

1 **Method to investigate and plan the application of low temperature district heating to existing hydraulic**
2 **radiator systems in existing buildings**

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6

7 **Abstract**

8 This study presents a method to adapt existing hydronic systems in buildings to take advantage of low temperature
9 district heating (LTDH). In this analysis, plate radiators connected to single and double string heating circuits were
10 considered in an optimization procedure, based on supply and return temperatures, to obtain the required
11 logarithmic mean temperature difference (LMTD) for a low temperature heating system. The results of the analysis
12 are presented as the average reduction of LMTD over the heating season compared to the base case design
13 conditions. For the double string system two scenarios were investigated based on the assumption of a likely cost
14 reduction of in the end users' energy bills of 1% for each 1 °C reduction of return and average supply and return
15 temperatures. The results showed possible discounts of 14% and 16% respectively, due to more efficient operation
16 of the radiators. For the single loop system, the investigated scenario assumed a cost reduction in the end users'
17 energy bill of 1% per each 1 °C lower reduction of average supply and return temperature. Although very low
18 return temperatures could not be achieved, the implementation of the method illustrates how to efficiently operate
19 these systems and for the given scenario a possible discount of 5% was quantified.

20 **Keywords:** Low temperature district heating, hydraulic radiators, modelling, temperature optimization

21 **Highlights**

- 22
- Application of low operating temperatures to existing hydraulic radiators
 - Method to investigate and plan the connection of existing buildings to low temperature district heating
 - Investigation to calculate performance of hydraulic radiator element
 - Method to optimize supply and return temperatures in low temperature district heating system
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27 **List of symbols and acronyms**

28 Table 1: List of symbols and acronyms

| List of symbols and acronyms | |
|-------------------------------------|--|
| DH | District heating |
| LTDH | Low-temperature district heating |
| LMTD | Logarithmic mean temperature difference (°C) |
| LMTD ₀ | Logarithmic mean temperature difference at design condition (°C) |
| ΔT | Delta T between supply and return temperature |
| TRV | Thermostatic radiator valve |
| SH | Space heating |
| DHW | Domestic hot water |
| Φ | Heating power at operating temperatures (W) |
| Φ_0 | Nominal heating power at design conditions (W) |
| n | Radiator exponent |
| \dot{m} | Mass flow rate (kg/h) |
| \dot{m}_0 | Max mass flow rate (kg/h) |
| c_p | Specific heat capacity of water (J/kg °C) |
| T_S | Supply temperature (°C) |
| T_{S_0} | Supply temperature at design conditions (°C) |
| T_R | Return temperature (°C) |
| T_{R_0} | Return temperature at design conditions (°C) |

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34 **1 Introduction**

35 In the EU households, heating for space heating (SH) and domestic hot water (DHW) consumes 79% of the total
36 final energy use (192.5 Mtoe), representing one of the largest carbon emitting sectors of the economy [1][2]. As a
37 consequence, decarbonizing the heat sector is being considered central to the EU energy policy to foster a carbon
38 neutral society and achieve the reduction in the greenhouse emission of 40% and 80% by 2030 and 2050
39 respectively to the level of 1990 [3]–[5]. Currently, heat supply in buildings in the EU is mainly provided by
40 individual heat sources installed in buildings or alternatively through district heating (DH) networks. The latter
41 are widely used in Scandinavian, Eastern European countries and Russia. District heating offers high flexibility
42 for the integration of renewable heat sources, though still faces the technical challenge of matching different heat
43 sources' supply temperature and demand. Driven by the need to use low carbon heat sources, the current focus is
44 to develop low temperature district heating systems, referred to as 4th generation district heating (4GDH) [6]. One
45 key design parameter in the development of 4GDH is the reduction of supply and return temperatures from the
46 current standard of 80/40 °C to load dependent temperatures with a target of 50/20 °C. As DH in general covers
47 the demand for SH and DHW, the limit for the supply temperature of 50 °C is imposed to avoid health problems
48 due to Legionnaires' disease in sanitary water [6], [7]. Recent studies show that buildings can be maintained at
49 comfortable temperature levels with low supply temperatures for the majority of the heating season and using a
50 4GDH system with flexibility to adjusting the temperatures according to heat demand during extreme low outdoor
51 temperatures. This would improve the overall efficiency of heat generation and reduce heat losses in the network
52 [8]–[10]. Therefore, one of the issues in the implementation of low temperature district heating (LTDH) is the
53 calculation of the optimal combination of supply and return temperature to operate the heating systems according
54 to heat demand. In fact, reducing supply temperature to 50 °C poses few technical problems in regard to the
55 capability of existing heating systems to guarantee the same thermal comfort. Commensurate with low-energy
56 buildings, which use efficient heat emitters such as low-temperature radiators or underfloor heating, water supply
57 temperatures of 50 °C or even lower would technically be adequate to meet SH demand all year round [11]–[13].
58 Hence, the challenge is to adapt the existing large building stock and the already installed hydronic heating systems

59 for the applicability of LTDH, without any major design and construction intervention, yet adjusting water
60 temperatures to heat demand.

61 *1.1 Aim*

62 The aim of the work presented in this paper was to develop a method to investigate and plan the introduction of
63 LTDH to existing hydraulic radiator systems in existing buildings. The scope of this work was to express the heat
64 demand as a function of logarithmic mean temperature difference (LMTD) between the water of the hydraulic
65 radiator and the heated building zone. The results of the investigation are expressed as an average reduction in
66 LMTD over the heating season compared to the design conditions. The needed LMTD can be reached by numerous
67 combinations of supply and return temperatures to the radiator; these have different economic benefits and
68 therefore an optimization process to define the best combination of supply and return temperatures is needed.
69 Hence, two different hydraulic radiator configurations were used to test the developed method and outline the
70 strategy to connect existing buildings to LTDH.

71 *1.2 Modelling performance of different types of heating elements for low temperature operation*

72 Lower return temperatures are beneficial for DH technology, by reducing the network distribution losses and mass
73 flow rates, as well as improving the efficiency of energy generation [14]–[17]; this is even more important for the
74 LTDH concept, where return temperatures have to be cooled to almost indoor temperature. In mature DH markets
75 such as in Denmark, Sweden and Finland, LTDH has been successfully applied and tested in real projects. Good
76 results proved the concept in case of low-energy buildings [8], [18], [19] and further investigations have been
77 carried out for existing buildings at different levels of refurbishment [20], [21]. However, none of these articles
78 includes an optimization process, based on the economic value of lower supply and return temperatures for DH
79 companies and end users, to define the optimal operating temperatures in the implementation of LTDH to existing
80 buildings with radiator based heating systems. Hence, to correctly address the challenge of operating existing
81 hydraulic radiators with low water supply temperatures, necessary considerations must be given both to the design
82 of the heat emitting radiators (hardware) and the modelling analysis to optimize the performance.

83 *1.2.1 Hardware part – type of heating systems*

84 Hardware considerations include the different types of heating elements, the way they are operated and controlled
85 in order to efficiently perform. Commonly, flat panel radiators are manufactured by combining up to three flat
86 plates and incorporating fins to augment the heat transfer area [22], [23]; they can have a high or low profile. By
87 far the most used hydraulic configuration for radiators is the double string system, consisting of two pipes, one for
88 supply and one for return. Typically, hot water is supplied to the top of a radiator to let the water flow diagonally
89 downwards and cool gradually before leaving from the opposite bottom corner [24]. Although low level panel
90 radiators are used in some cases, especially if there are space restrictions, they can lead to slightly higher return
91 temperatures compared to taller ones, due to the reduced height; hence particular attention is necessary during the
92 selection of the element if low return temperatures have to be attained. Another possible hydraulic configuration
93 for radiators is the one string system, characterized by only one pipe for both supply and return; the radiators are
94 connected in a way that a fraction of the water flow in the main string runs through the radiator and exits back to
95 the main string. The temperature though is gradually reduced as this enters to each successive radiator. This
96 solution fosters the system to work with higher mass flow rates and lower temperature difference (ΔT). If carefully
97 designed by increasing the size of each successive radiator [25], as reported in the study commissioned by the
98 Swedish DH association [26], return temperatures can be as low as in double string systems in typical DH
99 networks. Nonetheless, as difficult to properly control, it is common to experience higher return temperatures and
100 smaller ΔT in the substation, hence this reduced their attractiveness in comparison to double string systems, in
101 particular when connected to district heating [27]. Similar to the radiators with single string hydraulic
102 configuration, heat convectors lead to higher return temperatures due to high flow rate and low ΔT . They are
103 characterized by heat transfer to the surrounding mainly by convection and the most common layout consists of a
104 finned long tube, which generally follows the perimeter of exposed walls and/or windows [22]–[24], [28], [29].
105 These heating elements – likewise water radiators with single string layout – still can be found in existing
106 buildings, but they are not recommended for DH in general and in particular not for LTDH applications, where

107 return temperatures close to room temperatures have to be achieved. Central to hardware discussion is also the
108 way radiator elements are controlled, typically by thermostatic radiator valves (TRVs). TRVs are passive water
109 flow regulating devices that maintain set-point room temperature; this guarantees the required indoor comfort in
110 an efficient way as well as the expected cooling of return temperatures. It also allows the heat output to modulate
111 and compensate for emitters that can be over-dimensioned during some periods of the heating season [30]–[32].
112 However, it is quite common in real applications for TRVs to operate poorly and negatively affect the overall
113 system efficiency. The work of Ziao et al. [33] found that in hydronic radiator systems, although TRVs were
114 installed in almost all the systems surveyed, in 65% of the cases they were performing poorly, mostly due to
115 occupants misuse, and generating thermal discomfort and wasted energy. Therefore it is important to limit the side
116 effect of human behavior on the effectiveness of TRVs [34], as these have a decisive role in overall system
117 efficiency and in the cooling of return temperatures. This was further highlighted by the investigations of Monetti
118 et al. [35], Xu et al. [36] and McNamara [37] who showed that properly installed and controlled TRVs can lead
119 to savings of 10%, 12.4% and 15% respectively, with relatively low-cost retrofitting investment and short payback
120 periods.

121 *1.2.2 Modelling part – calculation of heating demand of rooms and heating power of radiators*

122 The thermal performance of existing hydraulic radiator systems operating at lower temperature should comply
123 with current EU design practices and standards and computer modelling allows accurate prediction of water
124 temperature profiles in the radiator and heating capacity [38], [39]. It is important that the emitters are correctly
125 sized and operated to deliver the heat needed; thus the challenge is to outline the optimal temperature of supply
126 and return to meet the heat demand. Hydronic systems are typically sized based on the worst case scenario of
127 steady-state heat output that meets winter design conditions and do not consider sources of heat gains. This leads
128 to over-sizing systems and guarantees a larger surface area, in the case of radiators, and a positive effect when
129 lowering temperatures [14], [15], [21], [40]. Lauenburg [41] showed that heating systems sized for design
130 temperatures only required full load during a short period when outdoor temperatures are very low, demonstrating
131 that for most of the heating season consistently lower water supply temperatures can be appropriate to meet the

132 heat demand. The reliability of software outputs is crucial because it provides a powerful tool for professionals at
133 the time of investigating and foreseeing the use of low temperatures to existing hydraulic radiators. It is important
134 to choose an adequate radiator element and correctly define the physical characteristics of the heating element,
135 including control by TRV. For instance, the open-source EnergyPlus, one of the most used and powerful software
136 for energy simulations, only gives the user the option of a ‘hot water baseboard heater with radiation and
137 convection’ [42], [43]. This element has both radiative and convective components as with a radiator, but in reality
138 is a convector. Therefore, the user can still perform accurate dynamic energy simulations for the building in
139 analysis, but the accuracy could be affected if the focus of the investigation is specifically related to the cooling
140 of the return temperatures in existing hydraulic radiator elements at time of lowering the operating temperatures
141 of the system. From this perspective, the paper adds new knowledge by developing an alternative method to
142 investigate and plan the application of LTDH to existing buildings, outlining an optimization strategy to define
143 the best combination of supply and return temperatures to operate existing hydraulic radiators.

144 **2 Methodology**

145 *2.1 Hardware part – type of heating system*

146 The investigation related to the application of LTDH to existing buildings with a characterization of heating
147 systems with respect to the type of heating loop and heating elements. The characterization mainly addressed the
148 possibilities of operating the systems with low return temperatures. An example of a system with low return
149 temperature is a double string system with panel radiator, whereas the examples of systems with high return
150 temperature are:

- 151 1. single string with all type of heating elements
- 152 2. double string or single string with convectors

153 *2.2 Modelling part – calculation of heating demand of rooms and heating power of radiators*

154 The method used in the investigation is based on modelling in a number of steps and illustrated with a specific
155 case as follows.

156 2.2.1 *Step a: calculation of part load duration curve*

157 This is to define the part load duration curves for each room of the building considered. The starting point was the
158 characterization of the design conditions of the heating system: this was made for the case study by performing
159 steady-state simulations to outline the design heat load for each room according to Danish standards [44], assuming
160 no heat gains and the design winter temperature of -12 °C. Once the design conditions were defined, detailed
161 dynamic simulations were performed to outline the realistic heat load distribution for an entire year using a weather
162 file for Copenhagen based on a 20 year historical database; this allowed the specific part load duration curves to
163 be obtained for each room on an hourly basis.

164 2.2.2 *Step b: calculation of the relationship between part load and logarithmic mean temperature difference of*
165 *the hydraulic radiator elements*

166 This is to calculate for each room how the hydraulic radiators have to be operated to meet the heat demand outlined
167 in *step a*. This was established for this study by associating to each part loads the specific LMTD for the specific
168 radiator size of the room.

169 2.2.2.1 *Hydraulic radiator formulation*

170 The empirical formula used to evaluate radiator performance and the capacity of cooling the return water
171 temperatures is based on analysis of the heat emitted as a function of the LMTD between water and room
172 temperature. The general formula is described by Equation 1 [38], [39]:

$$\varphi = \left(\frac{LMTD}{LMTD_0} \right)^n \varphi_0 \quad (1)$$

173 where φ and φ_0 present the heating power at operating temperatures and design conditions (W), $LMTD$ and $LMTD_0$
174 denote the logarithmic mean temperature difference between radiator and surroundings at the operating
175 temperatures and design conditions (°C), whereas n is the radiator exponent and describes the exponential
176 relationship between the mean temperature difference and the heat emitted from the radiator – 1.3 is the typical
177 value for hydraulic radiators [12].

178 The logarithmic mean temperature distribution, included in the Danish standard [45], is expressed by Equation 2.

$$LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \quad (2)$$

179 where T_S is the supply temperature (°C), T_R the return temperature (°C) and T_i is the indoor operative temperature
180 (°C).

181 2.2.3 *Step c: calculation of the duration curve of logarithmic mean temperature difference*

182 Given the hourly heat load duration curve in *step a* and the relation of part load and LMTD obtained in *step b*, in
183 *step c* the duration curve of LMTD has to be calculated. The application of the method allows calculation of the
184 LMTD duration curves for each room and all buildings in the analysis of an area in the process of being connected
185 to LTDH. Within all the curves, the worst cases represented by the highest LMTD duration curves have to be
186 carefully assessed and possibly excluded from the analysis. These cases may represent typical errors in radiator
187 design, undersized systems or unheated rooms; therefore they need to be investigated separately and improved by
188 reducing heating demand or increasing heating capacity of radiators in order to operate more efficiently and
189 guarantee the expected cooling of return temperatures. However, this part is not included in the results as the case
190 in this study is with one room and one building. The full application of the method will be part of a future project.

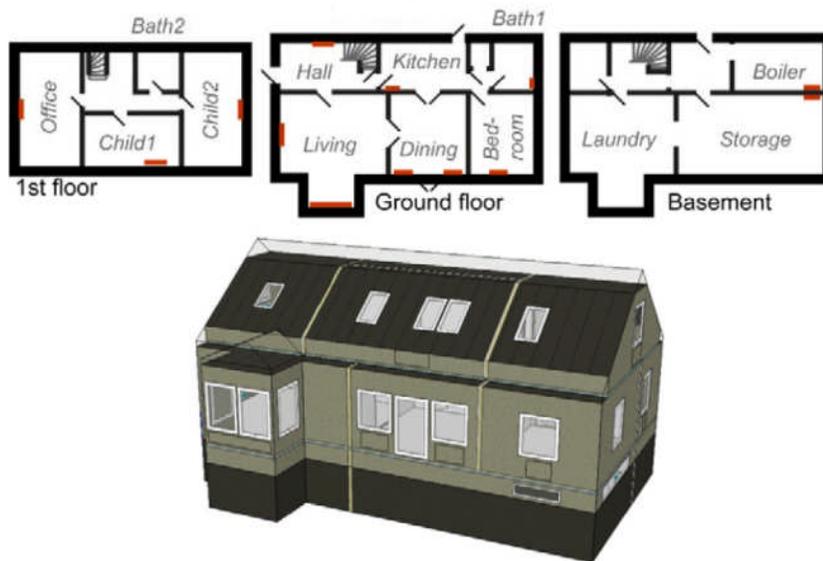
191 2.2.4 *Step d: calculation of the optimal supply and return temperature to provide the necessary logarithmic* 192 *mean temperature difference*

193 *Step d* is the calculation of the optimal combination of supply and return temperatures to provide the necessary
194 LMTD obtained from *step c*. The optimal combinations of supply and return temperatures have to be presented
195 for all relevant LMTD. The goal of the optimization is to minimize the operating supply and return temperatures
196 in order to assess the capability of existing hydraulic radiators to be operated with low temperatures without any
197 intervention to the building or to the heating system, in the prevision of being connected to LTDH. This was
198 addressed by formulating the optimization problem based on the *objective function* and *constraints*. These vary
199 according to the different scenarios investigated and each of them is illustrated in details in section 4.

200 **3 Description of the case study building**

201 *3.1 Danish single family house*

202 The method was tested by the use of a specific case based on a typical Danish single-family house from the 1930s,
203 sited in Copenhagen. A model was created in the dynamic simulation software IDA-ICE [46] as presented in Fig.1.
204 The software has been validated in accordance with standard DS/EN 15265, which describes dynamic simulation
205 of energy performance of buildings [47], [48].



206
207 Fig. 1: Floor plans, radiators (in red) and IDA-ICE model [46]

208 The building is made of red brick cavity walls, red tile roof and a basement. Typical of Danish buildings from
209 1930s, old windows and radiators have been replaced, as well as improvement to roof insulation. Table 1 shows
210 the main properties of the house.

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Table 2: Key data and construction elements

| General parameters | |
|---|-----------------------------------|
| Number of occupants | 2 |
| Total floor area /basement area (m ²) | 320/118 |
| Heated part of basement [m ²] | 47 |
| Annual heating consumption [MWh] | 20 |
| Design winter temperature (°C) | -12 |
| Building construction elements | |
| | U-value (W/m²K) |
| External wall – insulated cavity brick wall | 0.78 |
| Roof -Tiles, wood beams and insulation | 0.15 |
| Windows – 2 pane energy efficient glazing | 1.55 |

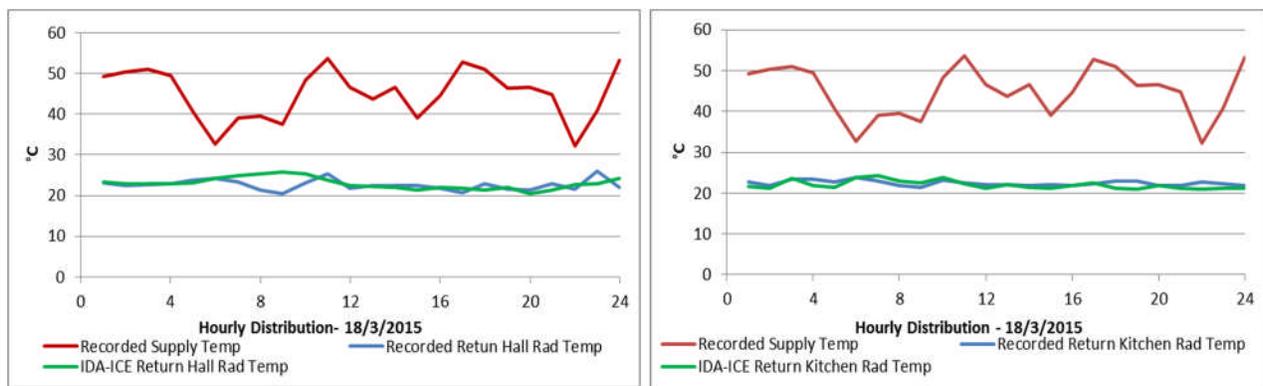
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219 The presence of occupants and their use of equipment was modelled on weekly schedules. Compared to average
 220 Danish values for heat gains in domestic building environments [49], conservative values of 0.81 and 1.55 W/m²
 221 were assumed respectively for heat gains from occupants and equipment [50]. The natural ventilation was assumed
 222 to be fixed at 0.3 l/s per m² of floor area, which corresponds to the standard ventilation required in the Danish
 223 Building Code [46], and includes infiltration from opening of windows and doors in the winter time.

224 3.2 Example of hydraulic radiator return temperatures based on the radiator formula

225 A comparison was made between real measurements and the simulations' outputs to identify the capacity of IDA-
 226 ICE to correctly model the cooling of return temperatures. The analysis was performed considering the radiators
 227 installed in the single family house presented in section 3.1. The radiator formula is used as model for the heating
 228 element performance in the simulation program IDA-ICE. The house was examined and the size and type of
 229 radiators in all rooms was measured and checked; the number and the location of each radiator are shown in the
 230 plans of Fig. 1. In addition, indoor temperatures, heating system temperatures and heating consumption over the
 231 course of one month, between 10th March and 13th April 2015, were monitored and collected on an hourly basis.

232 During the monitored period, the energy demand for SH and DHW was provided by a condensing natural gas
 233 boiler, placed together with a hot water tank of 110 litres in the basement. The building was switched to district
 234 heating during the following June, after the measurements in the house had been taken. The heating system consists
 235 of double string hydraulic radiators and electric floor heating is installed in both bathrooms. The existing radiators
 236 in the house were simulated using their correct dimensions, nominal design conditions, exact location, and a TRV
 237 was set for each of them. In order to accurately model the operating conditions of the hydronic system and achieve
 238 reliable results, the simulations were run using the real hourly weather data for the period in analysis; the
 239 recordings were obtained from measurements taken by the Danish Meteorological Institute, whereas the diffuse
 240 and direct solar radiation were collected at the nearby weather station of the Technical University of Denmark
 241 [52]. Also, the performance of the heating elements available in the software were evaluated by running the
 242 simulations using the supply temperature curve obtained from the measurements, and the simulated results for the
 243 return temperatures out of the radiators in selected rooms were compared to the measured ones on an hourly basis.
 244 The average supply temperatures in the period recorded for the SH demand was 45 °C and it was enough to
 245 guarantee the expected indoor comfort; the mean outdoor temperature was 5.3 °C and the lowest value registered
 246 was -2.5 °C.



247
 248 Fig.2: Kitchen and Hall radiators' temperature comparison

249 The comparison between the IDA-ICE outputs and the real return temperatures collected from the radiators over
 250 24 hours, using dedicated temperature sensors, is presented in Fig. 2 for two selected rooms. The importance of
 251 comparing the results over an interval of 24h was driven by the necessity of testing the accuracy of the software

252 to reflect the influence that all the dynamic variables involved have on the performances of the radiators throughout
253 a typical day. The results obtained show a good match between the simulations and the real measurements of the
254 return temperatures for the period considered. The average return temperatures calculated by the software were
255 22.0 °C and 22.9 °C for the kitchen and hall respectively, whereas the average data collected were 22.4 °C and
256 22.5 °C. Therefore, the hydraulic radiator unit available in IDA-ICE provides robust results and can efficiently
257 model the cooling of the return temperatures. It is also important to notice how the real data collected shows how
258 existing hydraulic radiators can be operated with low temperatures and connected to LTDH, guaranteeing the
259 expected indoor comfort.

260 **4 Results and discussion**

261 *4.1 Hardware part – type of heating system*

262 Two scenarios were investigated to test the application of the method developed:

- 263 1. A heating system with low return temperatures – double string with plate radiators
- 264 2. A heating system with high return temperatures – single string with plate radiators

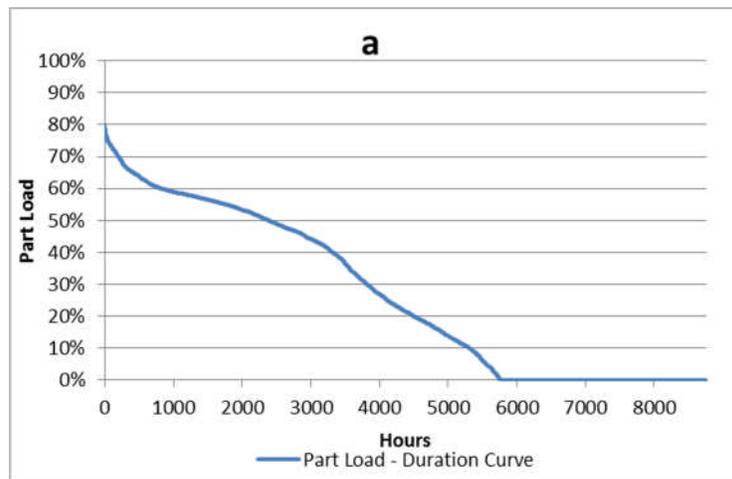
265 It was assumed for all the scenarios a direct connection without any heat exchanger. However, the performed
266 analysis can also include the presence of heat exchangers by accounting for their efficiency.

267 *4.2 Modelling part – calculation of heating demand of rooms and heating power of radiators in double string* 268 *system*

269 The developed method was intended to be applied to an area in the process of being connected to DH and it was
270 supposed that the building chosen, in the scenario with double string with plate radiators, was representative of
271 the urban area in analysis. The application of the method was tried on one selected room, the hall of Fig. 1, and
272 the results for the four steps described in the methodology are presented as follows.

273 4.2.1 Step a: calculation of part load duration curve

274 According to the steady-state simulations based on the Danish standard [44], the design heat load calculated for
275 the specific room was 884 W. Also, the dynamic simulation outputs are presented in Fig. 3 and depict the part load
276 duration curve for the room in analysis on an hourly basis for the entire year.



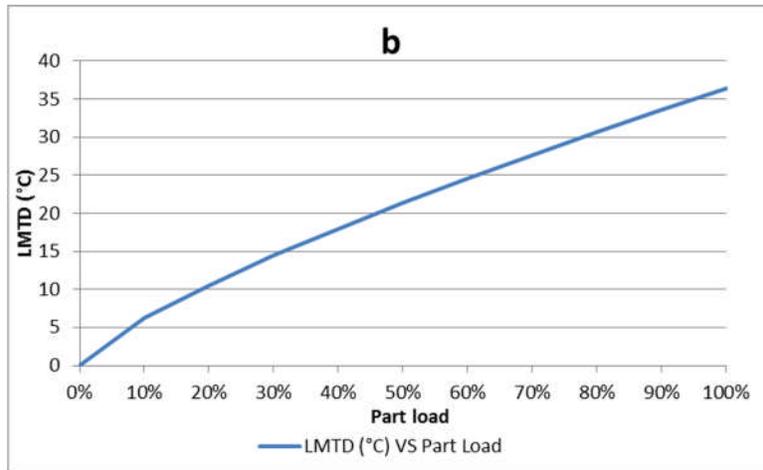
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Fig. 3: Part load duration curve

279 4.2.2 Step b: calculation of the relationship between part load and logarithmic mean temperature difference of
280 the hydraulic radiator elements

281 The results for *step b* presented in Fig. 4 illustrate the relationship between each part load and the specific LMTD,
282 expressing how the radiators need to be operated. It was assumed that the radiators in the double string
283 configuration at design conditions were operated with supply and return temperatures of 80/40 °C. In addition, to
284 correctly perform the calculations of LMTD per each part load using Equation 1, n was assumed to be 1.3, φ_0 was
285 the design heat load of 884 W, whereas $LMTD_0$ was obtained from Equation 2 using the design temperatures of
286 80/40 °C and set indoor temperatures of 20 °C.



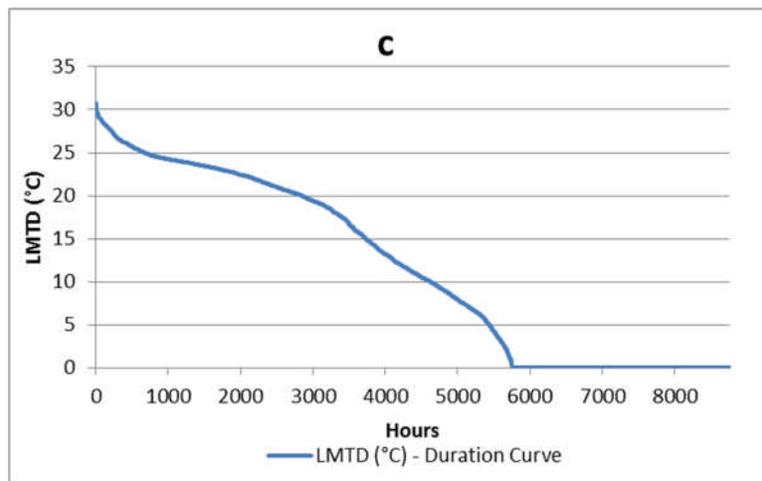
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288

Fig. 4: LMTD VS Part load

289 4.2.3 Step c: calculation of the duration curve of logarithmic mean temperature difference

290 The part load duration curve presented in Fig. 3a and the general relation between the part load and LMTD in Fig.
 291 3b allowed calculation of the duration curve of LMTD on an hourly basis as described in Fig. 3c. The graphical
 292 combination of the curves of Fig. 3, 4 and 5 provides a tool to clearly identify the number of hours per each range
 293 of part load or per each degree °C difference of LMTD, hence the exact amount of energy necessary to guarantee
 294 the expected indoor comfort through the radiators. These curves and in particular the curve of fig. 3c can be used
 295 to compare different buildings and different rooms, helping to define the conditions and the boundaries to be
 296 investigated for implementing LTDH in an urban area.



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Fig. 5: LMTD duration curve

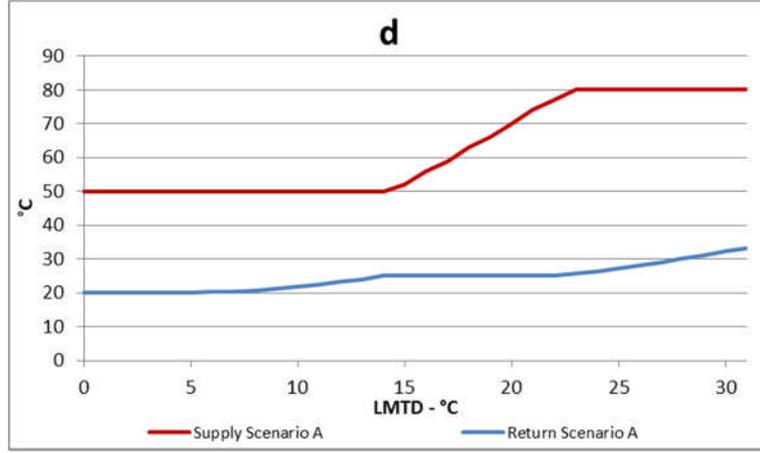
299 4.2.4 *Step d: calculation of the optimal supply and return temperature to provide the necessary logarithmic*
300 *mean temperature difference*

301 Two different scenarios, A and B, were investigated and consequently the formulation of the optimization problem
302 followed two different strategies. Both scenarios assess the impact that different DH markets have on the definition
303 of the optimal combination of supply and return temperatures to operate the same hydraulic radiators. The results
304 are presented in Fig. 6 and 8 and illustrate on one hand the technical and economic factors affecting the selection
305 of the optimal temperatures; on the other hand, to which extent temperatures can be lowered without any
306 intervention to the thermal envelop of the building or to the heating system.

307 4.2.4.1 *Scenario A: typical Danish DH network*

308 In Danish DH market more than 70% of heat is produced taking advantage of CHP technology and the price of
309 heat unit only includes all the necessary costs related to supply heating, as DH companies are not allowed to make
310 any profits [53]. Also, as achieving lower supply and return temperatures reduces the costs associated to heat
311 generation and distribution losses, typically DH companies incentivize their customers through *motivation tariffs*
312 to reduce temperatures in exchange of a discount in their energy bills. These are normally customized according
313 to the specific characteristics of DH systems and relative end-users connected. From this perspective, Scenario A
314 was designed assuming the figures of a real motivation tariff related to an existing Danish DH company [54],
315 where the heat generation is based on a biomass boiler with flue gas condenser. For the considered DH network,
316 the company is able to guarantee to end users a discount of 1% in their energy bill (up to a maximum of 20%) for
317 each °C lower in their return temperatures compared to the reference DH yearly average return temperature. The
318 assumed reference average yearly supply and return temperatures were 80/40 °C as typical for Danish DH
319 networks. The discount offered is compensated by the savings made by the DH company due to the lower supply
320 and return temperatures. In fact, at actual market conditions, according to their cost analysis [54], lower return
321 temperatures have higher economic value due to the savings in buying energy at the generation point, compared
322 to the reduction in the distribution heat losses due to lower supply and return temperatures. Hence, the strategy of

323 the optimization was based on the minimization of the supply and return temperatures of Equation 2 set equal to
 324 the specific LMTD for each value of the duration curve presented in Fig. 6.



325
 326 Fig. 6: Scenario A supply and return temperatures: optimization results

327 The strategy followed three different paths clearly delimited by the breaking points related to LMTD of 14 °C and
 328 23 °C corresponding to the change in the gradient of the optimized supply and return curves calculated – i.e. Fig.
 329 3d. The objective functions and relative constraints are presented for all specific LMTD as follows:

330 i. For $LMTD < 14$ °C:

$$\text{minimize } (T_R), \text{ for } LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \quad (3)$$

331 Subject to:

$$T_S = 50 \text{ °C} \quad (4)$$

$$\dot{m} \leq \dot{m}_0 \quad (5)$$

332 ii. For $14 \text{ °C} \leq LMTD \leq 23 \text{ °C}$:

$$\text{minimize } (T_S), \text{ for } LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \quad (6)$$

333 Subject to:

$$T_R = 25 \text{ °C} \quad (7)$$

$$\dot{m} \leq \dot{m}_0 \quad (8)$$

334 iii. For $LMTD > 23 \text{ }^\circ\text{C}$

$$\text{minimize } (T_R), \text{ for } LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_L}{T_R - T_i}\right)} \quad (9)$$

335 Subject to:

$$T_S = 80 \text{ }^\circ\text{C} \quad (10)$$

$$\dot{m} \leq \dot{m}_0 \quad (11)$$

336 where T_S is the supply temperature ($^\circ\text{C}$), T_R is the return temperature ($^\circ\text{C}$), T_i is the indoor operative temperature
337 ($^\circ\text{C}$), fixed at $20 \text{ }^\circ\text{C}$, \dot{m} is the mass flow rate associated to the generic combination of T_S and T_R (kg/h) and \dot{m}_0 is
338 the max mass flow rate at design conditions (kg/h).

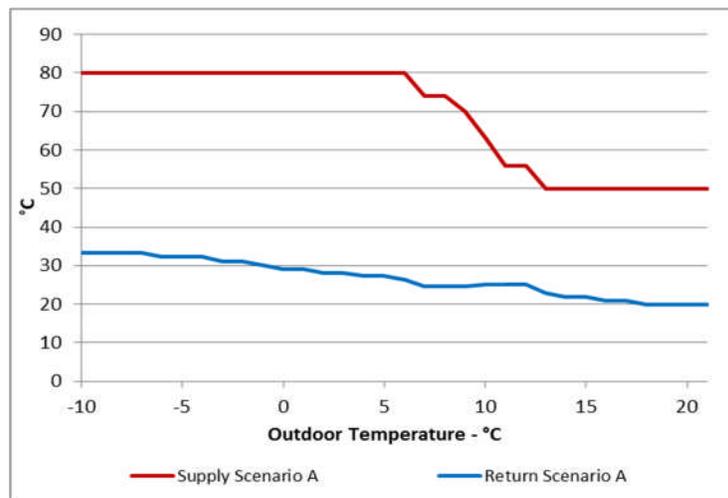
339 The max mass flow rate of 19 kg/h was obtained from Equation 12:

$$\varphi_0 = 3600 \cdot \dot{m}_0 \cdot c_p \cdot (T_{S_0} - T_{R_0}) \quad (12)$$

340 where φ_0 presents the nominal heating power at design conditions (W), \dot{m}_0 is the max mass flow rate (kg/h), T_{S_0}
341 is the supply temperature at design conditions ($^\circ\text{C}$), T_{R_0} is the return temperature at design conditions ($^\circ\text{C}$) and c_p
342 is the specific heat capacity of water (J/kg $^\circ\text{C}$).

343 In the resolution of the optimization problem all the combinations of temperatures fulfilled the constraints' criteria.
344 The lower supply temperature limit of $50 \text{ }^\circ\text{C}$ is imposed by national standards to avoid the risk of Legionnaires'
345 disease in DHW [6], [7] and it was assumed that supply and return temperatures of $50/20 \text{ }^\circ\text{C}$ out of the heating
346 season were enough to meet the DHW demand. The upper limit of $80 \text{ }^\circ\text{C}$ instead was assumed as the maximum
347 inlet temperature according to the specific DH network. In addition, according to normal operation practices of
348 radiators, a target return temperature of $25 \text{ }^\circ\text{C}$ was set as a realistic value given the indoor room temperature of 20
349 $^\circ\text{C}$. This was in fact one of the constraints in the minimization of the supply temperatures for all LMTD included
350 in the range between $14 \text{ }^\circ\text{C}$ and $23 \text{ }^\circ\text{C}$. These two points, corresponding to the change in the gradient of the
351 optimized curves proposed, illustrate that for LMTD lower than $14 \text{ }^\circ\text{C}$, due to the combination of low heat demand
352 and low mass flow rates, the return temperatures were always below the target temperature of $25 \text{ }^\circ\text{C}$ and supply
353 temperatures could be set as low as $50 \text{ }^\circ\text{C}$; contrarily, for a LMTD higher than $23 \text{ }^\circ\text{C}$ the combination of high heat

354 loads and high mass flow rates led to return temperatures always higher than 25 °C and supply temperatures were
355 fixed to 80 °C to guarantee the expected indoor comfort and avoid unnecessary high return temperatures.
356 Comparing to other studies where LTDH concept was applied to low-energy buildings [8], [18], [19] and to
357 existing buildings at different levels of refurbishment [20], [21], the outcomes presented in Fig. 6 show for this
358 scenario that existing heating system based on double string radiators, if properly controlled, can be operated more
359 efficiently and achieve low return temperatures for each LMTD without any intervention to the building, but
360 simply adjusting temperatures to heat demand. Thus, the calculated combination of supply and return temperatures
361 can be used by the district heating company to efficiently operate the network, controlling the supply temperatures
362 according to the optimal level. To this extent, Fig. 7 presents the relationship between the optimized supply/return
363 and outdoor temperatures. This outlines the strategy to be followed by the DH company to meet the heat demand
364 for the hypothesized urban area, assuming that the building and the room chosen were representative.



365
366 Fig. 7: Scenario A: relation between optimized supply/return and outside temperatures

367 The curves were calculated by finding the hourly peak load from the heat load profile of Fig. 3 for each °C of the
368 outdoor temperatures and associating for specific LMTD the optimal temperature combination from the results
369 presented in Fig. 6. The use of hourly peak loads for each °C of outdoor temperature is a conservative choice that
370 guarantees the temperatures would deliver the heat demand in all conditions. Different approaches considering
371 more realistic peak values, based on daily, 12 or 6 hour averages, are possible, but the evaluation has to be linked

372 to the characteristic of the network in analysis and its capacity to adjust temperatures and pressures to the customers
 373 connected and to the use of weather forecasts. Therefore, operating the DH network and the radiators as proposed
 374 would lead to implementing lower temperatures in the area and result in a possible discount of 14% in end users'
 375 energy bill according to the assumed *motivation tariff*, due to the lower return temperatures achievable compare
 376 to the reference yearly average of 40 °C assumed as also presented in Table 2.

377 4.2.4.2 Scenario B: future DH market

378 In the second scenario, the importance of integration of renewable and low carbon heat sources for future DH
 379 markets was evaluated. Lowering supply temperatures compared to the present market would increase the
 380 economic benefit for DH companies. Furthermore, lower supply temperatures allow heat sources such as heat
 381 pumps to operate more efficiently by increasing the COP, to recover waste heat, to connect solar plants with
 382 seasonal storage and to reduce the impact of distribution losses [5]. These future conditions were integrated in the
 383 analysis of this scenario, by assuming a *motivation tariff* where the DH company would guarantee a discount of
 384 1% to end users in their energy bill (up to a maximum of 20%) for each °C lower in the average of supply and
 385 return temperatures compared to the reference DH average supply and return. This was assumed as 80/40 °C for
 386 this case study. Therefore, the key element of the optimization was expressed as the minimization of the average
 387 of supply and return temperatures of Equation 2 set equal to the specific *LMTD* for each value of the duration
 388 curve defined in Fig. 5. The objective function and constraints are presented as follows:

389 *i. For all LMTD:*

$$\text{minimize } (Average(T_S; T_R)), \text{ for } LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \quad (13)$$

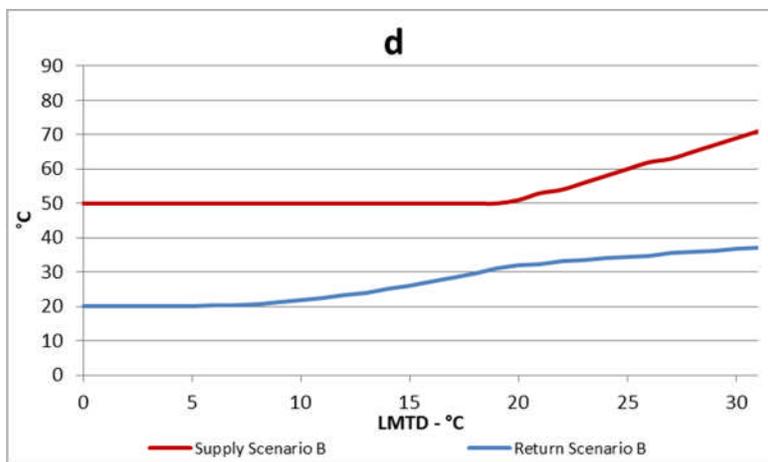
390 Subject to:

$$50^\circ\text{C} \leq T_S \leq 80^\circ\text{C} \quad (14)$$

$$\dot{m} \leq \dot{m}_0 \quad (15)$$

391 For this scenario the indoor temperature T_i was set at 20 °C and max mass flow rate \dot{m}_0 from equation 12 was 19
 392 kg/h. Each combination of supply and return temperatures fulfilled the constraints' criteria for hydraulic and supply

393 temperature limits. As presented in Fig. 8, even in this case, well-controlled double string radiators can achieve
394 low return temperatures, without any intervention to the thermal envelop of the building.



395
396 Fig. 8: Scenario B supply and return temperatures: optimization results

397

398 However, compared to scenario A, the outcomes illustrate that the optimal strategy to operate the radiators resulted
399 in a reduction of the supply temperatures and an increased return temperature profile for each LMTD. This was
400 related to the higher economic value associated to the supply temperatures in this scenario. A critical analysis of
401 the curves presented in Fig. 6 and 8 shows for LMTD up to 14°C the optimal supply and return temperatures are
402 identical for both cases; above that value the curves show the higher the supply temperatures the lower the return
403 ones for each LMTD. This clearly indicates the compromise to decide whether and to which extent lowering supply
404 and return temperatures is strictly related to the economic benefit that those have for the specific DH system in
405 analysis. To this extent, the strategy to operate the DH network in this scenario and deliver the heat demand in the
406 area by controlling the supply temperatures according to the optimal level is described in Fig. 9.

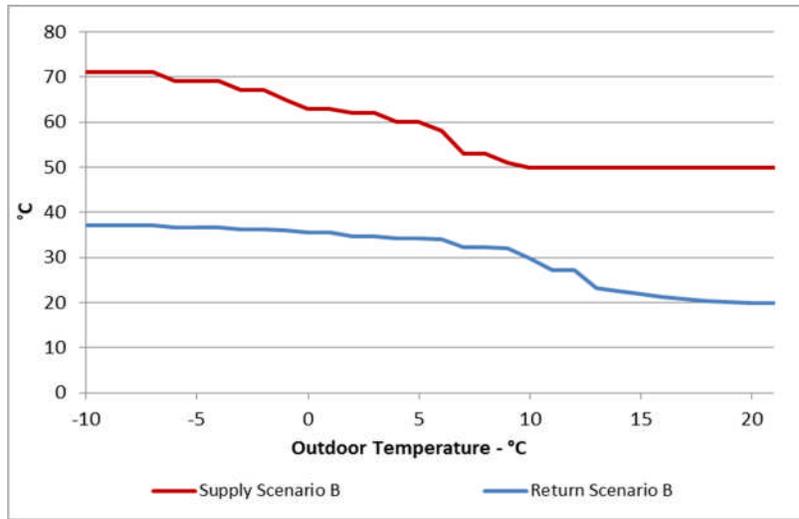


Fig. 9: Scenario B relation between optimized supply/return and outside temperatures

407

408

409 The curves show the relationship between the optimal supply and return temperatures linked to the hourly peak
 410 load associated to each 1 °C of outdoor temperature as described in section 4.2.4.1. Hence, operating the DH
 411 network and the radiators as proposed in Fig. 8 and 9 would define the strategy to implement LTDH in the area.
 412 In fact, as presented in study [8], LTDH is described as a system operating with supply temperature of 50-55 °C
 413 and return of 25-30 °C with the capability of increasing supply to 60–70 °C and return of 40 °C when necessary
 414 according to heat demand. In addition, the new operation of the heating system would guarantee to end users a
 415 discount of 16% in their energy bills according to the assumed *motivation tariff* due to lower average supply and
 416 return temperatures obtained in comparison with the reference scenario. This is presented in Table 3 comparing
 417 the discount achievable between the two proposed scenarios in relation to the average supply and return
 418 temperatures achieved.

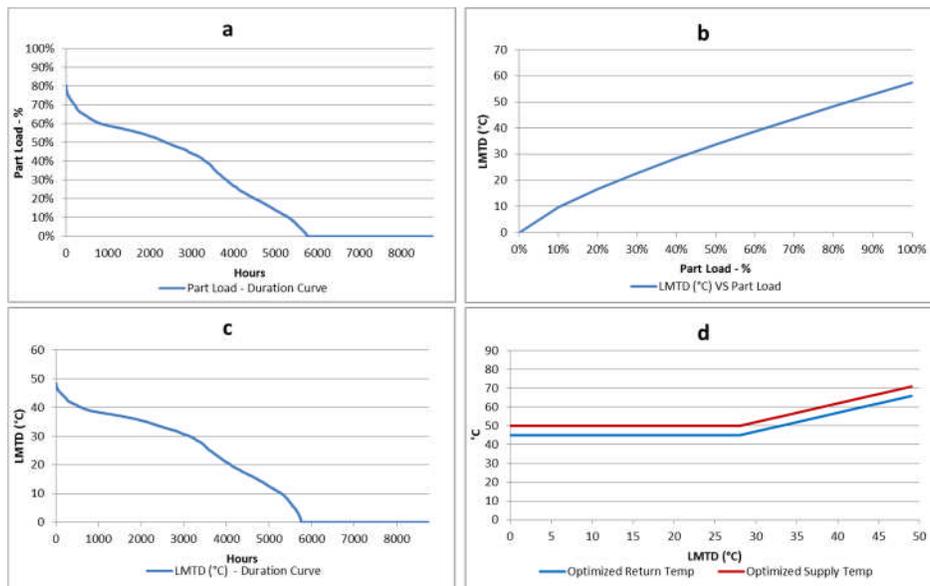
419

Table 3: Energy savings for double string radiators: scenarios A and B

| | Reference scenario | Scenario A | Scenario B |
|--|--------------------|------------|------------|
| Average return temperature (°C) | 40 | 26 | -46 |
| Average supply/return temperature (°C) | 80 | 70 | 65 |
| End-users savings (%) | - | 14 | 16 |

420 4.3 Modelling part – calculation of heating demand of rooms and heating power of radiators in a single string
421 system

422 As described in section 1.2.1 single string systems based on plate radiators are operated with higher mass flow
423 rate and lower ΔT between supply and return temperatures. In the Danish experience, the typical operation of single
424 string systems shows how in many cases it is difficult to obtain the expected cooling of return temperatures. In
425 fact, as documented in this Danish report [55], although in some cases it could be necessary and recommended to
426 replace these systems with double string ones, it is appropriate as first step, technically and economically, to try to
427 adjust the operation of these systems and improve the ΔT . In this direction, the objective of this part of the
428 investigation was to illustrate the capability of the proposed methodology to improve the operation of single string
429 systems. This was applied to the same single-family house assuming in this case the heating system based on
430 single string with plate radiators for only one scenario. The hall room – presented in Fig 1 – was the selected one
431 to demonstrate the method and the outcomes are presented for the four steps in Fig. 10.



432
433 Fig.10: a) Part Load duration curve; b) LMTD VS Part Load duration curve
434 c) LMTD duration curve; d) Optimized supply/return temperatures

435 *4.3.1 Step a: calculation of part load duration curve*

436 The design heat load calculated for the specific room, as presented in section 4.2.1, was 884 W according to the
437 steady-state simulations based on the Danish standard [44]. In addition, the same dynamic simulation outputs are
438 presented in Fig. 10a and depict the part load duration curve on an hourly basis for the room.

439 *4.3.2 Step b: calculation of the relationship between part load and logarithmic mean temperature difference of*
440 *the hydraulic radiator elements*

441 The relationship between each part load and the specific LMTD is presented in Fig. 10b as a result of the
442 calculations made in *step b*. The relationship defines how the radiators need to be operated to deliver the specific
443 heat load outlined in *step a*. It was assumed in this case that the radiators in the single loop were operated at design
444 conditions with supply and return temperatures of 80/75 °C. The calculations of LMTD for each part load were
445 performed using Equation 1 and assuming: 1.3 for n , 884 W for φ_0 , while the $LMTD_0$ was calculated from
446 Equation 2 using the design temperatures of 80/75°C and set indoor temperatures of 20 °C.

447 *4.3.3 Step c: calculation of the duration curve of logarithmic mean temperature difference*

448 The duration curve of LMTD based on hourly values is presented in Fig. 10c and was obtained from the results of
449 the part load duration curve obtained in *step a* and the relation of part load and LMTD defined in *step b*.

450 *4.3.4 Step d: calculation of the optimal supply and return temperature to provide the necessary logarithmic*
451 *mean temperature difference*

452 The single string systems based on plate radiators are operated with high mass flow rate to guarantee sufficient
453 inlet temperature to all the radiators connected in series. Due to the typical small temperature difference, assuming
454 a properly designed and controlled system, the strategy to obtain lower return temperatures is related to the
455 possibility of keeping the supply temperatures as low as possible. It was hypothesized for this system a constant
456 ΔT of 5 °C between the supply temperature in the first radiator – assumed as the radiator of the hall room – and
457 return temperature from the last one. A higher ΔT of 10 or 15 °C could have been considered, but the objective of
458 the analysis was to test the method in the worst case possible. In addition, it was assumed for this scenario a

459 *motivation tariff* defining a discount of 1% in the end users' energy bill (up to a max of 20%) for each 1 °C
460 reduction in their average supply and return temperature compared to the reference case of the DH network where
461 the building was ideally connected. The reference yearly average supply and return temperature assumed for the
462 DH were 80/40 °C.

463 Hence, the main criterion of the optimization was expressed as the minimization of the average of supply and
464 return temperatures of Equation 2 set equal to the specific LMTD for each value of the duration curve of Fig. 10c.

465 The objective function and constraints for this scenario are presented as follows:

466 i. For all *LMTD*:

$$\text{minimize } (Average(T_S; T_R)), \text{ for } LMTD = \frac{T_S - T_R}{\ln\left(\frac{T_S - T_i}{T_R - T_i}\right)} \quad (16)$$

467 Subject to:

$$\Delta T = 5 \text{ °C} \quad (17)$$

$$50\text{°C} \leq T_S \leq 80 \text{ °C} \quad (18)$$

$$\dot{m} \leq \dot{m}_0 \quad (19)$$

468 The indoor temperature was fixed at 20 °C while the maximum mass flow rate obtained from Equation 12 was
469 152 kg/h. All the optimal combinations of supply and return temperatures are presented in Fig. 10d and fulfilled
470 the constraints' criteria. In particular, as a constant ΔT of 5 °C was assumed, the optimized supply temperatures
471 presented in Fig. 10d is the optimized inlet temperature for the hall room radiator – assumed as the first in the
472 single string system, whereas the return temperatures describe the temperatures out of the last radiator.

473 Similarly to double string system, the supply temperatures are limited to 50 °C and out of the heating season it
474 was assumed that temperatures of 50/20 °C were enough to meet the DHW demand. Although very low return
475 temperatures – close to room temperature – were not achieved, the outcomes of the optimization show that these
476 systems can be operated more efficiently and in particular unnecessary high supply and return temperatures can
477 be avoided. In fact, operating the single string system as proposed, if properly designed and controlled, a possible

478 discount of 5% in the end users' energy bills could be obtained according to the hypothesized *motivation tariff*
479 without any intervention to either the building or the heating system.

480 **5 Conclusion**

481 The developed methodology was used to investigate and plan the application of LTDH to hydraulic radiators in
482 existing buildings. The results related to the double string scenarios showed the optimal operation of the existing
483 plate radiators, properly controlled through TRVs and DH network, by adjusting the supply temperatures to the
484 optimal level, achieved low return temperatures. This would allow existing buildings to be connected to LTDH
485 without any intervention in the thermal envelope, through simply adjusting the temperatures according to demand,
486 and obtain cost savings in the end users' energy bills. The strategy proposed for both scenarios A and B illustrated
487 that a possible discount of 14% and 16% respectively could be achieved in annual energy bills. Furthermore, the
488 design curves suggest the strategy to be followed for lowering supply and return temperatures has to be related to
489 the economic impact those have in the DH network in analysis. For the case of single string systems with plate
490 radiators, the results also illustrate that very low return temperatures were not possible due to the differences in
491 the way these systems are operated. If the objective of the investigation in the area is to obtain return temperatures
492 close to room one, if technically and economically feasible, these systems should be replaced or converted to
493 double pipes. However, it should be noted that the application of the method, even for this type of heating system,
494 allowed the heating system to operate more efficiently and avoid unnecessary high supply and return temperatures.
495 This was quantified for the assumed scenario by a possible discount of 5% in the end users' energy bills. This
496 research project demonstrates the application of the methodology in a typical Danish single-family house assuming
497 the worst case radiator in the hydronic system. Due to the promising results obtained the focus is now to expand
498 the investigation by implementing it in a real DH case study. Finally, it is central in the discussion to stress the
499 importance of having well-controlled hydraulic radiators and limiting the impact of occupants misuse of equipment
500 in order to efficiently operate the heating system and reach the expected cooling of return temperatures.

501

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506

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