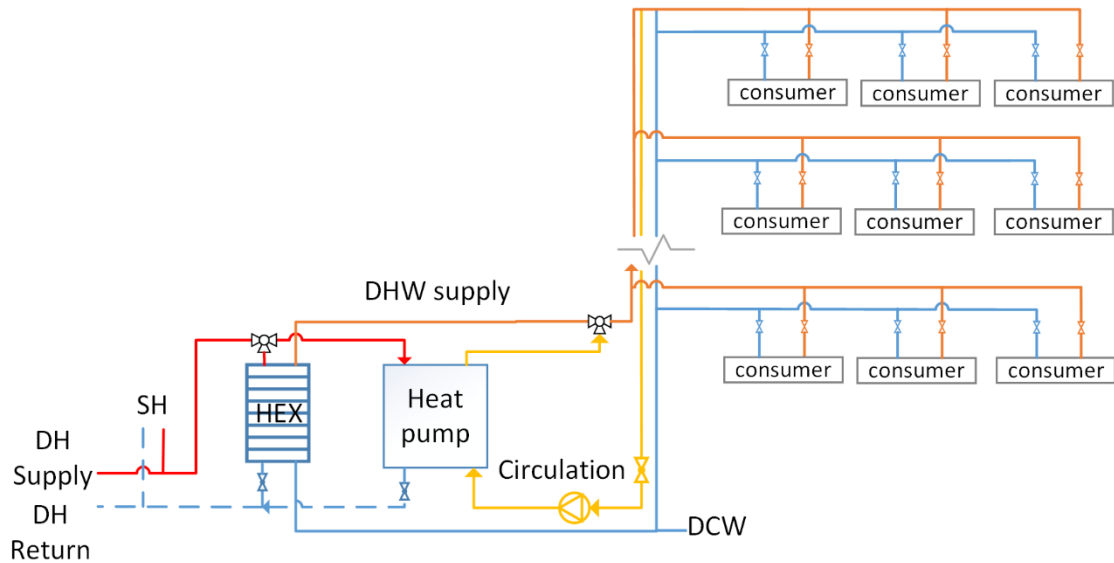
- 206 1) A central heat exchanger combined with a heat pump, which could be a solution for  
207 DHW supply with LTDH in multi-storey buildings where substantial renovations are  
208 not feasible.
- 209 2) An IHEU system with better-insulated distribution pipes and using bypass flow for  
210 bathroom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

211 houses and multi-storey buildings. This would be best in new buildings or in existing  
212 buildings where deep renovation for the space heating and DHW system is possible.  
213 3) Electric heat tracing combined with dynamic control. This could be applied in multi-  
214 storey buildings where the DHW circulation pipes can be replaced and in buildings  
215 that have special requirements for DHW hygiene, such as hospitals or nursing  
216 homes.

217 2.1.1 Central heat exchanger combined with heat pump

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

223



224

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

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

234 2.1.2 Improved decentralized system with instantaneous heat exchanger unit (IHEU)

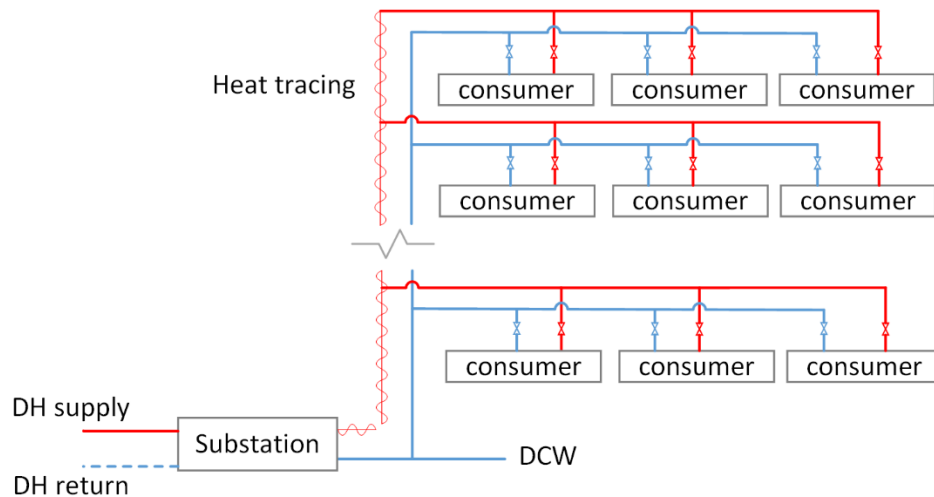
235 The schematics are similar to those shown in Fig. 2 (b) and Fig. 3 (b), but the heat  
236 exchanger needs optimized design to improve the efficiency with low supply  
237 temperature, so that comfort temperature of DHW (45 °C) and low return temperature

238 can be achieved. The DHW is prepared instantaneously through the IHEU, so the  
239 capacity of the unit needs to be sufficient to cover the peak load for DHW, which is 32.3  
240 kW [17]. The conventional way of operating IHEUs requires a bypass to ensure the 10s  
241 waiting time. However, mixing the bypass flow with the DH return flow will increase the  
242 return temperature to district heating, which limits the efficiency of LTDH. One possible  
243 improvement might be to redirect the bypass flow to bathroom heating, so that the  
244 return temperature can be much reduced after heating the bathroom. According to the  
245 Danish building code, the air change rate in the bathroom is 15L/s [18]. To keep the tiled  
246 bathroom floor at a comfort temperature of 24-29 °C, 116 W space heating demand is  
247 required for each home for only heating the air flow through the bathroom from 20 °C  
248 to 26 °C. If the insulation of the supply pipe is adequate, the bathroom heating flow will  
249 be able to reach the end user with very limited temperature drop, and keep the supply  
250 pipe warm. As a result, the space heating demand may increase during the non-heating  
251 season, but cost savings will be available in the DH system due to the reduced return  
252 temperature to district heating. Moreover, the thermal comfort of the bathroom will be  
253 improved.

#### 254 2.1.3 Electric heat tracing

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





260

261

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

262

Since the supply line can be kept warm by the electric tracing cable, the storage tank

263

and circulation pipe are unnecessary, saving much heat loss. Compared to the

264

conventional system with DHW circulation, the electric heat tracing system can reduce

265

the distribution heat loss by 50% [12]. The electricity consumption of the electric heat

266

tracing system depends greatly on the control method. Smart control methods of the

267

cable based on DH load profile plays a role in saving the power consumption.

268

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

269

Since ULTDH is insufficient to heat DHW to the temperature required by the comfort or

270

hygiene regulations, supplementary heating is needed. One solution is the IHEU

271

combined with an electric micro tank, which can be easily installed in a new building or

272

an existing building with IHEU. Another solution is the micro heat pump system, which is

273

applicable for single-family houses.

274 2.2.1 Combination of IHEU and micro tank

275 The instantaneous electric heater can heat DHW to the required temperature

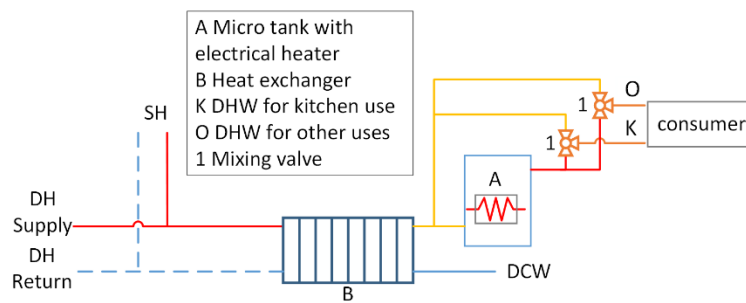
276 instantaneously, but when the DH supply temperature is much lower than the comfort

277 temperature (45 °C), the electricity peak load can be very high, which makes it difficult

278 to install with the normal power supply. To address this problem, this study proposes

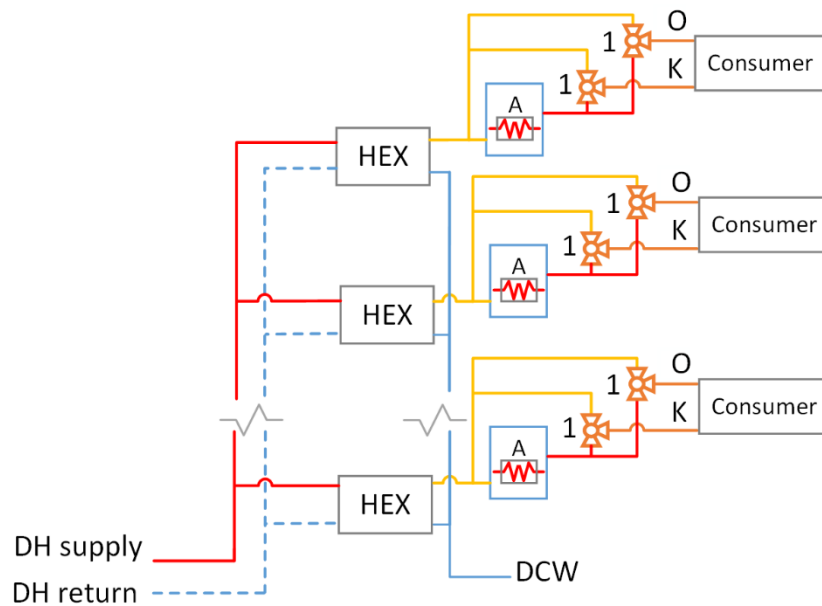
279 the new concept of using a micro tank with immersion heater to shave the peak power

280 load. A schematic of the micro tank solution is shown in the following diagram:



281

282 **(a) Implementation for single-family house**



283

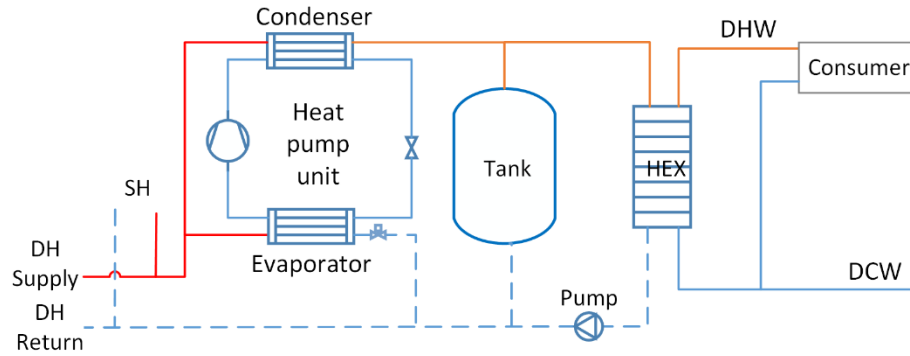
284 **(b) Implementation for multi-storey building**

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

286 The micro tank with an immersion electric heater is installed on the consumer side. The  
287 DHW is preheated by ULTDH through the heat exchanger. One stream of the preheated  
288 DHW is stored and further heated in the micro storage tank. To meet the requirement  
289 of Legionella prevention, the DHW in the tank is heated to 60 °C by the electric  
290 immersion heater. When DHW is drawn off, the DHW from the tank is mixed with the  
291 hot water preheated by the heat exchanger to achieve the comfort temperature. There  
292 are two thermostatic valves controlling the mixed temperature of DHW for kitchen use  
293 (45 °C) and for other uses (40 °C). Compared to the instantaneous electric heater, the  
294 micro tank solution can be designed to be compatible with the normal electricity supply.  
295 Moreover, since the micro tank can provide DHW immediately, no bypass is needed for  
296 the heat exchanger in this solution, so the average DH return temperature is also  
297 reduced. The micro tank system can be applied in both single-family houses and multi-  
298 storey buildings with instantaneous heat exchanger units.

299 2.2.2 Micro heat pump

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



303

304

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

305

The heat source of the heat pump is ULTDH supply water. The electricity is only used to

306

lift the energy quality of the DH water. Compared to direct electric heating, therefore,

307

the micro heat pump system consumes much less electricity than other supplementary

308

heating devices to heat an equivalent amount of DHW. The storage tank helps to

309

maintain stable operating conditions for the heat pump. Since the tank is installed on

310

the primary side, the risk of Legionella is eliminated

311

2.3 Evaluation models for different scenarios

312

Three DH scenarios were defined as the background for the evaluation models: 1)

313

medium-temperature district heating (MTDH) with a supply temperature of 65 °C, which

314

ensures the comfort and hygiene of DHW supply without any supplementary heating.

315

This scenario can be considered as the first step of the transition to 4<sup>th</sup> generation

316

district heating. The conventional DHW system can be retained in this phase. 2) Low-

317

temperature district heating (LTDH) with a supply temperature of 50 °C, which is

318

sufficient to heat DHW to a comfortable temperature, but which will require certain

319

solutions to prevent Legionella. 3) Ultra-low-temperature district heating (ULTDH) with

320 a supply temperature of 35 °C, which is insufficient to meet either comfort or hygiene  
321 requirements.

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

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

#### 336 2.3.1 Evaluation model for energy performance

337 The energy performance model evaluates the DH heat and electricity consumption for  
338 DHW preparation, also including heat loss from the equipment and distribution pipes  
339 inside the building. The relative DH heat and electricity consumption depend on the

340 different DHW system configurations and corresponding operating temperatures. The  
341 operating temperature for each case was as described in previous sections.

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

$$344 \quad Q_{tot} = Q_{dhw} + Q_{eq} + Q_p \quad (\text{Eq.1})$$

345 where

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

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

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

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

350 To make the cases of each building topologies comparable, all the DHW preparing  
351 methods were modelled to meet the same DHW demand, with a standardized volume  
352 (250L/m<sup>2</sup>·yr) of DHW [19, 20] produced at a comfortable temperature (45 °C), assuming  
353 that the required energy for DHW preparation can be much reduced due to the  
354 evolution of new technologies and efficient operation in the future. Considering the  
355 different operation modes, some systems may prepare DHW at a higher temperature  
356 due to the threat of Legionella, but the tap temperature can be adjusted to 45 °C  
357 ultimately by mixing with DCW.

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

373 Heat loss from the distribution pipes inside the buildings was only taken into account for  
374 the multi-storey building. The distribution heat loss inside each apartment was not  
375 included in the model since it can be identical for all cases. For the systems with bypass  
376 or circulation, each flat was assumed to have 6 m of distribution pipe. For the electric  
377 heat tracing system, the distribution pipe only included 3 m supply pipe in the model.  
378 The pipe diameter of the riser was assumed to 40mm, while the diameter of the  
379 circulation pipe was assumed to 15mm. Advanced pipe insulation with polyurethane

380 foam was selected for the model, the corresponding heat coefficients are 0.157 W/m·K  
381 and 0.094 W/m·K according to the existing product. The ambient temperature for  
382 calculating the heat loss was assumed to be 15 °C.

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

389 The heat loss from the pipe can be calculated as

$$390 \quad Q_p = \sum L_i * q_i * (t_i - t_{amb}) * \tau \quad (\text{Eq.2})$$

391 where

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

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

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

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

396  $\tau$  is the time of the calculation period [h].

397 As an important performance parameter, the volume-based average return

398 temperatures to district heating of the different scenarios were investigated. For the



399 storage tank system with MTDH, the average return temperature to district heating was  
400 calculated based on the design return temperature in the product catalogue and the  
401 energy balance of the practical situation. For the IHEU system, the return temperature  
402 to district heating was calculated as the volume-averaged return temperature of the  
403 water-heating flow and the bypass flow for the MTDH scenario. The supply/return  
404 service pipe was assumed to be 5 m long, which connects the building to the DH  
405 transmission network. The set-point temperature of the bypass was assumed to be  
406 45 °C to ensure the 10s waiting time required by the comfort standard [17, 20]. The  
407 flowrate of the bypass should be sufficient to provide 45 °C to the most remote  
408 consumer. For the LTDH scenario, the bypass of the IHEU was redirected to bathroom  
409 heating to reduce the return temperature to district heating. Thus, the volume-based  
410 average return temperature was calculated from the water-heating flow and the  
411 bathroom-heating flow. The return temperature of the bathroom-heating flow was  
412 assumed to be 25 °C with effective cooling. With effective heat exchanger, the water-  
413 heating flow at the outlet of the IHEU can be cooled down to 20 °C for MTDH and  
414 18.8 °C for LTDH [19, 23]. The bypass flow and the bathroom-heating flow can be  
415 calculated as follows:

$$416 \quad V_{bypass} = L_{bypass} * q_i * (t_i - t_{amb}) / (\Delta t_{bypass} * 4200) * 3600 * 24 \quad (\text{Eq.3})$$

$$417 \quad V_{bath} = q_{bath} / ((t_{bs} - t_{br}) * 4200) * 3600 * 24 \quad (\text{Eq.4})$$

418 Where

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

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

421  $\Delta t_{bypass}$  is the temperature drop of the bypass flow along the supply line [°C],

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

423  $q_{bath}$  is the space heating demand of the bathroom (116W/apartment according to

424 section 3.2) [W],

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

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

427 Therefore, the return temperature to district heating of the IHEU system can be

428 calculated as:

429 
$$\overline{t_{ret}} = (t_{de} * V_{wh} + t_b * V_b) / (V_{wh} + V_b) \quad (\text{Eq.5})$$

430 where

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

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

433  $t_b$  is the temperature of the bypass flow (MTDH) or bathroom heating return flow

434 (LTDH) [°C],

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

436  $V_b$  is the volume of the bypass (MTDH) or bathroom heating flow (LTDH) on a daily basis

437 [L/day].

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

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

448 **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 <sup>2</sup> /year]	250	250	250	250	250
T_dhw [°C]	45	45	45	30	30
Set point T of the equipment [°C]	60	-	-	60	50
Equipment heat loss rate [W]	60W for tank	-	-	14W for micro tank	100W for heat pump

449

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

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

451 **\* Pipe\_r means the riser, Pipe\_c means the circulation pipe.**

452 2.3.2 Evaluation model for economic performance

453 Economic performance depends on the investment cost, operation and maintenance

454 (O&amp;M) costs, and the energy cost. However, the investment cost and O&amp;M costs are

455 strongly dependent on the specific case, so only the DH heat and electricity costs were

456 included in the economic model. The prices of DH heat and electricity were assumed to

457 be 0.1 [24] and 0.25 [25] €/kWh, respectively.

458 
$$C_{tot} = Q_{dh} * P_{dh} + Q_{el} * P_{el} \quad (\text{Eq.6})$$

459 where

460  $C_{tot}$  is the total energy cost [€],

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

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

463 In addition to the savings inside buildings, the benefits of low return temperatures to  
464 the DH system was also investigated for each scenario. According to Svend and Sven  
465 [22], the cost reduction from the low return temperature is estimated to be 0.16  
466 EURO/MWh · °C. The cost reduction due to the low return temperature comparing to  
467 the conventional 80/40 °C DH scenario was therefore calculated.

468 
$$E_s = \varepsilon \cdot Q_{sup} \cdot \Delta t \quad (\text{Eq.7})$$

469 Where,

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

471  $\varepsilon$  is the cost saving ratio, here is 0.16 [EURO/MWh · °C],

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

473  $\Delta t$  is the temperature difference between the calculated return temperature of the  
474 suggested solution and the conventional return temperature to DH, here the  
475 conventional return temperature is 40 [°C].

476 2.3.3 Evaluation model for exergy performance

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

487 
$$\eta_{ex} = Ex_{out}/Ex_{in} \quad (\text{Eq.8})$$

488 
$$Ex_{out} = Q_{dhw} \left( 1 - \frac{T_0}{T_{dhw} - T_{dcw}} \ln \frac{T_{dhw}}{T_{dcw}} \right) \quad (\text{Eq.9})$$

489 
$$Ex_{in} = Q_{dh} \left( 1 - \frac{T_0}{T_{sup} - T_{ret}} \ln \frac{T_{sup}}{T_{ret}} \right) + W_{el} \quad (\text{Eq.10})$$

490 where

491  $\eta_{ex}$  is the exergy efficiency of the DHW supply system [%],

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

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

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

495  $T_{dhw}, T_{dcw}$  are the temperatures of DHW and DCW, which were assumed to be 45 and  
 496 10 respectively [ $^{\circ}\text{C}$ ],  
 497  $T_{sup}, T_{dcw}$  are the supply and return temperatures of the district heating water [ $^{\circ}\text{C}$ ],  
 498  $Q_{dh}$  is the supply heat from district heating [kWh],  
 499  $W_{el}$  is the electricity consumption for DHW supply, which can be completely converted  
 500 into useful work [kWh].

### 501 3. Results

#### 502 3.1 Results of the energy performance evaluation

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

505 **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

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

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

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

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

520 **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

521

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

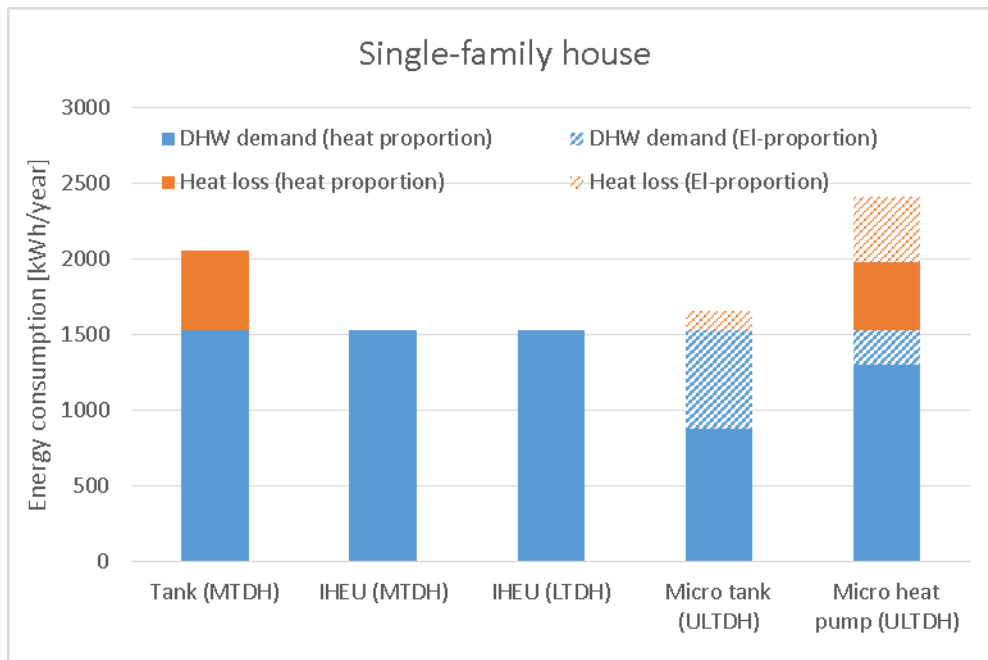
	Multi-storey building					
	MTDH		LTDH		ULTDH	
	With tank and circulation	IHEU with bypass	Central HEX with heat pump	IHEU with bathroom heating	El-tracing	Micro tank
Average return temperature [°C]	28	24	20	23	19	16

523

524 For the IHEU system supplied with LTDH, if the bypass is retained, the calculated return  
 525 temperatures to DH were 31 °C for single-family houses and 26 °C for multi-storey



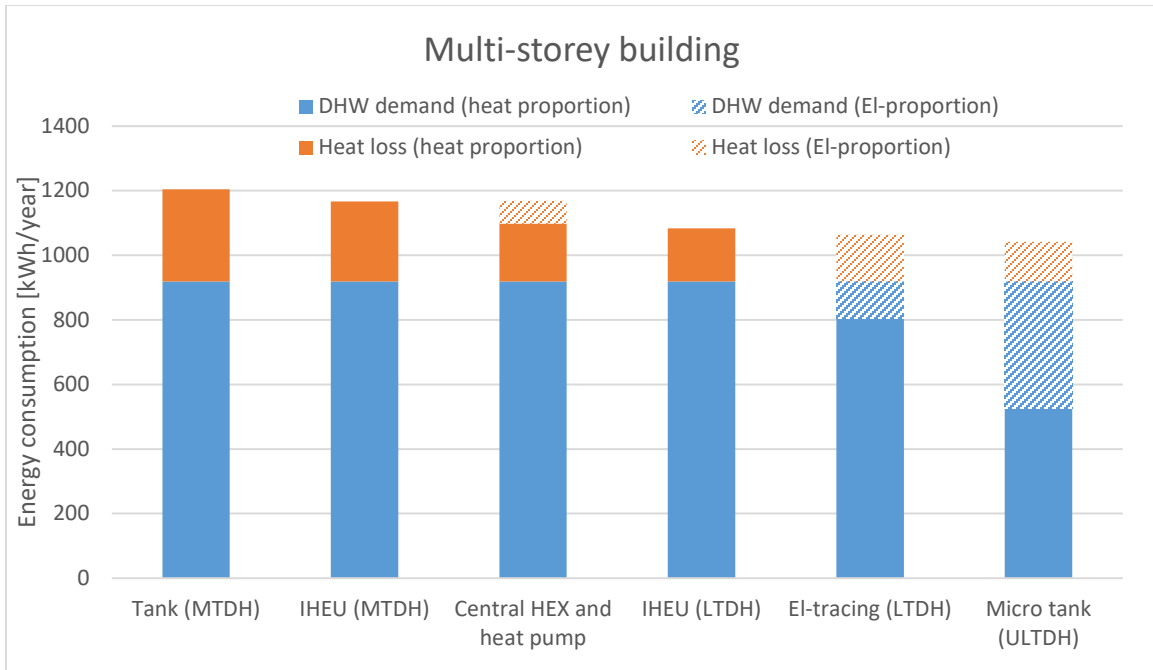
526 buildings based on the information in Table 4. However, as the bathroom heating is  
 527 applied, the average return temperature can be reduced to 22 °C and 23 °C instead. The  
 528 electric heat tracing and micro tank systems provided lower return temperatures to  
 529 district heating since no bypass or hot water circulation was operated for those systems.  
 530 The energy performances of the investigated systems are shown in the Fig. 8.



531

532

(a)



533

534

(b)

535

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

536

From the results, the systems with MTDH supply are all able to provide DHW demand

537

using just DH heat. The IHEU system requires less DH heat than the system with central

538

storage tank. In the LTDH scenario, IHEU system and electric heat tracing system

539

required less overall energy for DHW preparation. However, the electric heating tracing

540

system requires more electricity for supplementary heating and covering the heat loss.

541

Considering the different primary energy factors of heat and electricity, the IHEU

542

method might be the best solution for the LTDH scenario, since it generated less heat

543

loss than other methods and consumed no electricity. For the ULTDH scenario, the

544

micro tank system had much less heat loss compared with the micro heat pump system.

545 3.2 Results of the economic performance evaluation

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

548 **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

549

550 **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

551

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

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

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

### 568 3.3 Results of the exergy performance evaluation

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

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

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

571

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

	<b>Multi-storey building</b>					
	MTDH With tank and circulation		LTDH Main HEX with heat pump		ULTDH 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%

573

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

#### 577 4. Discussion

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

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

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

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

## 618 5. Conclusion

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

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

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