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### 1 Replacing critical radiators to increase the potential to use low-temperature district heating – a case

#### 2 study of 4 Danish single-family houses from the 1930s.

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#### 6 **Abstract**:

7 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 8 9 heating temperatures are lowered. This case study evaluated the actual radiator sizes and heating demands in 10 4 existing Danish single-family houses from the 1930s. A year-long dynamic simulation was performed for each 11 of the houses to evaluate the potential to lower the heating system temperatures. The results indicate that 12 there is a large potential to use low-temperature district heating in existing single family houses. In order to 13 obtain the full potential of low-temperature district heating, critical radiators must be replaced. Based on a 14 novel method, a total of nine radiators were identified to be critical to ensure thermal comfort and low return 15 temperatures in two of the case-houses. If these radiators were replaced it would be possible to lower the 16 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

### 19 **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 4<sup>th</sup> 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], [3]. The concept of 4<sup>th</sup> generation low-temperature district heating is well described with respect to network 24 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.

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

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

- 68 II. A supply temperature strategy was suggested for each of the case-houses based on the average
- 69 heating power and average heating demand in the house. The strategy was used to illustrate the
- 70 potential to lower the heating system temperatures in each of the case-houses.
- 71 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.
- 74 IV. Critical radiators were replaced and a new year-long simulation was performed to verify the benefits of
   75 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.

79 **3** Simulation models

## 80 **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 insulation in Houses 1, 3 and 4. Key data describing the houses are given in Table 1. As seen in the table most of
the houses have only 2 occupants, but the heated floor area differs greatly between the houses. The
construction elements of the houses and their U-values are given in Table 2. The U-values reflect standard
values for the given building constructions according to the Danish Energy Agency [30], the Danish Building
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 <sup>2</sup> ]	150 / 48	165 / 69	320 / 118	241 / 118
Heated part of basement [m <sup>2</sup> ]	48	55	47	110

### 99 Table 2

100 Construction elements of the case-houses

House:	1	2	3	4	
External walls	Cavity I	prick wall with cavity	wall insulation (U = 0	.78 W/m² K)	
Basement walls		30cm concrete (U = 1.1 W/m <sup>2</sup> K)			
Basement floor	20 cm concrete (U = 0.48 W/m <sup>2</sup> K)				
Internal floors	Wooden beams with clay				
Internal walls	12cm brick and 10cm wooden frames with insulation				
Roof insulation	20cm insulation	10cm insulation	25cm insulation	20cm insulation	
	$(U = 0.2 W/m^2 K)$	$(U = 0.37 \text{ W/m}^2 \text{ K})$	$(U = 0.15 \text{ W/m}^2 \text{ K})$	$(U = 0.2 \text{ W/m}^2 \text{ K})$	
Windows main floor/basement	2-pane energy glazing double glazing/1 pane				
Windows main noory basement		$(U = 2.3/4.3 \text{ W/m}^2 \text{ K})$			

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

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
- 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.

### 118 **3.3 Model assumptions**

119 The houses were modelled in accordance with the constructions and geometry shown in Table 2 and Fig. 1. 120 Table 3 shows the linear heat losses that were applied in the simulations. Table 3 furthermore shows the 121 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 122 123 number of occupants, their behaviour, and special conditions such as people working from home or who have 124 retired. The average values are given in  $W/m^2$  floor area, excluding the basement area, and are somewhat 125 lower than the standard values for internal heat gains in Denmark, which are 1.5W/m<sup>2</sup> for occupants and 126 3.5W/m<sup>2</sup> for equipment [35]. This is probably because most of the case-houses have only 2 occupants, but 127 other studies also suggest that actual internal heat gains could be somewhat lower than the standard values 128 [36].

### 129 Table 3

130 Linear heat losses and heat gains applied in the simulation models.

¥1				
House:	1	2 3		4
Linear loss windows [W/m]		0.1	1	
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 <sup>2</sup> ]	0.84	1.42	0.81	1.42
Heat gain equipment [W/m <sup>2</sup> ]	1.78	2.18	1.55	2.23

131 The natural ventilation of the houses was assumed to be fixed at 0.3 l/s per m<sup>2</sup> floor area, which corresponds to

the standard ventilation required in the Danish Building Code [35], [37]. This includes infiltration from opening

of windows and doors in the winter time. None of the houses are equipped with mechanical cooling, so we
 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

The existing radiators in the houses were included in the simulation model with their correct dimensions and locations. The design heating power of each radiator was estimated on the basis of its dimensions and type. This was done using a tool designed by the Danish Technological Institute, which was acquired through personal communication. The tool is based on empirical data for typical radiators in Denmark. According to a number of tests, the tool was found to have an accuracy of approximately  $\pm 10\%$ . The tool provided the design heating power of each radiator at the temperature set 90° C / 70° C / 20° C. The installed design heating power in each of the case-houses is shown in Fig. 2 in W per m<sup>2</sup> heated room area.





158 **Fig. 2.** Design heating power in the case-houses at the temperature set 90° C/70° C/20° 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 on measurements taken by the Danish Meteorological Institute, and diffuse and direct sunlight measured at a 163 164 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 ±0.5 °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/m<sup>3</sup>
- and the boiler efficiency was assumed to be 1.06 [30]. The measured and calculated heat consumptions
- 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 <sup>3</sup>	172.3	257.9	214.2	319.5
Measured consumption in kWh/m <sup>2</sup>	13.4	19.9	10.0	16.0
Simulated heat consumption in kWh/m <sup>2</sup>	12.5	18.7	10.1	15.7
Deviation from measured	6.7%	6.0%	1.0%	2.0%

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

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 1<sup>st</sup> 205 September and 31<sup>st</sup> 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 calculated as the 90<sup>th</sup> percentile of the hourly heating demands at that temperature, as shown in Fig. 3. 210





**Fig. 3.** Hourly heating demands and 90<sup>th</sup> 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.

216

## 4.2 Required heating system temperatures

217 Each radiator needs to be supplied with a heating system temperature set that enables the radiator to cover 218 the calculated heating demand in the room. The heating system temperatures that were required in order to 219 cover the calculated heating demands were visualized using the LMTD. The LMTD required to cover the 220 calculated heat demand in a given room was calculated based on the heating power of the radiator in the 221 room. Because this analysis is focused on low-temperature district heating, the calculations were based on a 222 radiator exponent of n = 1.1 for all radiators except in Child's room3 in House 1, where it was set to n = 1.5223 because the room is equipped with a convector. These values were chosen on the basis of a recent study 224 describing the calculation of heat emitted from radiators during low-temperature operation [42]. The 225 calculations were performed by use of Equation 1.

- 226  $\Delta T = (\Phi / \Phi_0)^{\wedge} (1/n) \cdot \Delta T_0$
- 227 where

12

(1)

- 228 ΔT is the LMTD necessary to satisfy the heating demand
- 229 ΔT<sub>0</sub> is the LMTD between radiator and surroundings for the design conditions
- 230  $\Phi$  is the heating demand at a given outdoor temperature
- 231  $\Phi_0$  is the design heating power of the radiator
- 232 n is the radiator exponent

242

- 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
- house. This corresponds to a case where the entire house is considered as one room with one big radiator. The
- 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
- as for each case-house on average are seen in Fig. 4-Fig. 7. Rooms that require higher heating system
- temperatures than the average are marked in the graphs. The LMTDs obtained with typical heating system
- temperatures are seen in Table 6 for an indoor temperature of 20° C.



#### House 1 - Required heating temperatures

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









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

250 Table 6

248

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

Supply / Return	70/40	60/35	50/35	50/30	55/25	50/25	45/25
ΔT log [° C]	33.0	25.5	22.4	18.0	14.4	13.2	11.8

252 Rooms that require a higher heating system temperature than the average house may be critical for the 253 potential to lower the supply temperature without compromising thermal comfort or causing the return 254 temperature to increase. The figures show that there are a few rooms with critical radiators in all houses. For 255 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 256 257 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 258 259 severe critical radiators that require an LMTD that is approximately 15° C or more above the average.

# 260 5 Supply temperature strategy

261 A strategy for low temperature heating was suggested for each of the case-hoses based on the calculated average LMTD required in the houses. Thereby the strategies reflect the current potential to lower the heating 262 263 system temperatures in the case houses if critical radiators are not taken into account. The strategies consist of 264 a weather compensation curve where the supply temperature in each of the case-houses is controlled 265 according to the required LMTD in the house. The strategies were designed to maintain a low supply 266 temperature of 50° C for as long as possible. This supply temperature is the minimum temperature required to 267 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 268 269 15° C cooling in the heating system with a supply temperature of 50 °C.

270 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 LMDTs.

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 m<sup>2</sup>. 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.

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



299

302

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



Fig. 10. Expected and simulated heating system return temperatures in the case-houses during the heating season whensupply 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

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

Fig. 10 shows that the return temperatures in House 1 and 3 were only rarely above 30° C, while it was found

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

return temperatures were found to be quite a lot higher than expected according to the suggested

temperature strategy. The reason for this was found to be that the critical radiators as indicated in Fig. 4-Fig. 7

had a large effect on the heating system return temperatures. House 3 was not affected noticeably by the

316 critical radiators.

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

temperature district heating was evaluated through a new year-long simulation. In this simulation the

identified critical radiators were replaced by new radiators with a higher design heating power. The heating

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.

In order to obtain the full benefits of low-temperature district heating in the case-houses it was necessary to
 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/m<sup>2</sup> and 162 W/m<sup>2</sup>
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 casehouses could be heated with average heating-season supply and return temperatures of approximately 50° C/27° C, without compromising thermal comfort.





### 342 8 Uncertainty of results

340

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  $m^2$  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

improved to correct the biases of human behaviour. Further studies are therefore needed to test the results ofthis 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

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

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

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
- described provides a first step in the development of tools to assist the process of lowering the district heating
- temperatures in existing building areas, and thereby an important step towards an efficient future energy

396 system.

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