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Replacing critical radiators to increase the potential to use low-temperature district heating – a case study of 4 Danish single-family houses from the 1930s.

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Abstract:

Low-temperature district heating is a promising technology for providing homes with energy-efficient heating in the future. However, it is of great importance to maintain thermal comfort in existing buildings when district heating temperatures are lowered. This case study evaluated the actual radiator sizes and heating demands in 4 existing Danish single-family houses from the 1930s. A year-long dynamic simulation was performed for each of the houses to evaluate the potential to lower the heating system temperatures. The results indicate that there is a large potential to use low-temperature district heating in existing single family houses. In order to obtain the full potential of low-temperature district heating, critical radiators must be replaced. Based on a novel method, a total of nine radiators were identified to be critical to ensure thermal comfort and low return temperatures in two of the case-houses. If these radiators were replaced it would be possible to lower the average heating system temperatures to 50 °C / 27 °C in all four houses.

Keywords: *Low-temperature district heating, IDA ICE, radiators, single family houses, dynamic simulation of heat demand*

1 Introduction

More than 60% of homes in Denmark are heated by district heating [1]. This means that optimization of district heating systems can play a large role in strategies for improving the energy efficiency of heating in Danish homes. One way of improving energy efficiency is to implement modern 4th generation district heating, which

23 aims to obtain district heating temperatures as low as 50 °C supply and 20 °C return for most of the year [2],
24 [3]. The concept of 4th generation low-temperature district heating is well described with respect to network
25 design, in-house substations, and technical solutions for preparation of domestic hot water [4]–[8]. However
26 only few studies describe the possibility of reducing district heating temperatures in existing buildings without
27 compromising the thermal comfort of building occupants. The subject has been investigated through building
28 simulations based on theoretical standard values for heating power and indoor temperatures [9], [10], but no
29 study has been performed to evaluate the actual conditions in the existing buildings. This paper provides a new
30 practical aspect to the current knowledge by reporting on a case study of 4 Danish single-family houses from
31 the 1930s. The performed analysis took into account actual measured indoor temperatures in the case-houses
32 and heating powers of existing radiators. Thereby the study presents new knowledge on how occupant
33 behaviour and existing heating system design affects the potential to use low-temperature district heating.

34 A number of studies have investigated the potential of using lower district heating temperatures. Some of
35 these have focused on performing tests in which the district heating supply temperature is lowered in a limited
36 urban area [11]–[15] or the temperatures in the district heating network are lowered through continuous
37 temperature optimization [16]–[18]. However, such network studies might not illustrate the full potential of
38 low-temperature district heating, because the district heating temperatures may be higher than necessary in
39 order to make up for malfunctions or faults in the building systems [19]. This could play an important role,
40 because studies have found that up to 70% of existing district heating substations are not operated optimally
41 [20]–[22]. A number of studies have therefore investigated the possibility of lowering the district heating
42 temperatures in specific buildings by improving the district heating substations and the control of the heating
43 installations. These studies include field studies of a number of Swedish apartment buildings [23]–[26] and
44 Danish single-family houses [17], [18]. The results of these studies confirm the hypothesis that existing
45 buildings can be heated by low-temperature district heating for much of the year. However, some of the

46 studies also show that not all radiators are large enough for low-temperature heating [11], [27], [28]. Therefore
47 it may be relevant to identify and replace critical radiators [18]. In this study the case-houses were analysed on
48 a detailed room-to-room basis. This made it possible to perform a novel investigation to identify critical
49 radiators that were a barrier to obtain the full potential of low-temperature district heating in the houses. The
50 results of the study provide new knowledge on the prevalence of critical radiators and the benefits obtained by
51 replacing these. This is valuable information for future analyses on the cost and benefits of introducing low-
52 temperature district heating. The detailed method described in this study is furthermore a valuable first step in
53 the development of new methods for identification of critical radiators in buildings supplied by district heating.
54 Such methods are important tools in the process of lowering district heating temperatures in existing building
55 areas and thereby important tools in the process towards an efficient future energy system.

56 **2 Method**

57 The investigations in this study were performed through case studies of four Danish single-family houses from
58 the 1930s. Each case-house was thoroughly examined, indoor temperatures in all rooms were measured, and
59 heating powers of radiators in all rooms were estimated. The case-houses were modelled in the dynamic
60 simulation tool IDA ICE. Relevant information about the case-houses and the simulation models were provided
61 in Section 3.

62 The study was based on a novel method for identification and evaluation of critical radiators in existing single-
63 family houses. The method consists of four steps as described below. Each step is described in detail in section
64 4-7 along with the results of each analysis.

- 65 I. Critical radiators were identified by using the simulation models to calculate the heating demands in
66 each room of the case-houses over a typical year. The supply and return temperatures necessary to
67 cover the calculated heating demand in each room were calculated on the basis of the radiator sizes.

- II. A supply temperature strategy was suggested for each of the case-houses based on the average heating power and average heating demand in the house. The strategy was used to illustrate the potential to lower the heating system temperatures in each of the case-houses.
- III. The supply temperature strategy was tested in a year-long simulation of the heating consumption in each house. This was done in order to evaluate the effect of critical radiators on thermal comfort and heating system return temperatures.
- IV. Critical radiators were replaced and a new year-long simulation was performed to verify the benefits of replacing the identified critical radiators.

The potential to lower the district heating temperatures in existing single-family houses from the 1930s was evaluated based on the simulations performed. Sections 8 and 9 discuss the uncertainties of the study and summarises the results of the analyses.

3 Simulation models

3.1 Description of case-houses

The case-houses investigated in the study are illustrated in Fig. 1, which shows the geometries and the floor plans of the houses. The houses are typical Danish single-family houses from the 1930s. All of the houses are detached houses except for House 1, which is a terraced house connected to neighbouring houses on both sides.

All of the houses are brick houses with insulated cavity walls and all have basements. The construction details were either identified during visits to the houses, based on inputs from occupants, or estimated according to standards at the time of construction [29], [30]. Only House 3 has been through major renovations, during which the first floor was added to the house and some radiators were replaced. Apart from this, the main improvements that have been made to the houses consist of new windows in Houses 1, 2 and 3, and extra roof

90 insulation in Houses 1, 3 and 4. Key data describing the houses are given in Table 1. As seen in the table most of
91 the houses have only 2 occupants, but the heated floor area differs greatly between the houses. The
92 construction elements of the houses and their U-values are given in Table 2. The U-values reflect standard
93 values for the given building constructions according to the Danish Energy Agency [30], the Danish Building
94 Research Institute [29], and the Danish standard for calculation of heat loss from buildings [31].

96 **Fig. 1.** The four case-houses investigated in the study. The red lines on the floor plans indicate the location of radiators.

97 **Table 1**

98 Key data for the case-houses. All areas are based on external measurements as is the custom in Denmark.

House:	1	2	3	4
Number of occupants	1-7	2	2	2
Total floor area / basement area [m ²]	150 / 48	165 / 69	320 / 118	241 / 118
Heated part of basement [m ²]	48	55	47	110

99 **Table 2**

100 Construction elements of the case-houses

House:	1	2	3	4
External walls	Cavity brick wall with cavity wall insulation ($U = 0.78 \text{ W/m}^2 \text{ K}$)			
Basement walls	30cm concrete ($U = 1.1 \text{ W/m}^2 \text{ K}$)			
Basement floor	20 cm concrete ($U = 0.48 \text{ W/m}^2 \text{ K}$)			
Internal floors	Wooden beams with clay			
Internal walls	12cm brick and 10cm wooden frames with insulation			
Roof insulation	20cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)	10cm insulation ($U = 0.37 \text{ W/m}^2 \text{ K}$)	25cm insulation ($U = 0.15 \text{ W/m}^2 \text{ K}$)	20cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)
Windows main floor/basement	2-pane energy glazing ($U = 1.5 - 1.6 \text{ W/m}^2 \text{ K}$)			double glazing/1 pane ($U = 2.3/4.3 \text{ W/m}^2 \text{ K}$)

101 The houses are all naturally ventilated, and during the period of the study they were all heated by individual
 102 condensing natural gas boilers. District heating was installed in the houses after this study had been conducted.
 103 The heating system in all houses consists of hydraulic radiators, but electric floor heating has been installed in
 104 one bathroom in House 1 and in both bathrooms in House 3.

105 3.2 IDA ICE

106 Simulation models of each of the case-houses were built in the commercially available dynamic simulation
 107 software IDA ICE [32]. The software has been validated in accordance with standard DS/EN 15265, which
 108 describes dynamic simulation of energy performance of buildings [33], [34]. The program is a node based multi-
 109 zone simulation tool that can be used to perform calculations on the energy consumption and indoor climate in
 110 buildings. Simulations can be performed according to various time periods and climate data. This makes it
 111 possible to perform year-long simulations with Design Reference Year weather files or short simulations
 112 incorporating actual weather data for a given time period and location. The program provides a high detail

level in the computations taking into account amongst others thermal inertia of building elements, air flows between zones, and solar heat gains. The heating system can be modelled in detail by use of pre-defined radiator elements. The design heating power can be defined for each radiator individually and IDA ICE calculates the heat emitted from the radiators based on the logarithmic mean temperature difference (LMTD). The maximum mass flow through the radiator corresponds to the mass flow at the design conditions.

3.3 Model assumptions

The houses were modelled in accordance with the constructions and geometry shown in Table 2 and Fig. 1. Table 3 shows the linear heat losses that were applied in the simulations. Table 3 furthermore shows the averaged values of the internal heat gains from occupants and equipment that are included in the models. The presence of occupants and their use of equipment were modelled on weekly schedules taking into account the number of occupants, their behaviour, and special conditions such as people working from home or who have retired. The average values are given in W/m² floor area, excluding the basement area, and are somewhat lower than the standard values for internal heat gains in Denmark, which are 1.5W/m² for occupants and 3.5W/m² for equipment [35]. This is probably because most of the case-houses have only 2 occupants, but other studies also suggest that actual internal heat gains could be somewhat lower than the standard values [36].

Table 3
Linear heat losses and heat gains applied in the simulation models.

House:	1	2	3	4
Linear loss windows [W/m]	0.11			
Linear loss wall/roof [W/m]	0.14	0.26	0.12	0.22
Linear loss wall/wall [W/m]	0.23	0.47		
Linear loss wall/floor [W/m]	0.7			
Heat gain occupants [W/m ²]	0.84	1.42	0.81	1.42
Heat gain equipment [W/m ²]	1.78	2.18	1.55	2.23

The natural ventilation of the houses was assumed to be fixed at 0.3 l/s per m² floor area, which corresponds to the standard ventilation required in the Danish Building Code [35], [37]. This includes infiltration from opening

133 of windows and doors in the winter time. None of the houses are equipped with mechanical cooling, so we
134 assumed that cooling is provided through opening of windows/doors when indoor temperatures exceed 25 °C.

135 All the houses were equipped with condensing natural gas boilers and hot water tanks that were located in the
136 basements. Heat losses from the heating installations were based on standard values described by the Danish
137 Energy Agency [30]. The hot water tanks in all houses were approximately 110L, and hot water consumption
138 was assumed to be 41.0 L of 55 °C hot water per occupant per day [38]. The heat loss from each tank was
139 assumed to correspond to 70W. Heat losses from pipes were included in the models in proportion to the pipe
140 lengths and insulation thicknesses measured in the houses. The values were calculated in accordance with the
141 differences between indoor temperatures and heating system temperatures that were measured in the
142 houses. In most cases, the temperatures measured approximated to an average of 45 °C for space-heating
143 pipes, 50 °C for domestic hot water circulation pipes and 20 °C for indoor air. The total heat losses are given in
144 Table 4 and differ greatly. As most basement rooms in the case-houses are heated, the heat losses from pipes
145 contribute greatly to the space heating most of the year. In Houses 1 and 2 there are also short pieces of
146 heating pipe in the cold attic and in the ground respectively. Risers in the heated zones of Houses 1 and 3 were
147 disregarded in the model.

148 **Table 4**
149 Heat losses from pipes and installations in the case-houses.

House:	1	2	3	4
Total heat loss from space-heating pipes [W]	675	745	338	1232
Heat loss from hot water circulation [W]	128	123	-	241

150 The existing radiators in the houses were included in the simulation model with their correct dimensions and
151 locations. The design heating power of each radiator was estimated on the basis of its dimensions and type.
152 This was done using a tool designed by the Danish Technological Institute, which was acquired through
153 personal communication. The tool is based on empirical data for typical radiators in Denmark. According to a

154 number of tests, the tool was found to have an accuracy of approximately $\pm 10\%$. The tool provided the design
 155 heating power of each radiator at the temperature set $90^{\circ}\text{C} / 70^{\circ}\text{C} / 20^{\circ}\text{C}$. The installed design heating power
 156 in each of the case-houses is shown in Fig. 2 in W per m^2 heated room area.

157
 158 **Fig. 2.** Design heating power in the case-houses at the temperature set $90^{\circ}\text{C} / 70^{\circ}\text{C} / 20^{\circ}\text{C}$.

159 3.4 Measurements and simulation models

160 The calculated heating demand in each of the case-houses was compared to the measured natural gas
 161 consumption in the houses in March-April 2015. A one-month simulation was therefore performed for each
 162 case-house based on actual weather data and measured indoor temperatures. The weather data were based
 163 on measurements taken by the Danish Meteorological Institute, and diffuse and direct sunlight measured at a
 164 weather station at the Technological University of Denmark, which is close to the case-houses [39]. Indoor
 165 temperatures were measured in each room of the case houses on an hourly basis. The temperature
 166 measurements were made using temperature loggers with an internal probe. According to the manufacturer,
 167 the loggers have an accuracy of $\pm 0.5^{\circ}\text{C}$. Where possible, the indoor temperature loggers were located away
 168 from heating sources, cold windows or sunlight. However, it was not possible to locate the sensors in the
 169 middle of the rooms, so in some cases the temperatures measured may differ from the average indoor
 170 temperatures. Often it was only possible to locate the loggers on furniture near walls where the air might not
 171 be perfectly mixed. The loggers were located at heights between 0.5m and 2.0m and the maximum room

172 height was 2.75m. According to earlier studies on similar cases the vertical temperature difference under these
173 conditions is no more than 0.3° C [40], [41].

174 The calculated heating consumption (including domestic hot water) was compared with the natural gas
175 consumption measured during the period. The natural gas was assumed to have a heating value of 11kWh/m³
176 and the boiler efficiency was assumed to be 1.06 [30]. The measured and calculated heat consumptions
177 including heat for domestic hot water are shown in Table 5.

178 **Table 5**
179 Heat consumption based on natural gas measurements and calculated heat consumption in the case-houses

House:	1	2	3	4
Measurement period	11/3-13/4	11/3-10/4	11/3-12/4	11/3-10/4
Measured gas consumption in m ³	172.3	257.9	214.2	319.5
Measured consumption in kWh/m ²	13.4	19.9	10.0	16.0
Simulated heat consumption in kWh/m ²	12.5	18.7	10.1	15.7
Deviation from measured	6.7%	6.0%	1.0%	2.0%

180 As the table shows, the deviations between the measured and calculated consumption ranged from 1.0% to
181 6.7%. We considered this to be reasonably good agreement, as the standard EN 15265 defines accuracy levels
182 for differences of 5%, 10%, and 15%, where the most accuracy simulations have differences below 5% [33]. It
183 can be expected that the actual heat demand is slightly higher than the calculated one due to the assumed low
184 infiltration and high boiler efficiency.

185 **4 Identification of critical radiators**

186 **4.1 Calculation of heat demand**

187 The first step of this study was to use the simulation models to provide an indication of radiators that could be
188 critical for the opportunity to lower the district heating temperatures. This was done by calculating the heat
189 demand in each room of the case-houses and comparing this to the available radiator heating power. For this

190 purpose a year-long dynamic simulation was performed in IDA ICE to calculate the heat demand in each room
191 of the case-houses during a typical year. To calculate the heat demand in each room in IDA ICE, the rooms are
192 equipped with a so-called ideal heater, which supplies the exact amount of heat that is required to maintain
193 the indoor temperature set-point in each room. The calculation was carried out using the weather file for the
194 Design Reference Year of Copenhagen. The weather file consists of average weather data for a year based on
195 measurements made from 2001 to 2010. Indoor temperature set-points were chosen so as to obtain the
196 indoor temperatures measured in the houses, but assuming a steady operation profile with constant indoor
197 temperatures, without night setback, and with well-functioning temperature control. In cases where the indoor
198 temperatures measured were found to vary, the higher indoor temperatures measured were used in the
199 models. In some cases, the temperatures were adjusted slightly to ensure that the temperature set-points
200 were similar in rooms that are directly connected through openings or open doors. The operative indoor
201 temperatures that were maintained in the rooms of the houses according to the measurements are shown in
202 Fig. 9 in the Results section.

203 The hourly heating demands calculated in the dynamic simulations were analysed in order to estimate the
204 typical heating demands in each room of the case-houses during the heating season (the period between 1st
205 September and 31st May). The summer period was removed from the data because we assumed the
206 temperature requirements for domestic hot water would be dimensioning during this time. The calculated
207 hourly heating demands in each room were sorted according to the outdoor temperatures. However, the
208 heating demands in the rooms at a given outdoor temperature vary due to differences in heat gains and heat
209 accumulated in the constructions. The heating demand at a given outdoor temperature was therefore
210 calculated as the 90th percentile of the hourly heating demands at that temperature, as shown in Fig. 3.

Fig. 3. Hourly heating demands and 90th percentile of the heating demands in the dining room of House 1.

By using this method, it is possible to avoid choosing heating systems temperatures according to extreme situations that only rarely occur. Instead, it is accepted that the heating system return temperatures or the indoor temperatures may vary slightly from the set-point for 10% of the time.

4.2 Required heating system temperatures

Each radiator needs to be supplied with a heating system temperature set that enables the radiator to cover the calculated heating demand in the room. The heating system temperatures that were required in order to cover the calculated heating demands were visualized using the LMTD. The LMTD required to cover the calculated heat demand in a given room was calculated based on the heating power of the radiator in the room. Because this analysis is focused on low-temperature district heating, the calculations were based on a radiator exponent of $n = 1.1$ for all radiators except in Child's room3 in House 1, where it was set to $n = 1.5$ because the room is equipped with a convector. These values were chosen on the basis of a recent study describing the calculation of heat emitted from radiators during low-temperature operation [42]. The calculations were performed by use of Equation 1.

$$\Delta T = (\Phi / \Phi_0)^{1/n} \cdot \Delta T_0 \quad (1)$$

where

228 ΔT is the LMTD necessary to satisfy the heating demand
 229 ΔT_0 is the LMTD between radiator and surroundings for the design conditions
 230 Φ is the heating demand at a given outdoor temperature
 231 Φ_0 is the design heating power of the radiator
 232 n is the radiator exponent

233 The calculations were performed for each individual room as well as for the houses on average. The average
 234 LMTD required in each house was calculated from the total heating power and the total heating demand in the
 235 house. This corresponds to a case where the entire house is considered as one room with one big radiator. The
 236 average LMTD provides an indication of the potential of using low-temperature district heating in the case-
 237 houses when rooms with critical radiators are not taken into account.

238 The resulting LMTDs required to satisfy the heating demand in each individual room of the case-houses as well
 239 as for each case-house on average are seen in Fig. 4-Fig. 7. Rooms that require higher heating system
 240 temperatures than the average are marked in the graphs. The LMTDs obtained with typical heating system
 241 temperatures are seen in Table 6 for an indoor temperature of 20° C.

242
 243 **Fig. 4.** Graph of required heating temperatures at varying outdoor temperatures – Case-House 1.

Fig. 5. Graph of required heating temperatures at varying outdoor temperatures – Case-House 2

Fig. 6. Graph of required heating temperatures at varying outdoor temperatures – Case-House 3

Fig. 7. Graph of required heating temperatures at varying outdoor temperatures – Case-House 4

Table 6

Logarithmic mean temperature difference of typical heating system temperatures at an indoor temperature of 20°C

Supply / Return temperature [° C]	70/40	60/35	50/35	50/30	55/25	50/25	45/25
$\Delta T \log [^{\circ} C]$	33.0	25.5	22.4	18.0	14.4	13.2	11.8

Rooms that require a higher heating system temperature than the average house may be critical for the potential to lower the supply temperature without compromising thermal comfort or causing the return temperature to increase. The figures show that there are a few rooms with critical radiators in all houses. For Houses 1 and 3, only a few radiators are problematic, and this may be compensated for by the well-functioning radiators in the remaining rooms. Houses 2 and 4 were seen to have four or more critical radiators each. While many of the radiators in Houses 2 and 3 have similar requirements for heating system temperatures, there are bigger differences in the temperatures required in Houses 1 and 4. Both House 1 and House 4 are seen to have severe critical radiators that require an LMTD that is approximately 15° C or more above the average.

5 Supply temperature strategy

A strategy for low temperature heating was suggested for each of the case-houses based on the calculated average LMTD required in the houses. Thereby the strategies reflect the current potential to lower the heating system temperatures in the case houses if critical radiators are not taken into account. The strategies consist of a weather compensation curve where the supply temperature in each of the case-houses is controlled according to the required LMTD in the house. The strategies were designed to maintain a low supply temperature of 50° C for as long as possible. This supply temperature is the minimum temperature required to provide domestic hot water through an instantaneous heat exchanger. The supply temperature was increased if the required LMTD exceeded 22.4 °C in cold periods, indicating that it was no longer possible to maintain a 15° C cooling in the heating system with a supply temperature of 50 °C.

The resultant supply temperature strategy suggested for each of the case-houses is seen in Fig. 8.

Fig. 8. Suggested supply temperature curves and corresponding return temperatures in the case-houses according to the required average LMTDs.

274 The figure indicates that the average heating power available in the case-houses is not a hindrance to lower the
275 heating system temperatures for most of the year. In Houses 1 and 3 the supply temperature was lowered to
276 50° C until the outdoor temperature reached -5° C. In Houses 2 and 4 the supply temperature was increased in
277 cold periods and return temperatures between 30° C and 40° C were accepted for a longer part of the year. The
278 different supply temperature strategies underline the individuality of existing single-family houses. The
279 differences were also visible in Fig. 4-Fig. 7 where the average required LMTDs in Houses 2 and 4 were seen to
280 be 5-10° C higher than those in Houses 1 and 3. This was despite the fact that Houses 2 and 4 were found to
281 have the highest installed heating power per m². One reason for this could be the fact that the indoor
282 temperatures measured in Houses 2 and 4 were quite high compared to those in House 1 and 3. Another
283 explanation could be the fact that Houses 2 and 4 have received the least energy renovation.

284 **6 Effect of critical radiators**

285 Radiators that require a higher LMTD than the average could potentially be critical for the possibility to
286 maintain thermal comfort and obtain low return temperatures. In order to evaluate the effect of the critical
287 radiators, a year-long simulation was performed in IDA ICE for each of the case-houses with the suggested
288 supply temperature strategy. The houses were modelled with the same settings as before but included actual
289 radiator dimensions and radiator exponents as described in Section 4.2. The results of the simulations were
290 evaluated with regard to thermal comfort and return temperatures. Thermal comfort was evaluated by
291 comparing the simulated indoor temperatures to the indoor temperature set-points in the rooms of the case
292 houses. The temperature set-points were based on the indoor temperature measured in each room of the
293 case-houses and thereby they represent the thermal comfort requirements of the occupants. The return
294 temperatures were evaluated by comparing the simulated return temperatures to the return temperatures
295 expected according to supply temperature strategy for each house.

296 Fig. 9 shows the operative indoor temperature set-points in the rooms and illustrates where the operative
 297 indoor temperature was in periods found to be more than 0.5° C below the preferred set-point. Fig. 10 shows
 298 the simulated and expected return temperatures.

300 **Fig. 9.** Indoor temperature set-points and marking of rooms where indoor temperatures were occasionally found to be
 301 more than approximately 0.5°C below set-point temperature.

303 **Fig. 10.** Expected and simulated heating system return temperatures in the case-houses during the heating season when
 304 supply temperatures are based on the supply temperature strategy in Fig. 8.

305 Fig. 9 show that there are several rooms in House 2 and House 4 where the thermal comfort will be
 306 compromised if the supply temperature strategy is implemented. The results indicate that it is necessary to
 307 replace the radiators in a number of rooms in these houses in order to meet the thermal comfort requirements

308 with the given temperature strategy. In most of the rooms, however, the air temperatures did not go more
309 than 0.5° C below the indoor temperatures measured in the rooms, and generally the indoor temperatures in
310 the models were in a reasonable range in all living areas.

311 Fig. 10 shows that the return temperatures in House 1 and 3 were only rarely above 30° C, while it was found
312 to be above 35° C for approximately a third of the heating season in Houses 2 and 4. For Houses 1, 2 and 4 the
313 return temperatures were found to be quite a lot higher than expected according to the suggested
314 temperature strategy. The reason for this was found to be that the critical radiators as indicated in Fig. 4-Fig. 7
315 had a large effect on the heating system return temperatures. House 3 was not affected noticeably by the
316 critical radiators.

317 Based on these results it was concluded that Houses 1 and 3 were suited for low-temperature heating already
318 at the current state. Houses 2 and 4 were not suited for the suggested supply temperature strategy at the
319 current state, as some of the radiators in these houses were seen to be critical for the possibility to maintain
320 thermal comfort and provide low return temperatures.

321 **7 Replacing critical radiators**

322 The number of critical radiators that needed to be replaced in order to obtain the full benefits of low-
323 temperature district heating was evaluated through a new year-long simulation. In this simulation the
324 identified critical radiators were replaced by new radiators with a higher design heating power. The heating
325 powers of the new radiators were carefully chosen to ensure that the LMTDs required in the critical rooms
326 corresponded to the average LMTD required in the house.

327 In order to obtain the full benefits of low-temperature district heating in the case-houses it was necessary to
328 replace a number of critical radiators in Houses 2 and 4. Four radiators were replaced in House 2 – the ones in

the entrance, the office, the living room, and the basement storage room. In House 4 the radiators in the kitchen, the hall, the office, the bathroom, and guest room1 were replaced. A total of 9 radiators were replaced, increasing the design heating powers in House 2 and House 4 to 175 W/m² and 162 W/m² respectively. After replacing the critical radiators the four case-houses had approximately the same heating system temperature requirements. The supply temperature strategies in Houses 2 and 4 were therefore changed to correspond to that of House 3 as seen in Fig. 8.

The year-long simulation showed that after replacing the critical radiators, it was possible to maintain the desired indoor temperatures in all rooms of Houses 2 and 4. The return temperatures from the heating systems in the case-houses after replacing the radiators are seen in Fig. 11. Replacing the radiators meant that all case-houses could be heated with average heating-season supply and return temperatures of approximately 50° C/27° C, without compromising thermal comfort.

Fig. 11. Heating system return temperatures in the case-houses before and after replacing critical radiators.

8 Uncertainty of results

This study was based on dynamic simulations and temperature measurements. Therefore the results are subject to some uncertainty. The simulation models that were used for this study were validated against

345 measurements from the case-houses. However, the calculated heating demands were still subject to some
346 uncertainty due to assumptions made in the models. One assumption that was found to have a large effect on
347 the results was the modelling of the natural ventilation or infiltration in the houses. The models assumed that
348 there was a constant infiltration of 0.3 l/s per m² building area in accordance with building code requirements.
349 In some cases, this may be higher than the actual infiltration, because studies show that the air change rates in
350 existing buildings are often lower than the building code requires [43]. During periods with high wind velocities,
351 however, the infiltration may be higher, which can have a large effect on heating demand in houses that are
352 not airtight. Such situations were not taken into account in this study. In cases where high infiltration rates
353 cause poor thermal comfort in a house, it can be assumed that the occupants would be interested in spending
354 money on sealing the building envelope. Alternatively, the district heating supply temperature could be
355 increased in periods with high wind velocity.

356 Our assumptions about occupant behaviour were also found to have a large effect on the results. In general,
357 the simulated occupant schedules were found to cause the internal heat gain in the houses to be lower than
358 standard average values. This means the results of this analysis are on the safe side, because increased internal
359 heat gains would provide supplementary heating to the rooms. The most important assumptions about
360 occupant behaviour, however, were found to be the indoor temperature set-points and the opening of doors
361 between rooms. In the models, it was assumed that occupants controlled their heating system in a reasonable
362 way, allowing the heating system to work properly. This was a necessary assumption because the focus of the
363 study was on investigating the radiator dimensions without biases from malfunctions or misuse of control of
364 the heating system. In reality though, it may be necessary to provide information to occupants to ensure that
365 heating set-points do not differ in rooms that are directly connected through an open door and that heating
366 set-points are not varied during the day or by using night setback. If such occupant behaviour is to be taken
367 into account, either the heating power must be increased or the control of the heating system must be

368 improved to correct the biases of human behaviour. Further studies are therefore needed to test the results of
369 this study in real-life conditions.

370 The study was based on indoor temperatures measured at a certain location in the rooms of the case-houses
371 during one month in March-April. The measurements did therefore not take into account temperature
372 gradients in the rooms or variations in the indoor temperatures during the year. The indoor temperatures
373 applied in this study were therefore not expected to provide a precise representation of the indoor
374 temperatures in the rooms of the case-houses at all times. However by basing the indoor temperature set-
375 points on the measured indoor temperatures, it was possible to provide an example of how actual indoor
376 temperatures may vary from house to house or room to room. Furthermore it was possible to evaluate how
377 these variations affected the possibility of using low-temperature district heating.

378 **9 Conclusions**

379 The results of this study indicated that there is a large potential to lower the district heating temperatures in
380 areas with existing single-family houses. It was found that two of the investigated single-family houses could be
381 heated with low-temperature district heating at the current state. In the remaining two houses it was
382 necessary to replace a total of nine critical radiators in order to maintain thermal comfort in all rooms and
383 obtain low return temperatures. After replacing the critical radiators it was found that the average heating
384 system temperatures could be lowered to approximately 50° C/27° C in all four houses.

385 The study presented a method that made it possible to identify critical radiators based on the actual conditions
386 in each house. The method was based on calculations with a dynamic building simulation tool and consisted of
387 four steps:

- 388 1. Comparison between heat demands and existing heating power
- 389 2. Suggestion of supply temperature strategy based on average heat demand and heating power

390 3. Evaluation of thermal comfort and return temperatures for the suggested temperature strategy

391 4. Replacement of radiators where thermal comfort was not met and return temperatures were high

392 By following this method it was possible to identify critical radiators that needed to be replaced in order to
393 lower heating system temperatures without compromising thermal comfort of occupants. The method
394 described provides a first step in the development of tools to assist the process of lowering the district heating
395 temperatures in existing building areas, and thereby an important step towards an efficient future energy
396 system.

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402 **References**

- 403 [1] Danish Energy Agency, *Energy statistics 2013*. 2014.
- 404
- 405 [2] H. Lund, S. Werner, R. Wiltshire, S. Svendsen, J. E. Thorsen, F. Hvelplund, and B. V. Mathiesen, "4th
406 Generation District Heating (4GDH): Integrating smart thermal grids into future sustainable energy
407 systems," *Energy*, vol. 68, pp. 1–11, 2014.
- 408
- 409 [3] Dansk Fjernvarmes F&U konto, "Varmeplan Danmark 2008 [Heating Plan Denmark 2008]," 2008.
- 410
- 411 [4] H. I. Tol and S. Svendsen, "Improving the dimensioning of piping networks and network layouts in low-
412 energy district heating systems connected to low-energy buildings: A case study in Roskilde, Denmark,"
413 *Energy*, vol. 38, no. 1, pp. 276–290, Feb. 2012.
- 414
- 415 [5] M. Brand, J. E. Thorsen, and S. Svendsen, "Numerical modelling and experimental measurements for a
416 low-temperature district heating substation for instantaneous preparation of DHW with respect to
417 service pipes," *Energy*, vol. 41, no. 1, pp. 392–400, May 2012.
- 418
- 419 [6] M. Brand, A. D. Rosa, and S. Svendsen, "Energy-efficient and cost-effective in-house substations bypass
420 for improving thermal and DHW (domestic hot water) comfort in bathrooms in low-energy buildings
421 supplied by low-temperature district heating," *Energy*, vol. 67, pp. 256–267, Apr. 2014.
- 422
- 423 [7] O. Paulsen, J. Fan, S. Furbo, and J. E. Thorsen, "Consumer Unit for Low Energy District Heating Net," in
424 *The 11th International Symposium on District Heating and Cooling*, 2008.
- 425
- 426 [8] Danish Energy Agency and EUDP 2010-II, "Guidelines for Low-Temperature District Heating," 2014.
- 427
- 428 [9] M. Brand and S. Svendsen, "Renewable-based low-temperature district heating for existing buildings in
429 various stages of refurbishment," *Energy*, vol. 62, pp. 311–319, 2013.
- 430
- 431 [10] M. Harrestrup and S. Svendsen, "Changes in heat load profile of typical Danish multi-storey buildings
432 when energy-renovated and supplied with low-temperature district heating," *Int. J. Sustain. Energy*, vol.
433 34, no. 3–4, pp. 232–247, 2013.
- 434
- 435 [11] N. B. Andersen and M. Grimmig, *Lavtemperaturvarme i Eksisterende Boliger [Low-temperature heating
436 in existing homes]*. The Danish Technological Institute, 1988.
- 437

- 438 [12] B. Jørgensen, *Lavtemperaturdrift af eksisterende fjernvarmenet [Low-temperature operation of existing*
 439 *district heating networks]*. The Danish Technological Institute, 1988.
 440
- 441 [13] B. Aastrup, B. Haurballe, and F. Hammer, "Fjernvarmens temperatur er væsentlig, når der skal bygges
 442 decentrale k/v-anlæg [District heating temperature is vital when building decentralised combined heat
 443 and power stations]," *Fjernvarmen [District Heating]*, vol. 30, no. 5, pp. 10–13, 1991.
 444
- 445 [14] M. Røvs Hansen and C. Larsen, *Lavtemperaturfjernvarme [Low-temperature district heating]*. Aalborg
 446 University, 1989.
 447
- 448 [15] A. H. Pedersen and F. Hammer, "Energi og bymiljø - Spændende samarbejde mellem Århus Kommune
 449 Værker og Stadtwerke Kiel [Energy and urban environment - Interesting collaboration between Århus
 450 Kommune Værker and Stadtwerke Kiel]," *Fjernvarmen [District Heating]*, vol. 32, no. 1, pp. 56–59,
 451 1993.
 452
- 453 [16] Dansk Fjernvarmes F&U konto, "Etablering af lavtemperaturfjernvarme i eksisterende
 454 fjernvarmeforsyning [Establishment of low-temperature district heating in existing district heating
 455 systems]," COWI, 2014.
 456
- 457 [17] Danish Energy Agency and EUDP 2010-II, "Demonstration i Sønderby – Fuldskalademonstration af
 458 lavtemperaturfjernvarme i eksisterende bebyggelser - Journalnr. 64010-0479 [Demonstration in
 459 Sønderby – Full scale demonstration of low-temperature district heating in existing buildings]," 2014.
 460
- 461 [18] Danish Energy Agency and EUDP 2010-II, "Demonstration i Tilst Energistyrelsen – Fuldskala
 462 demonstration af lavtemperatur fjernvarme i eksisterende bebyggelser - Journalnr. 64010-0479
 463 [Demonstration in Tilst – Full scale demonstration of low-temperature district heating in existing
 464 buildings]," 2014.
 465
- 466 [19] H. Gadd, "TO ANALYSE MEASUREMENTS IS TO KNOW!," Ph.D. thesis, Lund University, 2014.
 467
- 468 [20] H. Gadd and S. Werner, "Heat load patterns in district heating substations," *Appl. Energy*, vol. 108, pp.
 469 176–183, 2013.
 470
- 471 [21] H. Gadd and S. Werner, "Achieving low return temperatures from district heating substations," *Appl.*
 472 *Energy*, vol. 136, pp. 59–67, 2014.
 473
- 474 [22] Dansk Fjernvarmes F&U konto, "Anvendelse af varmeenergimåleren med fjernaflæsning til diagnose og
 475 fejlretning af varmeanlæg, med særlig henblik på energiøkonomi og afkølingsforhold [Use of heating
 476 energy meters for diagnosis and fault correction in heating systems with special focus on]," 2008.

477

- 478 [23] J. Wollerstrand, P. Ljunggren, and P. O. Johansson, *Optimal reglering av radiatorsystem [Optimal*
479 *regulation of radiator systems]*. Svensk Fjärrvärme [Swedish District Heating], 2007.
480
- 481 [24] J. Wollerstrand and P. Lauenburg, *Fältförsök med adaptiv reglering av radiatorsystem [Field experiment*
482 *with adaptive regulation of radiator system]*. Svensk Fjärrvärme [Swedish District Heating], 2009.
483
- 484 [25] A. Trüschel, *Värdet av injustering [The value of balancing]*. Svensk Fjärrvärme [Swedish District Heating],
485 2005.
486
- 487 [26] P. Lauenburg and J. Wollerstrand, "Adaptive control of radiator systems for a lowest possible district
488 heating return temperature," *Energy Build.*, vol. 72, pp. 132–140, 2014.
489
- 490 [27] F. Linnebjerg Rasmussen, "Kunders huse sat under lup i Århus," *Fjernvarmen [District Heating]*, vol. 49,
491 no. 9, pp. 32–34, 2010.
492
- 493 [28] Danish Energy Agency and EUDP 2008-II, "CO₂-reductions in low energy buildings and communities by
494 implementation of low-temperature district heating systems. Demonstration cases in EnergyFlexHouse
495 and Boligforeningen Ringgården - Journalnr. 63011-0152," DTU BYG, 2011.
496
- 497 [29] K. B. Wittchen and J. Kragh, *Danish building typologies - participation in the TABULA project*. Danish
498 Building Research Institute, 2012.
499
- 500 [30] Danish Energy Agency, *Håndbog for energikonsulenter. Enfamiliehuse. Beregnet forbrug - 2012*
501 *[Handbook for energy consultants. Single-family houses. Calculated consumption - 2012]*. 2012.
502
- 503 [31] Danish Standards, "DS 418:2011 - Beregning af bygningers varmetab [Calculation of heat loss from
504 buildings]," 2011.
505
- 506 [32] Equa Simulation, "User Manual IDA Indoor Climate and Energy," 2013.
507
- 508 [33] Danish Standard, "DS/EN 15265 - Energy performance of buildings - Calculation of energy needs for
509 space heating and cooling using dynamic methods - General criteria and validation procedures," 2007.
510
- 511 [34] Equa Simulation, "Validation of IDA Indoor Climate and Energy 4 . 0 with respect to CEN Standards EN
512 15255-2007 and EN 15265-2007," 2010.
513

- 514 [35] S. Aggerholm and K. Grau, *Bygningers energibehov - PC-program og beregningsvejledning [Energy*
515 *demand of buildings - PC-program and calculation guide]* - SBI-anvisning 213. Danish Building Research
516 Institute, 2005.
517
- 518 [36] M. Brand, P. Lauenburg, J. Wollerstrand, and V. Zboril, "Optimal Space Heating System for Low-Energy
519 Single-Family House Supplied by Low-Temperature District Heating," in *Papers presented at the*
520 *conference Passivhusnorden 2012*, 2012.
521
- 522 [37] Danish Energy Agency, "Bygningsreglementet [Building Regulations]," 2014. [Online]. Available:
523 <http://bygningsreglementet.dk/>. [Accessed: 07-Sep-2015].
524
- 525 [38] B. Bøhm, F. Schrøder, and N. C. Bergsøe, *Varmt Brugsvand - måling af forbrug og varmetab fra*
526 *cirkulationsledninger [Domestic hot water - measurements of consumption and heat loss from*
527 *circulation pipes]* - SBI 2009:10. 2009.
528
- 529 [39] E. Andersen, J. Dragsted, T. V. Kristensen, and L. Kokholm Andersen, "Upgrade and Extension of the
530 Climate station at DTU Byg," 2014.
531
- 532 [40] A. Hasan, J. Kurnitski, and K. Jokiranta, "A combined low temperature water heating system consisting
533 of radiators and floor heating," *Energy Build.*, vol. 41, no. 5, pp. 470–479, May 2009.
534
- 535 [41] B. W. Olesen, E. Mortensen, J. Thorshauge, and B. Berg-Munch, "Thermal Comfort in a Room Heated by
536 Different Methods - Technical paper no. 2256," in *Los Angeles Meeting, ASHRAE Transactions 86*, 1980,
537 pp. 34–48.
538
- 539 [42] O. Paulsen and F. Rosenberg, "Dimensionering af radiatorer til lavtemperatursystemer [Dimensioning of
540 radiators for low temperature systems]," *HVAC*, vol. 48, no. 1, pp. 46–53, 2012.
541
- 542 [43] G. Bekö, T. Lund, F. Nors, J. Toftum, and G. Clausen, "Ventilation rates in the bedrooms of 500 Danish
543 children," *Build. Environ.*, vol. 45, no. 10, pp. 2289–2295, 2010.
544