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

A number of studies have investigated the potential of using lower district heating temperatures. Some of these have focused on performing tests in which the district heating supply temperature is lowered in a limited urban area [11]–[15] or the temperatures in the district heating network are lowered through continuous temperature optimization [16]–[18]. However, such network studies might not illustrate the full potential of low-temperature district heating, because the district heating temperatures may be higher than necessary in order to make up for malfunctions or faults in the building systems [19]. This could play an important role, because studies have found that up to 70% of existing district heating substations are not operated optimally [20]–[22]. A number of studies have therefore investigated the possibility of lowering the district heating temperatures in specific buildings by improving the district heating substations and the control of the heating installations. These studies include field studies of a number of Swedish apartment buildings [23]–[26] and Danish single-family houses [17], [18]. The results of these studies confirm the hypothesis that existing buildings can be heated by low-temperature district heating for much of the year. However, some of the studies also show that not all radiators are large enough for low-temperature heating [11], [27], [28]. Therefore it may be relevant to identify and replace critical radiators [18]. In this study the case-houses were analysed on a detailed room-to-room basis. This made it possible to perform a novel investigation to identify critical radiators that were a barrier to obtain the full potential of low-temperature district heating in the houses. The results of the study provide new knowledge on the prevalence of critical radiators and the benefits obtained by replacing these. This is valuable information for future analyses on the cost and benefits of introducing low-temperature district heating. The detailed method described in this study is furthermore a valuable first step in the development of new methods for identification of critical radiators in buildings supplied by district heating. Such methods are important tools in the process of lowering district heating temperatures in existing building areas and thereby important tools in the process towards an efficient future energy system.

2 Method

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

The study was based on a novel method for identification and evaluation of critical radiators in existing single-family 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.

I. 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.

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 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].

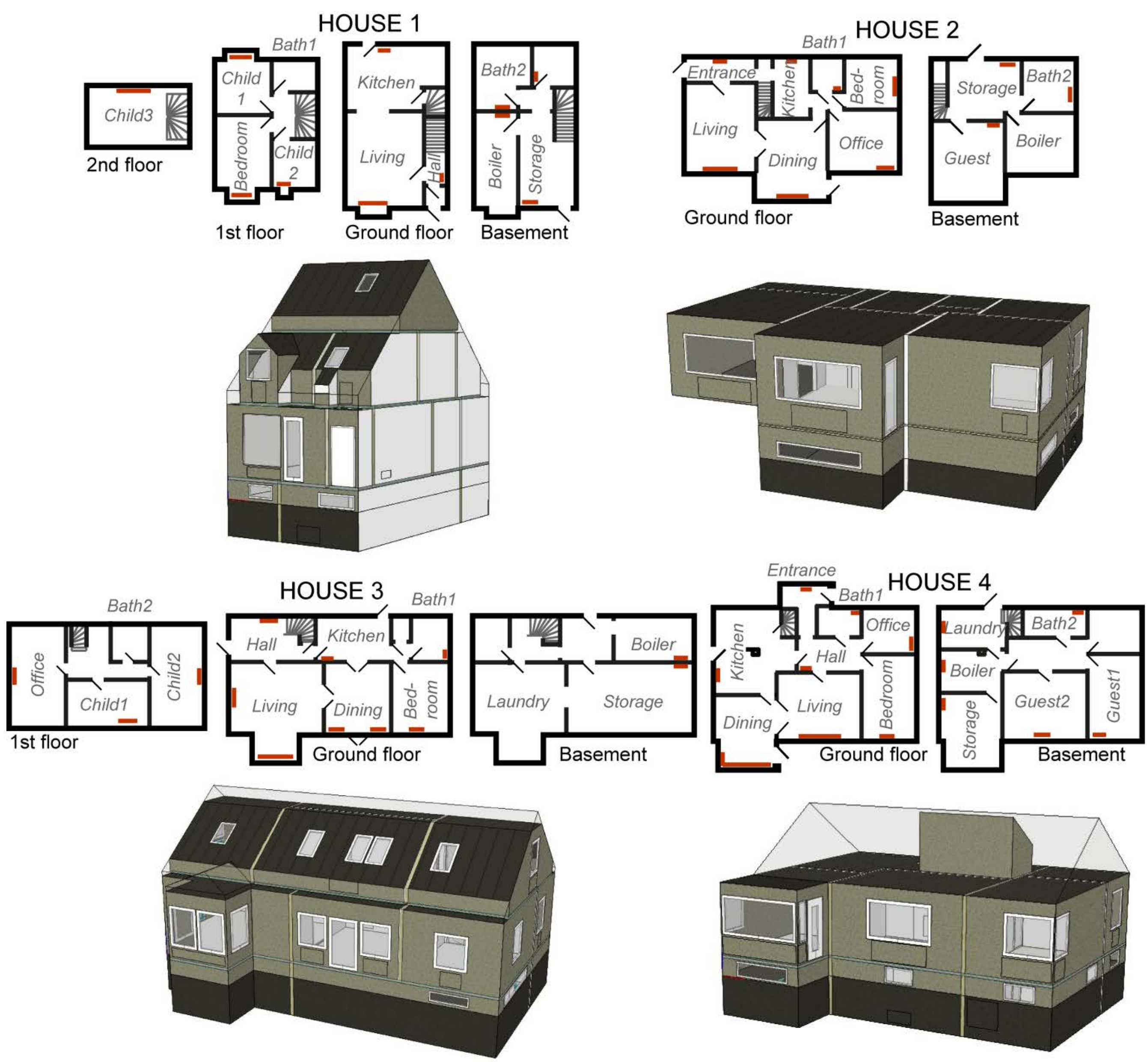

Fig. 1. The four case-houses investigated in the study. The red lines on the floor plans indicate the location of radiators.

Table 1
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 [m²]	150 / 48	165 / 69	320 / 118	241 / 118
Heated part of basement [m²]	48	55	47	110

Table 2
Construction elements of the case-houses

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

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

3.2 IDA ICE

Simulation models of each of the case-houses were built in the commercially available dynamic simulation 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-zone simulation tool that can be used to perform calculations on the energy consumption and indoor climate in buildings. Simulations can be performed according to various time periods and climate data. This makes it 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.

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/m^2 floor area, excluding the basement area, and are somewhat lower than the standard values for internal heat gains in Denmark, which are $1.5 W/m^2$ for occupants and $3.5 W/m^2$ 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 m^2 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.

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

Table 4
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 ±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 m² heated room area.

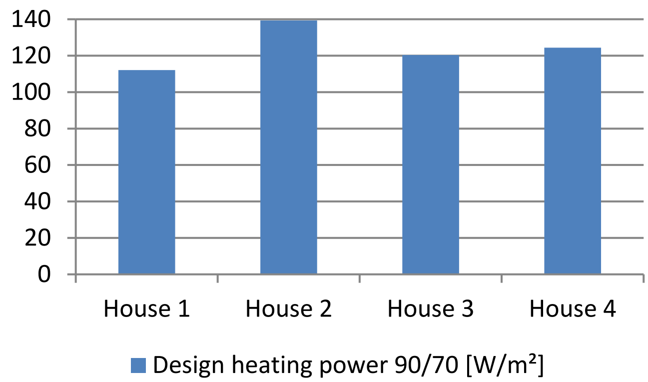

Fig. 2. Design heating power in the case-houses at the temperature set 90° C/70° C/20° C.

3.4 Measurements and simulation models

The calculated heating demand in each of the case-houses was compared to the measured natural gas consumption in the houses in March-April 2015. A one-month simulation was therefore performed for each 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 weather station at the Technological University of Denmark, which is close to the case-houses [39]. Indoor temperatures were measured in each room of the case houses on an hourly basis. The temperature measurements were made using temperature loggers with an internal probe. According to the manufacturer, the loggers have an accuracy of ±0.5 °C. Where possible, the indoor temperature loggers were located away from heating sources, cold windows or sunlight. However, it was not possible to locate the sensors in the middle of the rooms, so in some cases the temperatures measured may differ from the average indoor temperatures. Often it was only possible to locate the loggers on furniture near walls where the air might not be perfectly mixed. The loggers were located at heights between 0.5m and 2.0m and the maximum room height was 2.75m. According to earlier studies on similar cases the vertical temperature difference under these conditions is no more than 0.3° C [40], [41].

The calculated heating consumption (including domestic hot water) was compared with the natural gas consumption measured during the period. The natural gas was assumed to have a heating value of $11 kWh/m^3$ 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.

Table 5
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%

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.

4 Identification of critical radiators

4.1 Calculation of heat demand

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

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

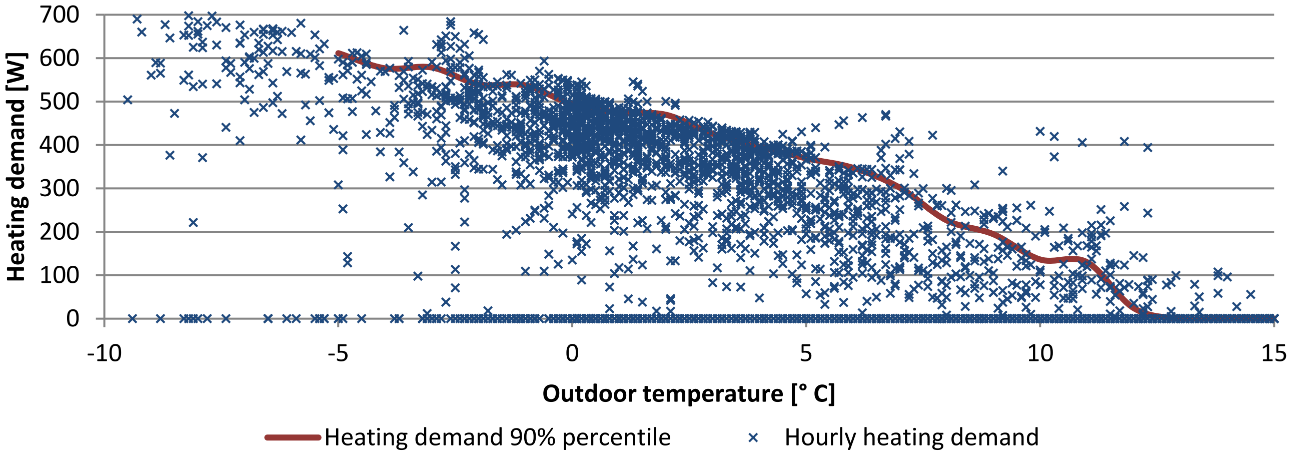

Fig. 3. Hourly heating demands and 90th percentile of the heating demands in the dining room of House 1.

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.

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

where

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

The calculations were performed for each individual room as well as for the houses on average. The average 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-houses when rooms with critical radiators are not taken into account.

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.

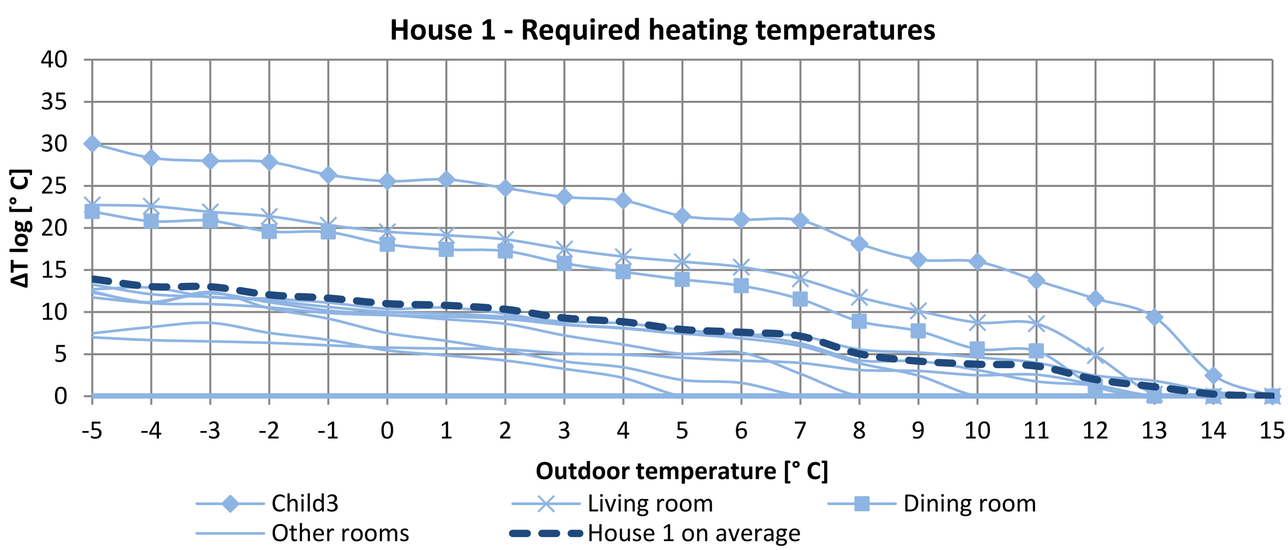

Fig. 4. Graph of required heating temperatures at varying outdoor temperatures – Case-House 1.

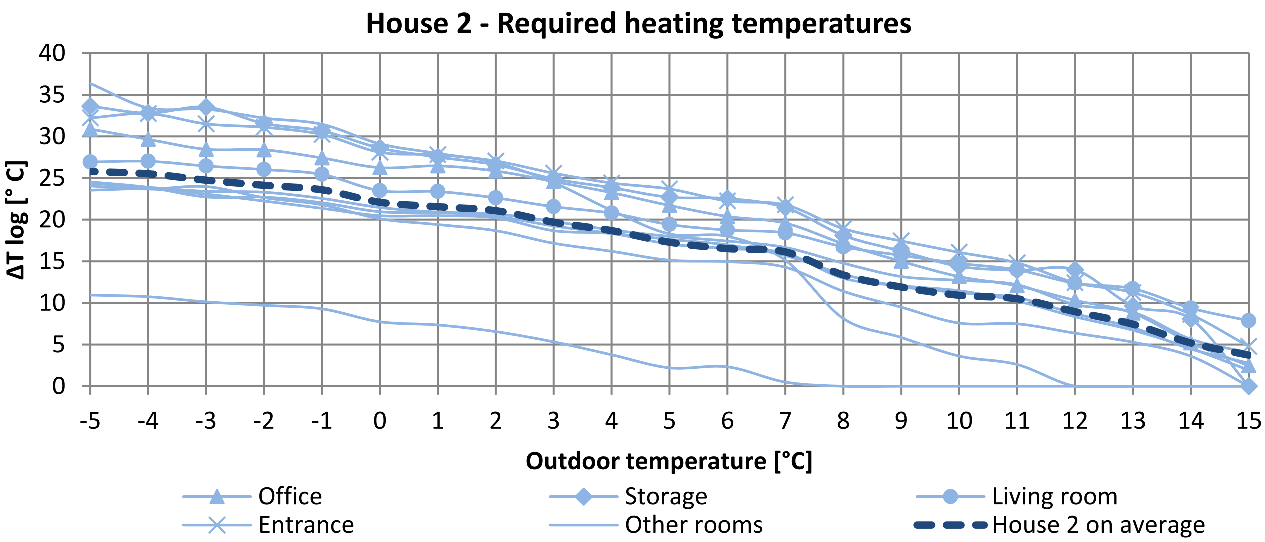

Fig. 5. Graph of required heating temperatures at varying outdoor temperatures – Case-House 2

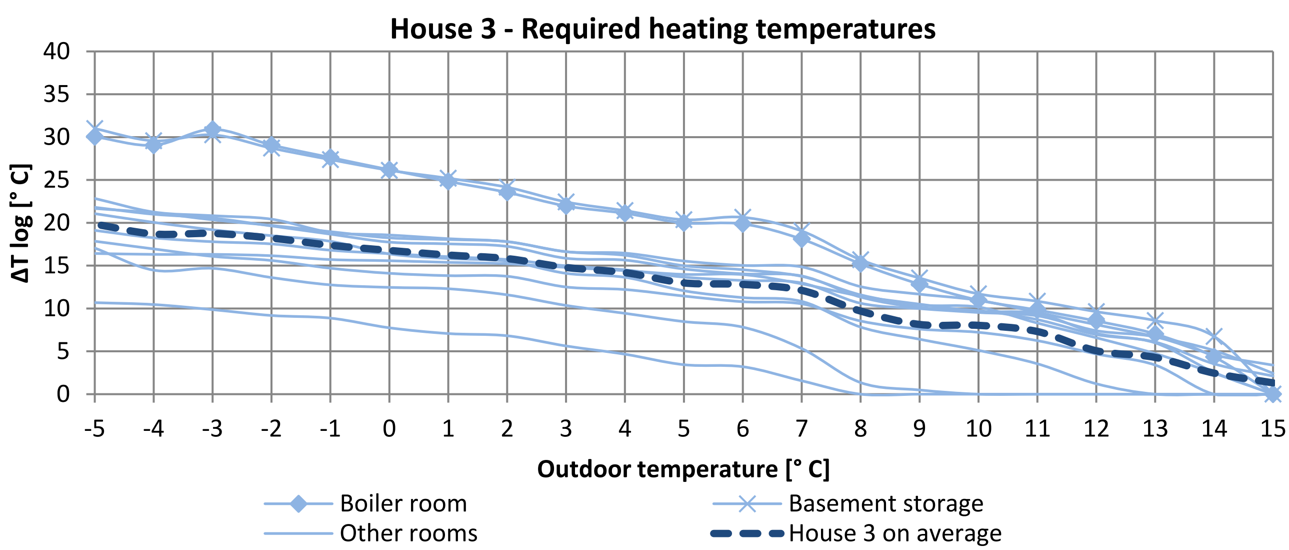

Fig. 6. Graph of required heating temperatures at varying outdoor temperatures – Case-House 3

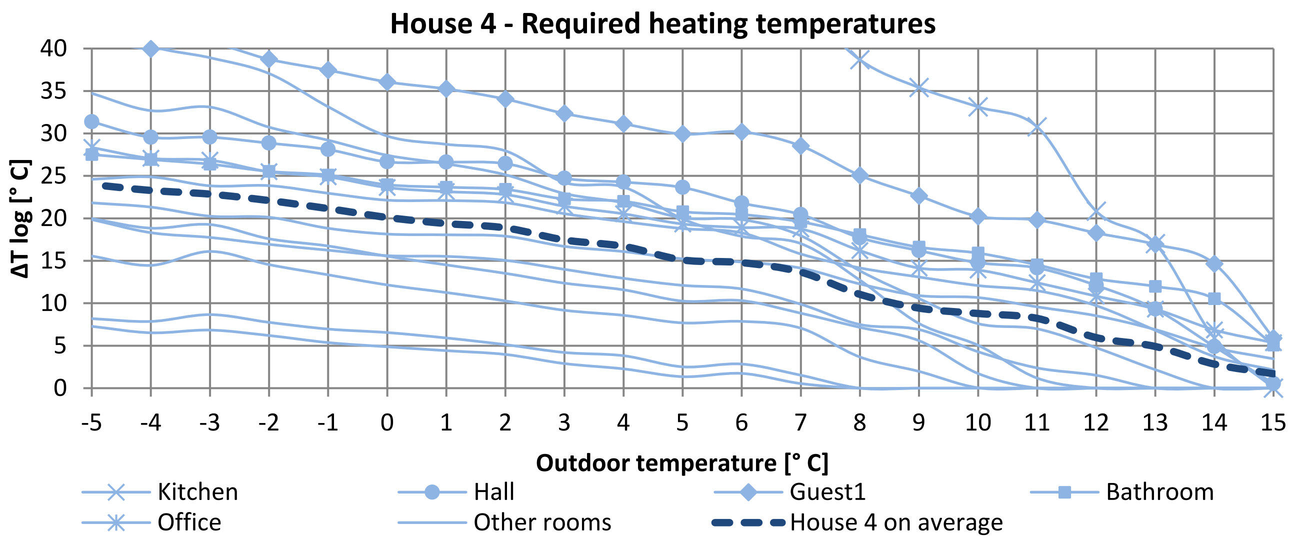

Fig. 7. Graph of required heating temperatures at varying outdoor temperatures – Case-House 4

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
ΔT log [° 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-hoses 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.

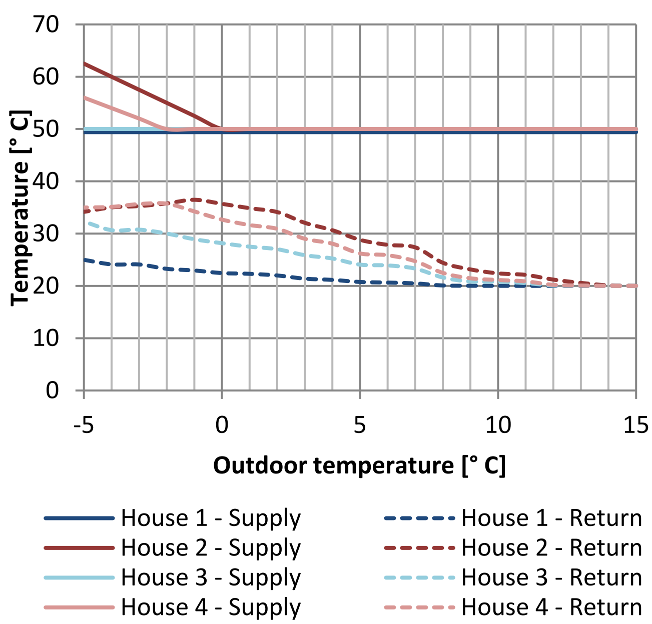

Fig. 8. Suggested supply temperature curves and corresponding return temperatures in the case-houses according to the required average LMDTs.

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

6 Effect of critical radiators

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

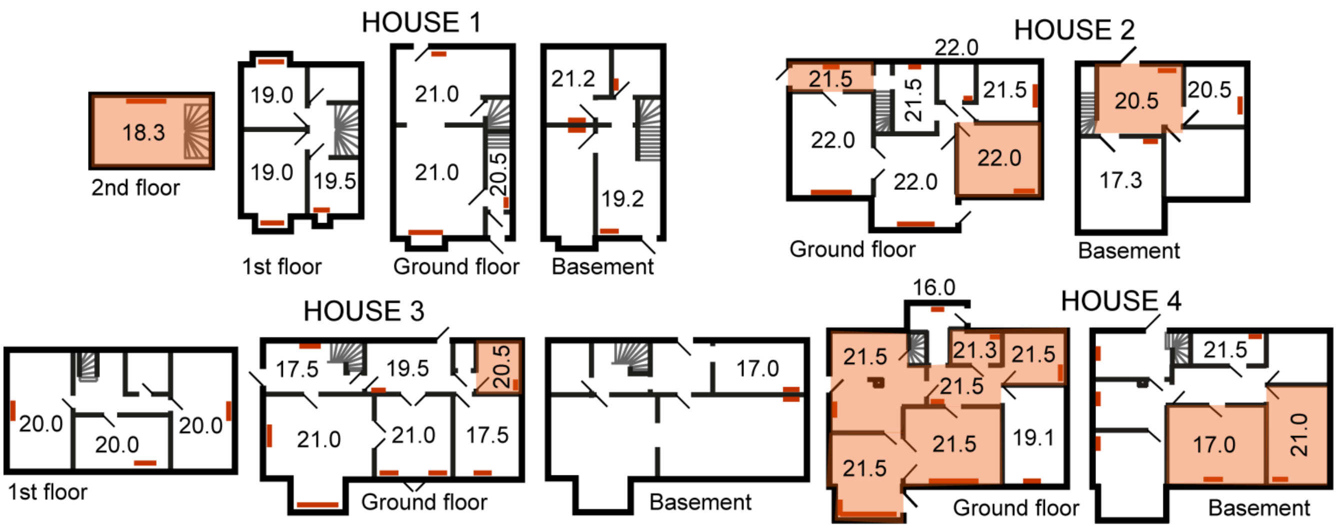

Fig. 9. Indoor temperature set-points and marking of rooms where indoor temperatures were occasionally found to be more than approximately 0.5°C below set-point temperature.

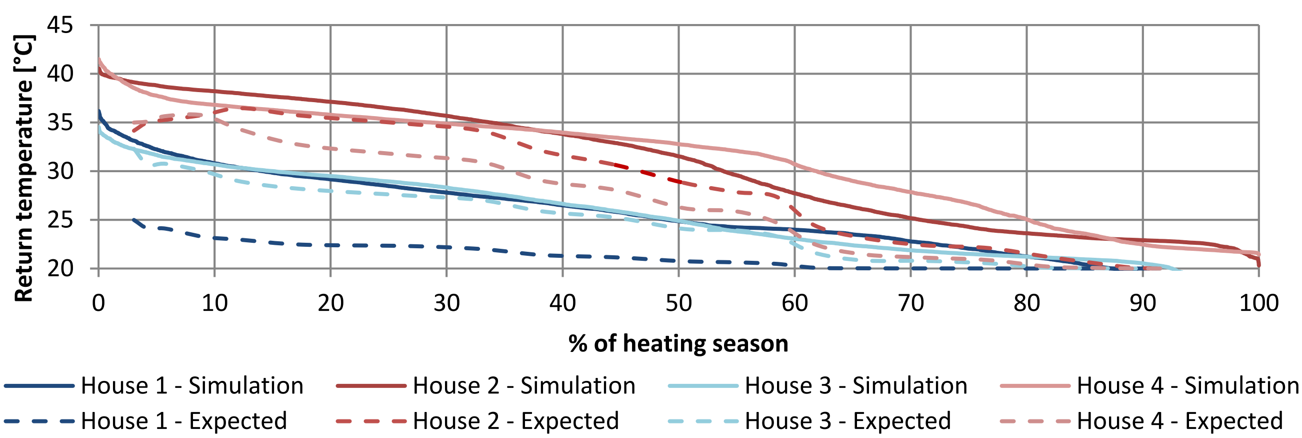

Fig. 10. Expected and simulated heating system return temperatures in the case-houses during the heating season when supply temperatures are based on the supply temperature strategy in Fig. 8.

Fig. 9 show that there are several rooms in House 2 and House 4 where the thermal comfort will be compromised if the supply temperature strategy is implemented. The results indicate that it is necessary to 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 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.

7 Replacing critical radiators

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 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^2 and 162 W/m^2 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.

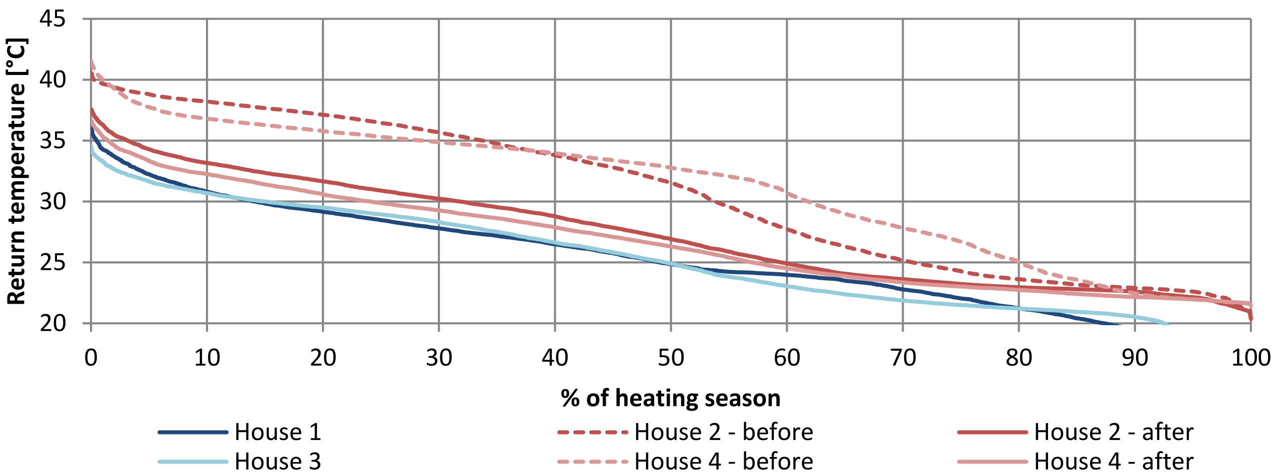

Fig. 11. Heating system return temperatures in the case-houses before and after replacing critical radiators.

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 measurements from the case-houses. However, the calculated heating demands were still subject to some uncertainty due to assumptions made in the models. One assumption that was found to have a large effect on the results was the modelling of the natural ventilation or infiltration in the houses. The models assumed that there was a constant infiltration of 0.3 l/s per m^2 building area in accordance with building code requirements. In some cases, this may be higher than the actual infiltration, because studies show that the air change rates in existing buildings are often lower than the building code requires [43]. During periods with high wind velocities, however, the infiltration may be higher, which can have a large effect on heating demand in houses that are not airtight. Such situations were not taken into account in this study. In cases where high infiltration rates cause poor thermal comfort in a house, it can be assumed that the occupants would be interested in spending money on sealing the building envelope. Alternatively, the district heating supply temperature could be increased in periods with high wind velocity.

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

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

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:

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

3. Evaluation of thermal comfort and return temperatures for the suggested temperature strategy
4. Replacement of radiators where thermal comfort was not met and return temperatures were high

By following this method it was possible to identify critical radiators that needed to be replaced in order to 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 system.

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