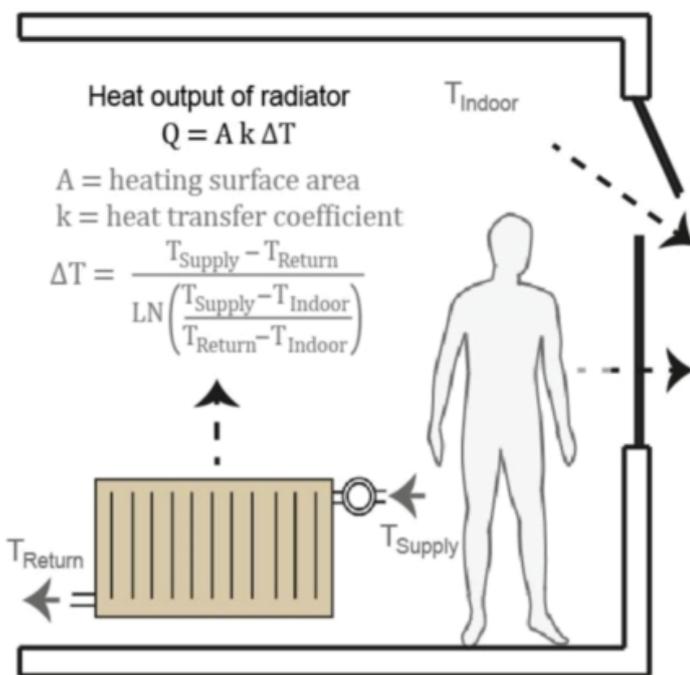


Heating of existing buildings by low-temperature district heating



Dorte Skaarup Østergaard

PhD Thesis

Department of Civil Engineering
 2018

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Preface

This thesis presents the final overview of research I conducted at the Department of Civil Engineering, Technical University of Denmark in the period between June 2014 and August 2018. The thesis is part of the 4DH project, funded by Innovation Fund Denmark.

The research presented would not have been possible without the help and support from many wonderful people, to whom I wish to send a huge thank-you! First of all, I would like to express my sincerest gratitude to my supervisor, Svend Svendsen. Thank you for always respecting my opinion and taking the time to discuss our different perspectives during endless supervision meetings (where you almost always ended being right). Thank you for the valuable guidance that you have provided, and for letting me go my own way at times. And thank you for the humour and laughter that is generally present in our meetings, for the discussions about tomatoes, and for your genuine care about my well-being.

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I would also like to thank my colleagues at DTU for the laughter and discussions that have made every day at DTU worthwhile. A special thank-you is due to those of you I have worked closely with – Maria and Xiaochen – thank you for forming with me a wonderful team of three young women working on district heating, Kevin – thanks for your great engagement and discussions on every aspect of life (and for eating slower than me at lunch), and Marie – thanks for your energetic enthusiasm and all the cake!

Life is, of course, much more than district heating, and therefore I would also like to thank my wonderful friends! Thank you Kristina Mærsk for simply being a perfect friend and always being interested and supportive of this (to some people boring) project. Thanks to Ditte Resendal Gotfredsen for unexpected friendship and support in being a new mum at work. Thanks to all of Sommerhusbanden who simply make my life so much more fun and Morten Stig who inspired me to strive for perfectionism.

Finally, I would like to thank my wonderful family. I feel extremely lucky to have been born into this amazing crowd. In tough times, I have always felt that I could find myself again in your company, and even have a laugh about all the stuff that feels tough. And of course, there is the family I chose myself: Mikkel Østergaard – thanks for being so cute, and Thomas Østergaard – thank you for teaching me about trees that fall in the forest when no one is listening, for improving my skills in discussion and argumentation, for bearing with my complaints when the work was hard, and for supporting me in all aspects of life. It is amazing that I managed to finish this PhD despite the fact that spending time with the two of you is so amazing.

Abstract

This thesis presents the results of four years of research on the possibility of providing existing buildings with space heating based on low-temperature district heating. The study consisted of three main parts. First, we investigated the sizes of current heating elements in existing buildings and the potential for using these heating elements for low-temperature heating. Secondly, we investigated several case study buildings in order to evaluate whether the control and operation of their heating systems constituted a barrier to realizing the full potential of the radiators installed. Thirdly, we investigated the possibility of applying various tools to realize the potential available for low-temperature district heating.

The results showed that there is a big potential for using lower temperatures for space heating because as much as 80% of heating systems are currently over-dimensioned. Temperatures can often be reduced for much of the year even in under-dimensioned heating systems because heating systems are designed for very low outdoor temperatures that only rarely occur in reality. We found several examples of existing single-family houses that have been successfully heated with low-temperature district heating. However, in some of the houses investigated, the results indicated that poor control and heating system design caused heating system return temperatures to be unnecessarily high. Poor hydraulic control was a major issue and this was caused by simple problems like hydraulic short-circuits, thermostats not working optimally, occupants using the thermostats in the wrong way, and a few radiators being too small. It should be possible to overcome such problems by improving the hydraulic control in heating systems and in some cases by replacing a few critical radiators that have a large impact on the overall heating system return temperature.

To ensure long-lasting results, it is vital that continuous fault detection can be carried out. Current research indicates that this can be based on monitoring data from energy meters or heat cost allocator devices. Monitoring of data needs to be combined with a physical inspection of the heating systems to identify crucial design errors, such as hydraulic short-circuits. One drawback of the methods currently used to correct heating system malfunctions is the fact that they are often based on simplifications that do not fit well with the actual conditions in the buildings. It is therefore suggested that these methods should be improved and new efficient tools to ensure proper hydraulic control should be developed, such as a new radiator thermostat with a return temperature sensor or a pump control system that would minimize excess water flows. Finally, in order to ensure that the improvements are carried out, customers must have an incentive to invest in a well-functioning heating system, and there is a need for personnel who can offer the correct service agreements and drive the transition.

The overall conclusion of the study is that there is a large potential for using low-temperature district heating for space heating in existing buildings, and the current results indicate that it is economically feasible to realize this potential between now and 2050. To support the realization of this potential, future work should focus on improving the technical solutions and practical methods for implementing proper heating system control in existing buildings.

List of papers

This doctoral thesis is based on the following papers and publications:

Appended papers:

- I. Østergaard, DS & Svendsen, S 2016, 'Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s', *Energy and Buildings*, vol 126, pp. 375–383. DOI: 10.1016/j.enbuild.2016.05.034
- II. Østergaard, DS & Svendsen, S 2018, 'Are typical radiators over-dimensioned? An analysis of radiator dimensions in 1645 Danish houses', Submitted to *Energy and Buildings*
- III. Østergaard, D & Svendsen, S 2017, 'Space heating with ultra-low-temperature district heating – A case study of four single-family houses from the 1980s', *Energy Procedia*, vol 116, pp. 226–35. DOI: 10.1016/j.egypro.2017.05.070.
- IV. Østergaard, DS & Svendsen, S 2016, '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', *Energy*, vol 110, pp. 75–84. DOI: 10.1016/j.energy.2016.03.140
- V. Østergaard, DS & Svendsen, S 2018, 'Experience from a practical test of low-temperature district heating for space heating in five Danish single-family houses from the 1930s', *Energy*, vol 159, pp. 569–578. DOI: 10.1016/j.energy.2018.06.142
- VI. Østergaard, DS & Svendsen, S 2016, 'Case study of low-temperature heating in an existing single-family house – A test of methods for simulation of heating system temperatures', *Energy and Buildings*, vol 126, pp. 535–544. DOI: 10.1016/j.enbuild.2016.05.042
- VII. Østergaard, DS, Paulsen, O, Sørensen, IB, & Svendsen, S 2018, 'Using information from electronic heat cost allocators to identify heating system malfunctions', Submitted to *Energy and Buildings*
- VIII. Østergaard, DS & Svendsen, S 2018, 'The costs and benefits of lowering the district heating temperatures in existing building areas', Submitted to *Energy*

Other publications:

- IX. Østergaard, DS, Sipilä, K, & Rämä, M, 2016, 'Lower temperatures for existing systems in Middelfart', in: *IEA DHC | CHP Annex TS1 Low Temperature District Heating for Future Energy Systems Subtask D : Case studies and demonstrations*, pp. 35–41

Co-authored papers that are part of the PhD study, but not included in the thesis:

- X. Tunzi, M, Østergaard, DS, Svendsen, S, Boukhanouf, R & Cooper, E 2016, 'Method to investigate and plan the application of low temperature district heating to existing hydraulic radiator systems in existing buildings', *Energy*, vol 113, pp. 413–421. DOI: 10.1016/j.energy.2016.07.033
- XI. Lund, RS, Østergaard, DS, Yang, X & Mathiesen, BV 2017, 'Comparison of Low-temperature District Heating Concepts in a Long-Term Energy System Perspective', *International Journal of Sustainable Energy Planning and Management*, vol 12, pp. 5–18.

Table of contents

Preface	3
Abstract	5
List of papers	6
1. Introduction	9
1.1 Low-temperature district heating – background and definitions	9
1.2 Aim and scope	11
1.3 Hypothesis and thesis outline	12
2. State of the art.....	13
2.1 Heating elements and heating demands.....	13
2.2 Heating system control	14
2.3 Identification and correction of faults	17
3. Method.....	18
3.1 Radiator dimensions	18
General investigations of radiator dimensions	19
Dynamic building simulations.....	20
3.2 Heating system control	21
Measurements.....	21
Dynamic building simulations.....	22
3.3 Methods for identification and correction of heating system faults	23
Simple identification of faults	23
Monitoring heating system temperatures	23
4. Results and discussion	25
4.1 Radiator dimensions – the potential for low-temperature heating.....	25
4.2 Heating system control – a barrier for low-temperature heating?	29
4.3 Identification and correction of faults	33
5. Feasibility of low-temperature district heating.....	37
5.1 Cost and benefits for district heating customers	38
5.2 Costs and benefits in the total energy system.....	39
6. Conclusions	42
7. Perspectives and further work	44
References	45

1. INTRODUCTION

1.1 Low-temperature district heating – background and definitions

The future energy system should be free of fossil fuels and should not cause a net emission of CO₂ into the atmosphere. This is an ambitious, but necessary goal, as fossil fuels are a limited resource, and continuous CO₂ emissions will cause climate change that will endanger our way of life. The main issues to address in current energy research therefore are what new energy sources we can rely on and how we can transform our energy system in the cheapest way.

One technology that has the potential to play a large role in the transition of the energy system is district heating. District heating provides an efficient way to make use of renewable energy sources and heat sources that would otherwise be wasted, such as geothermal heat, solar thermal heat, and surplus heat from industry and power production based on biomass or waste [1]. District heating can also increase the flexibility of the energy system by using heat pumps and large thermal storages. Due to these benefits, recent energy system analyses suggest that district heating systems should optimally cover between 53% and 70% of the Danish heating demand in the future [2,3], and that the use of district heating should be expanded in other European countries as well [4].

District heating technology can be categorized according to the system temperatures it uses [5]. Modern systems are often based on lower temperatures, which ensure increased efficiency in both heat production and heat distribution. To achieve an inexpensive transition to a new sustainable energy system, the future district heating system should therefore be based on temperatures that are lower than the current district heating temperatures of around 80–85 °C and 40–45 °C for supply and return [5–7]. Simple estimations show that if for example the district heating temperatures are reduced from 80/40 to 60/30, the costs of delivering district heating based on heat from a mix of solar heating and heat pumps can be decreased by as much as 22% [8].

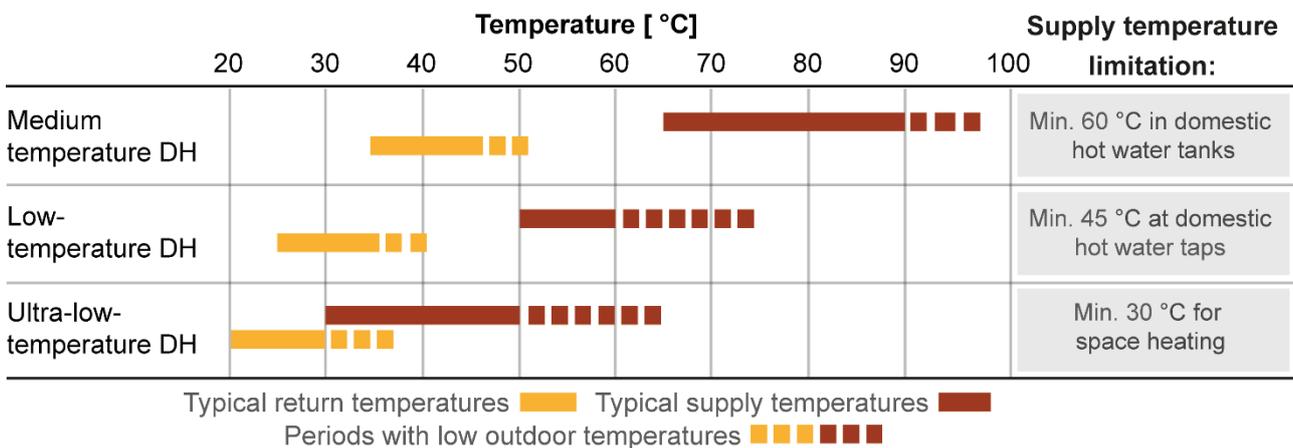


Fig. 1. Definition of temperature levels for different district heating temperature schemes.

The limits to district heating temperatures are set by customer demands, as illustrated in Fig. 1. For most homes, these demands consist of the possibility of maintaining an indoor air temperature of up to 22 °C and to having access to hot water at a temperature of 40–45 °C. Current district heating systems usually have supply temperatures above 65 °C in order to reduce the risk of Legionella bacteria in domestic hot water tanks, but there are several other ways of avoiding this risk. These are described by Yang [9,10] and Li et al. [11], and

include chemical treatments [9], apartment sub-stations [12], and electric tracing of circulation pipes [13]. If the risk of Legionella can be avoided, it is reasonable to reduce the supply temperature to 50–55 °C, which is sufficient to prepare domestic hot water with a temperature of 40–45 °C. Even further temperature reductions can be obtained, if domestic hot water is prepared using supplementary electric heating [14]. This type of district heating is often referred to as ultra-low-temperature district heating or cold district heating, and in this case supply temperatures may ideally be as low as 30 °C for areas with low-energy houses equipped with floor heating. In all cases, district heating temperatures are expected to vary during the year in accordance with variations in space heating demands [15–17]. Space heating demands comprise the majority of the system heat load, which therefore increases on cold winter days [18], making it necessary to increase district heating temperatures. Fig. 1 summarizes the definitions and limitations for the various district heating temperature levels discussed in this thesis, based on the supply temperature requirements of the building installations.

A large number of studies investigating the possibility of lowering district heating temperatures have been published over the past decade. In Denmark, several demonstrations have been made [19,20], where low-temperature district heating has been used for the heating of new terraced houses [21] and existing detached houses [22,23]. Several district heating companies have taken various steps to begin temperature reductions, for example installing automatic network temperature optimization or improving the service of customer installations [15,24]. Guidelines on how to design low-temperature district heating networks have been drawn up [17] and new district heating substations have been developed for supplying low temperatures [25–27]. Even ultra-low-temperature district heating networks have been demonstrated [28–30], based on the development and testing of special substations using supplementary electricity for the preparation of hot water [14,29,31].

The optimal temperature level in a given district heating network depends on local conditions, such as heat density, type of end-users, and available heat sources, as described by Averfalk et al. [32]. Ultra-low-temperature district heating may be efficient for very low-density areas [28], while optimal temperature levels may be somewhat higher in dense city areas with a large number of old buildings [33]. However, low-temperature district heating seems to be an efficient choice for wide implementation [30,34]. It has been found to be a good option for ensuring cost-efficient district heating even in new energy-efficient building areas [35,36], and there are many examples of new buildings and district heating networks designed for low-temperature operation [21,37–41]. Nevertheless, the greatest impact will be achieved when the concept is implemented in existing district heating networks and existing building areas, where the temperature reductions are carried out within the limits of current pipe networks and heating installations.

Two main constraints complicate the transition towards lower temperatures in existing district heating networks. Firstly, the district heating company can make a decision to reduce the supply temperature, but the return temperature is a result of the customer demands and installations, and this cannot be controlled directly [16]. Secondly, both supply and return temperatures must be reduced equally, because a smaller temperature difference between supply and return would cause an increased mass flow that might not be sustainable with the current pipe dimensions. This poses a general problem, because several tests in existing building areas show that, while supply temperatures can often be reduced quite a lot without causing problems for the comfort of customers, there is no guarantee that the return temperature will be reduced by a corresponding amount [23,42–44]. This makes it difficult to reduce the temperature further without exceeding the pressure limits of the pipes [15,24,45], and in winter periods with high heating demands, this leads to supply temperatures far above what is necessary for space heating in the buildings. An initial reduction in the current return temperatures is therefore a necessary step on the road to low-temperature district heating. The reduced return temperature leads to reduced heat losses from the district heating pipes, increased network capacity, and

increased efficiency in heat production based on biomass and waste incineration [16,46], which is very beneficial in the intermediate energy system. In the long run, however, low-temperature district heating should be implemented, because heating demands in buildings have been reduced and the efficiency of new heat sources depends on low supply temperatures. Fig. 2 illustrates the two steps towards low-temperature district heating.

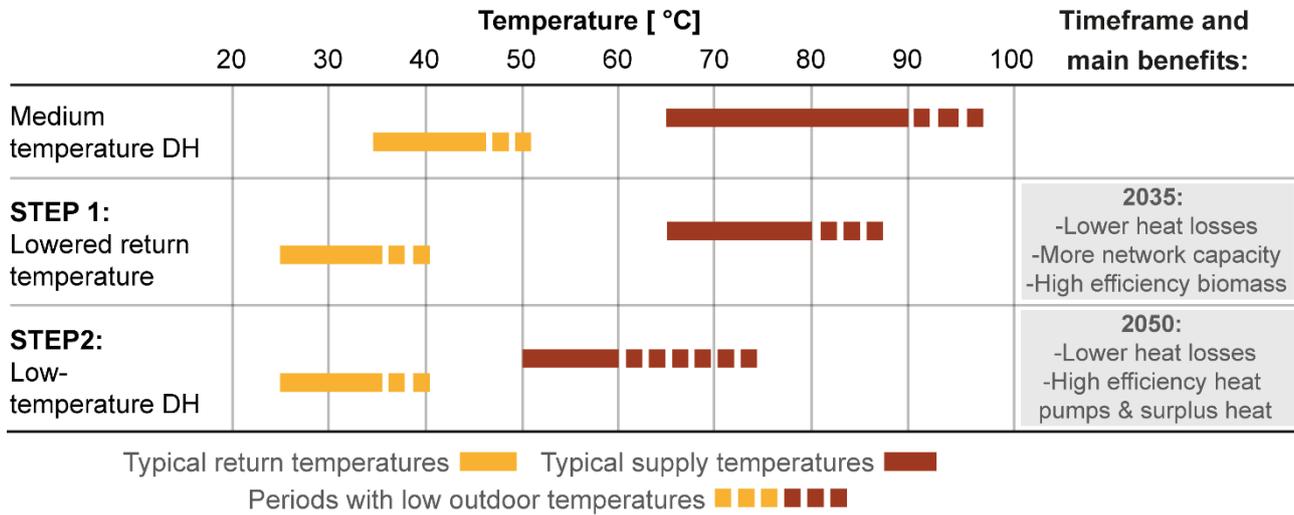


Fig. 2. Description of the two-step approach

Although installations for domestic hot water pose the most apparent limitation to the reduction of current district heating temperatures, existing space heating systems also have a great influence on not only the cost, but even the very possibility of transforming existing district heating systems into low-temperature district heating. Existing heating systems were often designed for high temperature supply, and the operation of the space heating system is of major importance for the return temperature [47]. Despite this, not much is known about the state of typical space heating temperatures in existing buildings [32]. Measurements from heating systems in Switzerland indicate that supply temperatures as low as 50–55 °C may be common in existing buildings already today, while return temperatures on the other hand were found to be relatively high, and the typical difference between them was only 5–10 °C [32]. Similar tendencies have been seen in several case-specific studies, where low-temperature heating has been defined [48] and applied [40,49] with relatively high return temperatures. This is not desirable in low-temperature district heating systems, where both supply and return temperatures should be low. There are examples of existing heating systems operated with low-temperatures that achieve supply and return temperatures close to 50 °C and 30 °C respectively [50,51], but there are very few of them, and little is known about the possibility of applying such temperatures on broad scale. Such knowledge is crucial for estimating the costs and feasibility of converting existing district heating networks to low-temperature district heating. The current project therefore set out to investigate the possibility and feasibility of heating existing buildings with low-temperature district heating.

1.2 Aim and scope

The aim of the current research was to investigate the possibility and feasibility of heating existing buildings with low-temperature district heating. To carry out this investigation, three different aspects were addressed. Firstly, we investigated the sizes of current heating elements in existing buildings and the potential for using these heating elements for low-temperature heating. Secondly, we investigated the control and operation of

heating systems in several case study buildings in order to evaluate whether they provided a barrier to realizing the full potential of the heating elements installed. Thirdly, we investigated the possibility of applying various tools to realize the available potential for low-temperature district heating. The results of these three investigations were combined to assess the feasibility of converting existing building areas to future 4th generation low-temperature district heating.

The research conducted was limited to focus on the Danish building stock. The investigations were therefore limited to heating systems with hydraulic radiators, which is the main type of heating system in existing Danish buildings. The analyses focus on the potential to operate existing heating systems with lower temperatures. They do generally not consider the connection to the district heating system, which has been described in many previous studies.

1.3 Hypothesis and thesis outline

The hypothesis that corresponds to the given aim was formulated as follows:

Typical existing buildings can be heated by low-temperature district heating before 2050 in a way that ensures that investments in corrections of heating system errors and malfunctions can be financed by the energy savings obtained by the district heating companies and owners of the buildings.

The main hypothesis comprises three sub-hypotheses:

- 1) Current heating elements in existing buildings are large enough to ensure proper thermal comfort even if district heating temperatures are lowered
- 2) The control of existing heating systems can be improved to ensure a proper cooling of the district heating medium
- 3) Malfunctions and errors in the heating systems of existing buildings can be identified and corrected by use of simple and efficient methods

If all of the sub-hypotheses are true, it should be inexpensive to transform the current heating systems to low-temperature district heating, and the main hypothesis is therefore true.

The hypotheses were investigated in the appended papers and publications, as shown in Table 1. Please note that some papers are relevant to more than one of the hypotheses. This thesis serves to combine the conclusions of the publications to provide an answer to the hypotheses of the PhD project. Table 1 refers to the chapters of the thesis that describe the overall methods, results, and conclusions for each of the hypotheses. For detailed information on specific methods and results, please refer to the papers appended at the end of the thesis.

Table 1. How to read the thesis and the papers in the PhD.

Content	Chapters	Hypotheses	Papers
Current heating elements – the potential for low-temperature space heating	3.1 and 4.1	Sub-hypothesis 1	I, II, III, IV
Control of heating systems – the barriers to the introduction of low-temperature district heating	3.2 and 4.2	Sub-hypothesis 2	III, IV, V
Identification and correction of faults – how to overcome the barriers	3.3 and 4.3	Sub-hypothesis 3	IV, V, VI, VII, IX
Summary of costs and benefits of low-temperature district heating in existing building areas	5	Main hypothesis	VIII

2. STATE OF THE ART

2.1 Heating elements and heating demands

The *potential* for heating a building with low temperatures generally depends on the relationship between the heat output of the heating elements and the heating demand of the building. Most existing heating elements were designed for high-temperature heating systems [32], and when the heating system temperatures are reduced, their heating output will also be reduced. Nevertheless, there are four reasons why existing heating elements may still be sufficient to provide the required heating even with lower temperatures. These are illustrated in Fig. 3 and consist of: reduced heating demands due to energy renovation, increased internal heat gains from equipment, original dimensioning of heating elements based on extreme design methods, and the limited choice of element sizes available at the time [52]. Several studies have suggested that there are good reasons to believe that components in existing heating systems are often over-dimensioned [22,41,53–55]. These studies were based on both investigations of existing homes and reference to earlier design procedures. Brand et al. [39] have shown that the application of typical design procedures for extreme outdoor temperatures and static conditions could result in an over-dimensioning of radiators by 12–27%. Hasan et al. [41] have also suggested that many heating systems are over-dimensioned because they were designed on the basis of rough rules of thumb. However, there are also studies that report cases where the heating elements are under-dimensioned [20,53,54,56].

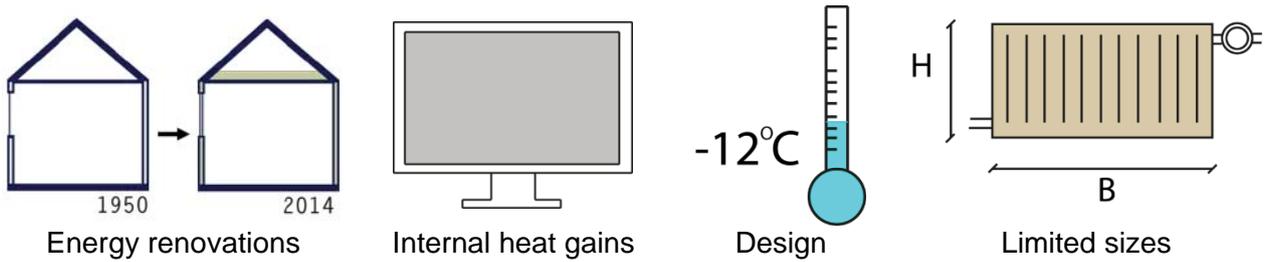


Fig. 3. Four reasons why existing heating elements may be suited for low-temperature operation

The heat output from a radiator (Φ) depends on the surface area of the heating element (A), the heat transfer coefficient (k), and the logarithmic mean temperature difference between the radiator and the surrounding air (ΔT_{log}), as shown in Eq. (1). When the space heating demand decreases, the required heat output decreases, which makes it possible to reduce the heating system temperatures. The main reason it is possible to reduce heating system temperatures for most of the year is therefore the fact that the heat output needed from the radiators during a typical year is much lower than their design heat output, which is calculated for an extremely low outdoor temperature.

$$\text{Eq. (1)} \quad \Phi = A k \Delta T_{log}$$

$$\text{where } \Delta T_{log} = \frac{T_{supply} - T_{return}}{\ln\left(\frac{T_{supply} - T_{indoor}}{T_{return} - T_{indoor}}\right)}$$

If it is desirable to lower the heating system temperatures further, Eq. (1) also reveals that there are three general approaches that will allow this to be done: further energy renovation to reduce the heat output needed, increases in the area of the heating elements, or an increase in the heat emission coefficient of the heating

elements [57]. These three solutions have been widely studied in the literature. Studies on the effect of energy renovations by Brand & Svendsen [58] and Wang et al. [59] showed that typical Danish and Swedish homes can be heated with low-temperature heating if some energy renovation is carried out. Harrestrup & Svendsen [60] showed that, even in old historical buildings, heating system temperatures can be dramatically reduced if a thorough energy renovation is carried out. A similar tendency has been demonstrated in Albertslund, Denmark, where the renovation of more than 1500 homes reduced heating demand by 60%, enabling low-temperature district heating with supply and return temperatures of 55 °C and 30 °C respectively [15]. However, energy renovation does not always reduce the heating demand as much as expected, because occupants often increase their comfort temperature after a renovation [61]. Furthermore, even though energy renovation provides energy savings and should therefore be carried out to some extent, it is still an expensive option compared to investment in heating system improvements [62,63]. A recent Danish study therefore suggests that it might be more cost-efficient to increase the heating surface area of a couple of radiators instead [22]. Similarly, Nagy et al. [49] suggest that heating system temperatures can be reduced dramatically just by increasing the size of the heating elements, which could be beneficial in old historical buildings where energy renovation can be difficult to carry out for aesthetic reasons. The size of the heating elements can be increased either by installing larger low-temperature radiators or through the installation of floor heating or heating panels – all of which provide good alternatives [38,40,64]. The installation of new heating elements may provide additional benefits, such as increased comfort, aesthetic improvements, and improved indoor air quality [48,65]. Nevertheless, new heating elements can also be expensive, and the cheapest way to increase the heat output is probably to increase the heat transfer coefficient of the existing radiators. This can be done by installing add-on fan blowers that increase the convective heat transfer of the heating elements [66,67]. This solution can also be combined with an air inlet to preheat ventilation air [64,68,69], giving the additional benefit that a minimum air change rate can be ensured. Studies suggest that this type of forced convection along the heating surface can make it possible to lower the supply temperature by 8–10 °C [64,66]. Other solutions that could increase the heat transfer coefficient might be ensuring the correct connections and location of the radiator, and avoiding concealers or cabinets that can reduce heat output by as much as 25% [70–72].

In conclusion, there are a lot of technical solutions that can enable the use of low-temperature heating. *The main question therefore is how often such solutions need to be applied. This depends on the dimensions and heat output from current heating elements, which need to be investigated in detail in order to estimate their potential for heating existing buildings with lower temperatures.*

2.2 Heating system control

If there is a big potential for using low-temperature heating in existing buildings, it may seem strange that this potential has not been realized. Current research suggests that the main explanation for this is poor control, hydraulic short-circuits, and malfunctions in heating installations [47]. To avoid these types of issue, various control components are therefore typically installed.

While Eq. (1) describes the heat transfer from the radiator to the air, the heat delivered from the central heating unit to each radiator depends on the heating system temperatures (T_{supply} and T_{return}) and the water mass flow rate (m) as given in Eq. (2). Due to conservation of energy, the two equations describing the heat transferred from the water to the radiator and the heat output from the radiator to the air should always be equal.

$$\text{Eq. (2).} \quad \Phi = m c_p (T_{supply} - T_{return})$$

If enough pump pressure is available and no proper control components are installed, the water mass flow rate through a radiator can become very high. This will impact the thermal comfort of occupants, as the heat output of the radiator increases. Nevertheless, the heat output only increases to a certain point; see Fig. 4 (left), which shows an example of the relationship between the water mass flow rate and the radiator heat output. A bigger effect of insufficient mass flow control is seen in the efficiency of the heating system. Fig. 4 (right) shows the relationship between mass flow and return temperature for a normal load situation (50% load), a design load situation (100% load), and if a large uncontrolled mass flow occurs. The uncontrolled mass flow means a high return temperature, which will have a large impact on the overall system return temperature, because the total volume of water can easily be more than 10 times greater than the volume of water flowing through a properly regulated radiator. To ensure correct heating system operation, control components are therefore designed to regulate the heating system supply temperature and water mass flow and thereby ensure that the correct amount of heat is delivered to each radiator.

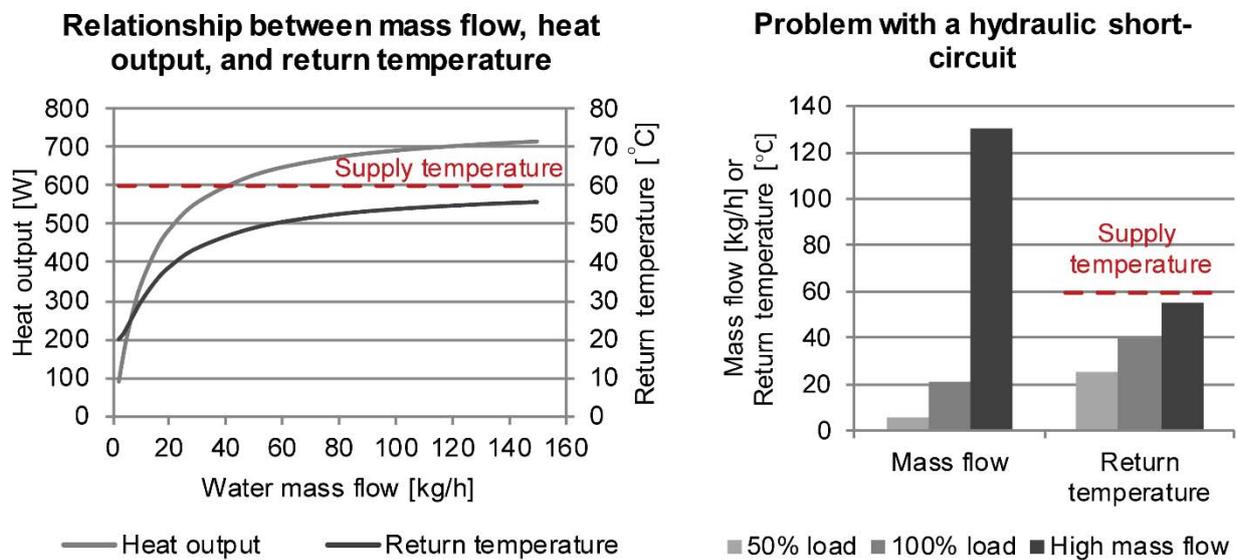


Fig. 4. Illustration of the relationship between water mass flow, heat output, and return temperature of a radiator (left) and illustration of how a short circuit in one radiator can cause problems for the total heating system efficiency (right)

Typical Danish installations for district heating and space heating consist of a substation, either direct or indirect, a double-pipe distribution system, and a number of radiators. The central control system typically consists of a weather compensation system where the supply temperature in the heating system is controlled in relation to the outdoor temperature, and a pump that ensures that there is enough pressure difference in the pipe system to keep the water circulating. Additionally, individual thermostatic radiator valves are installed on all radiators to control the water mass flow rate passing through the radiator in accordance with the required heat output. To do this, the valve opening, and thereby the water mass flow rate, is increased if the indoor temperature is below the thermostat set-point, and reduced if the indoor temperature is above the set-point. A typical heating system including control components is illustrated in Fig. 5.

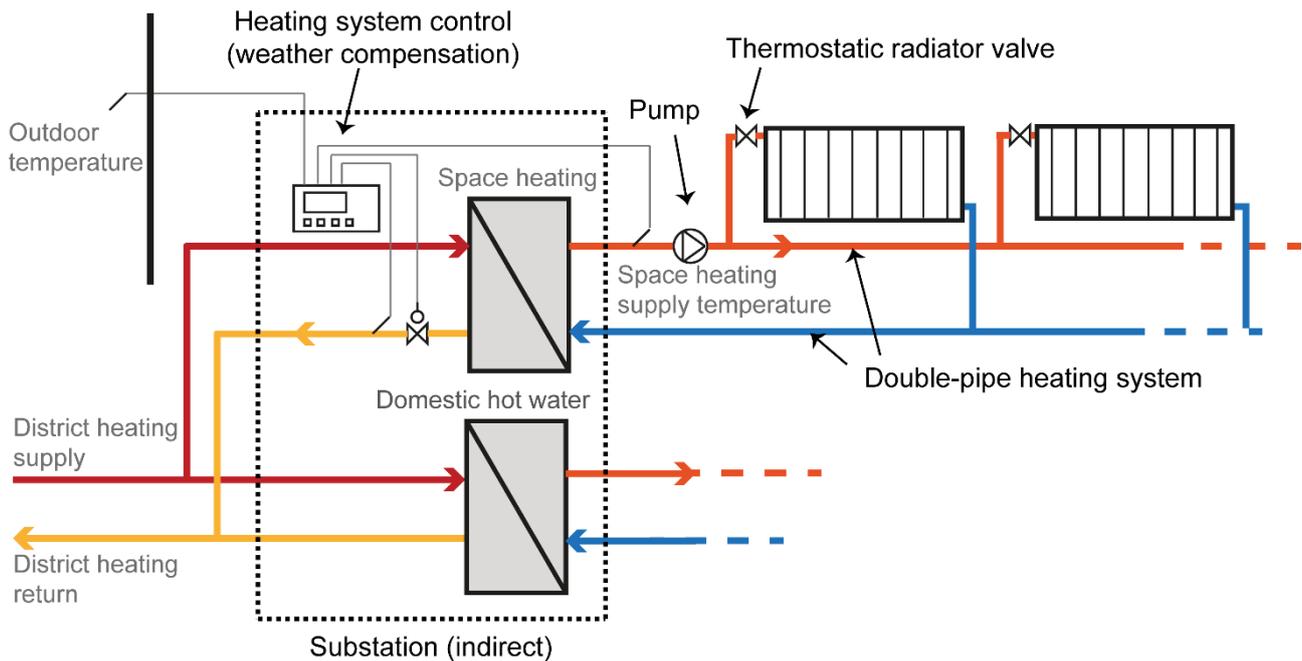


Fig. 5. Simplified illustration of typical heating installations in a Danish building with an indirect district heating substation (Paper V)

Despite the control components installed, the operation of current heating systems is often far from optimal. Studies have shown that there are faults in the operation of up to 75% of substations [73] and that these faults commonly lead to heating system malfunctions [16]. Several studies have therefore investigated how heating systems can be made to operate properly. The main aim of these studies was to investigate various ways of achieving energy savings and ensuring the proper thermal comfort of occupants through improved heating system control [51,55,62,63,74–78]. The results highlight the following measures, which have been shown to have a great impact on the efficiency of the heating system control [32,63]:

- Improved control (weather compensation, adjusted heat operation times)
- Hydraulic balancing (using pre-settable thermostatic radiator valves to adjust valve openings and ensure equal pressure difference across all radiators)
- Improved pump control (efficient variable speed pumps, and removal of by-passes).

Very few studies have performed detailed investigations on the effect that proper heating system control has on heating system temperatures, although faults in the heating system have been found to be a major cause of high return temperatures [79]. However, the subject has been given some focus especially in Swedish studies [52,79,80]. To achieve the lowest possible return temperature, these studies suggest that the ideal strategy would be to balance the heating system using a low-flow approach and make use of the highest possible heating system supply temperature available in the district heating system [79–81]. In addition to low return temperatures, the low-flow method also reduces pressure differentials, the pumping power required, and noises in the heating system [79]. Furthermore, the method imposes high valve authority, which simplifies design and balancing. One drawback to the low-flow method is that the system is less robust than a heating system that is balanced for a high flow rate [79,81–83]. It may therefore require a higher level of expertise to ensure the proper functionality of a heating system balanced for a low flow rate. The complexity of the task is further increased by the interaction between the different heating system components [83] and the fact that

thermostatic radiator valves do not always provide perfect control [39,84,85] and are often not operated properly [55,74,86,87].

Nevertheless, if the hydraulic control is designed correctly, this can produce large benefits for the operation of the heating system [51], and recent research suggests that, if both substation and internal heating installations are working properly, return temperatures can be as low as 30 °C [79]. Such low return temperatures are not typical in practice, but not much is known about the reason for this, because there is not much detailed knowledge on the operation of current heating systems in practice. *In order to estimate the cost of the transition to low-temperature district heating, there is therefore a need for new knowledge on the details of heating system operation in practice so that the specific issues in heating systems that lead to heating system return temperatures being higher than expected can be identified.*

2.3 Identification and correction of faults

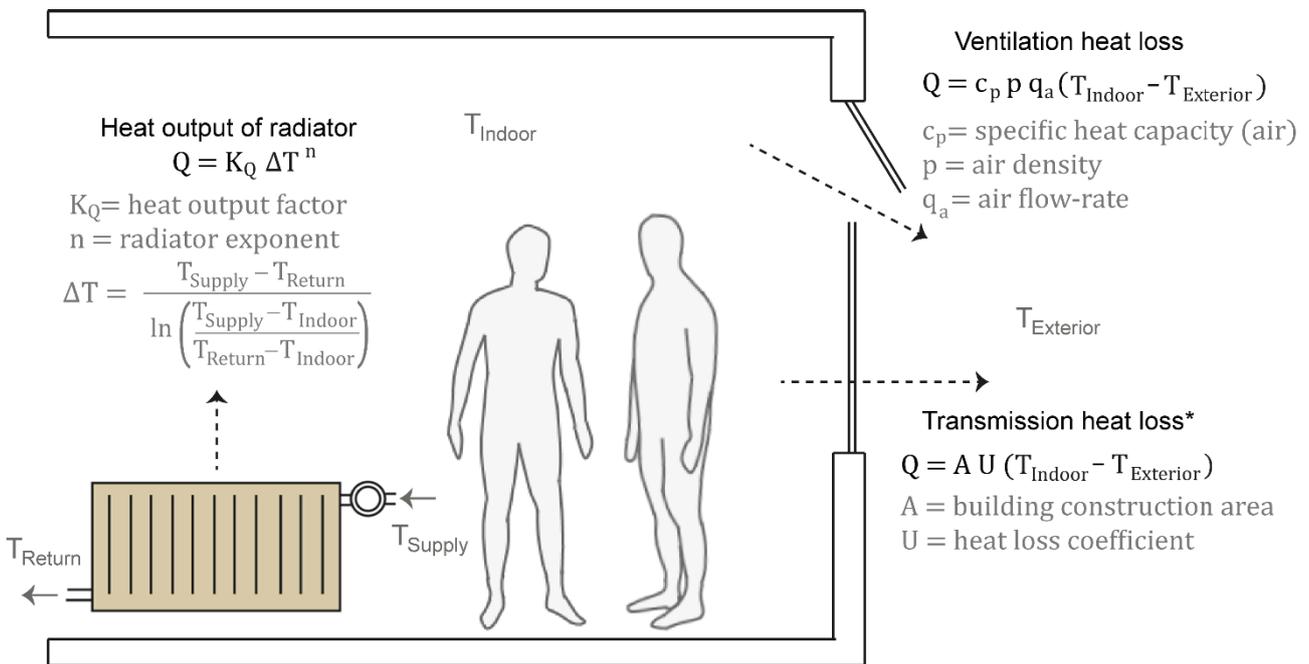
Various tools can be applied to make sure that heating system components are up to date and meet the requirements for low-temperature operation. The current Danish building regulations prescribe that new heating elements should be designed for low-temperatures, that individual thermostatic control should be available in all rooms, and that the heating system supply temperature should be controlled in accordance with outdoor temperatures [88]. Local district heating companies can impose additional requirements for new installations to ensure that district heating substations meet the specifications for low-temperature operation within a reasonable time horizon [15,32]. However, several studies indicate that even where proper heating system control components have been installed, they do not always work as intended, because they have not been adjusted correctly by technicians [32,55]. Furthermore, there are good reasons to check the operation of a heating system regularly, because heating system settings get modified over time [51], and faults constantly arise in the control of a heating system [7]. Since occupants are not likely to react to poor heating system control unless their comfort is jeopardized, there is a need for tools to identify faults so that technicians can ensure that heating systems work properly [55,74].

Several studies have described the faults that occur in district heating substations [7,16,89,90], and how they can often be identified through analysis of data collected wirelessly from energy meters [91]. The central heating substation is often easily accessible for service managers, which makes fault correction easier, as illustrated by Petersson & Werner [79]. The service and supervision of district heating substations are also common tools employed by district heating companies working to reduce district heating temperatures [15,32]. Malfunctions that occur in a space heating system may be more difficult to identify and correct, due to occupants' right to privacy. In Denmark, customers are sometimes encouraged to have regular service checks carried out by specially trained plumbers who can provide advice on the dimensions and control of heating elements. Alternatively, end-users may be encouraged to react to heating system malfunctions themselves if the correct economic incentive can be found, such as the introduction of bonuses or penalties depending on customer return temperatures [15,32,92]. This is often combined with increased dialogue and special help for consumers with particularly high return temperatures. Recent research indicates that these tools have a beneficial effect on the temperature levels in the district heating network [92], but generally only limited data is available on the efficiency of applying these types of tools. Furthermore, most of the available tools are not applicable in multi-family buildings, where it is difficult to identify the occupants actually causing the problems in the heating system. *To support the process towards low-temperature district heating there is therefore a need not only for more knowledge on the efficiency of currently available tools such as service checks, but also for new and inexpensive ways of identifying faults in the heating systems of apartment buildings.*

3. METHOD

3.1 Radiator dimensions

The first sub-hypothesis concerned the current radiator-dimensions. Four studies contributed to the investigation of this sub-hypothesis. They all focused on comparing the heating demand in existing buildings with the heat output of the installed radiators, in order to provide new knowledge on the potential for heating current buildings with lower heating system temperatures. The heating demand in a building depends on heat losses, while the heat output of a radiator depends on the size and type of radiator and the heating system temperatures applied. Fig. 6 illustrates the basic equations used to describe the heat loss in a building and the heat output of its radiators. To maintain a stable indoor temperature, the two should always be equal.



* Linear heat losses from connections can be added if these are not included in the general U-values of the construction elements, and heat gains from occupants, equipment, and the sun can be taken into account where appropriate.

Fig. 6. The heating demand in a room compared with the heat output of a radiator

The figure shows that the heat loss from a building is driven by the temperature difference between indoor air and outdoor air, while the heat output from the radiator is driven by the temperature difference between the radiator surface and the indoor air. The heat output of a radiator therefore has to be given in relation to a specific heating demand situation and the heating system temperatures available. This study investigated a two-part method for doing this.

In the first part, the dimensions of the current heating elements were investigated with regard to the design situation, in order to provide a simple reference for the heat output of the radiators installed in the building. In Denmark, heating elements must be designed to cover the design heat loss in the building, as described in the Danish standard DS 418 [93]. The design situation is defined as follows: a design indoor temperature of 20 °C, a design outdoor temperature of -12 °C, and no heat gains. Design heating system temperatures are also defined in the building regulations, though they have changed over time, being typically 90/70/20 in the mid-1900s and 70/40/20 in the late 1900s, while in the current building regulations they are 60/40/20. The

relationship between the total design heat output and the design heating demand can thus be given by a factor that describes the dimensions of the heating elements. Here, this factor is referred to as the radiator factor and is defined as follows:

The radiator factor is the ratio between the design heat output of the radiator system with supply and return temperatures of 70 °C/40 °C and the current design heat loss of the building.

The advantage of using the radiator factor is that it provides a simple reference for the heating element dimensions. The factor makes it easy to compare the heating elements installed in different buildings even though they were originally designed for different temperatures and the buildings have gone through differing amounts of energy renovation. This means it is possible to investigate whether there is a difference between heating element dimensions in old buildings and in new buildings.

The second part of the method takes into account the actual part-load operation of the heating system during the year. Since the actual heating demands in a building are generally much lower than those that would occur under the extreme design conditions, this method generally highlights how much the actual heating system temperatures can be lowered from the design temperatures. In order to investigate this aspect, the heating demands in buildings during the year were investigated on the basis of typical Danish outdoor temperatures and more realistic indoor temperatures. Furthermore, heat gains from sun, occupants and equipment were included in these evaluations, because they affect the heat balance in buildings during the course of the year. When the heating demand has been calculated for the various outdoor temperatures, the heating system temperatures needed to cover these heating demands can be calculated in accordance with the dimensions of the heating elements. As noted earlier in Eq. (1), the heat output of a radiator depends on both the supply and the return temperature. Different heating system temperatures can therefore be applied to cover the same heat load, so the heating system temperatures suggested are given according to certain strategies. This research investigated two temperature strategies according to the defined path towards low-temperature district heating: a strategy aiming to achieve a low return temperature, and a strategy aiming to achieve a low supply temperature and a reasonable cooling in the heating system.

General investigations of radiator dimensions

The general dimensions of current heating elements in existing buildings were investigated in two different studies. In the first study, the heating demand and the heat output of radiators in typical Danish single-family houses were compared from a theoretical perspective. The investigation was based on the basic typologies of existing Danish single-family houses defined in the TABULA project [94]. Typical construction U-values were estimated for each of the building typologies and applied to investigate the heating demand of each single-family house in its original state. Heating elements were designed in accordance with the original construction U-values, the expected original design heating system temperatures, and typical procedures for the calculation of design heat losses applied throughout the 1900s. Next, various levels of energy renovation were taken into account when calculating the current heat loss of the typical houses. If energy renovations were kept to a minimum, we assumed that at least windows in houses from before 1950 would have been replaced with thermo-windows and that all roofs would include a minimum of 50 mm insulation. If energy renovations were carried out to a reasonable level, we assumed that all windows had been replaced with new double-glazing low-energy windows, all roof constructions included 100–200mm of insulation, and cavity walls and floors over unheated basements were equipped with 60mm and 100mm insulation respectively. Lastly, the steady-state heating demand of the homes at various outdoor temperatures was calculated, and a strategy was suggested for the supply temperatures necessary to cover the heating demands during the year using the current radiator dimensions. Fig. 7 illustrates the typologies of Danish single-family houses investigated in the

theoretical study according to construction period, and the assumed design heating system temperatures for each construction period.

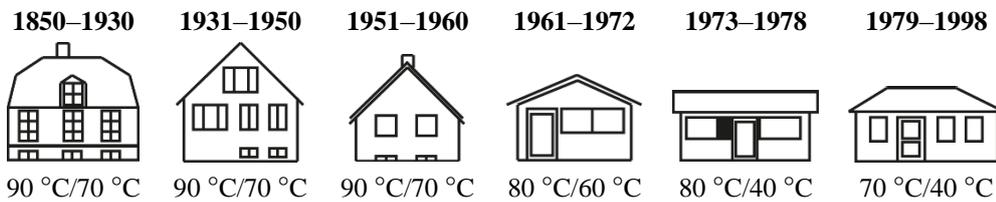


Fig. 7. Illustration of the typologies of Danish single-family houses investigated in the theoretical study (Paper I).

The second general study was based on an analysis of survey data on design heating demands and the design heat output of radiators in 1645 Danish homes. The data was obtained from a Danish scheme designed to provide service checks of heating installations in Danish homes supplied by district heating [95]. During the service checks, plumbers estimated both the design heating demand and the design heat output of radiators in the homes, by evaluating the insulation levels in the home and assessing heating element types and dimensions. These data were compared in order to evaluate whether the actual heating elements in Danish homes are over-dimensioned compared to the actual current state of the buildings. The data was additionally used to provide a forecast of the future when thorough energy renovations are expected to be carried out to reduce current energy demands. This was investigated by assuming that all of the buildings in the survey were renovated to have a maximum design heating demand for space heating of 60 W/m².

These two general investigations serve to provide an overview of the general state of the Danish building stock. However, it should be kept in mind that both analyses are based on rough simplifications, and that they therefore come with considerable uncertainty and fail to take the considerable differences between individual homes into account.

Dynamic building simulations

In order to take the individual details of various buildings into account, dynamic building simulations were used to provide in-depth investigations of the radiator dimensions in nine specific case buildings. The studies were conducted using the commercially available software IDA ICE [96], which is a node-based multi-zone simulation program that can be used to perform calculations on the energy consumption in buildings in accordance with current standards for building simulations [97]. Fig. 8 shows an illustration of the dynamic simulation models of two of the case buildings studied.

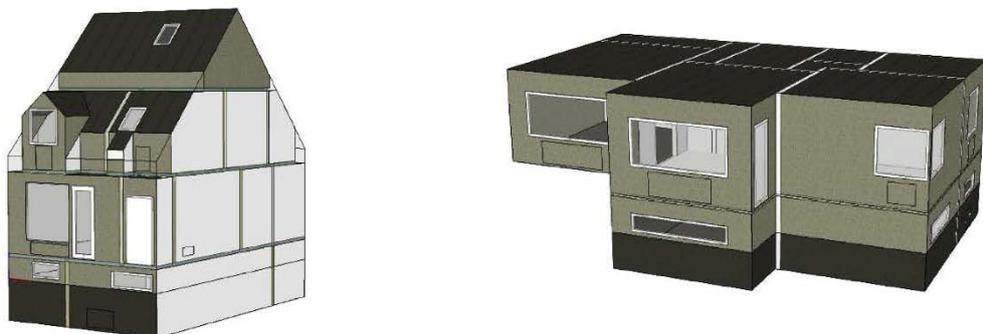


Fig. 8. Illustration of the models for the dynamic simulation of heat balance in two of the case buildings studied (Paper IV)

To build the simulation models, various input information was required for each specific building. The specific geometry of the buildings was based on construction drawings from old archives. These drawings also included information on the construction elements, which was combined with information from occupants, energy labels, and visits to some of the houses. This made it possible to estimate the current insulation level of the houses, on the basis of which U-values for the constructions were estimated from a catalogue over typical constructions in Danish homes [98]. The houses were naturally vented and the heat loss from ventilation was therefore included using a standard infiltration rate of 0.3 l/s per m² heated floor area, which corresponds to the minimum ventilation rate required in the building regulations. Internal heat gains from occupants and equipment were included using detailed schedules.

The simulation program includes a pre-defined radiator element from which the heat output is continuously calculated based on the equations given in Fig. 6. The design heat output of the radiators in each modelled home was estimated using an Excel tool and included in the models. The Excel tool is based on empirical data for the heat output of typical Danish radiators, and includes an uncertainty that may in the worst case be as much as 10–15% due to the big differences in actual heat emission from old radiators.

The building simulation models were used to calculate both the design heat loss of the case buildings and the variations in heating demand during a typical year. For the latter, typical Danish weather was taken into account by using climate data from the Danish Reference Year. The simulation program provides highly detailed results for the heating demand in the buildings, including such complex effects as the thermal inertia of building elements and air flows between zones. The dynamic simulation is a great tool for investigating the impact of well-defined modifications in the heating system or heat balance, or for investigating optimal heating system operation where mechanical faults in the heating systems are neglected. On the other hand, the results from the simulation models are limited by the chosen input, which makes it difficult to investigate unanticipated heating system faults, and makes the results very dependent on the assumptions made for the input parameters.

3.2 Heating system control

The second sub-hypothesis concerned heating system control. Since heating system control depends on individual building installations and occupant behaviour, this sub-hypothesis was investigated through detailed case studies. The investigations covered ten Danish single-family houses where measurements were conducted to investigate the heating system operation and heating system temperatures. Dynamic simulation models were used to represent the expected optimal heating system operation and evaluate how possible changes in heating system design and control would affect the heating system operation. The measurements were compared with the models to provide information about the barriers to achieving the optimal heating system temperatures and about the effect of unanticipated heating system faults and malfunctions.

Measurements

The measurements conducted in the heating systems of the case houses were of indoor temperatures, radiator return temperatures, and overall heating system temperatures. Indoor temperature measurements were conducted with loggers in each room. As far as possible, the loggers were located within the height of the occupied zone and away from heating sources or cold exterior surfaces. The measurements provided an estimate of the occupants' preferred indoor air temperature, although the actual air temperature often varied throughout each room, and occupant comfort was affected for example by surface temperatures and drafts in the rooms. The radiator return temperatures were measured by mounting a temperature logger on the outside of the radiator return pipes, and covering it with insulation, as shown in Fig. 9. Due to the relationship between return temperature and water mass flow mentioned earlier, these measurements provide a good indication of

the heating system control. The measurements are not very accurate, but they are sufficient to monitor temperature changes and provide an indication of the heating system operation. The overall heating system supply and return temperatures were measured using either energy meters where temperature sensors were cut into the pipes, or temperature probes that were connected more carefully and permanently to the heating system pipes, which enabled a more accurate measurement of the heating system temperatures.



Fig. 9. Temperature measurements on the radiator return pipes in some of the houses (Paper V)

Measurements were carried out in the case buildings for a whole heating season, and temperatures were logged approximately every hour and transmitted via a wireless network. This made it possible to monitor the heating systems and both identify and react to faults that occurred over time. If the radiator return temperature measured was continuously much higher than expected from the results of the dynamic simulations, this could indicate the presence of a permanent fault or malfunction, whereas a sudden increase in radiator return temperature could indicate the occurrence of a new fault or malfunction perhaps due to a change in the heating system control. The causes of the heating system faults and malfunctions identified through the measurements were investigated through continuous dialogue with the occupants, and several visits to the case buildings.

Due to the uncertainty of the measurement method chosen, it should be noted that it was not possible to use the measurements to calculate the water mass flow through each radiator. This means that average heating system temperatures could not be calculated based on volume flows, but only as an average over time, which should be kept in mind when average temperatures are provided.

Dynamic building simulations

We used dynamic building simulations to investigate how various changes in heating system design or occupant behaviour would affect the heating system operation. The models were built as described in section 3.1, and whole-year simulations were run to calculate the heating system temperatures during a typical year. The simulation models were used to investigate the expected heating system temperatures during a standard year and to investigate whether any radiators were too small to meet the thermal comfort requirements of occupants and still deliver a low return temperature. If even a few radiators were too small, this was regarded as a fault in the heating system that could lead to return temperatures higher than necessary. The investigation was carried out by evaluating the mean heating system temperatures that were necessary to cover the heating demand of the entire house during the year taking into account the combined heat output of all the radiators installed. This temperature curve was compared with the individual temperature curves necessary for

individual radiators to cover the heating demand in individual rooms. In this way, it was possible to discover whether any radiators required much higher heating system temperatures than average, so that it would be possible to reduce heating system temperatures dramatically by replacing just a few critical radiators. Although the results are subject to many uncertainties due to the assumptions made in the models, they provide a valuable theoretical basis for drawing conclusions on the expected benefits of changes in heating system design and control that would be expensive to test in practice.

3.3 Methods for identification and correction of heating system faults

The third sub-hypothesis aimed to investigate simple ways of identifying and correcting heating system faults. This sub-hypothesis provided a common theme in all the studies conducted in the sense that a major goal in all the studies was to provide good examples of how the heating systems of existing buildings could be brought to operate with low temperatures. The case studies conducted, including house-visits, simulation models, and measurements, all provided input for the evaluation of possible ways of identifying and correcting heating system malfunctions. We also evaluated two methods of continuous fault detection. First, we reported on the reduction in district heating temperatures that has been achieved in Middelfart's district heating by using automatic temperature optimization in the network and providing continuous monitoring and service of customer substations. Second, we investigated a new way of identifying heating system faults, whereby return temperatures from radiators in apartment buildings were estimated and monitored based on data from already installed electronic heat cost allocators.

Simple identification of faults

When the case studies of single-family houses were performed, the heating installations and heating elements were generally checked for apparent malfunctions, faults, or missing control components. A similar type of service check is offered on a regular basis by specially trained plumbers through Fjernvarmens Serviceordning, which is supported by many local district heating companies. In this study, we therefore investigated the following conditions that are typically also included in a standard service check:

- Radiator types and sizes
- Connections and installation of radiators
- Radiator valves and thermostats
- The location and installation of heating system pipes
- Substation components and control curves

The observed conditions provided a general impression of the state of current heating system design and control, while actual heating system operation was investigated through dynamic simulations and measurements. In this way, we were able to evaluate whether a relatively simple physical inspection of the heating system installations would make it possible to identify the components causing problems for the heating system control. In some cases, it was also possible to test whether proposed changes in the heating system would help correct problems identified in the operation of the heating system. However, these tests depended on the willingness of occupants to change habits and the cost of the heating system improvements suggested.

Monitoring heating system temperatures

The potential benefits of performing service checks based on the continuous monitoring of substation temperatures were evaluated through a case study of the Danish district heating company in Middelfart. The district heating company installed an automatic network temperature optimization tool and hired someone to

help achieve the reductions in customer return temperatures that would be necessary to enable further reductions in supply temperatures. The employee monitors data from the energy meters of district heating customers and reacts to any indications of faults in the customer installations. Customers with high district heating return temperatures and customers who are subject to a sudden increase in district heating return temperatures are contacted and offered a service check and advice on how to solve the problems identified. We therefore reported on how it has been possible to reduce the district heating temperatures in Middelfart as a consequence of the introduction of automatic temperature optimization and the continuous monitoring of customer installations.

In order to meet the need for a tool to monitor heating system operation in apartment buildings, a new method for identifying heating system faults was developed and tested as part of the research. The method is based on data from electronic heat cost allocators that are already installed on all heating elements in many Danish and European apartment buildings to enable the distribution of the heating bill between the various occupants of the buildings. The heat cost allocators provide a cheap source of data on the heating system operation in these apartment buildings. The heat cost allocators continuously measure the indoor air temperature and the radiator surface temperature in order to estimate the heat emitted from each radiator. Since the allocator is electronic, the information on the emitted units of heat can be transmitted via a wireless network which makes it possible to monitor the data online. The data on heat emissions can be correlated to the return temperature of each radiator, as illustrated in Fig. 10 (left). The relationship is based on numerical equations that were derived by Otto Paulsen from the Danish Technological Institute as a result of an integration of the basic equations for heat output from radiators, as illustrated in Fig. 10 (right). The accuracy of the method has been tested in a case study of an apartment building in Frederiksberg, Copenhagen [99], where the calculated return temperatures were compared with measured radiator return temperatures.

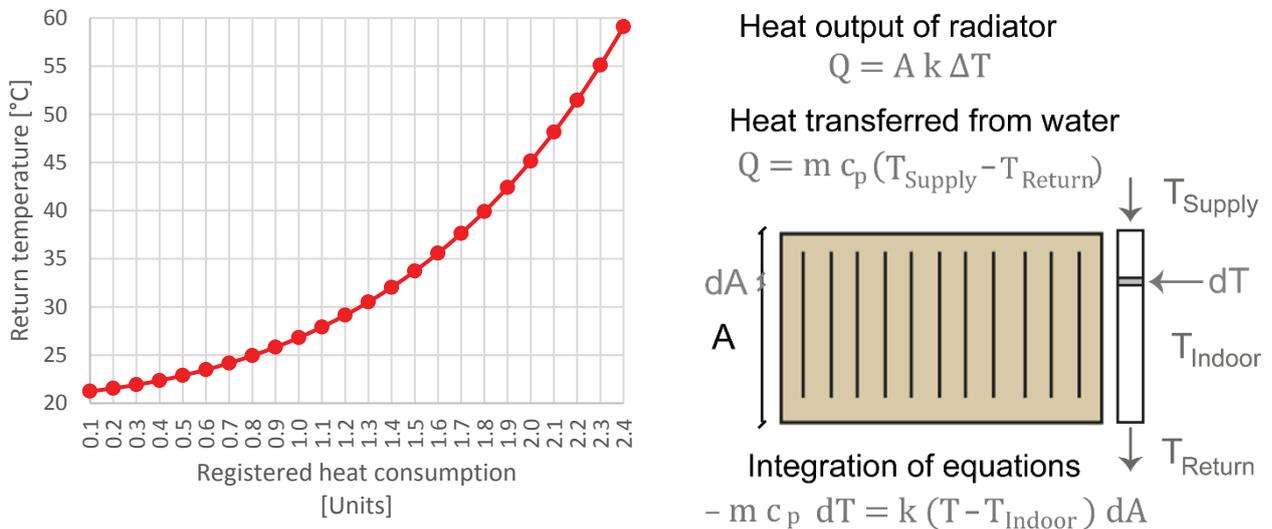


Fig. 10. Example of the relationship between emitted units of heat registered by a heat cost allocator and calculated radiator return temperatures (left) and basic equations for the derivation of the relationship between data from heat cost allocators and radiator return temperatures (right) (Paper VII).

4. RESULTS AND DISCUSSION

4.1 Radiator dimensions – the potential for low-temperature heating

Fig. 11 shows the results of the investigations on the dimensions of existing radiators, as illustrated by the radiator factor (a radiator factor of 1.0 implies that the heating system is dimensioned exactly to cover the design heating demand of the building with the heating system temperatures 70 °C/40 °C). The blue bars represent the results of the theoretical analysis, where the upper part of the bar represents a case where all the houses are equipped with double-glazing low-energy windows, all roof constructions include 100–200 mm of insulation, and cavity walls and floors over unheated basements have 60 and 100mm insulation respectively. The lower part of the bar represents a case where the houses from before 1950 are equipped with thermowindows and all the houses have a minimum of 50 mm insulation under the roof. The boxes and whiskers represent the results of the analysis of survey data, where the box represents the radiator factors of 25–75% of the data, while the top and bottom whiskers represent the top 5% and bottom 5% of the data. The red crosses indicate the radiator dimensions of the case buildings investigated.

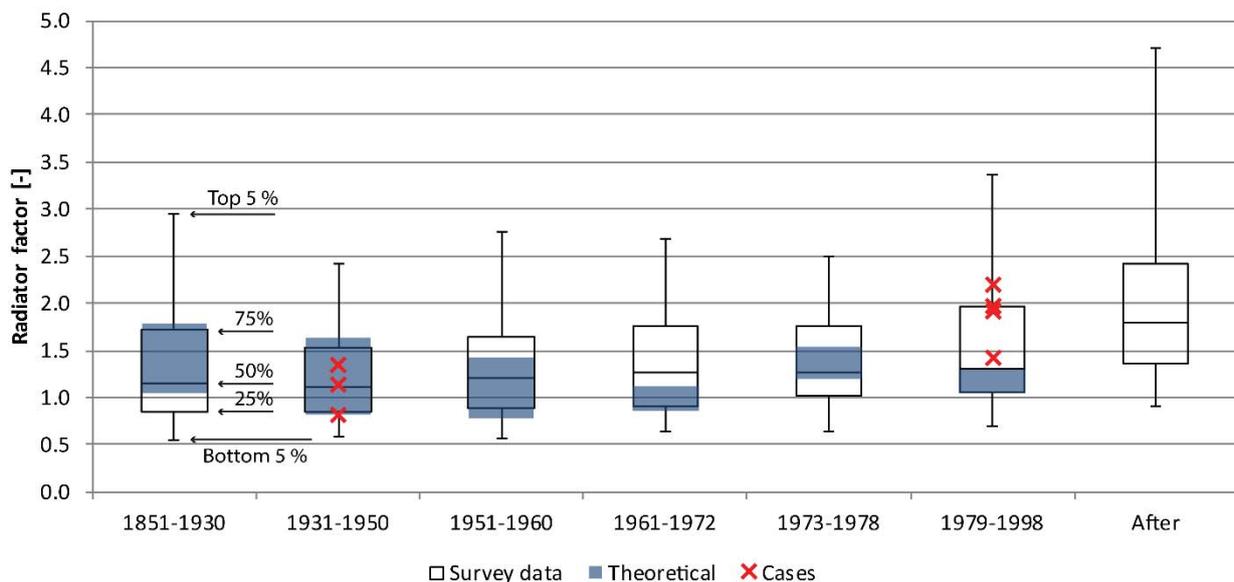


Fig. 11. Radiator factor for the buildings studied in Papers I–VI.

As indicated by the figure, the results of this research support the consensus that typical existing heating elements are over-dimensioned, because the majority of the heating systems have a radiator factor above 1.0. However, the results also show that heating systems that are under-dimensioned compared to the design temperature set 70 °C/40 °C are not uncommon.

The results from both the case studies and the analysis of the survey data indicate that heating systems are likely to have a radiator factor above 1.0 in new as well as old homes, though this is true for a larger share of heating systems in new buildings. This is reasonable, because heating systems in new houses were often designed for temperatures of either 70 °C/40 °C or 60 °C/40 °C from the beginning. Heating systems in older houses were designed for higher temperatures, but nevertheless many still meet the requirements of recent standards. This can be explained by energy renovation carried out in the existing buildings and possibly also by a general tendency towards over-dimensioning of heating elements due, for example to the limited

availability of radiator sizes and simple rules of thumb that may have been applied for the heating system design in some cases.

Both sets of studies also indicate that the energy renovations that are expected to be carried out in the future to reduce current energy demands will contribute to a substantial increase in the radiator factor in existing buildings. This was illustrated in the theoretical study, where the upper part of the blue bars in Fig. 11 represents the radiator factor of houses that have gone through energy renovations. The study of the case houses from the 1930s also showed that the houses that had gone through more energy renovation had a higher radiator factor and were easier to heat with lower temperatures. Lastly, as shown in Fig. 12, the analysis of the survey data showed that only 8% of heating systems would have a radiator factor below 1.0 if all existing buildings were renovated to meet a design heating demand of 60 W/m².

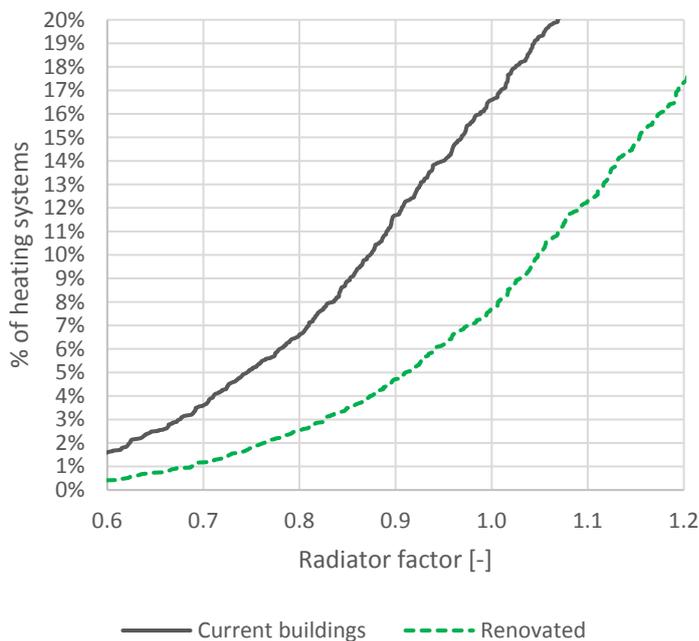


Fig. 12. Radiator factors in current buildings today and in an expected future scenario where all houses have been renovated to meet a design heating demand of 60 W/m² (Paper II).

In conclusion, it is common that heating system dimensions in existing buildings meet the requirements of recent standards. Since current standards are based on an extreme outdoor temperature of $-12\text{ }^{\circ}\text{C}$, existing buildings can therefore generally be heated with supply temperatures much below $70\text{ }^{\circ}\text{C}$ for most of the heating season, when outdoor temperatures are typically in the range between $-5\text{ }^{\circ}\text{C}$ and $15\text{ }^{\circ}\text{C}$. Fig. 13 shows an example of the supply temperature strategies that were found to be applicable in typical existing houses constructed in the period 1951–1972 according to the results of the theoretical study. The figure is based on a heating system cooling of $20\text{ }^{\circ}\text{C}$ and the upper and lower lines represent the supply temperatures applicable in houses that have gone through only general maintenance or thorough energy renovations respectively. As the figure shows, the applicable heating system temperatures are below even current heating system design temperatures of 60/40 for most of the year.

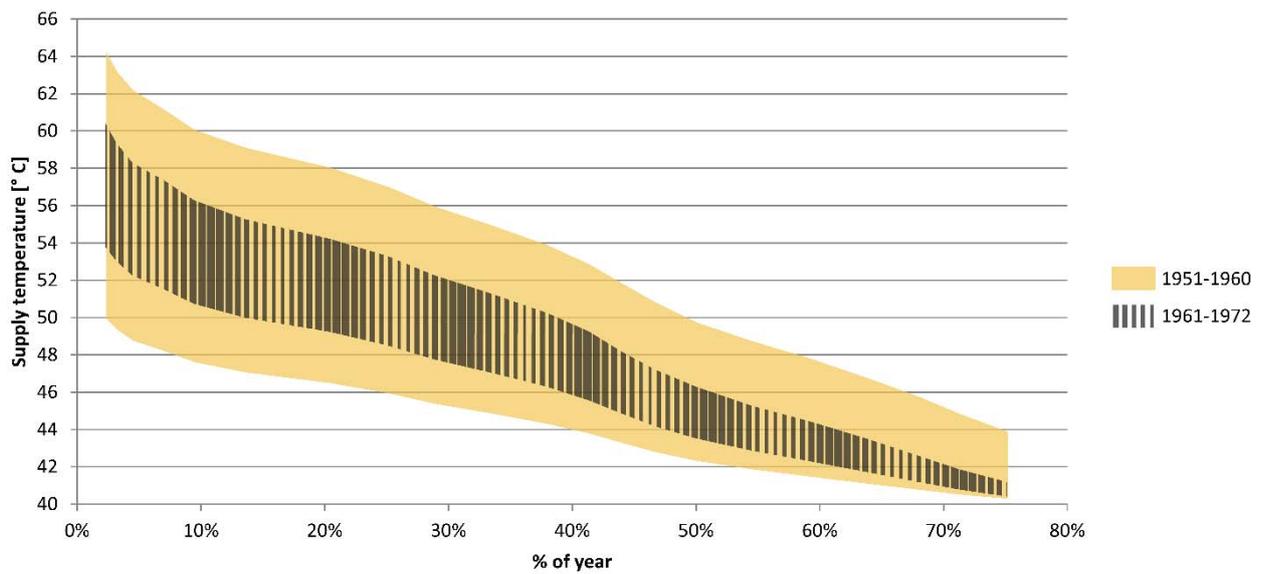


Fig. 13. Illustration of supply temperatures applicable in heating systems of typical single-family houses constructed between 1951 and 1972 during a typical year (Paper I)

For all heating systems with a radiator factor of 1.0 or above, it should therefore be possible to use temperatures below 70 °C/40 °C for most of the year. However, as illustrated in Fig. 14, actual heating system temperatures can be below this temperature level for most of the year, even for the few heating systems where the radiator factor is below 1.0. Alternatively, it should be possible to reduce the return temperatures of heating systems to achieve district heating return temperatures that are far below the current 40 °C when current district heating supply temperatures averaging around 80 °C are considered. Fig. 15 shows the potential return temperatures in buildings where the heating system has a radiator factor of 1.0 or below. It seems that buildings with underdimensioned heating systems are not necessarily a problem, if it can be accepted that these buildings have a somewhat higher return temperature.

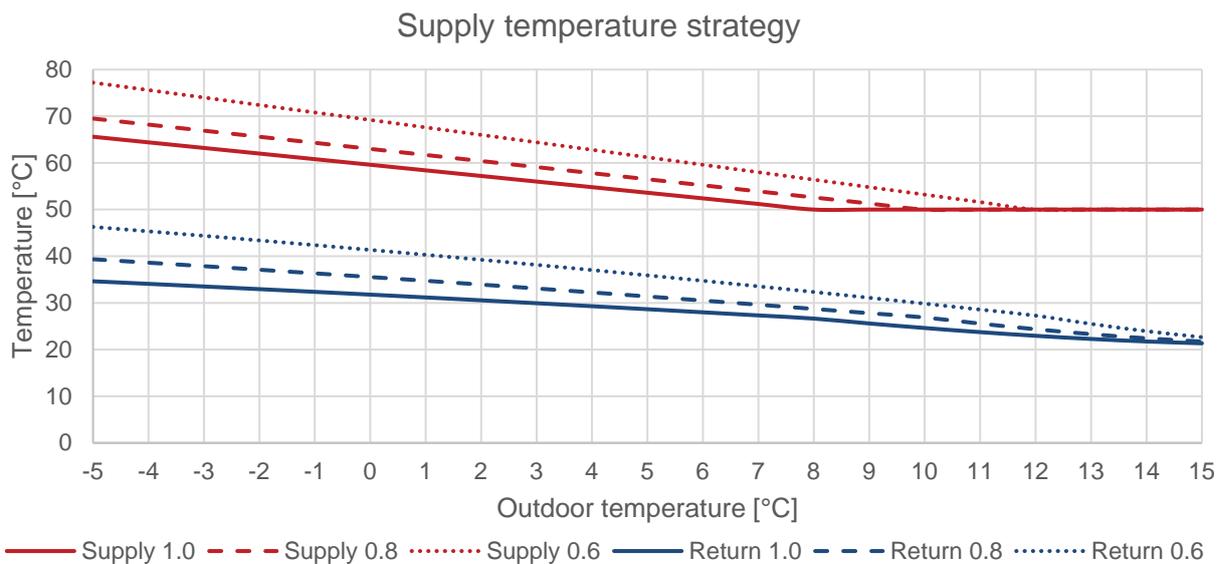


Fig. 14. Suggestion for supply temperature strategies in homes with heating systems with a radiator factor of 0.6, 0.8, or 1.0 (Paper II)

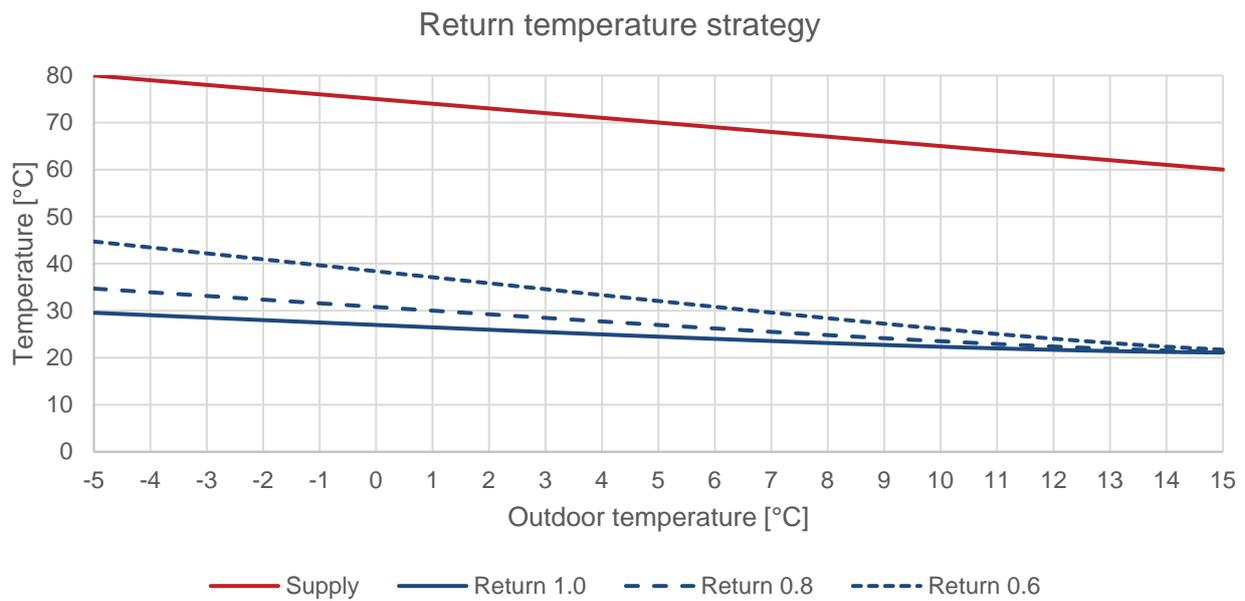


Fig. 15. Suggestion for return temperature strategies in homes with heating systems with a radiator factor of 0.6, 0.8, or 1.0 (Paper II)

The uncertainties in the assumptions of the simulation models and the simplifications made in the general studies must be expected to lead to some uncertainty in the results presented. Nevertheless, the temperature curves illustrated should be regarded as a general indication of the temperature strategies applicable in typical existing buildings. For each individual building, occupant preferences and individual variations must be taken into account and the temperature strategies should be adapted accordingly, but the following overall conclusions can be drawn based on the investigations:

- Current heating elements are usually over-dimensioned, even in terms of recent design standards. Amongst other things, this is due to the fact that maintenance and energy renovations reduce the heating demand of buildings so that lower temperatures can be applied.
- Current heating systems can be operated with temperatures far below the design temperatures for most of the year, because the actual heating demand of buildings is usually much lower than the extreme design heating demand.
- There is no reason to believe that there are any heating systems that cannot be operated with lower supply temperatures, but various return temperatures may have to be accepted due to differences in current heating element dimensions.

All these conclusions are in line with previous findings, which also indicate that heating elements in existing buildings are generally over-dimensioned [22,41,53–55] and show that heating system temperatures can be reduced for most of the year [50]. So, although the current investigation only covered single-family houses, it is not expected that the situation will be much different in other types of buildings, and investigations conducted during this research on an apartment building in Frederiksberg, Copenhagen [99], seem to support the current conclusions. Nevertheless, further analysis should be carried out to verify that the same tendency is also seen in other types of buildings.

4.2 Heating system control – a barrier for low-temperature heating?

Fig. 17 shows the heating system temperatures measured in four houses from the 1980s. The measurements were carried out during the heating season 2015–16 and, as the figure shows, the houses were successfully heated with very low supply and return temperatures, averaging 45 °C/30 °C. The measurements from these houses provide a valuable demonstration that it really is possible for heating systems to be controlled in a way that enables the use of low-temperature heating in existing buildings.

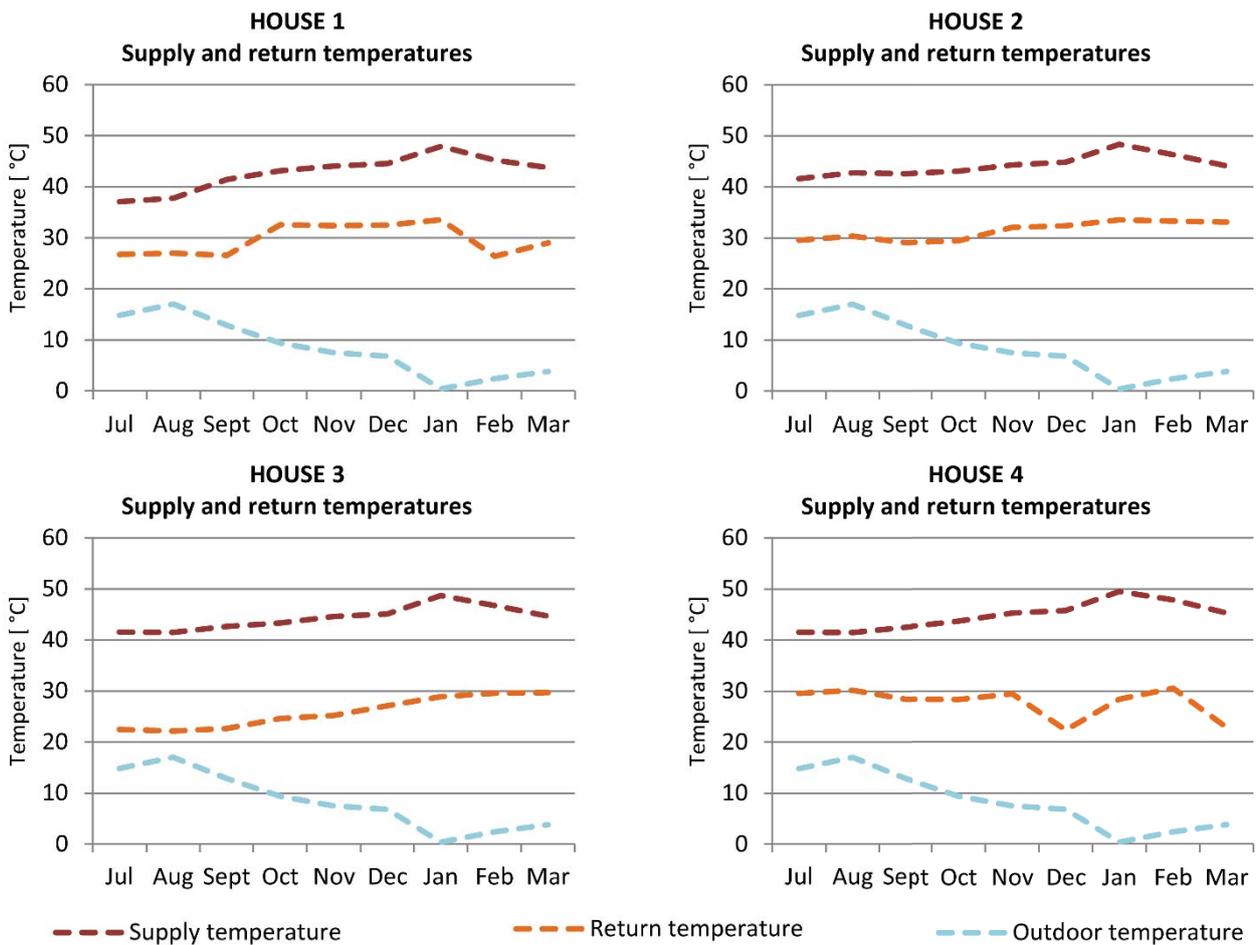


Fig. 16. Supply and return temperatures in four houses from the 1980s (Paper III)

Fig. 17 shows the average heating system return temperatures measured in five single-family houses from the 1930s in the period from 1st September 2015 to 1st April 2016. The houses were heated with supply temperatures as low as 55 °C for most of the measurement period. The colours indicate the return temperature measurements from all the radiators in the houses and from the heating system in total; blue colours indicate a low return temperature and red colours indicate a high return temperature. Please note that all measurements were conducted with probes mounted on heating system pipes, and that the temperatures illustrated are time-averaged. The measurements show that two of the houses had very low return temperatures, indicating that the heating system control in these two houses allows them to be heated with low-temperature heating. The return temperatures in the remaining houses were relatively high, mainly due to the high return temperatures of just a few radiators in the houses. These few radiators made a large impact on the overall system because the water mass flow through them was much greater than through the remaining well-functioning radiators, as indicated

earlier in Fig. 4. However, none of the occupants in the houses complained about poor thermal comfort, even though the supply temperatures were kept quite low. This shows that there is no reason to believe that a reduction in the heating system supply temperature in existing single-family houses will cause thermal comfort problems. However, the reduced supply temperature may cause an increase in the return temperatures in some houses, especially if a few radiators are under-dimensioned compared to their use.



Fig. 17. Variations in individual radiator return temperatures and the impact of few radiators on the overall heating system return (Paper V)

The problems that led to the high water-mass flows through some of the radiators were found to be very individual. They occurred due to both occupant behaviour and various faults in the heating system design. First, we discovered that many occupants turned their thermostats up and down or used night set-back in some rooms. This caused high water mass flows and peaks in the return temperature during some periods, because the thermostat valve opened up completely during the re-heating period to revert to the indoor temperature set-point. Second, many thermostats were found not to be working optimally. For example, Fig. 18 (left) shows the return temperatures of two radiators in the same room which had different heating patterns despite having similar set-points. These kinds of problems, combined with the fact that many occupants tended to neglect the maintenance of their thermostats and radiator valves, could easily cause the problems with high return temperatures. In two of the houses investigated, old manual radiator valves were found, and in one house, a radiator was built into a closet, causing great problems for heating system efficiency. This is illustrated in Fig.

18 (right) showing the change in the return temperatures measured after the closet enclosing the radiator was removed.

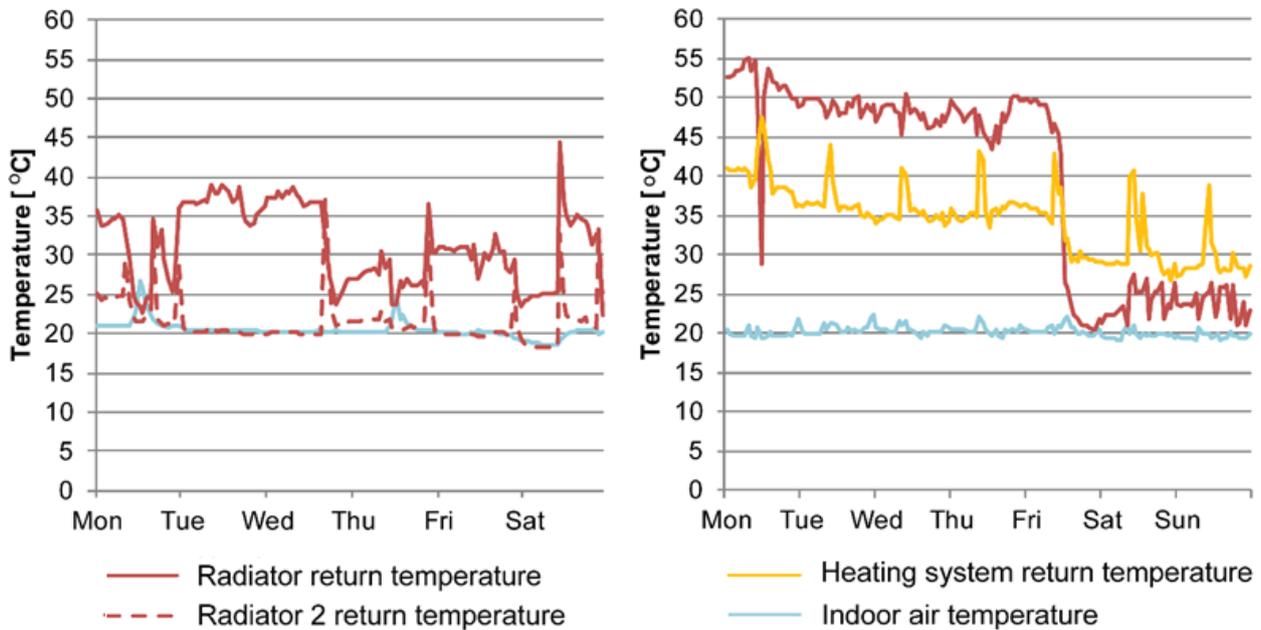


Fig. 18. Difference between return temperatures measured on two radiators in the same room with similar set-points (left), and the effect of removing an enclosing closet on the radiator return temperature and heating system temperature (right) (Paper V).

In some cases high radiator return temperatures seemed to occur because a radiator was too small to satisfy the heating demands of the occupants and still deliver low return temperatures. This type of problem had many different causes. The problem could occur in living rooms, where measurements revealed that high indoor temperatures of 22.5 °C or 23 °C were not uncommon. It could also occur simply because the radiators installed in kitchens were too small when walls had been opened up, or in basements where the radiators were a later addition. An example of how some radiators may require higher heating system temperatures than others is seen in Fig. 19. The figure shows an example from a simulation showing the total excess radiator temperature required in the heating system of one of the case houses when the average radiator heat output is compared to the average heat demand of the whole building or when each radiator and room is investigated separately. The figure shows that the house as a whole (dashed red) can be supplied with much lower temperatures than are required by the critical radiators in the boiler room and basement storage room. In this case, it would be reasonable to replace the few critical radiators with a large impact on the overall heating system temperatures.

In addition to the conclusion that under-dimensioned radiators can sometimes lead to a fault in the heating system control, these results also underline another conclusion. Even where the heating system in a house is found to be under-dimensioned, this does not necessarily mean that all the radiators in the house are too small and need to be replaced in order to reduce the current heating system temperature levels. Instead, it may often be just a matter of replacing a few critical radiators to bring the heating system up to date and enable low-temperature heating.

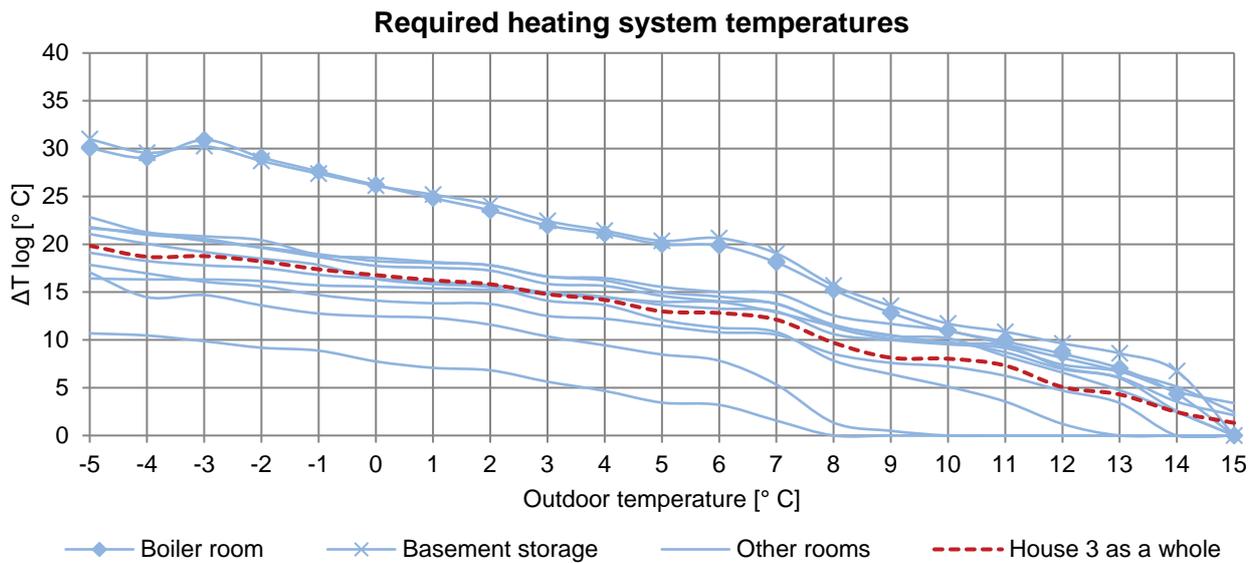


Fig. 19. Excess radiator temperature required for each radiator to heat their respective rooms compared with the house as a whole (Paper IV)

The results of the current studies have been supported by a study conducted on an apartment building in Frederiksberg, Copenhagen [99], although detailed data from this project has not yet been published. Heating systems in apartment buildings are generally larger and subject to the design choices and behaviour of many different people, which can make them more complex than those presented in this thesis. Moreover, it can be more difficult to ensure hydraulic balance and map the heating system to identify malfunctions. In this case, it took a while before a hydraulic short-circuit in the apartment building was identified, where the supply pipe was connected directly to the return pipe. But apart from this, the results of the measurements in the apartment building were similar to those presented here, and though more research on apartment buildings would be useful, the conclusions would probably be similar. The following strategy is therefore suggested as a general solution for improving heating system control:

- Identify and eliminate hydraulic short-circuits
- Ensure that the heating system control limits the maximum water mass flow through each radiator
- If necessary, replace any critical radiators that cause a significant and undesirable increase in the total return temperature

Some tests with improved occupant behaviour and small changes in heating system design have been conducted with promising results, as illustrated in Fig. 18 (right), but it was not possible to change the heating system fully in line with these recommendations, so unfortunately it was not possible to validate the total effect of the three suggested actions. Nevertheless, the first two suggestions are generally in line with the recommendations of earlier studies [32,63], which therefore support the current conclusions.

The results presented in the current analysis only provide information about the specific case houses investigated, and cannot therefore provide any information on the general state of Danish buildings, nor is it certain that the studies include all possible aspects of current heating system control in existing buildings. Nevertheless, the current main conclusions can be drawn from the results:

- Heating system control *can* work in a way that allows existing heating systems to be operated with low temperatures

- Poor heating system control and faults in the heating system can be due to very individual reasons and provide barriers to reducing heating system temperatures
- There is no evidence that lower supply temperatures will cause thermal comfort problems for occupants. It is more likely that heating system return temperatures will increase.

4.3 Identification and correction of faults

The case studies carried out in the current research suggest that simple physical inspection of heating installations could provide a useful tool for identifying and correcting heating system faults. Several large problems in heating system control and operation could be relatively easily identified during visits to the case houses. They included problems with hydraulic short-circuits, old manual or stuck radiator valves, and other individual design issues such as radiators being enclosed by cabinets or closets. If the inspection is performed during the winter, it may also be possible to get an impression of the heating system operation, simply by feeling the radiator return pipes. However, this would only provide a momentary impression of the heating system operation, and the current study indicates that it might be difficult to acquire solid information about it by other simple measures.

Fig. 20 illustrates how tricky it can be to evaluate radiator dimensions and heating demands for use in a hydraulic balancing of the heating system based on basic assumptions about heating system operation. The figure shows the results from a detailed simulation of the operation of the radiators in a single-family house. The figure shows that even the detailed simulation fails to provide a correct evaluation of the radiator return temperatures in all rooms, and more importantly, the simple simulation based on the assumption that the indoor temperature in all rooms is 20 °C takes us even further from the actual situation. This shows that it can be very difficult to identify and correct problems with poor hydraulic control or insufficient radiator dimensions using simple methods based on general assumptions, because they provide a poor fit to the actual individual reality. A similar conclusion was drawn when the results from simulations and measurements in the five single-family houses from the 1930s were compared.

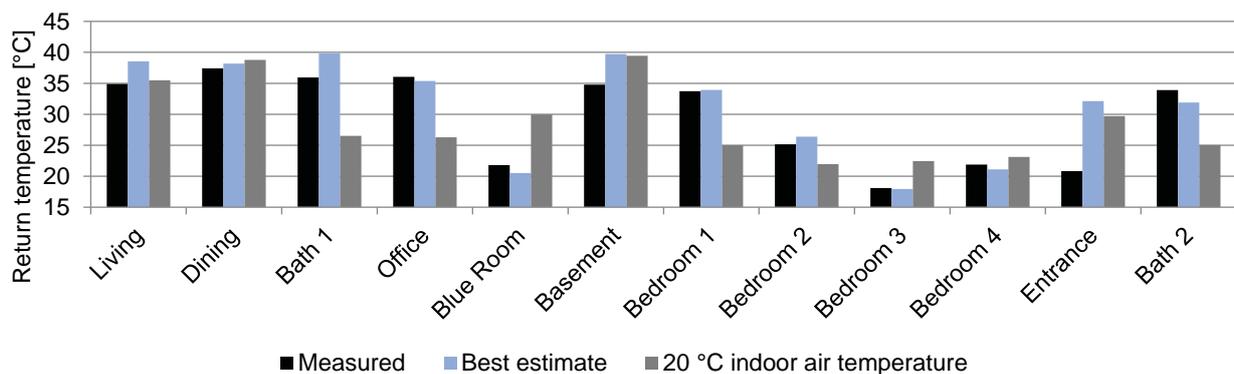


Fig. 20. Difference between measured radiator return temperatures and simulated radiator return temperatures for a best-estimate scenario and when an indoor temperature of 20 °C is assumed (Paper VI)

One major general problem with the simple correction of heating system faults was that it was not possible to identify efficient tools to ensure proper hydraulic control in the heating systems. Based on the measurements conducted, we therefore proposed the development of a robust technical solution that might solve this problem. Two suggestions were made. The first suggestion was to develop a new thermostat that controls the water mass flow through the radiator both with regard to indoor air temperature, but also with regard to a maximum return temperature. In this way, occupants would be able to use night set-back, open windows, or choose whatever

indoor temperature set-points they wanted without having to worry whether their behaviour would jeopardize the efficiency of the heating system. If the thermostat measured a return temperature above the chosen limit it would simply automatically reduce the water mass flow through the radiator. The second suggestion was to improve the control of current heating system pumps in a way that would limit the maximum water mass flow through each radiator and thereby reduce the impact of potential malfunctions. Preliminary results show that unnecessarily high pumping pressure combined with hydraulic short circuits in the heating system pipes or in uncontrolled heating elements could be the main reason for current high return temperatures. The results also indicate that the excess flows could be greatly reduced if all hydraulic short circuits were identified and corrected, all heating elements were equipped with a thermostat, and the pump pressure was limited in accordance with the load situation in the heating system. If either of these solutions could provide a robust result, they would provide an easy solution to the problem of ensuring that heating system return temperatures could be optimized during simple manual inspections of heating systems. Either solution could be adapted to some extent to the individual houses, to ensure that the thermal comfort of occupants is not jeopardized. Alternatively, they could help identify potentially critical radiators in collaboration with occupants by pointing out the radiators that cannot ensure both the requested thermal comfort and low return temperatures.

Despite the above-mentioned limitations of simple physical inspections, the case study of Middelfart’s district heating provided a good example of how much district heating temperatures can be reduced by using temperature optimization tools, continuous monitoring, and simple service of occupant substations. Fig. 21 shows the district heating temperatures measured in Middelfart’s district heating system in 2009 and 2015. The district heating supply temperatures were reduced by some 15 °C on average, while return temperatures were reduced by about 5 °C. The reductions in return temperatures indicate that the monitoring of substation temperatures and contacting occupants to provide a manual inspection of their heating installations can be useful tools in the transition towards low-temperature district heating. This result is in good agreement with other recent findings that many district heating companies have already made good use of these tools to reduce their district heating temperatures [15,92]. Nevertheless, the measurements illustrated also reveal that there is still a long way to go before the preferred low return temperatures of about 25–30 °C are realized.

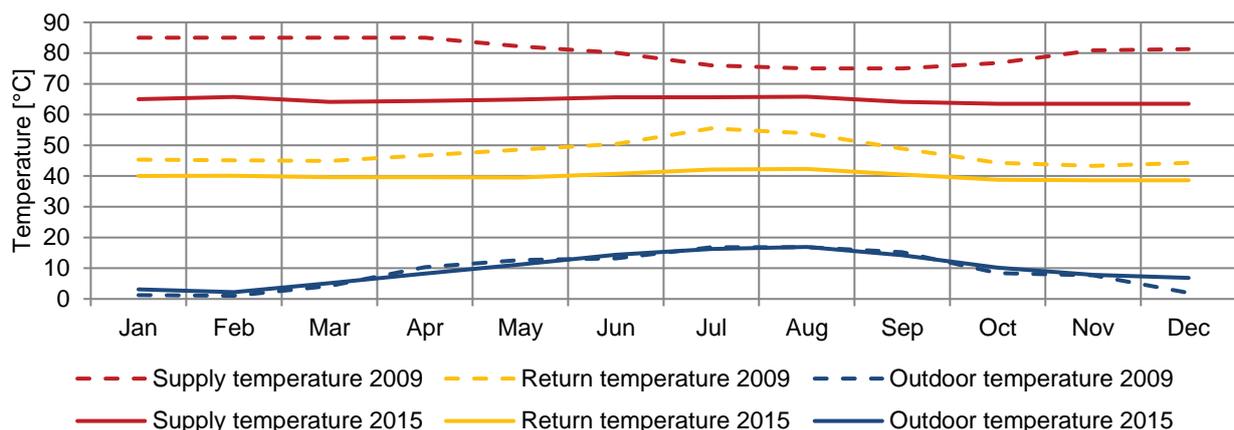


Fig. 21. Temperatures measured in Middelfart’s district heating system in 2009 and in 2015 (Publication IX)

The investigations into the possibility of using data from electronic heat cost allocators for fault detection also provided promising results. Fig. 22 shows four examples of calculated and measured radiator return temperatures (Paper VII).

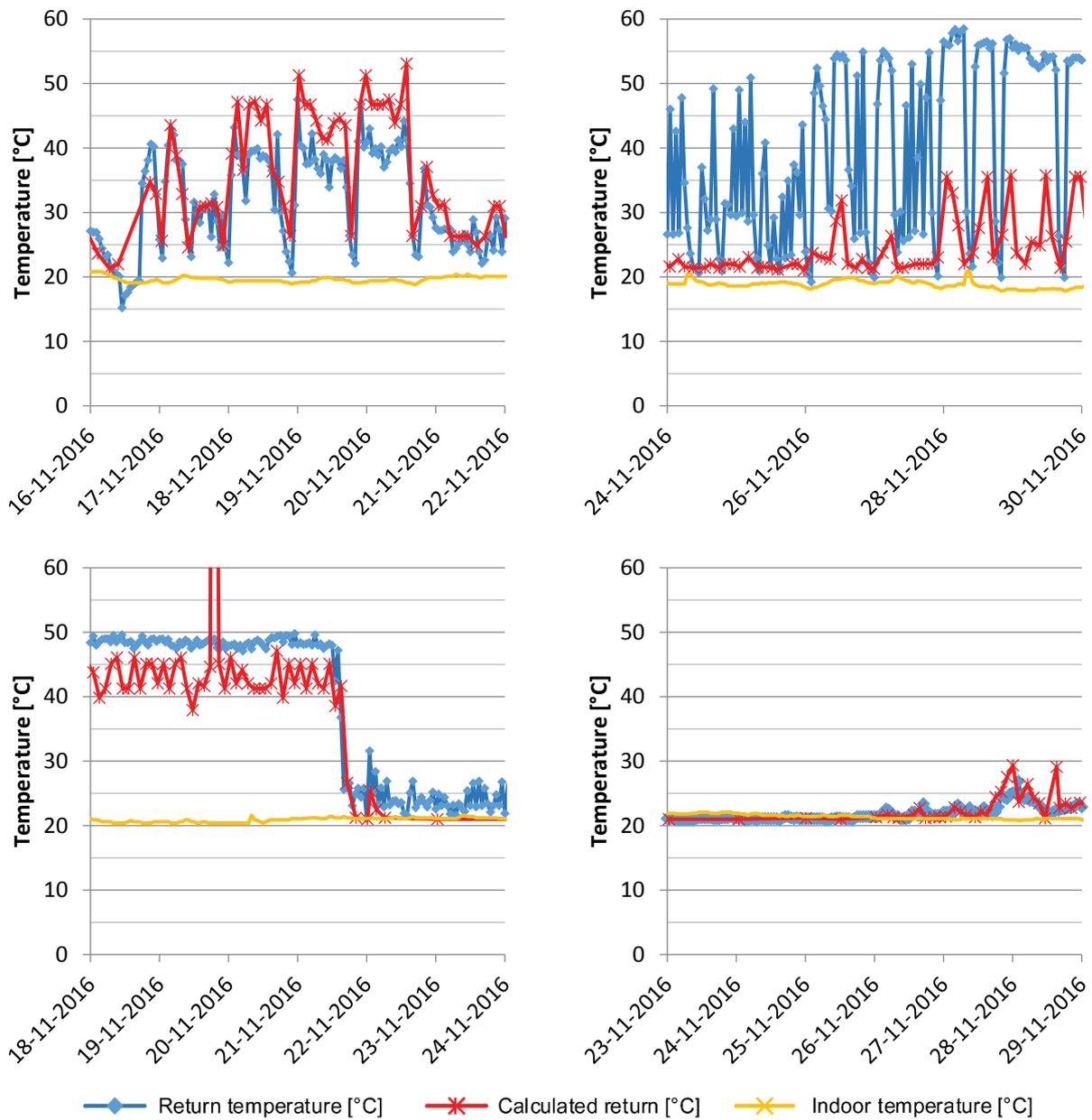


Fig. 22. Example of measured radiator return temperatures and return temperatures calculated using data from heat cost allocators (Paper VII).

As the figure shows, the calculation method generally provides reasonable estimates of the actual return temperatures, although there are also cases where the correlation was not as good. There could be various reasons for a deviation between measured and calculated return temperatures, including errors in the reference measurements or uncertainty in the input to the calculations. Fig. 23 shows that the results were very sensitive to input parameters such as the design heat output of the radiator and the air temperature in the rooms, which all have to be estimated to perform the calculations. So, although it provides a useful and cheap tool for monitoring heating system operation in apartment buildings and current results indicate that large heating system malfunctions can be identified, the method still needs to be further developed and tested to ensure that all faults are identified properly.

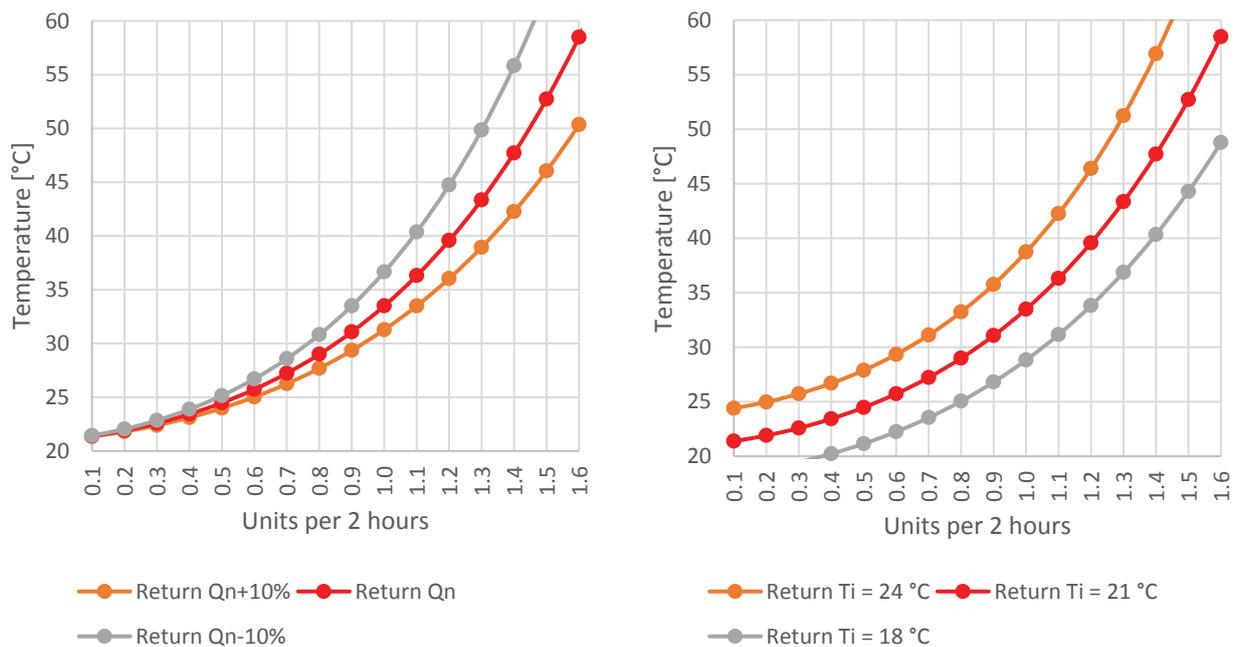


Fig. 23. Illustration of the uncertainty of the method proposed for calculation of radiator return temperatures with regard to input information on design radiator heat output and indoor air temperature (Paper VII).

Another drawback to this method is that data from heat cost allocators are only useful for identifying faults that occur in the terminal elements where the allocators are installed. This makes it difficult to identify hydraulic short-circuits that occur elsewhere – in the heating system risers or in towel rails that may be connected to the heating system – where there are no heat cost allocators. No matter how accurate the method, it needs to be combined with some form of manual service check.

It was not possible to show good examples of how to improve current heating system control and eliminate all identified heating system faults in any of the current studies. One main reason for this was that occupants were not likely to invest in the solutions suggested, as long as there was no economic incentive to do so. The results of the current study were therefore limited to providing good examples of tools for identifying heating system faults, while it was not possible to test efficient methods for correcting these faults. The following conclusions were therefore drawn based on the available results:

- Simple service checks are useful for identifying large heating system malfunctions such as hydraulic short-circuits, old inefficient radiator valves, or large heating system design problems. Furthermore, when substation temperatures are monitored to identify customers that need service checks, they provide a good tool for reducing district heating return temperatures.
- It can be difficult to carry out a simple evaluation of radiator dimensions and hydraulic balancing. Current service checks could therefore be improved if new simple solutions could be developed that would ensure efficient control of water mass flows in heating systems. Suggestions for such solutions include a new thermostat with a return temperature sensor or improved pump control.
- Data from heat cost allocators can be used to locate problems with poor heating system control in apartment buildings where it is often difficult to get access and investigate the conditions. However, this method needs further development and testing to ensure accurate results.
- An economic incentive is needed if customers are to make investments in their heating systems based on the advice of technicians carrying out service checks or monitoring the operation of a heating system.

5. FEASIBILITY OF LOW-TEMPERATURE DISTRICT HEATING

The feasibility of preparing existing space heating systems for low-temperature district heating was investigated from an economic point of view in Paper VIII. The analysis compared the cost of preparing existing space heating systems for low-temperature district heating with the benefits that can be obtained due to lower district heating temperatures, and it was carried out both from the perspective of the district heating customer and for the overall energy system in Denmark. The analysis starts from the district heating temperatures defined for the transition to 4th generation district heating by Lund et al. [100] and illustrated in Fig. 1. So the analysis concerns a reduction from current average district heating supply and return temperatures of 80 °C/45 °C to future low-temperature district heating with average temperatures of 55 °C/25 °C.

The costs of improving existing space heating systems for low-temperature district heating were estimated on the basis of two fictive standard buildings – a single-family house and an apartment building. The single-family house was assumed to have an annual space heating demand of 15 MWh with a heated floor area of 150 m² and 10 radiators. The apartment building was assumed to have an annual space heating demand of 183 MWh with a heated floor area of 2000 m² and 130 radiators. The heat production required to satisfy these heat demands was respectively assumed to be 17.9 MWh and 217.8 MWh, when a heat loss in the district heating network of 19% is taken into account [100]. Table 2 summarizes the information about the two fictive standard buildings used in the analysis.

Table 2 Definition of two standard building typologies (Paper VIII)

	Heat demand [kWh/m ²]	Heat demand [MWh/year]	Heat demand incl. heat loss [MWh/year]	Heated floor area [m ²]	Radiators [no.]
Single-family house	100	15	17.9	150	10
Apartment building	91.5	183	217.8	2000	130

The costs of various actions to improve the space heating systems were estimated based on a combination of communication with sector representatives and data about standard prices from Danish construction projects given in Molio price data [101]. The total cost consists of the price of the materials and the cost of labour, which was assumed to be EUR 70 per hour. This PhD thesis has argued for the development of two new products to improve heating system control: a return temperature thermostat and an improved pump control system. The price of the return temperature thermostat was assumed to be slightly higher than that of a current electronic thermostat, and it was assumed that the improved pump control system could be implemented by a craftsman within 3 hours in a single-family house and 8 hours in an apartment building. Table 3 shows the estimated cost of each action. All prices include VAT.

Table 3 Costs of improving various aspects of heating system control (Paper VIII)

	Single-family house			Apartment building		
	Work [hours]	Cost of materials [EUR]	Total [EUR]	Work [hours]	Cost of materials [EUR]	Total [EUR]
Pump	2	200	340	4	530	810
Radiator valve	0.5	30	65	0.25	30	47.5
Radiator	1.5	400	505	1.2	400	484
Improved pump control	3	-	210	8	-	560
Return temperature thermostat	0.15	48	58.5	0.15	48	58.5

The costs were converted to a cost per MWh of required heat production to make it possible to compare the total costs with the savings in the district heating system. This was done by using the information for the standard buildings in Table 2. For example, the cost of installing new valves in the apartment building was calculated by multiplying the cost of a new valve by the number of valves in the standard apartment building, and dividing this number by the total heat demand in the building:

$$\frac{47.5 \text{ Euro/valve} \cdot 130 \text{ valves}}{217.8 \text{ MWh}} = 28.4 \text{ Euro/MWh}$$

Table 4 shows the resulting costs for each of the actions.

Table 4 Costs of various improvements to heating system control per MWh of heat produced (Paper VIII)

Costs EUR/MWh	Single-family house	Apartment building
Pump	19.0	3.7
Radiator valve	36.4	28.4
Radiator	282.9	288.9
Improved pump control	11.8	2.6
Return temperature thermostat	32.8	34.9

5.1 Cost and benefits for district heating customers

From the perspective of the district heating customer, the main economic benefit of improved heating system control will derive from the sort of return temperature tariff schemes that some district heating companies have implemented. In this study, two examples of return temperature tariffs were used to calculate the savings of the customer: the tariff implemented in Copenhagen and the tariff implemented in Høje Taastrup, west of Copenhagen. In Copenhagen, the customer receives an extra bill if their annual average cooling of the district heating water is less than 27 °C, while they receive a benefit if it is above 37 °C. With an average supply temperature of 80 °C, this corresponds to annual average return temperatures of 53 °C and 43 °C. Both bonus and penalty amount to EUR 0.72 per °C per MWh consumed [102]. In Høje Taastrup the customers are subject to either a bonus or a penalty if their average annual return temperature is above or below 46 °C respectively. Both bonus and penalty amount to EUR 1.28 per °C per MWh consumed [103].

Two different customer cases were investigated. In the first case it was assumed that a standard single-family house with a heat consumption of 15 MWh provides an annual average return temperature of 40 °C. If this is reduced to 25 °C in accordance with the definition of low-temperature district heating, the customer will receive a bonus of EUR 162 per year or EUR 288 per year depending on the district heating company. In the second case, it was assumed that a standard apartment building with a heat consumption of 183 MWh has an annual average return temperature of 53 °C, which means that the customer will obtain a savings of EUR 2372 per year or EUR 6559 per year if a new annual average return temperature of 25 °C can be achieved. Four different hypothetical solutions for the problems leading to high return temperatures were investigated based on the results of the analyses of the design and control of current heating systems presented in sections 3 and 4. The solutions are listed in Table 5, where the cost of each solution is also given based on the costs in Table 3.

Table 5 Four hypothetical solutions to reducing heating system return temperatures and their costs (Paper VIII)

Cost of solution for improved heating system control [EUR]	Single-family house	Apartment building
1. Pump, new radiator valves	990	6985
2. Pump, improved pump control	550	1370
3. Pump, improved pump control, return temperature thermostats	1135	8975
4. Replacement of 30% of radiators	1515	20246

The simple pay-back time of the customer’s investment in improved heating system control was calculated based on these costs and savings, and the result is illustrated in Fig. 24. As the figure shows, the investments in the heating system have a simple pay-back time of between 0.2 and 9.4 years. The pay-back time is shorter for the apartment building, where the original return temperature was assumed to be higher, and it is generally shorter for customers in Høje Taastrup (HT) than those in Copenhagen (CPH) due to the size of the return temperature bonus. The longest pay-back time occurs when the solution requires the replacement of 30% of the radiators, while the shortest pay-back time is achieved if the improved pump control can be implemented with the estimated low costs.

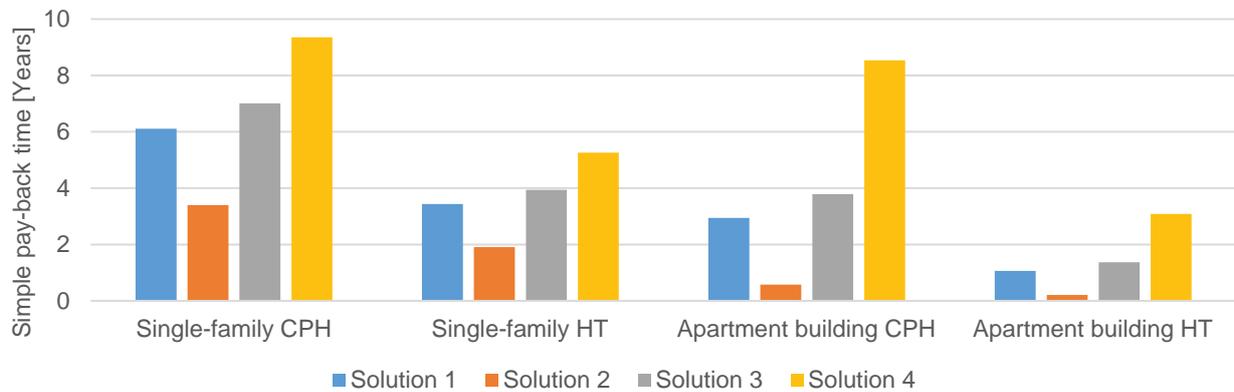


Fig. 24 Simple pay-back time on the investment in four different solutions for improved heating system control (Paper VIII)

The analysis shows that it is economically feasible for customers to improve their heating system control, if the district heating company has introduced a return temperature tariff similar to those investigated in this study. This conclusion is in line with studies conducted by Trüschel, who found that the simple pay-back time for improving heating system control in Swedish apartment buildings through hydraulic balancing is between 1.5 years and 6.5 years [51]. The results are also well in line with the costs identified for improved heating system control in northern Germany [63]. These costs were estimated to be in the range of EUR 2–7 per m² while the current costs range from EUR 0.7–10.1 per m².

5.2 Costs and benefits in the total energy system

Recent research on the energy system effects of converting existing district heating to 4th generation district heating by 2050 shows that an annual energy saving of EUR 10 per MWh heat produced can be achieved if the district heating supply and return temperatures are reduced from 80 °C/45 °C to 55 °C/25 °C [100]. To achieve this saving, the existing space heating systems need to be prepared for low-temperature operation. As indicated in this PhD thesis, this requires some investments in improvement of the heating systems. However, the transformation to low-temperature district heating is expected to take place gradually between now and

2050, so it is also expected that some improvements will be carried out in relation to the general maintenance of the heating systems and as current heating system components reach the end of their lifetime. Two scenarios were investigated for the cost of improving current heating systems in preparation for low-temperature operation. The first scenario can be considered a “worst-case scenario”, where a large number of heating installations were assumed to need improvement in relation to the introduction of low-temperature district heating. In this scenario, it was assumed that all buildings need improved pump control, 20% of buildings need new radiator valves, 20% of buildings need new return temperature thermostats, 40% of buildings need a new heating system pump, and 3% of radiators need to be replaced. The second scenario can be considered a “best-case” scenario, where most heating systems have been gradually updated. In this scenario, it was assumed that all buildings need improved pump control, 10% of buildings need new radiator valves, and 20% of buildings need new return temperature thermostats. The scenarios are summarized in Table 6.

Table 6 Two scenarios for requirements for improvements in existing heating systems (Paper VIII)

Action	Scenario 1 [% of buildings]	Scenario 2 [% of buildings]
Improved pump control	100%	100%
Return temperature thermostat	20%	20%
New pump	40%	-
New radiator valve	20%	10%
Radiator	3%	-

Based on these two scenarios and the costs given in Table 4, the total cost of improving buildings for low-temperature district heating was calculated in EUR/MWh heat produced. This cost was compared with the annual energy system savings of EUR 10 per MWh, to calculate the simple pay-back time for improvements in current heating systems. The results are illustrated in Fig. 25 under the assumption that 50% of the buildings in the district heating network are single-family houses and 50% of the buildings are apartment buildings. If a larger proportion of the buildings are apartment buildings, the costs are reduced, because the costs of some of the actions in EUR/MWh are estimated to be lower in apartment buildings than in single-family houses. It should be borne in mind that the costs included in this study only cover the space heating system, and that additional investments are expected to be necessary in the domestic hot water system and in the district heating network.



Fig. 25 Simple pay-back time of the two scenarios for investments to prepare existing space heating systems for low-temperature district heating (Paper VIII)

As the figure shows, the savings from implementing 4th generation district heating very quickly pay for the costs of improving current heating systems for low-temperature operation. The simple pay-back time on the investments in the heating systems is approximately 3.5 years in the worst-case scenario, while it is less than 2 years in the best-case scenario.

This analysis, however, should only be regarded as an indication of the expected total costs and benefits of preparing existing buildings for low-temperature district heating, because it includes a great deal of uncertainty and is based on a very simple estimation. The main uncertainty arises from the fact that the estimated costs were not based on actual demonstration projects, so it has still not been verified that the actions suggested can help reduce current return temperatures to the expected 25 °C. Another uncertainty arises because prices for suggested future components are difficult to estimate. Finally, the costs of monitoring heating system operation and identifying and correcting faults that continuously occur in heating systems were not included in this analysis, because it was assumed that the cost of such arrangements can be attributed to the general maintenance and servicing that is necessary for any heating installation. However, these uncertainties and assumptions can mean that the costs of improved heating system control may be higher than has been estimated in this study. On the other hand, the savings could also be a lot bigger, because the pay-back times illustrated do not include the additional benefits that will be achieved in the buildings due to the reduction in heating system temperatures. These benefits include both energy savings and fewer occupant complaints, and may in an apartment building add up to savings in the order of 15% of the energy consumption or EUR 1300 per year due to less time spent on complaints, as Trüschel points out [51]. Another benefit is reduced electricity consumption from the installation of new energy-efficient pumps. This can add up to an annual saving of EUR 50 in a Danish single-family house where the cost of electricity is about EUR 0.26 per kWh and a 40W pump is replaced by a new 5W pump. Furthermore, the increased comfort of occupants is also an additional benefit that can be difficult to quantify and was therefore not included in the analysis. Such benefits motivate the general improvement of current heating system installations and reduce the need for changes in the heating systems when district heating temperatures are reduced. All in all, it is therefore probable that the current analysis provides a reasonable estimate of the feasibility of preparing existing buildings for low-temperature district heating, within the limits of the information available on the topic.

6. CONCLUSIONS

This project aimed to investigate the following main hypothesis:

Typical existing buildings can be heated by low-temperature district heating before 2050 in a way that ensures that investments in corrections of heating system errors and malfunctions can be financed by the energy savings obtained by the district heating companies and owners of the buildings.

The hypothesis was researched through investigations of three sub-hypotheses. Table 7 gives summarized conclusions to the investigation of these sub-hypotheses.

Table 7. Conclusions to the investigation of the sub-hypotheses

Hypothesis	Conclusion
<i>Sub-hypothesis 1</i> <i>Current heating elements in existing buildings are large enough to ensure proper thermal comfort even if district heating temperatures are lowered</i>	True, heating systems are generally over-dimensioned even in terms of recent design standards, and it is possible to operate most heating systems with low temperatures during most of the year due to the fact that heating systems are generally dimensioned for outdoor temperatures that only rarely occur. When energy renovations are carried out during the years to come, there will only be very few under-dimensioned heating systems left in existing buildings.
<i>Sub-hypothesis 2</i> <i>The control of existing heating systems can be improved to ensure a proper cooling of the district heating medium</i>	True, several of the case-study houses were successfully heated with low temperatures and provided a proper cooling of the district heating water. However, poor control in some of the existing heating systems was found to be a major barrier to achieving proper cooling, and there is therefore a need to identify and correct faults in heating systems that do not work properly. Current research indicates that the main barrier to achieving proper heating system control is the problem of limiting the water mass flow in the heating system. Furthermore, it can sometimes be useful to replace the few under-dimensioned radiators that cause high return temperatures.
<i>Sub-hypothesis 3</i> <i>Malfunctions and errors in the heating systems of existing buildings can be identified and corrected by use of simple and efficient methods</i>	Largely true. The results indicate that manual inspection of heating systems and the monitoring of data from substations can be used to identify malfunctions in heating systems and ensure a reduction in the district heating return temperatures. Furthermore, results indicate that it might be possible to use data from heat cost allocators to identify large heating system malfunctions in apartment buildings. Nevertheless, the methods need to be further developed and improved. In this study it was not possible to demonstrate a good example of how faults in the heating system have been corrected, and therefore it is not possible to verify this part of the hypothesis. Possible methods for making the corrections were described along with the suggestion of two components that could be developed for this purpose: a thermostat with a return temperature sensor and improved control to limit the pressure provided by heating system pumps. Future research aims to verify the application of these.

An analysis of the costs of preparing existing space heating systems for low-temperature district heating was carried out on the basis of the results from the investigations of the three sub-hypotheses. This analysis showed that the expected investments in heating systems have short pay-back times that are in the range of 0.2–9.4 years for the customers making the investment and 1.8–3.5 years from the perspective of the overall energy system.

Based on the conclusions from the sub-hypotheses, and the investigation of the costs and benefits of preparing existing space heating systems for low-temperature district heating, the main hypothesis is therefore determined to be true.

The overall conclusion of the PhD study is as follows:

The results of this research generally indicate that it is possible to reduce the heating system temperatures in existing buildings for most of the year. In many cases the only barriers to achieving this temperature reduction are faults and malfunctions in current heating system control and a few critical radiators. Fig. 26 summarizes the technical improvements in existing space heating systems that are expected to be necessary when current district heating systems go through the two steps towards low-temperature district heating.

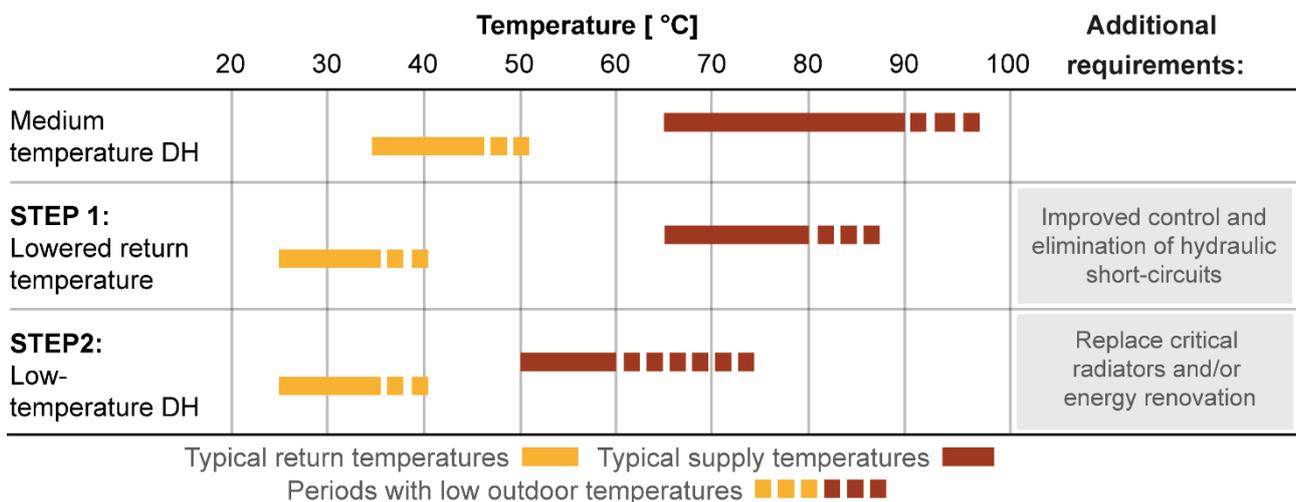


Fig. 26. Overview of technical changes needed to enable low-temperature district heating in existing buildings.

It is possible to identify heating system faults through the physical inspection of heating systems and the monitoring of data from district heating substations and heat cost allocators. However, it was not possible in the current study to provide a good demonstration of the comprehensive correction of identified heating system faults. This was partly because efficient technical solutions were not available and partly because occupants in the case buildings had very little incentive to invest in improved heating system control. If a proper economic incentive is provided through the introduction of return temperature tariffs, however, the current study indicates that investing in improved heating system control to enable the implementation of low-temperature district heating is economically favourable both for the individual customer and for the overall energy system.

7. PERSPECTIVES AND FURTHER WORK

The results of the current project show that there is considerable potential for implementing low-temperature space heating and that it is also economically feasible to invest in improved heating system control to realize this potential. Nevertheless, this conclusion needs to be further strengthened through additional research. First, the current work was to a large degree based on investigations of single-family houses. Future research needs to be carried out on apartment buildings and other types of buildings to confirm the conclusions here. This work is already under way. Second, in the current research, it was not possible to demonstrate a good way to improve the heating system control in an existing building and achieve the preferred low return temperature. This is therefore expected to be one focus area for future research, which is also expected to focus on the two specific suggestions for improved robust control made in this thesis: the development of a new thermostat with improved hydraulic control based on an additional return temperature sensor, and the development of an improved pump control system to limit excess water mass flow through radiators.

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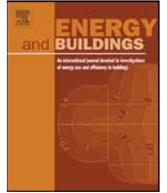
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Theoretical overview of heating power and necessary heating supply temperatures in typical Danish single-family houses from the 1900s



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ABSTRACT

As existing buildings are renovated and energy-efficiency measures are implemented to meet requirements for reduced energy consumption, it becomes easier to heat our homes with low-temperature heating. This study set out to investigate how much the heating system supply temperature can be reduced in typical Danish single-family houses constructed in the 1900s. The study provides a simplified theoretical overview of typical building constructions and standards for the calculation of design heat loss and design heating power in Denmark in the 1900s. The heating power and heating demand in six typical Danish single-family houses constructed in the 1900s were estimated based on simple steady-state calculations. We found that the radiators in existing single-family houses should not necessarily be expected to be over-dimensioned compared to current design heat loss. However, there is considerable potential for using low-temperature space heating in existing single-family houses in typical operation conditions. Older houses were not always found to require higher heating system temperatures than newer houses. We found that when these houses have gone through reasonable energy renovations, most of them can be heated with a supply temperature below 50 °C for more than 97% of the year.

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1. Introduction

Single-family houses account for approximately 60% of the residential sector in Denmark [1]. When reductions in the heat consumption of Danish homes are planned, single-family houses are therefore very important. In Denmark, approximately 40% of single-family houses are heated by district heating [1], which makes modern 4th generation district heating, with its low-temperature operation, a promising solution for improving the energy efficiency of the heat supply in areas with single-family houses [2,3]. The aim with 4th generation district heating is to get supply and return temperatures down to 55 °C and 25 °C, respectively. Such lowering of district heating temperatures will increase the efficiency of heat production and reduce the heat loss from the pipe systems. This is of great importance in low-density building areas, where the relative heat losses from district heating pipes are often high.

Earlier studies have investigated the possibility of supplying energy-efficient building areas with low-temperature district heating (LTDH) [4,5] and described how LTDH networks can be designed [6]. However, only a few studies have investigated the possibility

of heating existing houses with LTDH. These include investigations into the potential for using LTDH in a number of single-family houses from the 1970s, an area of single-family houses with floor heating from the 1980s, and an old apartment building in Copenhagen [7–11]. The use of low-temperature heating has also been studied in buildings supplied by natural gas or by heat pumps [12–15], but such studies may not provide good references for investigations on LTDH, because other heat sources do not necessarily require a similar focus on achieving low return temperatures.

Most of these investigations on low-temperature district heating were case studies. While case studies can provide good references, they are not necessarily representative of the general building mass. The aim of this study was therefore to provide new knowledge about the potential for the use of LTDH in existing single-family houses in general. The results of the study provide a new theoretical foundation for future discussions on the potential of low-temperature district heating.

1.1. Over-dimensioning of radiators

It is of great importance to ensure that occupant comfort is not compromised if district heating temperatures are lowered. This implies that the radiators must be able cover the heating demands in the existing houses with a lower temperature set than the current

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one. For this to be possible, the radiators must be over-dimensioned compared to the current heat demand in the buildings. Four main facts suggest that the existing radiators could be over-dimensioned to an extent that allows the heating system temperatures to be lowered for large parts of the year:

1. The radiators were dimensioned for a very low outdoor temperature that almost never occurs.
2. Internal heat gains from electrical equipment has increased.
3. Radiator dimensions are often larger than required because they come in a limited number of sizes.
4. The energy demands of many existing buildings have been reduced due to energy renovation.

Over-dimensioning of radiators has been investigated in a number of studies. In Denmark, the effects of operating district heating networks with lower temperatures have been tested in various studies since the late 80s [16–20]. Based on measurements of supply and return temperatures in the networks, the studies conclude that it is technically possible to provide space heating in existing buildings with supply temperatures as low as 60–65 °C even in cold periods. This indicates that the radiators in the buildings investigated were over-dimensioned, because the radiators were originally dimensioned for higher supply temperatures. These findings have been supported by more recent studies of a number of district heating networks where the annual supply temperatures were successfully reduced through continuous temperature optimization and improved building installations [8,10,21]. In Sweden, a number of field studies have investigated and improved the heating system operation in typical multifamily buildings [22–24]. The studies found that the heating system temperatures in the multifamily buildings investigated were around 50 °C/30 °C and 45 °C/35 °C even at outdoor temperatures around 0 °C [23,24]. These findings indicate that traditional dimensioning of radiators according to the temperature set 80 °C/60 °C often caused radiator sizes to be large enough for the buildings to be heated by low-temperature heating for large parts of the year.

In this study, we investigated over-dimensioning of radiators from two different perspectives. First, the design heating power in the typical Danish single-family houses was compared to the current design heat loss to evaluate whether the installed radiators are over-dimensioned compared to current design standards. Secondly, the heating system temperatures necessary to cover the heat demand in the houses at typical outdoor temperatures were calculated. The design conditions were compared to the temperature requirements during a typical year to evaluate whether the radiators are over-dimensioned for the actual operation requirements. Based on these analyses, the study provided new insights on the definition of over-dimensioned radiators. Furthermore, the study provided new knowledge on the condition of heating systems in typical existing-single-family houses.

2. Danish single-family houses and district heating

Typical single-family houses that represent the Danish building mass were identified in the TABULA project, which was aimed at developing typical building typologies for a number of European countries [25,26]. In the Danish contribution to the project, Danish homes were divided into categories depending on their construction period, changes in the building code requirements, and shifts in building traditions. The study looked at single-family houses constructed from before 1850 and to 2011.

Not all categories of single-family houses are of equal interest for a study on low-temperature district heating. As Fig. 1 shows, the single-family houses constructed after 2000 only form a small

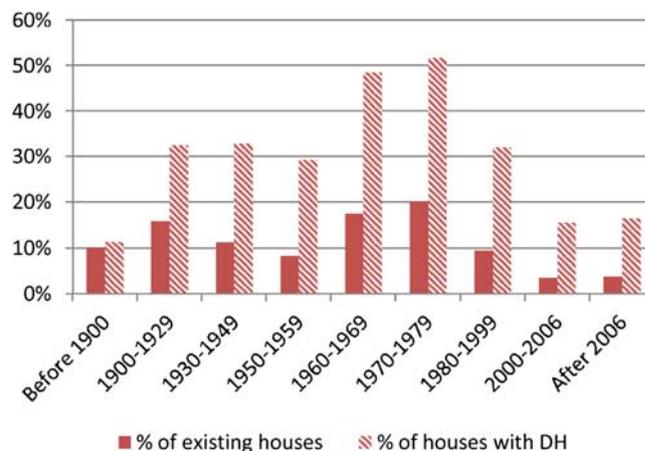


Fig. 1. Danish single-family houses by year of construction and heating source [1].

percentage of the total single-family houses in Denmark. Furthermore, only a small percentage of the single-family houses from before 1900 and after 2000 are heated with district heating. This study therefore focuses on typical Danish single-family houses constructed during the 1900s.

In the TABULA project, the houses constructed in the 1900s were divided into six categories of typical single-family houses. Each category was exemplified by an actual house representing the typical architecture, geometry, and construction of the given time period. The investigations reported in this paper were based on these actual houses. Key data describing the houses are given in Table 1. Basements are assumed not to be heated, and basement temperatures are assumed to be equal to dimensioning ground temperatures.

3. Method

3.1. Methods for the calculation of design heat loss

The design heating power in each of the representative single-family houses was estimated based on the design heat loss of the house at the time of construction. The procedure for calculating the design heat loss changed during the 1900s. The first Danish guideline for the calculation of dimensioning heat loss in buildings was published in 1953 by the Danish Engineering Association [27]. In the following years, it was printed in several editions, but the only major changes occurred in the version that was published in 1965 [28]. This guideline remained the main standard for the calculation of dimensioning heat losses in buildings until 1977 when the first version of Danish standard DS 418 was published. New versions of this standard were published in 1986, 2002 and 2011 [29,30].

Common for all the published standards is that the design heat loss of a building is calculated as the sum of transmission heat loss through the building components and ventilation heat loss. In the current standard, the transmission and ventilation heat losses are calculated using Eqs. (1) and (2) respectively.

$$\Phi_{trans} = \sum U \times A \times (T_i - T_e) + \sum \Psi \times l \times (T_i - T_e) \quad (1)$$

where

Φ_{trans} is the transmission heat loss

U is the U-value of the building component

A is the external area of the building component

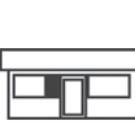
Ψ is the linear heat loss coefficient for windows and foundations

l is the length of connections around windows and foundations

T_i is the indoor temperature (20 °C)

Table 1

Key data for TABULA houses from 1850 to 1998 [25]. All areas are given with external measures.

	1850–1930	1931–1950	1951–1960	1961–1972	1973–1978	1979–1998
						
Heated area [m ²]	112	140	106	180	138	143
Roof area [m ²]	94	89	106	180	150	143
Wall area [m ²]	98	109	101	121	97	124
Floor area [m ²]	66	88	106	180	138	143
Window area [m ²]	15	22	28	34	22	25
Floors	2	2	1	1	1	1
Basement	Full	Full	Full	None	None	None
Ventilation	Natural	Natural	Natural	Natural	Natural	Natural

T_e is the external temperature (-12°C for air and 10°C for ground).

$$\Phi_{vent} = c \times \rho \times \frac{q_a}{1000} \times A \times (T_i - T_e) \quad (2)$$

where

Φ_{vent} is the ventilation heat loss

c is the heat capacity of air (1005 J/kgK)

ρ is the air density (1.205 kg/m³)

q_a is the air change rate (0.3 l/s pr m² heated floor area)

A is the heated floor area.

The calculation procedure was modified slightly from the publication of the first standard to the current. The old guidelines applied dimensioning temperatures of $18\text{--}22^\circ\text{C}$ indoors and -15°C outdoors, while more recent standards prescribe an indoor temperature of 20°C and an outdoor temperature of -12°C . Furthermore, the areas of building components were based on internal measurements in the old standards, while more recent standards mainly apply external measurements. In the old guidelines additional heat losses were included for rooms with several building elements facing the external air or for roof constructions that were affected by heat radiation to the sky. Linear heat losses were not included in the older standards. Eq. (3) shows the procedure for the calculation of transmission heat loss from a building according to the oldest standard from 1953.

$$\Phi_{trans} = f_1 \times \Sigma U \times A \times (T_i - T_e) \times f_2 \quad (3)$$

where

Φ_{trans} is the transmission heat loss

U is the U-value of the building component

A is the internal area of the building component

T_i is the indoor temperature ($18\text{--}22^\circ\text{C}$)

T_e is the external temperature (-15°C and 8°C for ground)

f_1 is a factor adding 3% to the heat loss for each additional cold surface (in this study assumed to be 1.075 for houses with 1 floor and 1.045 for houses with two floors)

f_2 is a factor which is 1.15 for roofs and 1.0 for other constructions.

The procedure for the calculation of ventilation heat losses has changed completely since the first standard. At that time, the ventilation heat loss was calculated on the basis of the length of connections around windows/doors and their frames. The calculation was carried out by estimating the lengths of connections between each window and the window frames as well as between the window frame and the external wall. The length of the connections was multiplied by a typical heat loss coefficient depending on the expected wind profile of the area where the building was situated. The calculation was based on Eq. (4). Fig. 2 shows the procedure for estimating the length of the connections.

$$\Phi_{vent} = f_3 \times f_4 \times \Sigma F \times L \times (T_i - T_e) \quad (4)$$

where

Φ_{vent} is the ventilation heat loss

f_3 is a factor between 0.75–1.0 reducing heat loss in rooms where windows have different orientations (here assumed to be 0.75)

f_4 is a factor between 1.0–1.3 depending on the orientation of the windows (here assumed 1.15)

F is the heat loss pr. m connection length (1.2)

L is the length of connections

T_i is the indoor temperature ($18\text{--}22^\circ\text{C}$)

T_e is the external temperature (-15°C).

Fig. 3 gives a summary of the changes in the calculation procedures on the publication of new standards.

3.2. Building constructions

The constructions of the original houses were determined based on information from the TABULA project [25] as well as Danish building regulation requirements and guidelines on typical constructions in old Danish buildings [31,32]. The constructions and insulation levels applied in the calculation of the original design heat loss in the houses are given in Table 2. The estimated U-values of the constructions are shown in Fig. 4.

3.3. Design heating temperatures

The heating systems in the houses were assumed to consist of two-string radiator-systems which is the most common Danish heating system. The radiators were assumed to be dimensioned in accordance with the design heat loss of each house as calculated according to the original constructions and the standards at the time of construction. The radiators were assumed to be over-dimensioned by 5% due to limitations in radiator sizes available. The design heating power of the radiators depends on the heating source and the design heating temperatures at the time when the radiators were installed in the houses. For instance, some houses were originally heated by an oil boiler, whereas they are now equipped with district heating. When the first hydraulic heating systems with radiators were introduced in the 1920s, the heating was typically delivered from stoves supplied by coal or coke.

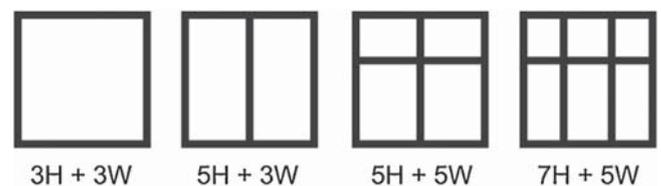


Fig. 2. Length of connections between windows/doors and wall.

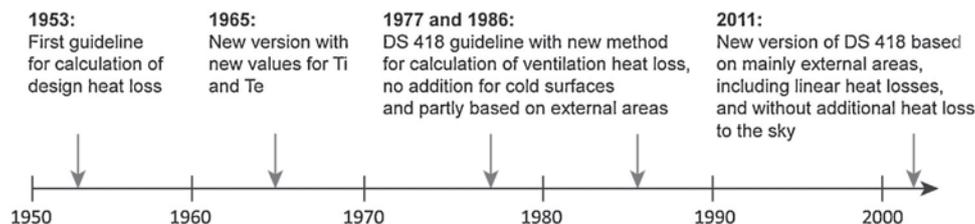


Fig. 3. Timeline showing the changes in the methods for the calculation of design heat loss in Danish standards.

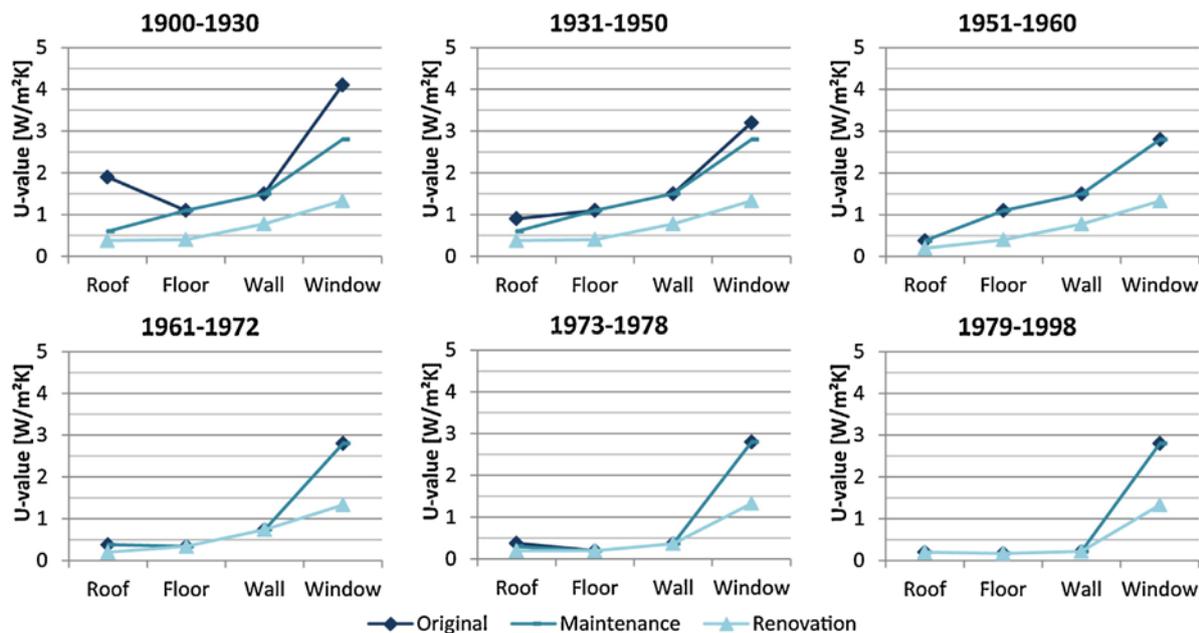


Fig. 4. U-values of the constructions in the TABLE houses in their original state, after general maintenance, and after thorough energy renovation.

Oil-burners became more typical in the 1950s at the same time as district heating expanded rapidly. Natural gas was introduced in the 1980s [33,34].

For the oldest houses, we assumed the design temperatures were $90^\circ\text{C}/70^\circ\text{C}$, because Danish radiators were tested for this temperature set until the new European norm DS/EN 442 was published in the mid-1990s [35]. Heating systems supplied by natural gas may have been designed according to this temperature set at first, but from the mid-1980s, it became common to use a temperature set of $80^\circ\text{C}/60^\circ\text{C}$ [36,37]. Since the mid-1990s the building code has required gas-fired heating systems to be designed according to a mean temperature of 55°C (corresponding to a temperature set of $62.5^\circ\text{C}/47.5^\circ\text{C}$) [38]. The same building code required that heating systems supplied by direct and indirect district heating systems should be designed for temperature sets of $70^\circ\text{C}/40^\circ\text{C}$ and $65^\circ\text{C}/35^\circ\text{C}$ respectively. Earlier heating systems supplied by district heating were typically designed for a temperature set of $80^\circ\text{C}/60^\circ\text{C}$ [31] or $80^\circ\text{C}/40^\circ\text{C}$ [32].

The design temperature sets that were used for the dimensioning of the radiators in the TABLE houses investigated are shown in Table 3.

3.4. Design heating power

The design heating power installed in each of the houses was estimated based on the calculated design heat loss in the original house at the time of construction. The design heat loss of each of the six single-family houses was calculated for the original building constructions as shown in Table 2 and in accordance with the calculation standard at the time of construction. The design heating power was calculated on the basis of the design heating temperatures at the time of construction as given in Table 3. An additional 5% heating power was added to the calculated design heating power to take into account over-dimensioning of the radiators due to limitations in radiator sizes available. The heating powers with the original temperature sets were converted to the temperature set $60^\circ\text{C}/40^\circ\text{C}$, which is the currently required temperature set for houses supplied by district heating in Denmark. The conversion was carried out using Eqs. (5) and (6). The radiator exponent was given the standard value of $n = 1.3$.

$$\phi = \left(\frac{\Delta T}{\Delta T_0} \right)^n \times \phi_0 \quad (5)$$

Table 2

Typical components, insulation levels, and window types in Danish single-family houses constructed in different time periods.

Constructions	1900–1930	1931–1950	1951–1960	1961–1972	1973–1978	1979–1998
Roof insulation	None	25 mm	100 mm	100 mm	100 mm	200 mm
Floor insulation	Clay	Clay	Clay	Singles	50 mm	150 mm
Wall type and insulation thickness	Cavity wall 0 mm	Cavity wall 0 mm	Cavity wall 0 mm	Cavity wall 80 mm	Brick/LWC 80 mm	Brick/LWC 120 mm
Window type	1 layer	some double	Thermo	Thermo	Thermo	Thermo

Table 3

Design heating system temperatures applied for the calculation of design heating power.

	1851–1930	1931–1950	1951–1960	1961–1972	1973–1978	1979–1998
Design temperatures [°C]	90/70	90/70	90/70	80/60	80/40	70/40

where

Φ_0 is the design heating power of the radiators in the house at the original temperature set

Φ is the heating power of the radiators at the temperature set 60°C/40°C

ΔT is the logarithmic mean temperature difference at the temperature set 60°C/40°C

ΔT_0 is the logarithmic mean temperature difference at the design temperatures

n is the radiator exponent.

$$\Delta T = \frac{T_s - T_r}{\ln \left(\frac{T_s - T_i}{T_r - T_i} \right)} \quad (6)$$

where

T_s is the supply temperature

T_r is the return temperature

T_i is the indoor temperature.

3.5. Current design heat loss

The current design heat loss of the houses depends on the renovations carried out since the construction of the houses. As a minimum, the houses from the first half of the 1900s were expected to have gone through general maintenance. This was assumed to correspond to a renovation where old windows were replaced by thermo windows and roofs were equipped with a minimum of 50 mm insulation. A large proportion of the houses constructed during the 1900s have been renovated to a further extent, adding insulation to the cavity walls or bringing windows or roof insulation to comply with modern standards. The design heat loss in the houses was calculated for two different stages of refurbishment corresponding to either general maintenance of the houses or a thorough energy refurbishment. The U-values of the constructions in the two scenarios are shown in Fig. 4 along with the original U-values of the constructions.

The design heat loss calculations were carried out in accordance with the current calculation standard. The design heat loss was compared to the design heating power in the houses, so that we could evaluate whether the existing radiators are over-

dimensioned compared to the current design heat loss and current design heating temperatures.

3.6. Actual heating demand

The actual heat demands in the houses at typical outdoor temperatures were calculated using stationary calculations. It was assumed that the indoor temperature in the houses was kept at 21°C. Transmission and ventilation heat losses were calculated according to Eqs. (1) and (2) and applying the key data for each house given in Table 1 and renovated constructions as shown in Fig. 4. Internal heat gains from occupants and equipment were included in the calculations and assumed to be a constant 5 W/m² as suggested in the Danish standards [39]. Heat gains from the Sun and extra heat losses due to high wind velocities were ignored, and no dynamic behaviour was included in the calculations.

The total heating demands in the houses were given as the sum of the transmission heat loss and the ventilation heat loss at each given outdoor temperature. The heating supply temperature necessary to cover the heat loss at the given outdoor temperature was calculated in accordance with the design heating power in the houses using Eqs. (5) and (6). The cooling of the heating system was assumed to be 20°C corresponding to the temperature difference between the supply and return temperature in the current design temperature set 60°C/40°C. The radiator exponent was assumed to be $n = 1.1$, because a recent study has shown that the radiator exponent describing heat emissions from typical Danish radiators during low-temperature operation is well below 1.3 [40]. The results were visualised in graphs (see Figs. 7–9 below) showing how large a percentage of the year a given supply temperature is sufficient to heat each of the houses.

4. Results and discussion

4.1. Estimated heating power and design heat loss in the TABULA houses

Fig. 5 shows the calculated design heat loss in typical Danish houses at the time of construction and in the current situation after either general maintenance or energy renovation. The design heat-

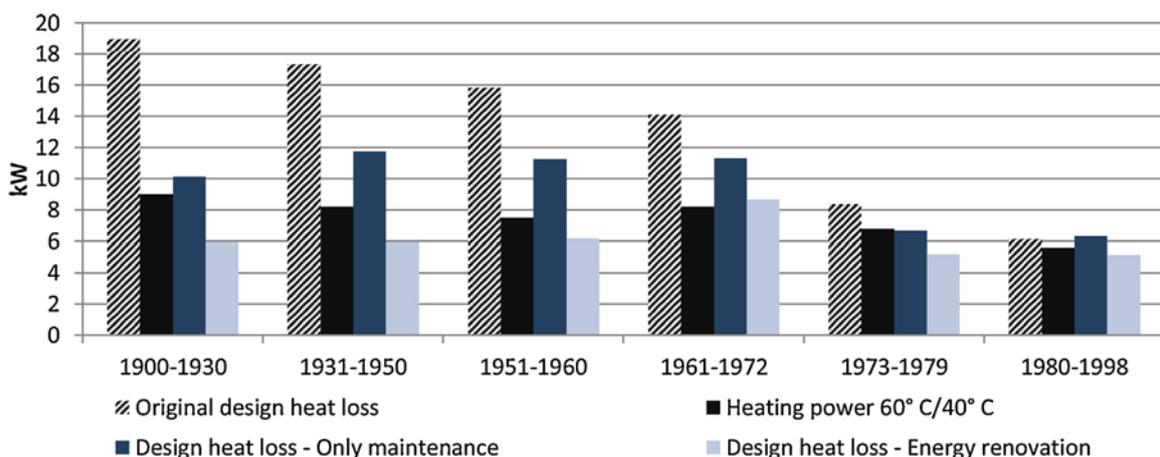


Fig. 5. Heating power and design heat loss of the houses after general maintenance and after energy renovation.

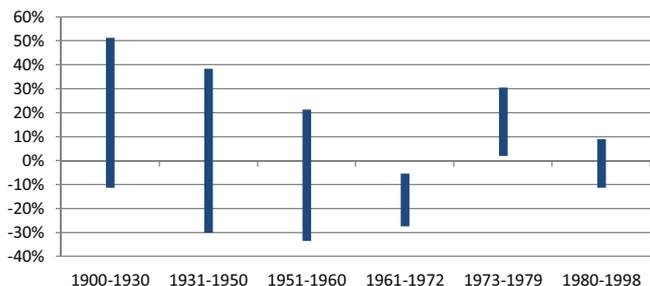


Fig. 6. Minimum and maximum over-dimensioning of design heating power of radiators versus design heat loss.

ing power of the radiators in the houses with a temperature set of 60 °C/40 °C is also included in the figure.

The figure shows that the heating power covers approximately 50% of the original design heat loss in the older houses, when the current design heating temperatures are taken into account. However, the design heat losses of the old houses are reduced greatly when the current standard and general maintenance of the houses is taken into account. Fig. 6 shows the radiator over-dimensioning in the houses according to the design calculations. The displayed minimum and maximum over-dimensioning correspond to the two scenarios of general maintenance and energy renovation of the houses, respectively.

The figure shows that the radiator systems in most of the houses from the 1900s are under-dimensioned in relation to the design temperature set if the houses have only gone through general maintenance. The heating systems in houses constructed between 1931 and 1972 can be under-dimensioned by as much as 30% in relation to the current design temperature set. The 1961–1972 house represents a case where there was a reasonable level of insulation in the original house and where the heating system was designed for high temperatures. The results show that the design heating power in this type of house can be expected to be lower than the design heat loss with the current design temperature set, even after energy renovation. However, the figure also shows that the heating systems in most of the houses from the 1900s can be expected to be over-dimensioned by 20–50% compared to current standards when the houses have gone through reasonable energy renovations.

4.2. Required heating system temperatures

Figs. 7–9 show the supply temperatures that are necessary to cover the calculated actual heat demand in the current houses. The figures are based on a return temperature that is 20 °C lower than the supply temperature. The outdoor temperatures have been converted to annual percentages in proportion to the occurrence of the temperatures in the weather data set for the design reference year in Copenhagen 2001–2010. The upper line of the areas marked corresponds to the situation where the house has gone through only general maintenance, while the lower line corresponds to the situation where the house was subject to an energy renovation. The areas marked between the lines visualise the expected supply temperatures necessary to cover the heating demands in typical existing Danish single-family houses at various levels of refurbishment. Fig. 7, for example, shows that a Danish single-family house constructed between 1900 and 1930 that has gone through general maintenance requires a heating supply temperature above 55 °C for approximately 5% of the year in order to maintain a 21 °C indoor temperature.

Fig. 9 shows that typical Danish single-family houses that were constructed after 1973 can be heated with a supply temperature of 55 °C for more than 97% of the year. Most of the houses built before 1973 can be heated with supply temperatures below 55 °C for the majority of the year as well. This means that there is not necessarily a correlation between the age of the house and the supply temperature required to heat the house. However, the old houses form a less uniform mass. In some cases, there is a difference of more than 10 °C between the supply temperatures required in an energy renovated house and those required in a house that has only gone through general maintenance.

The results show that the houses can be heated with a supply temperature below 60 °C for 97% of the year, even in a case where the heating system in a house is under-dimensioned by 25% compared to the current design heat loss. If all existing single-family houses go through reasonable energy renovation measures, a supply temperature below 54 °C was found to be sufficient to heat the houses for more than 97% of the year. In this respect, it could be argued that it is likely that the existing radiators in typical single-family houses from the 1900s are over-dimensioned for the actual heating demands in the houses. However, this would indirectly sug-

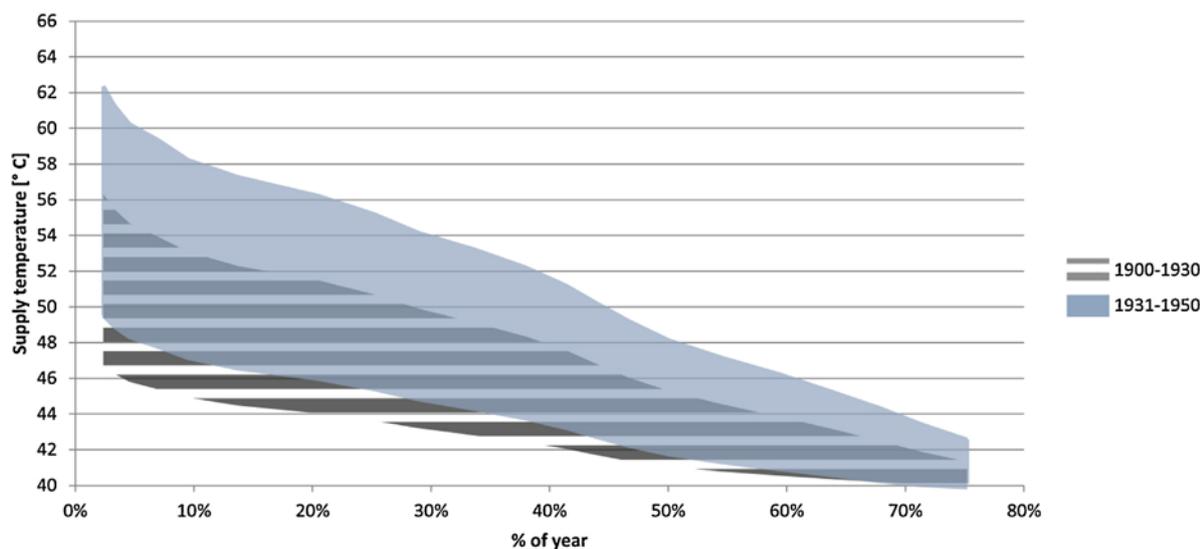


Fig. 7. Comparison between design heating power of the radiators in the TABULA houses calculated according to the old methods and the current stationary heating demand of the houses at different outdoor temperatures.

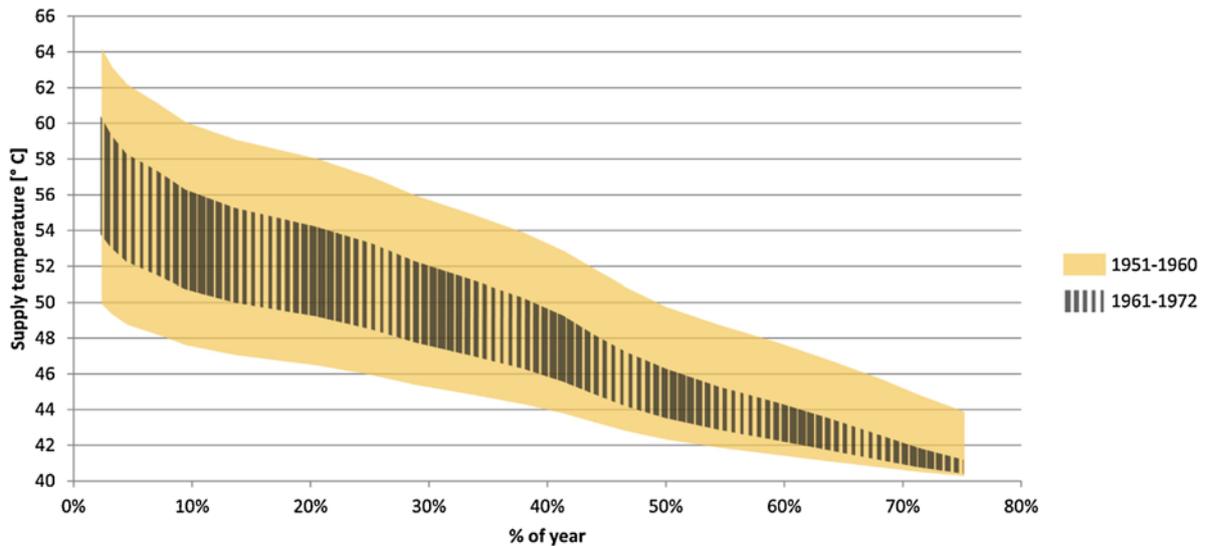


Fig. 8. Comparison between design heating power of the radiators in the TABULA houses calculated according to the old methods and the future stationary heating demand of the houses at different outdoor temperatures.

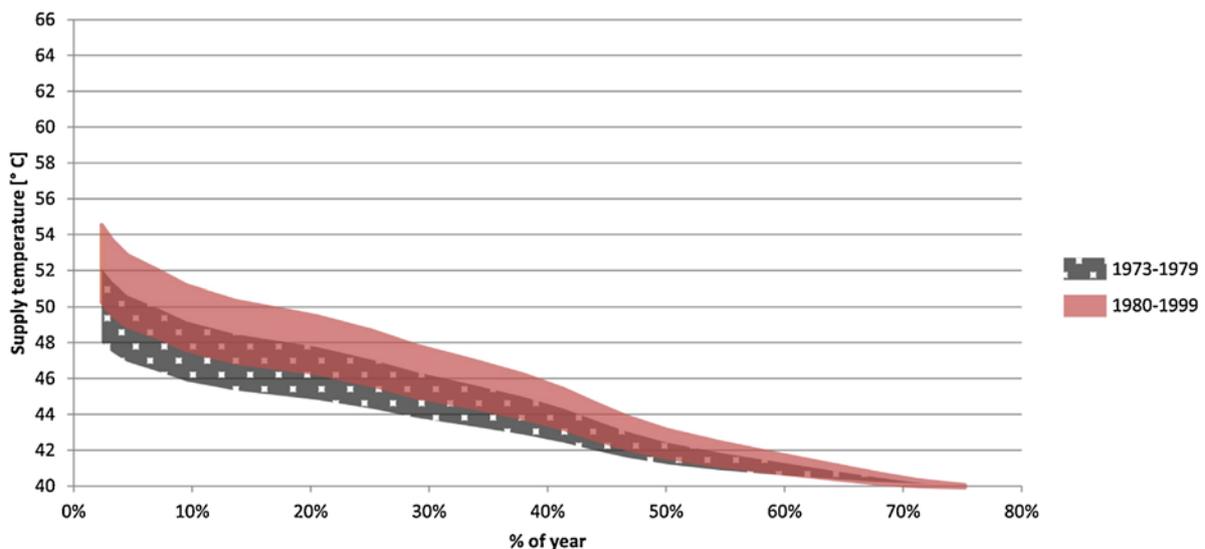


Fig. 9. Comparison between design heating power of the radiators in the TABULA houses calculated according to the old methods and the future stationary heating demand of the houses at different outdoor temperatures.

gest that heating systems are generally over-dimensioned when current design methods are applied.

5. Uncertainties and assumptions

The results presented in this paper are subject to a number of uncertainties, because the study conducted was largely theoretical. The results should only be used therefore as an overall indication of tendencies in the existing Danish building stock. The houses investigated were typical Danish single-family houses identified in the TABULA project [25], so they do not represent all existing Danish single-family houses. Original building constructions may differ from the constructions analysed in this study, as may the design heating system temperatures and the energy renovation measures that might be considered reasonable to carry out. These parameters have a large influence on the results, and the focus on a few representative houses means that a number of other building constructions were not analysed. However, the typical houses analysed in this study show a wide range of different types of construction

and design heating system temperatures. This means that they may be used to draw some general conclusions on the potential for using low-temperature district heating in existing single-family houses.

The estimated heating powers available in the existing houses were based on calculations of design heat loss. This method does not necessarily provide a reasonable estimate of the actual radiator heating power in existing houses. It can be expected that radiators were sometimes dimensioned according to the rule of thumb, engineering experience, or practical considerations, such as fitting the radiator into the available area under a given window or using similar radiators in all rooms of a house. Such design methods may have met the building regulations at the given time, but probably added to the over-dimensioning of the radiators in some houses and rooms. This means that radiators may be over-dimensioned to a larger extent than is illustrated in this study.

Because the study was based on a simplified analysis of data from the TABULA project, the building constructions and ventilation losses were not known or analysed in detail. The calculations carried out were simple stationary calculations, in which dynamic

properties were not taken into account. This means that the results only provide an indication of the possibility of heating existing houses with low-temperature heating. A detailed analysis should include the dynamic properties of, for example, heating systems, thermal building mass, and heat gains from direct sunlight.

To heat existing single-family houses with low-temperature heating as suggested in this study, the heating systems in the houses must function well and the heating power must be distributed evenly in the houses. The study does not take into account room partitions. This may be an important factor because radiator sizes may differ from room to room, or occupants may have changed or removed some radiators during refurbishment of their houses. If the radiators in some rooms are greatly under-dimensioned for the heating demand in a given room, it may be necessary to increase the supply temperature to maintain a 21 °C indoor temperature in all rooms. It can therefore be expected that it will be necessary to replace a few critical radiators in some houses to be able to use the low supply temperatures suggested in this study.

This study should be seen as a theoretical investigation of a number of standard houses that can serve as background knowledge about radiator dimensions in existing single-family houses. Furthermore, the study provides a reference for future investigations and an indication of the overall tendencies in the heating systems and heating demands of typical Danish single-family houses from the 1900s.

6. Conclusion

The results of this study indicate that it is not always accurate to assume that the radiators in typical Danish single-family houses from the 1900s are over-dimensioned compared to the design heat loss. On the other hand, the radiators might often be considered to be “over-dimensioned” for the current heat demands in the single-family houses.

The study found that typical existing Danish single-family houses can be heated with low-temperature heating with supply and return temperatures below 55 °C/35 °C for large parts of the year. Houses that have gone through reasonable energy renovations can often be heated with a supply temperature below 50 °C for more than 97% of the year. The results of the study indicate that the houses constructed in the beginning of the 1900s are not more difficult to heat with low-temperature heating than houses constructed in the latter half of the 1900s. However, there is a larger span between the heating system temperatures required in older houses, depending on the renovation measures that have been implemented in the houses. Typical house constructions after 1973 were found to have rather similar heating system temperature requirements.

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Corrigendum

Corrigendum to ‘Theoretical overview of heating power and necessary heating supplytemperatures in typical Danish single-family houses from the 1900s’,
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The authors regret that there was a mistake in the percentages of houses with district heating illustrated in Fig.1 of the paper. The correct figure should be:

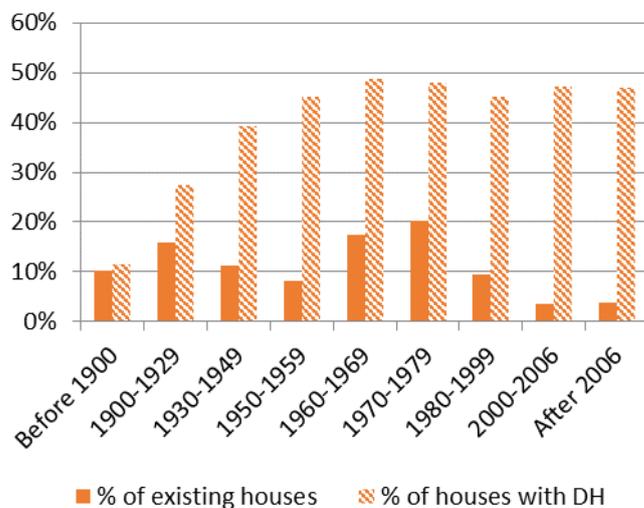


Fig. 1. Danish single-family houses by year of construction and heating source

The authors would like to apologise for any inconvenience caused.

II

Are typical radiators over-dimensioned? An analysis of radiator dimensions in 1645 Danish houses

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Abstract

This study analyses the heat load in a total of 11,584 rooms in 1645 Danish houses and the heat output of the radiators in them to evaluate whether typical radiators are over-dimensioned. The aim was to find out whether radiators in existing houses are suited for low-temperature district heating. We found that new houses are generally more likely to have over-dimensioned radiators, though the heat output of the radiators installed varies a great deal. We also found that many old houses can be equally fit for low-temperature district heating, especially if they have been through some energy renovation. Our results show that approximately 80% of heating systems are over-dimensioned relative to their current design heat load. This share will rise to about 92% as expected energy renovations are carried out towards 2050. Houses with currently over-dimensioned heating systems can be heated with supply temperatures below 60 °C for most of the year. Due to extreme design conditions, even under-dimensioned heating systems can be operated with low temperatures for much of the year, although slightly higher supply and/or return temperatures would have to be accepted.

Keywords: *Low-temperature district heating, low-temperature space heating, design heat output, design heating demand, space heating systems,*

Nomenclature

n = Radiator exponent [-]

Q_{annual} = Annual heating consumption [kWh/m²]

T_e = Exterior temperature [°C]

T_i = Indoor temperature [°C]

T_r = Radiator return temperature [°C]

T_s = Radiator supply temperature [°C]

U_{house} = Thermal transmittance pr. floor area of house under steady state [W/m² K]

ΔT_{log} = Logarithmic mean temperature difference [°C]

$\Delta T_{\text{log,design}}$ = Logarithmic mean temperature difference at design temperatures [°C]

$\Phi_{\text{design,load}}$ = Design heat load, total [W] or per floor area [W/m²]

$\Phi_{\text{design,output}}$ = Heat output of radiators at design temperatures, total [W] or per floor area [W/m²]

Φ_{load} = Heat load, total [W] or per floor area [W/m²]

Φ_{output} = Heat output of radiators at chosen temperatures, total [W] or per floor area [W/m²]

1 Introduction

The building sector accounts for some 40% of all energy consumption in the EU and by far the largest share of this energy consumption is for heating [1]. If we are to reduce fossil fuel consumption and avoid excessive climate change, there is therefore a great need to improve the energy efficiency of our heating systems.

One way of improving the energy efficiency of the heating sector is to reduce the supply and return temperatures for space heating. In the case of buildings heated with district heating, the main benefit from reduced temperatures is the increased efficiency of heat production from sources such as solar heating, geothermal heating, and boilers with flue gas condensation. Low heating-system temperatures are also very important for heat pumps, where the efficiency depends greatly on the temperatures. For example, Ploskić and Holmberg [2] have shown that operating a heating system with supply and return temperatures of 40 °C/30 °C instead of 55 °C/45 °C can improve heat pump efficiency by up to 25% and thus reduce CO₂ emissions from heating by up to 24%. In a review, Ovchinnikov et al. [3] report additional benefits from low-temperature heating, including reduced heat losses from distribution systems in multi-family buildings [4] and improved thermal comfort [5].

New buildings can easily be designed for low-temperature space heating, and the general trend in building regulations is towards lower design temperatures [3,6,7]. However, existing buildings make up the majority of the current building stock, and existing heating elements were often designed for higher temperatures. This could be a problem because the heat output of a radiator is reduced when the heating-system temperatures are reduced. On the other hand, several studies indicate that most current heating systems are over-dimensioned, meaning that the radiator sizes are so large, that the heat output of the radiators is greater than is needed to cover the heat loads in the rooms. One reason for this is that common design methods are either based on rough rules of thumb or extreme design conditions with no internal heat gains and extremely low outdoor temperatures. An example of this is reported in a study by Hasan et al. [8] who conclude that modern Finnish buildings could be well-suited for low-temperature heating due to the initial over-sizing of radiators using typical design methods. Moreover, several studies indicate that existing heating systems could be operated with temperatures lower than those expected, which can also be explained by the fact that the heating systems are over-dimensioned. These studies include Jangsten et al. [9] and Averfalk et al. [7], who have reported the heating system temperatures in several Swiss and Swedish heating systems, and Tunzi et al. [10], who have shown that heating-system temperatures in existing houses could be greatly optimized during actual operation.

Another reason that heating systems in existing buildings tend to be over-dimensioned is that the heat load in many buildings has been reduced through energy renovation. This was found in a theoretical investigation the current authors carried out on the expected heat output in existing Danish single-family houses [11]. Moreover, studies by Wang et al. [12], Brand et al. [13], and Harrestrup et al. [14] all indicate that typical existing buildings can be heated with low temperatures if they have been through energy renovation. Most of these reported findings, however, are based on case studies, theoretical considerations, or general experience, and although it is commonly noted that radiators are often over-sized [6,12,15,16], cases with under-dimensioned radiators have also been encountered [17,18].

To the best of the authors' knowledge, no large-scale study has previously been made to demonstrate that actual radiator sizes in existing buildings are in general over-sized. This is supported by the findings of a recent

European study that concludes that there is a general lack of knowledge about heating-system temperatures and heating systems inside existing buildings [7]. The current study therefore set out to produce new knowledge about the typical dimensions of radiators in existing Danish houses based on actual data from a large survey. Such knowledge is crucial for the future transition to low-temperature heating, because large savings can be achieved with very little investment if heating systems are in fact currently over-dimensioned and appropriate for low-temperature supply already today.

1.1 Aim of study

The aim of this study was to generate new knowledge about the heat output of radiators installed in existing houses, based on actual survey data. An analysis of the dimensioning of existing heating systems was carried out by comparing survey data on the heat load and the total heat output in existing Danish houses. Analyses were made to see if factors such as the age of the house and the energy efficiency of the building had an impact on the estimated total heat output. Secondly, the expected supply and return temperatures during the year were calculated for three different dimensions of heating system. The purpose of this was to illustrate how an under-dimensioning of the heating system would affect the potential for reducing the supply and return temperatures in the houses. The supply and return temperature strategies suggested here were based on heat supply from a district heating network, though other strategies could be applied based on other options for heat supply.

2 Method

This study consisted of two parts: an investigation of a large number of observations of the total heat output and the heat load in 1645 houses, and an investigation of actual heating system operating temperatures in houses with three different radiator dimensions. The following sections describe the methods applied in the two investigations.

2.1 Description of survey data

The main analyses in this paper are of estimated heat load and total heat output based on observations in approximately 11,600 rooms of Danish single-family houses and small apartment buildings. The observations were registered by plumbers performing service checks on heating system installations in houses supplied by district heating. The plumbers recorded the following information for each house (1–3) and for each room in the house (4–6):

1. Construction year (range: 1620–2014)
2. Geographical location (Danish postal code, which indicates a town or area)
3. Estimated design heat load (range: 20–150 W/m² floor area)
4. Estimated design heat output of radiators [W]
5. Floor area [m²]
6. Type of room [kitchen, bedroom, living room, dining room, bathroom, etc.]

The estimation of the design heat load is based on the plumber's individual evaluation of the state of the building construction. This evaluation was typically carried out by starting from a table of typical heat loads for houses based on their construction year, and then reducing the expected heat load by the savings expected from identified energy renovations carried out, such as the replacement of windows or extra insulation added on the roof. The design heat load was therefore an estimated average for the house as a

whole, and used for every room without adjustment for the individual room's external wall areas or window sizes.

The heat output of the radiators was estimated based on radiator type and heating surface area using a tool that calculates the heat emissions from typical Danish radiators. In rooms that contained more than one radiator, each radiator was included as an individual observation, and the total room area was split in proportion to the heat output of the individual radiator. This means that some rooms count as two rooms.

2.2 Pre-processing and overview of data

All the data was entered manually by the plumbers, and it was then checked for misprints and obvious mistakes before use in the analysis. During this pre-processing, the following types of observation record were excluded from the dataset:

- Records with unreasonable input values or likely misprints (e.g. a design radiator heat output of 0.06 W or a non-existent postal code)
- Records where important parameters (floor area, radiator heat output, heat load) were missing
- Records for rooms without a radiator (e.g. non-heated rooms – often hallways, sculleries, or basement rooms) or rooms that were heated by electrical heating or floor heating
- Records for houses with only one room (or two rooms, if it looked as if the data were incomplete or significantly non-typical)

The data was also slightly pre-processed in order to focus the analysis on the radiator sizes. For example, additional electrical heating (such as floor heating or towel rails in bathrooms) was ignored. In some cases observations of radiators had been noted without further room information. In this case, the radiator heat output was attributed to the room of the previous observation, because we assumed that the record represented a case of a room with more than one radiator.

To achieve an overview of the data and limit variation in the output, the processed data were grouped by construction period, geographical area, and heat load. The grouping of data by construction period was based on the typical construction periods defined in the Danish contribution to the European TABULA study of typical building constructions [19]. The distribution of observations across the various periods is shown in Fig. 1 (left) and was found to correspond well with the average distribution of single-family houses in Denmark, where a large number of houses were built during a building boom in 1960–1980 (groups 5–6) and in the period 1900–1950 (included in groups 2–3). The geographical grouping was based on six geographical areas in Denmark (Greater Copenhagen, Zealand, Funen, Southern Jutland, Mid Jutland, and Northern Jutland), as shown in Fig. 1 (right). Most of the observations were made in Zealand and in the Copenhagen area, while Funen and Southern Jutland were generally under-represented. However we do not think this had much effect on the results, because building customs are fairly similar in the various parts of the country.

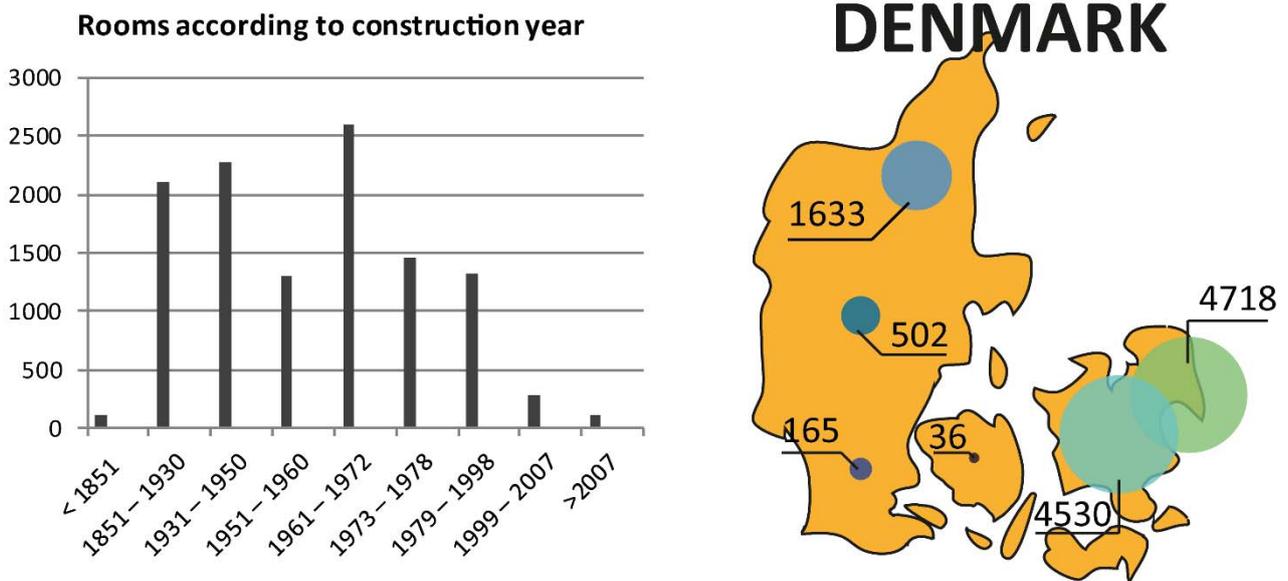


Fig. 1 Distribution of observations by construction period (left) and geographical location (right).

Due to the large amount of data, it was not possible to investigate all the input data in detail. Apart from the above-mentioned pre-processing of the data, it was therefore assumed that the observations were generally reliable.

2.3 Over-dimensioned radiators

The dimensioning of a heating system can be done in many ways, and discussion of whether a heating system is over-dimensioned requires a definition of the dimensions expected. A heating system could be over-dimensioned for the actual operation conditions, over-dimensioned relative to the dimensioning standards current at the time of the building's erection, or over-dimensioned compared to today's dimensioning standards. Furthermore, a heating system can be deliberately over-dimensioned in order to take into account rapid re-heating periods after night set-backs or vacations. In this study, we only considered the usual steady operation of the heating system, and our aim was to investigate whether the heat output of the radiators installed in existing houses is large enough to allow the use of low-temperature heating. We therefore considered whether the total heat output of the existing heating system could cover the existing design heat load of the houses using reasonably modern supply and return temperatures. Over-dimensioning in this study was therefore defined as follows:

The heating system is defined as over-dimensioned when: the design heat output of the heating system at the supply and return temperatures of 70 °C/40 °C is above the current design heat load of the heated building.

Supply and return temperatures of 70 °C/40 °C were commonly used in Denmark for a long period in the late 1900s [7,11]. This is therefore a common temperature set referred to for a large part of the existing building stock in Denmark. Moreover, it is close to the current Danish design temperatures of 60 °C/40 °C. In Denmark, the design heat load is the heat load required to maintain an indoor temperature of 20 °C, when the outdoor temperature is –12 °C and no heat gains are taken into account.

We investigated the question of over-dimensioned radiators by adding an extra parameter to the data set – the radiator factor. The factor describes the relationship between the design heat output of the heating system and the design heat load of the building. It was calculated for each house as a whole. It did not make sense to investigate this at room level because the estimated heat load of each room was not differentiated according to the external wall area and window area.

The radiator factor was calculated in the following way. First the design heat output was converted to the typical Danish temperature set with supply and return temperatures of 70 °C and 40 °C respectively. Most of recorded heat output data were already given at these temperatures, while a few were given at different temperature sets. The conversion was performed in accordance with Equation 1 and Equation 2, which are prescribed in current standards for the calculation of the heat output of radiators [20,21]. The equations are derived empirically to provide a simplification for calculations of the non-linear relationship between heat output and the temperature difference between radiator and the surrounding air [22], and they were applied using the logarithmic mean temperature difference and a standard radiator exponent of 1.3, as suggested in Danish guidelines [20].

$$\text{Equation 1} \quad \Phi_{\text{output}} = \Phi_{\text{design,output}} \cdot \left(\frac{\Delta T_{\text{log}}}{\Delta T_{\text{log,design}}} \right)^n$$

where

Φ_{output} is the total heat output of the radiators at the chosen temperatures 70/40/20 [W]

$\Phi_{\text{design,output}}$ is the total heat output of the radiators at design temperatures [W]

ΔT_{log} is the logarithmic mean temperature difference at the chosen temperatures 70/40/20 [°C]

$\Delta T_{\text{log,design}}$ is the logarithmic mean temperature difference at design temperatures [°C]

n is the radiator exponent

$$\text{Equation 2} \quad \Delta T_{\text{log}} = \frac{(T_s - T_r)}{\text{LN} \left(\frac{T_s - T_i}{T_r - T_i} \right)}$$

where

T_s is the supply temperature

T_r is the return temperature

T_i is the indoor air temperature

Secondly, the design heat output values for all the radiators in the house were summed and divided by the total heated room area of the house to obtain the design heat output in W per m² floor area. Lastly, the radiator factor was calculated by dividing the design heat output of the house by the estimated design heat load of the house, as shown in Equation 3.

$$\text{Equation 3} \quad \text{Radiator factor} = \frac{\Phi_{\text{design,output}}}{\Phi_{\text{design,load}}}$$

where

$\Phi_{\text{design,output}}$ is the total design heat output of the radiators in W per m² heated floor area

$\Phi_{\text{design,load}}$ is the design heat load of the house in W per m² heated floor area

The radiator factor thus indicates whether the radiators are over- or under-dimensioned (above or below 1 respectively).

2.4 Annual heating demands

The insulation standard of modern buildings can often be evaluated in terms of the annual heating demand, so we made estimations of the annual heating demands corresponding to the various design heat loads. These were calculated using the degree-day method, as given in Equation 4. First, the design heat load was divided by the design temperature difference to estimate the heat loss related to the temperature difference between indoors and outdoors in the design situation. In Denmark, the design indoor temperature is 20 °C while the design outdoor temperature is -12 °C. Second, this value was multiplied by the number of degree days for a normal year. The degree days are calculated by calculating the difference between the average daily outdoor temperature and an indoor temperature of 17 °C. This is done for all days where outdoor temperatures are below 17 °C and summed for the entire year. Finally, the value is multiplied by 24 and divided by 1000 to convert the unit to kWh. In these calculations, we applied a standard degree-day number for Denmark of 2808 °C/year [23].

$$\text{Equation 4} \quad Q_{\text{annual}} = \frac{\Phi_{\text{design,load}}}{T_{i,\text{design}} - T_{e,\text{design}}} \cdot DD \cdot 24/1000$$

where

Q_{annual} is the annual heating demand per heated floor area [kWh/m²]

$\Phi_{\text{design,load}}$ is the design heat load of the house [W/m²]

$T_{i,\text{design}}$ is the design indoor temperature of 20 °C

$T_{e,\text{design}}$ is the design exterior temperature of -12 °C

DD is the number of degree days, here 2808 °C/year

2.5 Energy renovations

To make it possible to evaluate whether the insulation standard of the houses would have an influence on the feasibility of shifting to low-temperature heating, the houses were divided into three categories according to their estimated design heat load. The grouping is illustrated in Table 1. Please note, that the category with the best insulation still has an estimated annual heating demand which is far higher than expected for typical modern low-energy houses.

Table 1 Grouping of houses according to insulation standard

Insulation level	Poor insulation	Medium insulation	Good insulation
Design heating demand	Above 85 W/m ²	55–85 W/m ²	Below 55 W/m ²
Estimated annual heating demand	Above 179 kWh/m ²	116–179 kWh/m ²	Below 116 kWh/m ²

In the years to come, the existing building stock is expected to go through energy renovation either as part of general maintenance or due to energy policies to reduce heat consumption. According to the Danish Building Research Institute, the energy renovations expected for typical Danish houses will lead to typical design heat loads below 60 W/m² [19]. When the heat load is reduced, the share of over-dimensioned heating systems will increase. The effect of such renovations was investigated by calculating the radiator factor for

the buildings in the data sample, assuming that the design heat load of each house was reduced to a maximum of 60 W/m².

2.6 Heating system operation temperatures

Even if the heating system is under-dimensioned and the radiator factor is found to be below 1, the heating system can still be operated with low temperatures for most of the year. This is because the calculated radiator factor only refers to the design situation with extreme outdoor temperatures and no heat gains. Actual operation conditions are very different, because typical outdoor temperatures are much higher than -12 °C and Danish standards suggest a typical internal heat gain of 5 W/m² from occupants and equipment. Typical heating system supply and return temperatures that would be applicable in typical Danish houses during the course of a year were therefore calculated for a theoretical house with a medium design heat load of 75 W/m² and a correctly dimensioned or under-dimensioned heating system (radiator factors of 1, 0.8, and 0.6 respectively). The calculations were carried out as follows:

The heat demand in the house was assumed to be linearly related to the difference between indoor and outdoor temperatures. The heat transmission coefficient of the house was therefore first calculated based on Equation 5.

$$\text{Equation 5} \quad U_{house} = \frac{\Phi_{design,load}}{T_{i,design} - T_{e,design}}$$

where

U_{house} is the heat transmission coefficient of the house per m² heated floor area [W/m² K]

$\Phi_{design,load}$ is the design heat load of the house in W per m² heated floor area (here 75 W/m²)

$T_{i,design}$ is the design indoor temperature of 20 °C

$T_{e,design}$ is the design exterior temperature of -12 °C

The heat loads of the house at typical exterior temperatures (T_e) between -5 °C and 15 °C were then calculated in accordance with Equation 6, by using the heat transmission coefficient and taking internal heat gains of 5 W/m² into account. For the typical heating system operation, we assumed that the actual indoor temperature is maintained at 21 °C throughout the year, which has been found to be more realistic than 20 °C for current Scandinavian homes [24].

$$\text{Equation 6} \quad \Phi_{load} = U_{house} \cdot (T_{i,actual} - T_e) - 5 \text{ W/m}^2$$

where

Φ_{load} is the heat load of the house at various outdoor temperatures in W per m² heated floor area

$T_{i,actual}$ is the assumed actual indoor temperature of 21 °C

T_e is the exterior temperature varying between -5 °C and 15 °C.

The heating systems investigated were assumed to have a radiator factor of 1.0, 0.8, or 0.6. The design heat output of the heating system was therefore assumed to be 100%, 80%, or 60% of the design heat load of 75W/m².

To calculate the heating system supply and return temperatures needed, we first calculated the logarithmic mean temperature difference needed to cover the heat load at the varying outdoor temperatures. This was done using Equation 1 and Equation 2. Finally, we calculated the supply and return temperature needed to

meet the logarithmic mean temperature difference required. This was done through an iterative process using Equation 2. Supply and return temperatures were varied to obtain the logarithmic mean temperature difference required to maintain an indoor temperature of 21 °C. The supply and return temperatures were calculated for two different strategies – a return temperature strategy and a supply temperature strategy. These strategies are described in Table 2. The strategies suggested are based on heat supplied from a district heating network, so they take into account the special requirements for cooling in a district heating system. Other temperature strategies can be designed for other heat supply options, because both condensing gas-boilers and heat pumps also benefit from low-temperature operation, or to take into account other local district heating temperature preferences.

Table 2 Description of return temperature strategy and supply temperature strategy for a district heating scenario

	Return temperature strategy	Supply temperature strategy
Aim	To achieve a return temperature as low as possible	To use a supply temperature that is as low as possible.
Motivation	A reduction in return temperature provides increased energy efficiency for current heating production with biomass boilers or waste incineration with flue gas condensation.	A low supply temperature is very beneficial in the case of heat supplied from e.g. a heat pump
Conditions	A supply temperature of at least 65 °C is available from the district heating network due to high temperature requirements of some buildings and old domestic hot water tanks.	A district heating supply temperature of at least 55 °C (50 °C in secondary systems) for the safe delivery of domestic hot water through instantaneous heat exchangers without risk of legionella. At least 30 °C cooling of the district heating water in winter due to capacity limitations in the district heating pipes.

3 Results and discussion

3.1 Survey results

Fig. 2 shows a box plot of the total heat output installed in the houses surveyed, grouped by construction period. For comparison, Fig. 3 shows a box plot of the estimated design heat load or annual heating demand of the houses included in the survey. As shown in Fig. 2, the boxes in both plots represent the 25, 50, and 75 percentiles of the houses, while the error margins show the minimum of the top 5% and the maximum of the bottom 5% of the houses.

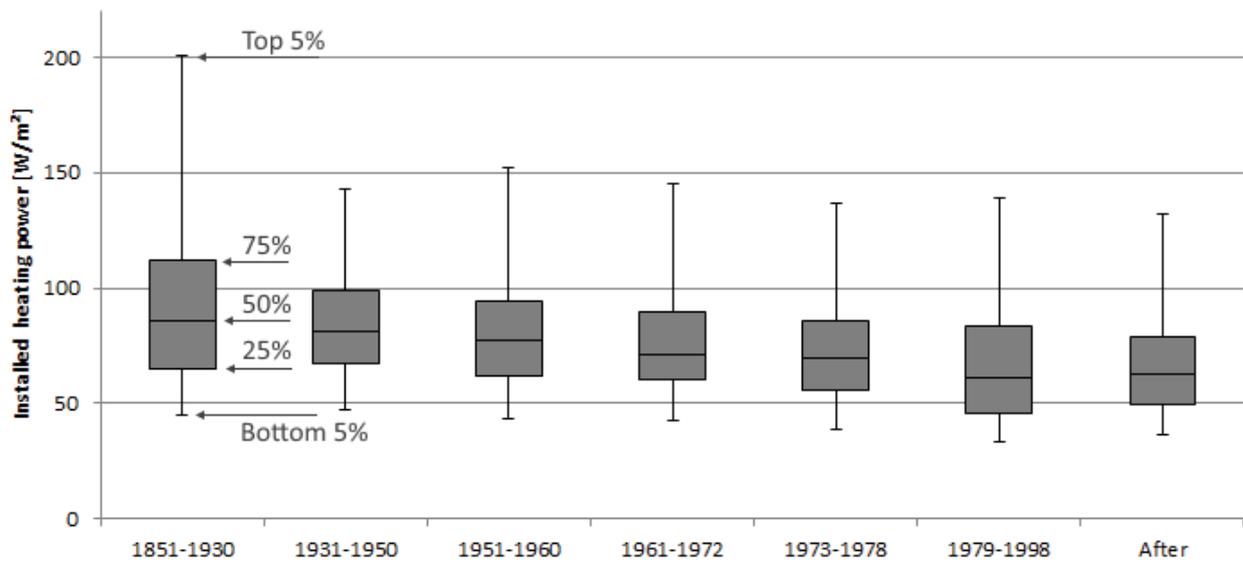


Fig. 2 Boxplot of the total heat output (in W/m^2 of heated floor area) installed in 1645 Danish houses. The heat output is given at supply and return temperatures of $70\text{ }^\circ\text{C}$ and $40\text{ }^\circ\text{C}$ respectively.

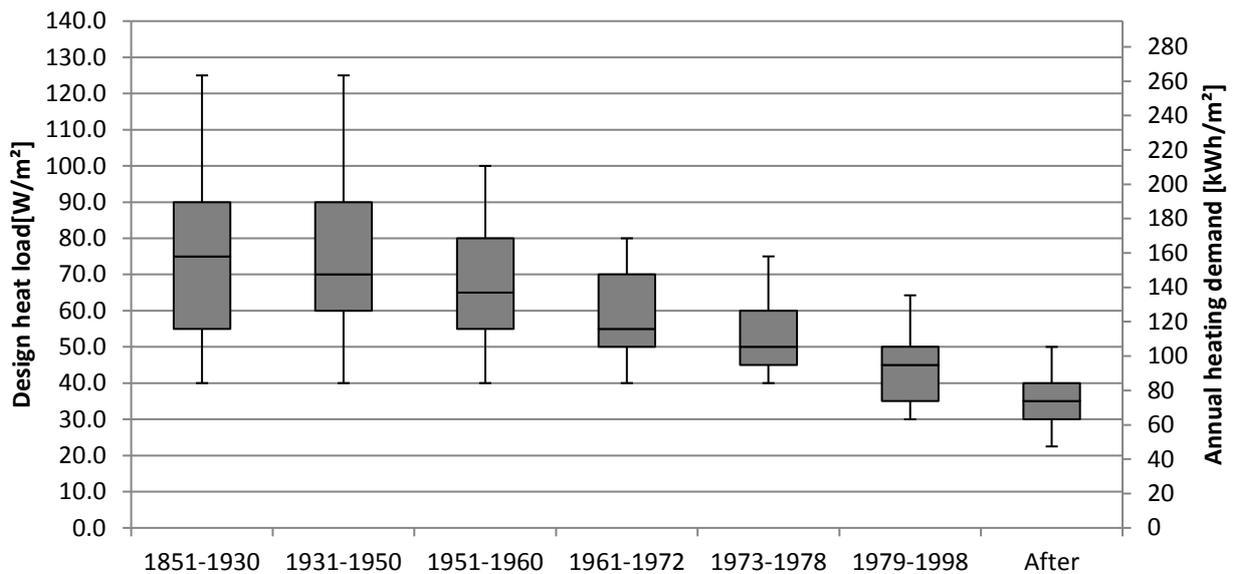


Fig. 3 The design heat load or annual heating demand of the houses included in the survey

The results show that new houses tend to have less design heat output installed. This is not surprising, because the heating demand is also lower in new houses, and radiators can therefore be expected to be designed to cover this lower demand. The results also show a large variation in the heat output installed in individual houses. While perhaps not so surprising in older houses, where the heating systems may have been designed at different points in time and in accordance with different guidelines, the reader might have expected that the total heat output installed in newer houses would deviate less due to standardized heating system design procedures and strict regulations on design heat load.

Fig. 4 shows a box-plot of the radiator factor in the houses surveyed, grouped by construction period.

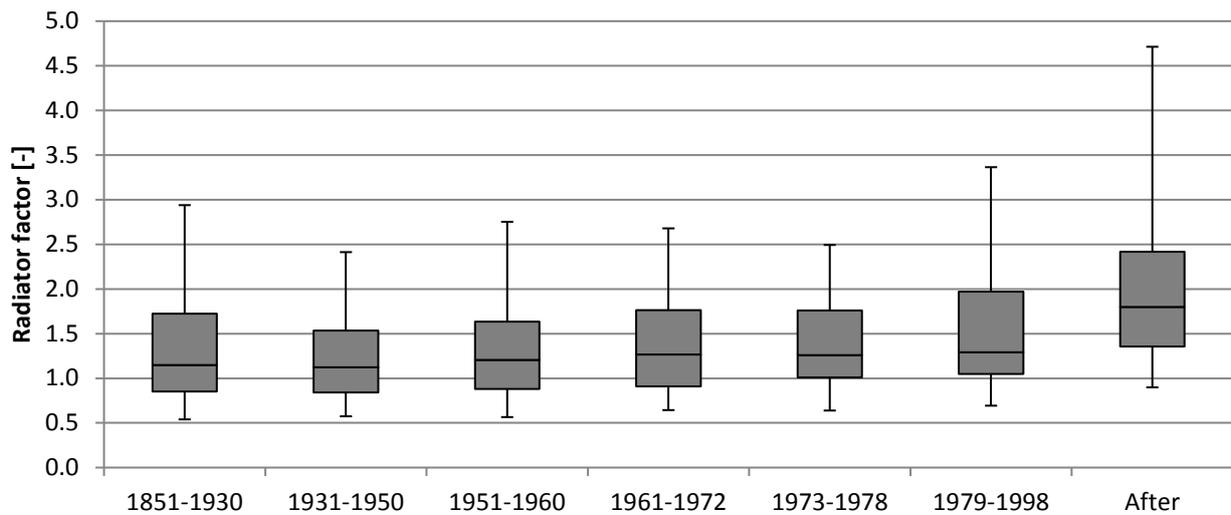


Fig. 4 The radiator factor for 1645 houses, grouped by construction period

The figure shows that the vast majority of heating systems are over-dimensioned relative to their estimated current design heat loads (with radiator factors between 1.0 and 4.5), while a small minority of the heating systems are slightly under-dimensioned (with radiator factors between 0.5 and 1.0). The figure also shows that the radiator factor of the houses is higher for new houses, especially for those built after 1998. This could be partly due to decreasing design heating-system temperatures that lead to new heating systems being made larger in size. This would indicate that it may be easier to heat new houses with low-temperature heating, since heating systems in new houses are more likely to be over-dimensioned. The figure shows that a very small percentage of houses constructed after 1972 have a radiator factor below 1.0, while more than 25% of the houses built before 1973 have a radiator factor below 1.0. Nevertheless, the figure also shows that an older house from 1930 may be just as easy to heat with low heating-system supply temperatures as a new house, because more than 50% of old houses also have a radiator factor of 1.1 or above.

3.2 Radiator factor and energy renovations

Fig. 5 shows a box-plot of the radiator factor in the houses, grouped by heat consumption.

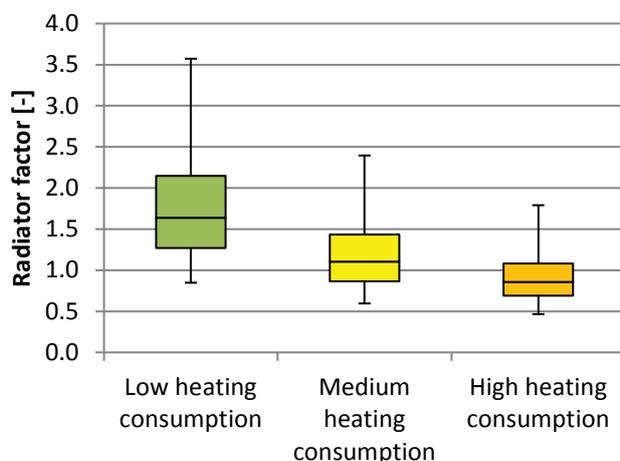


Fig. 5 The radiator factor in the houses, grouped by heating consumption

The figure shows that houses with a low design heat load are more likely to have over-dimensioned radiators. This is both because the insulation of the thermal envelope of the existing buildings has been improved and because new buildings, which were found to be more likely to have over-dimensioned radiators, generally belong to the group with low heating consumption.

Fig. 6 shows the percentage of heating systems that are over-dimensioned according to the current status of the houses surveyed (black line) and according to a scenario where all houses have been renovated to meet a maximum design heat load of 60 W/m² (green dashed line).

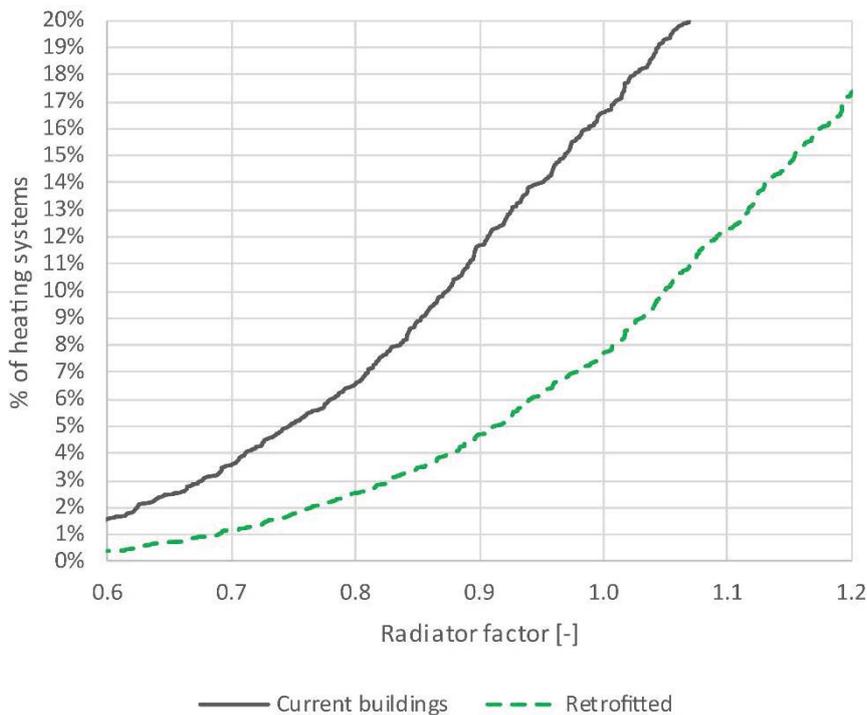


Fig. 6 Percentage of heating systems with a radiator factor between 0.6 and 1.2.

The graph shows that approximately 17% of the heating systems surveyed currently have a radiator factor below 1.0. If the houses are renovated, this percentage will be reduced to approximately 8%. Moreover, this does not mean that 8% of all radiators will need to be replaced before low-temperature heating can be used – as we will show in the next sections.

3.3 Actual heating-system temperatures

Even if some rooms have heating elements that are under-dimensioned relative to the design conditions (as illustrated by the radiator factor), they can be still over-dimensioned relative to the actual heating demand, which may differ greatly from the design situation. Fig. 7 and Fig. 8 give examples of supply and return temperature curves from a house with a medium heating consumption (a design heat load of 75 W/m²) and a heating system with a radiator factor of 0.6, 0.8, or 1.0.

Fig. 7 shows the supply and return temperatures that would apply in a scenario where medium supply temperatures are available, and the supply temperature is therefore chosen with a view to achieving a low return temperature.

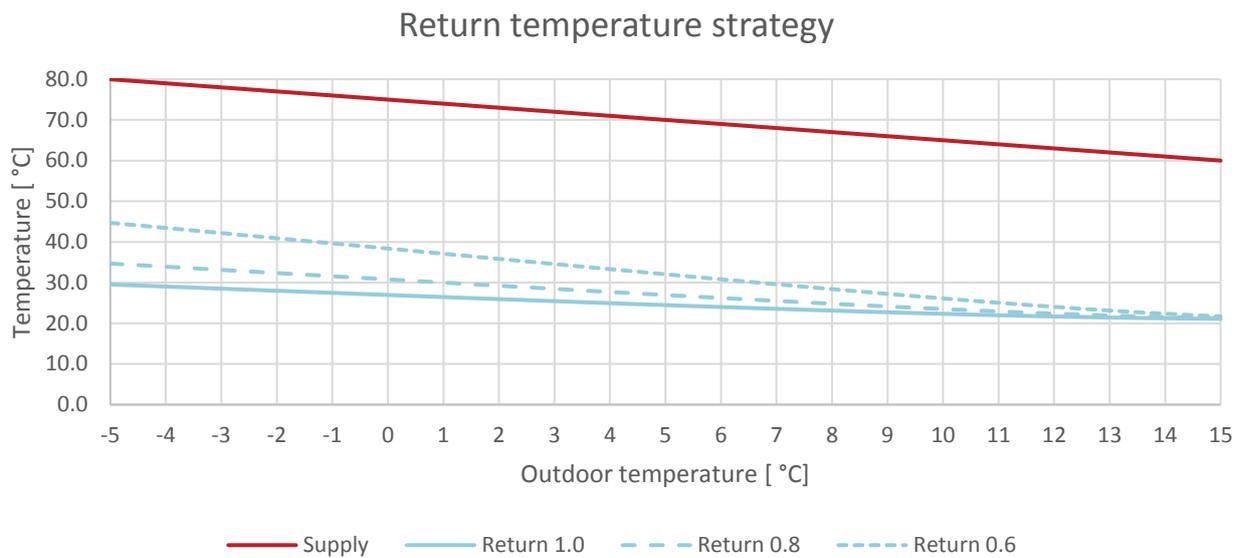


Fig. 7 Supply and return temperature curves for a house with a radiator factor of 0.6, 0.8, or 1.0 optimized for a low return temperature

As the figure shows, a heating system that is under-dimensioned by 40% causes the return temperature from the house to increase by up to 15 °C in cold periods. A house with a radiator factor of 1.0 would be able to deliver return temperatures below 30 °C for most of the year if a high heating system supply temperature is accepted. It can though be argued that lower heating supply temperatures would be preferable to avoid the risk of scalding on pipes and radiator surfaces.

Fig. 8 shows the supply and return temperatures that would apply in a scenario where temperatures are chosen with a view to achieving a low supply temperature.

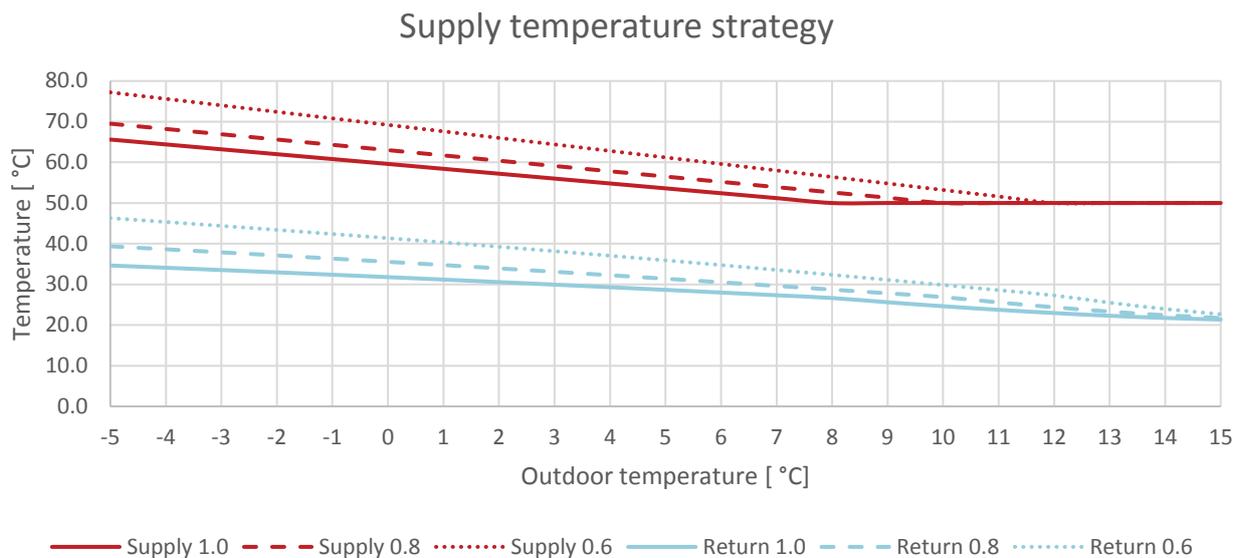


Fig. 8 Supply and return temperature curves for a house with a radiator factor of 0.6, 0.8, or 1.0 optimized for a low supply temperature

As the figure shows, if a house has a heating system with a radiator factor of 0.6 instead of 1.0, the supply temperature needs to be increased by about 12 °C in cold periods. However, even if the supply temperature is not increased in this way, occupants will probably have no problem maintaining thermal comfort. It would just have to be accepted that the return temperature from houses with radiator factors below 1.0 will need to be somewhat higher to maintain the required mean temperature difference of the radiator. As the figure shows, supply temperatures can be as low as 65 °C in the heating system (about 70 °C in the district heating network) in cold periods, if the existing houses have a heating system with a radiator factor of 1.0 or higher.

4 Comparison with other studies

To investigate the accuracy of the survey data, the estimated design heat load and installed heat output were compared with the findings of earlier studies. Fig. 9 shows a comparison of the annual heating demands calculated for the houses included in this study and the values found for Danish houses according to their energy labels [19]. As the figure shows, the average estimated annual heating demands of the houses in this study might be slightly under-estimated compared to the results of the energy labels. However, the deviation between the two sets of data is still rather small, and all in all, the data of this survey seems reasonable.

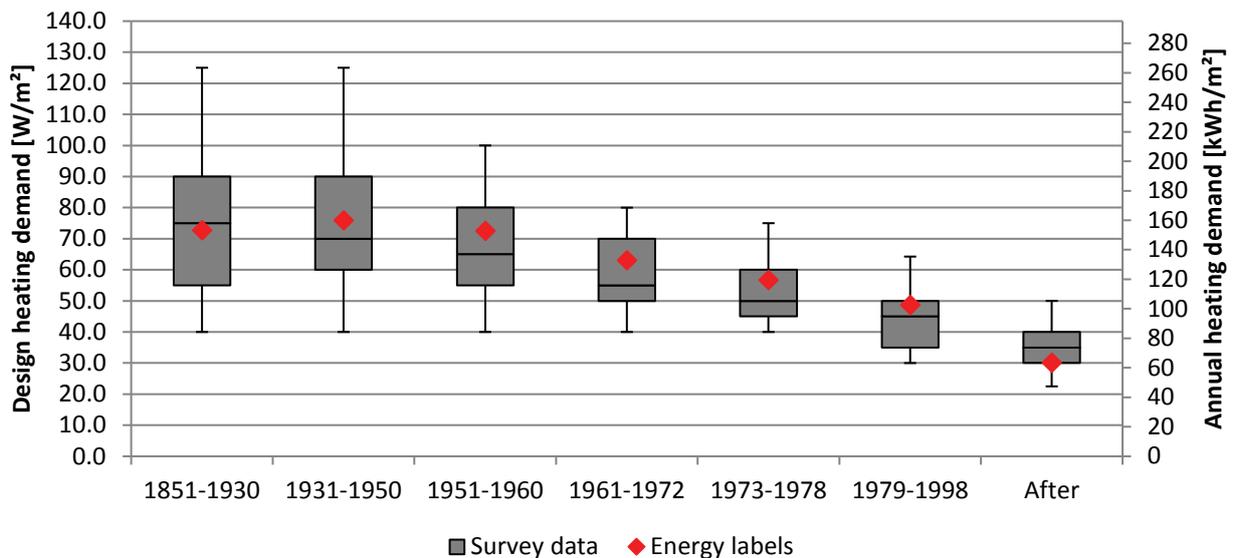


Fig. 9 Comparison of the heating demand estimated in the current survey with that found in a previous study of Danish houses [19]

Fig. 10 shows a comparison of the estimated total heat output according to the current study with our own expectations in our theoretical findings in previous work [11]. The figure shows that the findings of this study indicate that existing houses have a slightly higher installed heat output than we expected in our theoretical estimate. This difference could be explained by the fact that the theoretical estimate was based on a single case house which may therefore not be representative of the average of the houses included in the survey. The difference between the studies could also be because many house-owners have modified their heating system since the erection of the house, so that the actual heat output differs from the theoretical estimate. Nevertheless, the comparisons could indicate that the results from the survey tend to slightly over-estimate the radiator factor of existing houses.

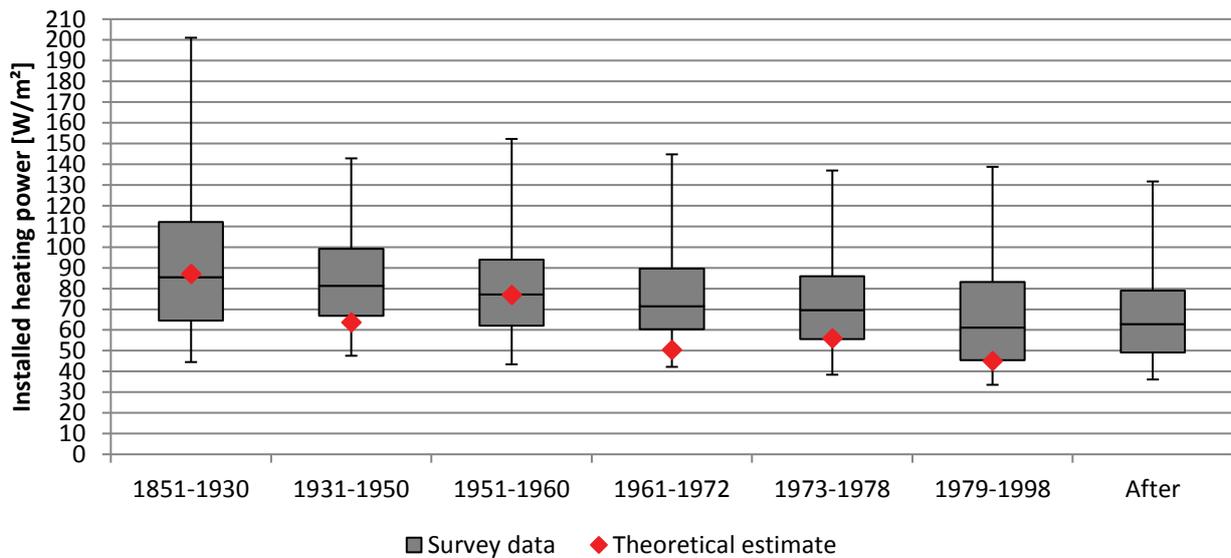


Fig. 10 Boxplot of total installed heat output (70 °C/40 °C) in 1645 Danish houses compared with our own previous theoretical estimate [11].

5 Uncertainties

This study set out to investigate the total heat output installed and the heating system dimensions typical of existing Danish houses. While this provides an indication of the potential for using low-temperature heating in the existing building stock, it does not give any information on how this potential can be realised. To make full use of the heat output of the radiators installed, both the heating system and the individual heat producing units must be properly controlled and operated.

Due to the uncertainties in the survey data presented, we do not recommend relying on individual data points or minimum/maximum measurements. The findings of this study are based on data that was estimated and manually recorded by plumbers, which will unavoidably have included some errors and misprints. So, although the recorded data was checked and pre-processed, it is impossible to be sure that it was correctly estimated and recorded. Nevertheless, the average measurements can still provide useful information, because the investigation included data from 1645 houses, which will reduce the effect of errors in some of the individual records. So, even if the results are not 100% accurate, we think they provide a good indication of the actual state of heating systems in Danish houses, and this view is supported by the comparisons with other existing data in section 4.

One large draw-back of the study lies in the fact that the heat output was investigated for each house as a whole and not on a room-by-room basis. In reality, the total heating system consists of a number of radiators heating individual rooms in the houses and every radiator has to be large enough to meet the heating demand of the given room. So, even if the results of this study show that a number of houses have a radiator factor below 1.0, this does not necessarily mean that all the radiators in these houses are under-dimensioned. And just because the results of this study show that many houses have a high radiator factor, this does not necessarily mean that all the radiators in these houses are large enough to meet thermal comfort preferences in all rooms, when operated with low heating system temperatures. Previous studies by the current authors

have found that the replacement of just a few critical radiators in houses with under-dimensioned heating systems is often enough to ensure that the heating system can be operated with low-temperature heating [25]. This suggests that the replacement of a relatively small number of radiators in houses with under-dimensioned heating systems will make it possible for all houses to be operated with the same low supply temperatures.

The results presented in this study were based on two slightly conservative estimates. Firstly, all additional electrical floor heating was ignored in the study. Additional electrical heating will supply extra heat output, which will reduce the number of under-dimensioned heating systems. Secondly, the supply and return temperature strategies illustrated were calculated by using the logarithmic mean temperature difference and a standard radiator exponent of 1.3. This method is known to slightly underestimate the heat output of typical radiators. On the other hand, the study did not include non-heated rooms in the analysis. If these were included, the total heat output installed per floor area would be slightly lower. Furthermore, the supply and return temperature strategies suggested in this study are based on the possibility of maintaining an indoor temperature of 21 °C in all rooms. This temperature may be somewhat higher in some rooms and somewhat lower in others, depending on occupant preferences. If higher indoor air temperatures are to be maintained, which seems indicated by recent trends, heating systems will need larger dimensions to ensure that the same temperature strategies can be utilized.

Since the results presented are evidently prone to some uncertainties, they should only be used to provide an indication of the state of the total heat output installed and heating system dimensions in typical existing Danish houses. The temperature profiles presented are intended to illustrate how low-temperature district heating can be used even in houses with under-dimensioned heating systems. Nevertheless, the actual temperatures in the individual houses will vary. If this study does in fact slightly over-estimate the radiator factor of existing houses, as indicated by the comparison with other sources, then the number of houses that need slightly higher heating system temperatures will be higher. On the other hand, the results of this study showed that the majority of existing heating systems are greatly over-dimensioned, and they can therefore be operated with much lower heating system temperatures than those presented in this study. In conclusion, low-temperature heating will be able to ensure proper thermal comfort in all houses, even without replacing any radiators, though it would mean that somewhat higher return temperatures would have to be accepted in houses with a low radiator factor.

6 Conclusions

This study set out to provide a factual basis to support the general statement that existing radiator heating systems are over-dimensioned and illustrate the potential for reducing heating-system temperatures in existing houses.

The results of the study show that most radiator heating systems are over-dimensioned in the sense that the estimated design heat output of the heating systems at supply and return temperatures of 70 °C and 40 °C is greater than the estimated design heat load. The results indicate that the newer the house and the smaller the heat load, the more likely it is that the heating system is over-dimensioned. This suggests that the potential for low-temperature heating is greatest in areas with newer houses or houses that have gone through a reasonable amount of energy renovation.

The results of the study show that there is a big potential for low-temperature district heating to heat houses with properly dimensioned or over-dimensioned heating systems. For houses with under-dimensioned heating systems, slightly higher supply and or return temperatures must be accepted, but since these houses comprise only a small portion of the total building stock, they may only have a small impact on the overall district heating system. As long as district heating pipe dimensions allow it, it is therefore possible to reduce district heating temperatures even though a few houses have under-dimensioned heating systems. Replacing all the radiators in existing houses in preparation for low-temperature heating would not only be very expensive, but is unnecessary. Nevertheless, further research should be carried out on the energy efficiency improvements that could be achieved in district heating systems by replacing critical radiators in the 8% of houses that can still be expected to have under-dimensioned heating systems when the time comes for low-temperature district heating.

Acknowledgements

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Space heating with ultra-low-temperature district heating – a case study of four single-family houses from the 1980s

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Abstract

District heating is predicted to play a large role in the future fossil free energy system. Apart from providing energy savings by utilizing surplus heat, the district heating system also provides flexibility to fluctuating electricity generation by bridging the electricity and the heating sector. These benefits can be maximized if district heating temperatures are lowered as much as possible. In this paper we report on a project where 18 Danish single-family houses from the 1980s were supplied by ultra-low-temperature district heating with a supply temperature as low as 45 °C for the main part of the year. The houses were heated by the existing hydraulic radiator systems, while domestic hot water was prepared by use of district heating and electric boosting. This paper evaluated the heating system temperatures that were necessary in order to maintain thermal comfort in four of the houses. First the four houses were modelled in the building simulation tool IDA ICE. The simulation models included the actual radiator sizes and the models were used to simulate the expected thermal comfort in the houses and resulting district heating return temperatures. Secondly measurements of the actual district heating return temperatures in the houses were analysed for different times of the year. The study found that existing Danish single-family houses from the 1980s can be heated with supply temperatures as low as 45 °C for the main part of the year. Both simulation models and test measurements showed that there is a large potential to lower the district heating temperatures.

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Keywords: Ultra-low-temperature district heating; radiator; IDA ICE; heating power; heat demand

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1. Introduction

District heating (DH) covers approximately 13% of the heat demand in the EU at the current state. This share is expected to increase in the future, as expansion of the DH networks has been found to be an economically beneficial tool in the transition to a low-CO₂ energy system [1]. The efficiency of the new DH systems can be increased significantly, if they are operated with low supply and return temperatures, according to the principles of 4th Generation District Heating [2]. A reduction of the DH temperature has two positive effects on the energy efficiency of the heat supply. Firstly, when the DH temperatures are reduced, the heat losses from the pipe networks are also reduced. This can generate significant energy savings, as the reductions in heat loss can be estimated to 30 % when supply and return temperatures are reduced from 80 °C/40 °C to 60 °C/30 °C. Secondly the efficiency of the heat production is increased for heat sources such as geothermal heat, heat pumps or solar heating. The efficiency of the heat production is estimated to increase by approximately 10 % in solar thermal plants and 30 % in heat plants supplied by heat pumps, if supply and return temperatures are lowered from 80 °C/40 °C to 60 °C/30 °C. Additionally the heat production efficiency is increased when return temperatures are lowered in heat plants with flue gas condensation supplied by natural gas or wet biomass. Consequently a reduction in the DH temperatures can amount to significant total energy savings.

Danish DH is characterized by a large outspread, and relatively low supply and return temperatures. However recent research has shown that there is further potential to lower the DH temperatures. Currently, approximately 47 % of the total Danish heat demand is covered by DH [3]. Even low-density areas are at times supplied by DH, for example approximately 40 % of the Danish single family houses are heated by DH [4]. Current supply and return temperatures are as low as 70/40 on average [5]. Nevertheless a large effort is currently taking place to reduce the temperatures further. This is done by the DH companies, through installation of automatic temperature optimization software [6] or through research projects that investigate the opportunity to lower the DH supply temperatures to 55 °C or 60 °C in both new and existing buildings [7].

The temperature reductions in the DH networks are limited by the demands and technical requirements in the buildings. In houses or commercial buildings these limitations are generally set by either the domestic hot water (DHW) requirements or the design of the space heating installations. The supply temperature in current Danish DH networks is generally limited by the DHW systems, which are typically designed for preparation of hot water at a temperature above 60 °C. When DHW is stored at this temperature, the risk of Legionnaires' disease is reduced, as the Legionella bacteria mainly grow at lower temperatures. If DH temperatures go below 55 °C, the DHW must be prepared through for example an instantaneous heat exchanger, to avoid Legionella growth in the DHW [8]. By use of the direct heat exchanger, or other solutions as described by Yang, Li & Svendsen in [9], the DH supply temperature can be lowered to around 50 °C, which is enough to deliver DHW at the required comfort temperature of 40-45 °C. This type of DH is commonly referred to as low-temperature district heating (LTDH).

The DH temperatures can be lowered further if the DHW is heated through a combination of DH and electricity. This is also referred to as ultra-low-temperature district heating (ULTDH). DH is used to heat the domestic hot water to a temperature of e.g. 35 °C and the temperature is then further raised to 40-45 °C by for example a micro heat pump [10] or an instantaneous electric heater. In this case the space heating systems are the limiting factor with regards to temperature reductions. For example it may not be possible to lower the supply temperature to 40 °C in old buildings where the heat loss is large and the heating elements are small. However recent research has shown that many existing buildings can be heated by low-temperature heating without problems. This is partly due to the fact that the supply temperature in a LTDH system can be increased in peak periods during cold winter times when the space heating requirements are higher. Ultimately the lower limit for the DH supply temperature could be as low as 30 °C in new buildings with floor heating. Fig. 1 summarizes the different types of DH based on the technical limitations and in correspondence with earlier definitions as described in [2,6,11].

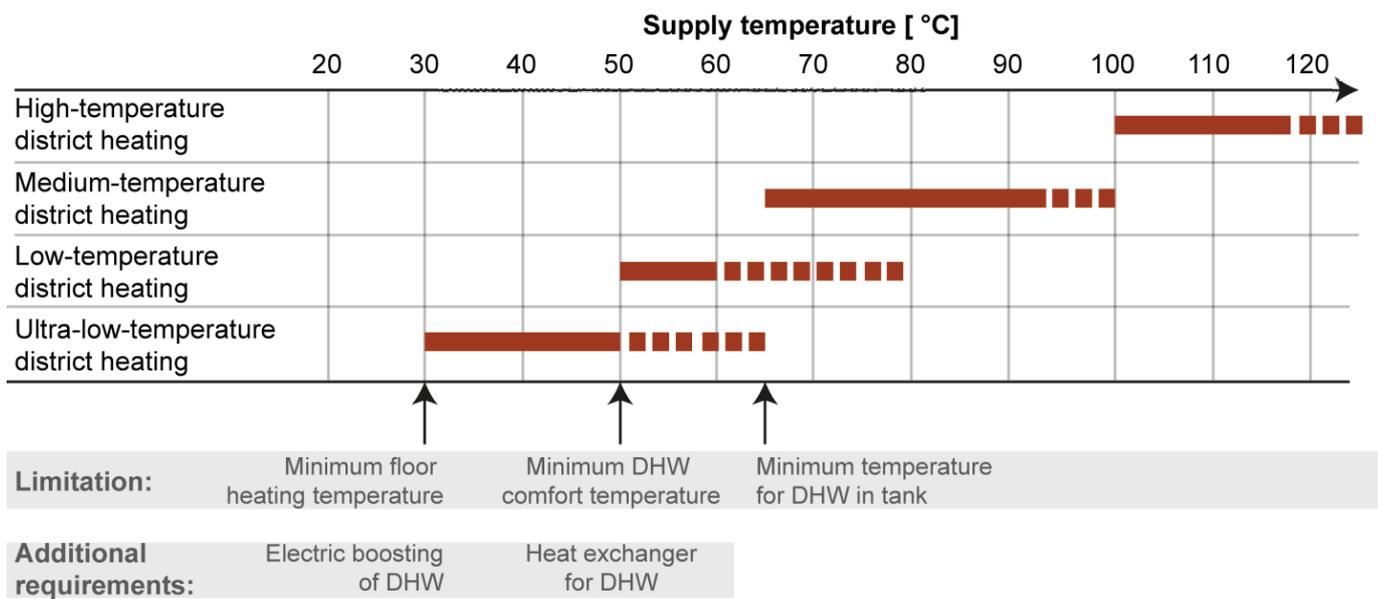


Fig. 1. Definition of four different types of district heating where temperatures are limited by the technical requirements of the buildings.

Since the space heating system is the limiting factor in ULTDH-systems, it is crucial to investigate the design of the space heating systems, when an existing building area is to be supplied by ULTDH. Most Danish houses are heated by hydraulic radiators that are designed for supply and return temperatures such as 90 °C/70 °C or 70 °C/40 °C. However even in these houses it is reasonable to expect that the typical space heating demands can be covered with low-temperature heating, since radiators are designed for extreme conditions with very cold outdoor temperatures. This was verified in our recent investigation of heating power and heating demands in typical Danish single-family houses from the 1900s [12]. Furthermore it is illustrated in several Danish pilot projects where the use of ULTDH in existing building areas has been successfully tested [6,10,11]. Nevertheless none of these projects investigated the limitations of the space heating systems in detail. This study therefore set out to perform a detailed analysis of the space heating systems in four Danish single-family houses heated by ULTDH.

1.1. Aim of study

This study aimed to investigate how far we can lower the heating system temperatures in existing Danish single-family houses without compromising thermal comfort. The study was carried out through measurements from a real test case where four houses were supplied by ULTDH. Since the actual heating system operation can be affected by technical malfunctions or occupant behaviour, the measurements were compared to results from dynamic simulation models, which were used to evaluate the ideal heating system temperatures and the thermal comfort in the houses.

2. Description of case houses

The investigations were carried out as a case study of four single-family houses built around 1980. The houses are illustrated in Fig. 2. All of the houses have 2-3 occupants and a heated floor area of around 150 m². House 1 and 2 furthermore holds an unheated basement. All building elements in the houses were well insulated at the time of construction, and due to the young age, the only renovations carried out is replacement of windows in some houses. The constructions of the houses are described in Table 1, together with the estimated U-values of each construction element. Linear heat losses are based on internal measures and assumed to be 0.07 W/mK around windows, 0.15 W/mK at foundations and exterior wall joints, and 0.12 W/mK for connections between roof and exterior walls. Both constructions and U-values correspond to the standard for this type of houses as given by the Danish Building Research Institute [13] and the Danish Energy Agency [14].

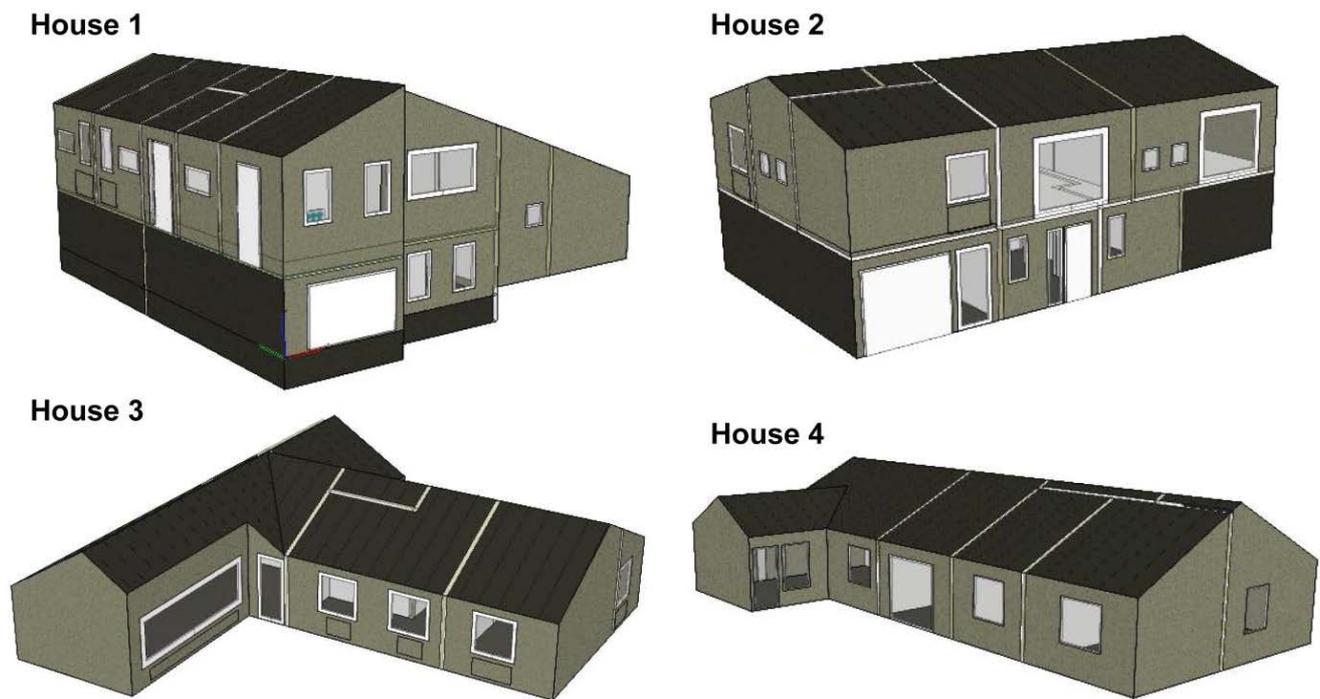


Fig. 2. Illustrations of the four case houses investigated in the study.

Table 1. Estimated U-values and description of constructions of the four houses.

Construction	House 1 ($W/m^2 K$)	House 2 ($W/m^2 K$)	House 3 ($W/m^2 K$)	House 4 ($W/m^2 K$)
External walls – Brick, insulation, and light weight concrete	U = 0.22	U = 0.32	U = 0.32	U = 0.32
Basement floor – Concrete, insulation, and Leca insulation	U = 0.26	U = 0.69	U = 0.28	U = 0.29
Roof – 200 mm insulation	U = 0.2	U = 0.2	U = 0.2	U = 0.2
Windows	U = 1.86	U = 2.68	U = 1.86	U = 2.68

All four single-family houses are supplied by DH and equipped with the original hydraulic radiator heating systems. DH is connected to the houses through a direct connection. The houses are equipped with different solutions for preparation of DHW by use of additional electric energy – these are described by Xiaochen in [15] and will not be described further here. The substation is not equipped with mixing valves or weather compensation control, as the overall DH supply temperature is controlled at plant level, according to outdoor temperature, as illustrated in Fig. 3(a). The radiators in the houses are standard Type 11 and Type 22 radiators, except from a few convector type radiators where windows begin at floor height. All radiators are equipped with individual thermostatic valves. The bathrooms in the houses are equipped with hydraulic floor heating systems, which are embedded in the concrete floors. The floor heating circuits are controlled by thermostatic valves. No central temperature control is installed in the houses.

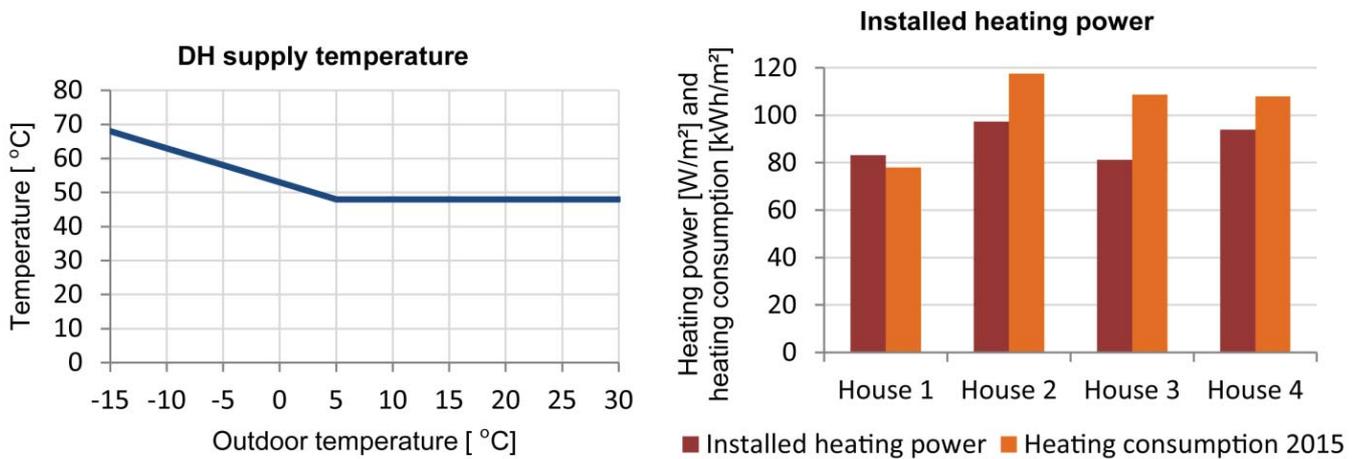


Fig. 3. (a) Variation of supply temperature from the district heating plant according to outdoor temperature; (b) Measured heating consumption in 2015 and installed heating power at the temperature set 70 °C/40 °C in the four case houses.

3. Method

3.1. Dynamic building simulations

The houses were modelled in the dynamic building simulation tool IDA ICE in order to calculate the expected heating system return temperature, and evaluate the thermal comfort in the houses, when the DH supply temperature is lowered. IDA ICE is a commercially available node based multi-zone simulation tool. The tool has been validated in accordance with standard DS/EN 15265, which describes the accuracy of dynamic simulations of energy performance in buildings [16,17]. The program calculates the heat balance of the buildings for every hour of the year, and has a high level of detail, that includes amongst others thermal inertia of building materials, and air flow between building zones. The program does not take into account temperature gradients in the rooms, and therefore air is assumed to be perfectly mixed in all rooms. This is not assumed to be a problem as none of the rooms in the investigated houses are too high.

The input data required to perform a specified simulation in IDA ICE includes for example air change rates and occupant schedules. This information was defined based on standard values for Danish single-family houses as given by [13,18]. All houses are naturally ventilated and it was assumed that the ventilation rate is 0.3 l/s per m² which is the standard minimum required air change rate in Danish single-family houses [19]. Internal heat gains from presence of occupants and use of equipment was modelled by weekly schedules that were constructed for each house according to the number of occupants. The total average internal heat gains in the houses according to the schedules were 4.11-5.08 W per m² living area, which corresponds well to the Danish standard value of 5 W/m² [18]. Energy consumption for domestic hot water was not included in the models and the simulation models were run with weather data for the Design Reference Year of Copenhagen 2001-2010. Measured heat consumption is therefore adjusted according to the number of degree days, before it is compared the calculated heat consumption.

The simulation models were used to calculate the average monthly heating system return temperatures. The program calculates the heating system temperatures based on the mass flows and return temperatures from the individual radiators in the houses. The radiator temperatures and mass flows are calculated for every hour of the year according to the indoor temperature set-point and heat loss in the given rooms. The radiators are therefore included in the models with the actual location, dimensions, and design heating power. Radiator types and dimensions were noted at a visit to the house, and used to find the design heating power of the radiators, by use of a tool that was acquired from the Danish Technological Institute through personal communication. The tool makes it possible to estimate the heating power of a given existing radiator based on empirical data. The average heating power installed in each house is summarized in Fig. 3(b). The figure also shows the total measured heat consumption in each of the houses during 2015. Each radiator is controlled by a P-control thermostatic radiator

valve with a P-band of 2 °C that controls the water mass flow through the radiator and aims to maintain the indoor temperature set-point. The floor heating was assumed to be controlled by similar thermostatic valves, and according to a constant flow, and a maximum coil temperature difference of 5 °C. The heating pipes were assumed to be located at a depth of 0.04m in the concrete slab with tile flooring. The heating system supply temperature was defined according to the weather compensated DH supply temperature. Due to the heat losses in the DH pipes, the supply temperature reaching the houses was assumed to be 6 °C lower than the temperature illustrated in Fig. 3(a), which was found to correspond well to the measured temperatures.

The thermal comfort in the houses was evaluated through an analysis of the calculated indoor air temperatures in each room of the houses. This was done by counting the number of hours during the year, where the indoor air temperatures, according to the simulations, were below the temperature set-point. For this analysis the occupants were expected to maintain an indoor temperature of 20 °C in living areas and 18 °C in the basement. Even so, it should be kept in mind that actual indoor temperatures usually vary greatly due to differences in occupant preferences [20, 21].

3.2. Heating system measurements

The actual space heating temperatures in the houses were evaluated for the period from July 2015 to March 2016, where the houses were supplied by ULTDH. The measurements were conducted by use of energy meters that have an accuracy of approximately $\pm 0.5\%$, according to the manufacturer. The meters were used to measure temperatures, volume, and mass flow of the DH water for the overall district heating connections, and for the preparation of domestic hot water, as illustrated in Fig. 4.

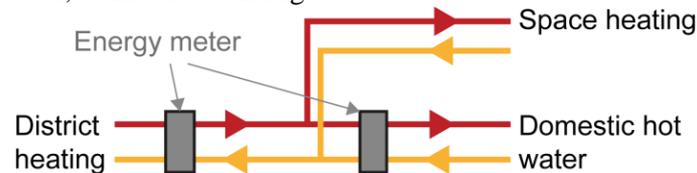


Fig. 4. Illustration of the measurement setup.

The average monthly space heating temperatures were calculated based on the measurements as follows.

First the volume of DH that was used for space heating purposes (V_{SH}) was calculated from the total volume of the DH water (V_{DH}) and the volume of DH used for DHW (V_{DHW}) as seen in Equation (1).

$$V_{SH} = V_{DH} - V_{DHW} \quad (1)$$

Afterwards the return temperature from the space heating ($T_{ret,SH}$) was calculated based on the volumes and the return temperature from the DHW ($T_{ret,DHW}$) and the DH in total ($T_{ret,DH}$). This was done according to Equation (2).

$$T_{ret,SH} = \frac{V_{DH} \cdot T_{ret,DH} - V_{DHW} \cdot T_{ret,DHW}}{V_{SH}} \quad (2)$$

The return temperatures were generally based on volume weighted averages. However for some months the DH return temperatures were calculated as an average of the daily volume weighted return temperature. This is not expected to cause significant inaccuracies, as there were rarely any large variations in the day to day measurements. Due to logger problems, it was not possible to calculate the space heating return temperature in house 4, until December. The space heating return temperature for this house, in the months before then, was therefore assumed to be equal to the DH return temperature. This was found to be reasonable, as the study generally found that the space heating return temperature and the DH return temperature were often merely the same.

4. Results

Table 2 shows a comparison of the degree day adjusted space heating consumption that was measured in the houses and the heating consumption that was calculated by use of the simulation models. It can be seen from the table that the measured and calculated heating consumption differs by up to 13.6 %. The deviation could be partly explained by a difference between the indoor temperatures assumed in the simulation, and the actual indoor temperatures in the house. Some of the houses are additionally heated by a fire stove, which could furthermore cause a deviation between the measured and the calculated heating consumption. Alternatively, the numbers could indicate that the simulation model for House 3 tends to overestimate the heating demand, while the model for House 4 underestimates it.

Table 2. Deviation between simulated and measured space heating consumption (July-March).

House	Calculated (MWh)	Measured (MWh)	Deviation (%)
1	11.64	11.72	0.6
2	13.16	13.95	5.7
3	10.39	9.52	-9.1
4	10.82	12.53	13.6

4.1. Supply and return temperatures

The average monthly space heating temperatures in the houses, according to the simulations and the measurements, are compared for all of the four houses in Fig. 5. The figure also holds the average monthly outdoor temperatures for the measurement period and the DRY weather file. The average outdoor temperatures in the winter of 2015-2016 were found to be somewhat higher than the temperatures in the weather file.

The results show that the space heating in the houses was generally delivered by supply and return temperatures around 40 °C/30 °C or 45 °C/35 °C. The measured space heating return temperature was found to be below 30 °C in a few months of the year in houses 1,3 and 4. Especially House 3 was seen to have a low space heating return temperature. As seen from Fig. 3(b) this does not seem to be explained by significantly lower heat consumption or higher installed heating power.

The simulated and measured space heating return temperatures were found to correspond well for most of the houses. This indicates that the technical potential to lower the heating system temperatures was met in most of the houses. The correlation between measured and simulated temperatures was striking especially in House 3, despite of the difference between the simulated and measured heating consumption. In House 2, on the other hand, it was found that there was a deviation between the simulated and measured return temperature of up to 10 °C. This could be due to the fact that the occupants in this house prefer higher indoor temperatures than the assumed 20 °C, which could be indicated by the high measured heat consumption seen in Fig. 3(b) and Table 2. Nevertheless, the simulation results could also indicate, that there is a potential to obtain significantly lower space heating return temperatures in house 2, if the heating system control is optimized.

4.2. Thermal comfort

In most of the rooms in the single-family houses, it was found that the indoor air temperature never dropped below the set-points of 20 °C and 18 °C. However the simulation results indicated that it was difficult to maintain the thermal comfort temperature in the restrooms in Houses 2-4, where the indoor air temperature was found to be around 19 °C for a large part of the year. These rooms are heated solely by floor heating, which is generally operated with a low supply temperature, and therefore the thermal comfort in these rooms should not be affected by the changes in the DH temperatures. Rather the results may suggest that the heating power of the floor was underestimated, due to uncertainties on the construction and operation of the floor heating. Fig. 6 shows a visualization of the number of hours during the year, where the indoor air temperature drops below the indoor temperature set-point.

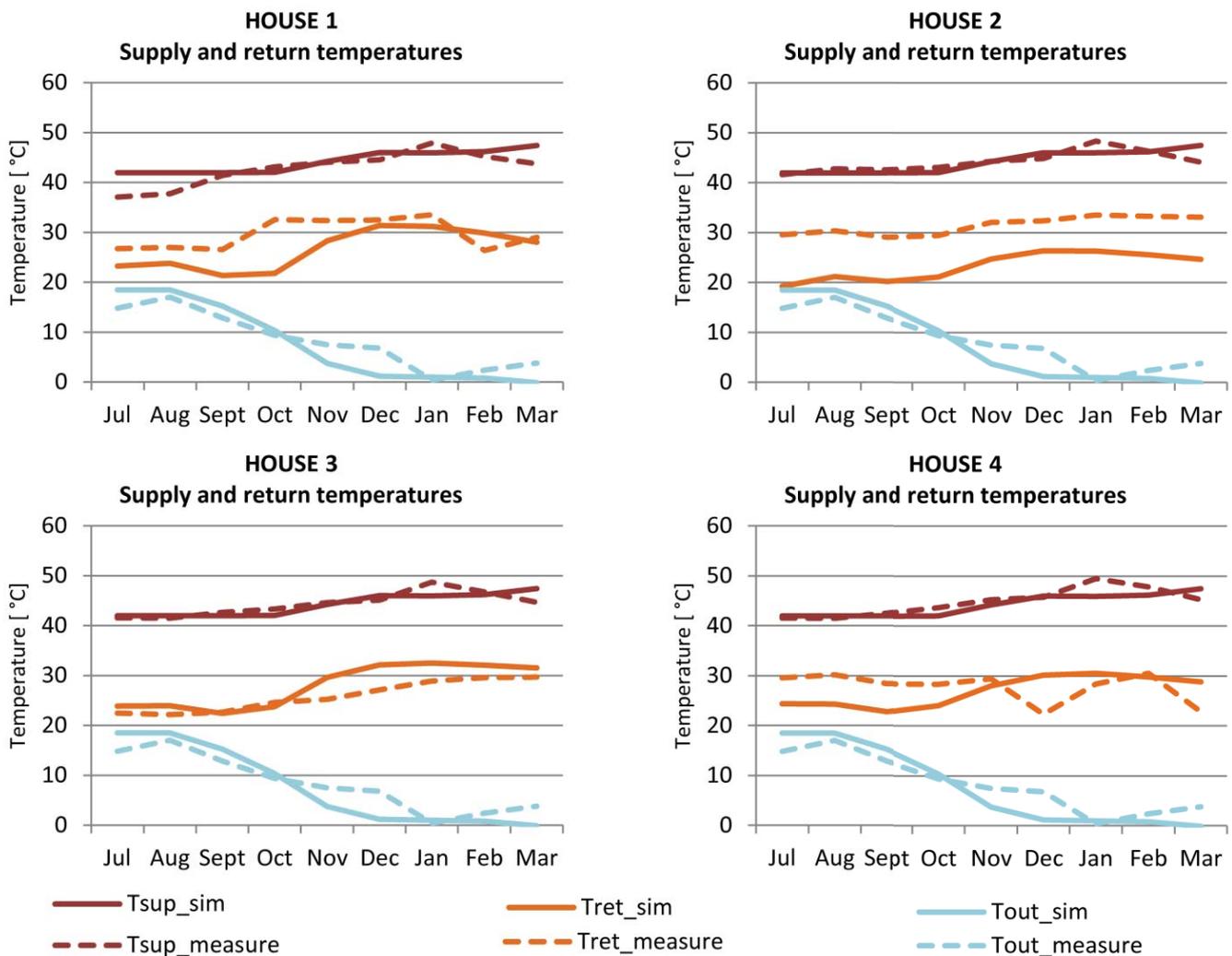


Fig. 5. Simulated and measured space heating temperatures in the four houses.

4.3. Uncertainties

There were found to be two main uncertainties in this study: the construction of the floor heating systems and the indoor temperature set-points. The impact of these uncertainties was evaluated through new simulations of the houses, where two changes were made in the models. Firstly, the floor heating was modelled as plain electric heating. Thereby the heating power of the floor was not affected by the floor construction, and the return temperature from the floor heating did not affect the overall space heating return temperature. Secondly, the indoor temperature was set to approximately 21.5 °C in all living areas. According to a recent study of typical British homes, an indoor temperature of 20 °C or lower, could be a reasonable estimate of average living room temperature, but it is only an average temperature, and actual indoor temperature in many living rooms is higher [21]. Likewise our own studies have showed that indoor temperatures of 21-22 °C are not uncommon in living and dining rooms of Danish single-family houses [22].

Despite of the simplification of the floor heating in the restrooms, the test simulations showed, similar to the first simulations, that it can be difficult to meet the thermal comfort criteria in the bathrooms of House 3 and 4. One explanation could be that the heating power of the floor heating was under-estimated. This seems more likely than the explanation, that the rooms are lacking heating power, as the occupants do not complaint about poor comfort, and floor heating capacity should not be affected by the lowered temperatures. Generally, the results of the test

simulations showed, that indoor temperatures of approximately 21.5 °C could be maintained in all living areas of the houses. Even when the indoor temperature was increased, the return temperature from the radiators only increased slightly. In houses 1-3, the radiator return temperature was found to increase by 1-2 °C in the winter months, while in house 4 it was increased by approximately 4.5 °C. The increased return temperature in house 4 was mainly found to occur due to high return temperatures from the radiators in the entrance and the restroom, where indoor temperatures were also set at 21.5 °C. The results of the test simulations suggest that the findings of the study are generally robust to uncertainties on occupant preferences and indoor temperature set-points. This conclusion is further underlined by the measurements and the fact that none of the customers' complained about problems with the indoor temperature during the test period with ULTDH.

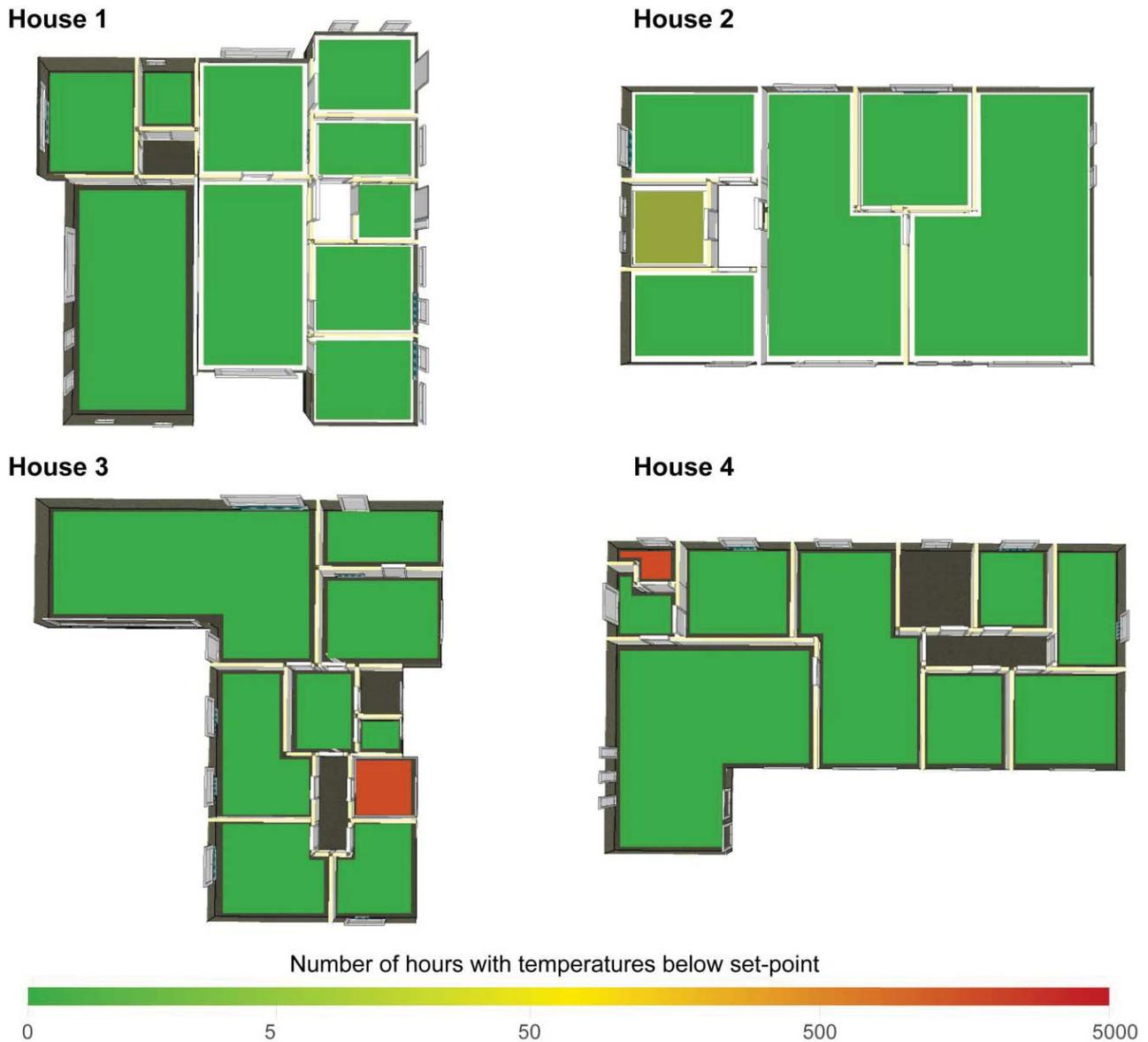


Fig. 6. Visualization of the simulated thermal comfort in the houses

5. Conclusions

The results of this study showed that there is a great potential to heat existing single-family houses with hydraulic radiator systems, with ultra-low-temperature district heating. Simulation results indicated that even when the heating

system supply temperature was lowered to 45 °C for most of the year, this did not jeopardize the thermal comfort of the occupants living in the houses. This was further underlined by the fact that no consumers' complained about poor thermal comfort during a test with lowered return temperatures in a period from 2015-2016.

Both results from a simulation of the heating system operation in four single-family houses, and measurements from the test operation with ultra-low-temperature district heating, showed that there is a large potential to lower the district heating temperatures in existing single-family houses. Average supply and return temperatures for space heating in the houses were found to be 44 °C and 31 °C respectively.

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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.

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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

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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 (IDA Indoor Climate and Energy). 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].

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 LMTD (logarithmic mean temperature difference). The maximum mass flow rate through the radiator corresponds to the mass flow rate 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

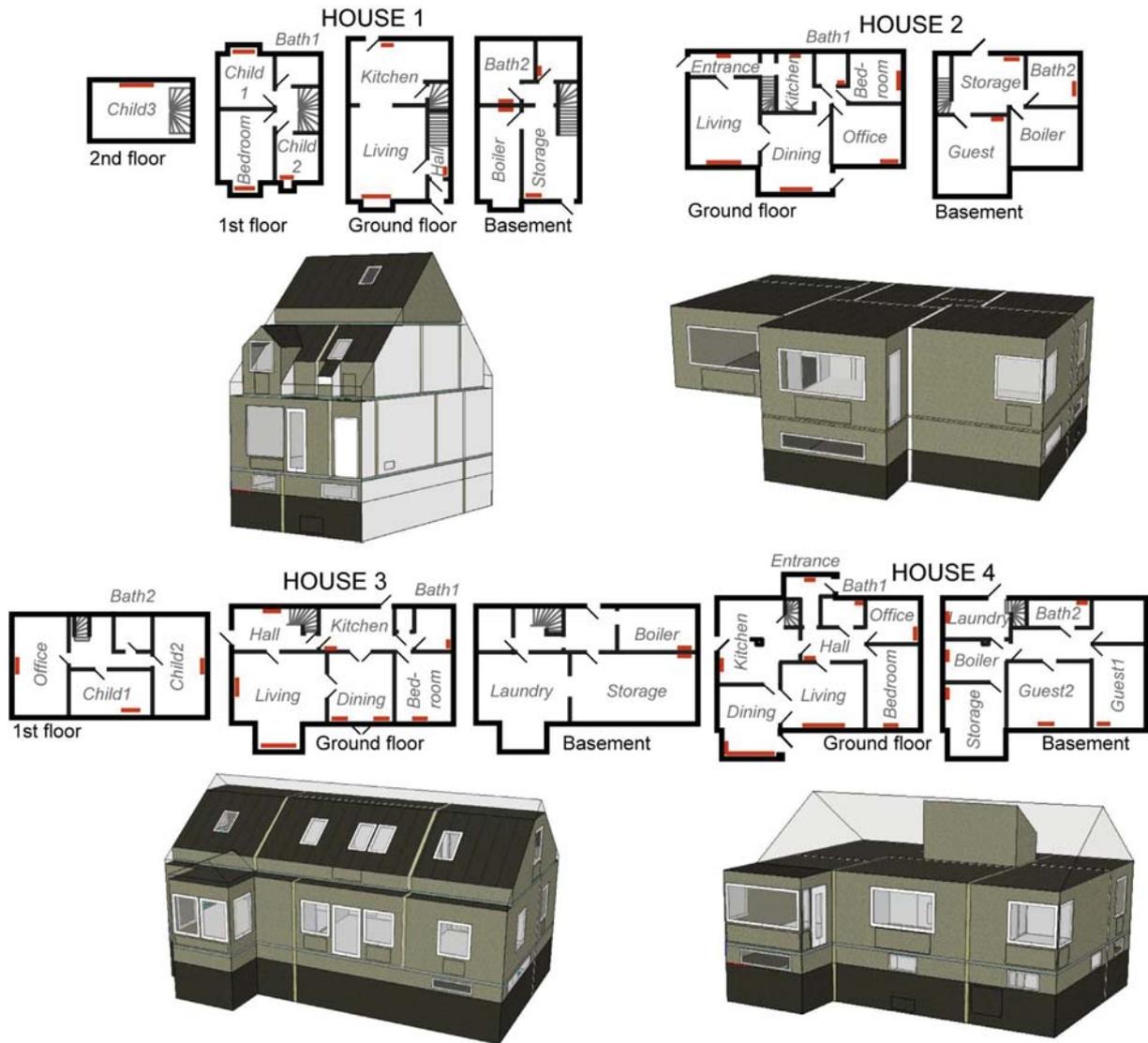


Fig. 1. The four case-houses investigated in the study. The red lines on the floor plans indicate the location of radiators. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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 [m ²]	150/48	165/69	320/118	241/118
Heated part of basement [m ²]	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 ($U = 0.78 \text{ W/m}^2 \text{ K}$)			
Basement walls	30 cm 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	12 cm brick and 10 cm wooden frames with insulation			
Roof insulation	20 cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)	10 cm insulation ($U = 0.37 \text{ W/m}^2 \text{ K}$)	25 cm insulation ($U = 0.15 \text{ W/m}^2 \text{ K}$)	20 cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)
Windows main floor/basement	2-pane energy glazing ($U = 1.5\text{--}1.6 \text{ W/m}^2 \text{ K}$)			double glazing/1 pane ($U = 2.3/4.3 \text{ W/m}^2 \text{ K}$)

occupants, but other studies also suggest that actual internal heat gains could be somewhat lower than the standard values [36].

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 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.

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	0.11	0.11	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	0.47	0.47
Linear loss wall/floor [W/m]	0.7	0.7	0.7	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

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 110 L, 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 70 W. 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.

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.

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.

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

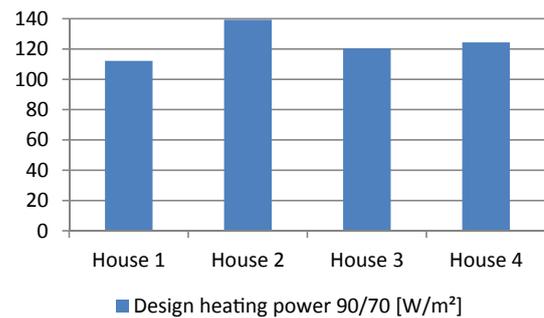


Fig. 2. Design heating power in the case-houses at the temperature set 90 °C/70 °C/20 °C.

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 0.5 m and 2.0 m and the maximum room height was 2.75 m. 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/m³ 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.

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 accurate 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

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%

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.

By using this method, it is possible to avoid choosing heating system 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

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 Figs. 4–7. 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.

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

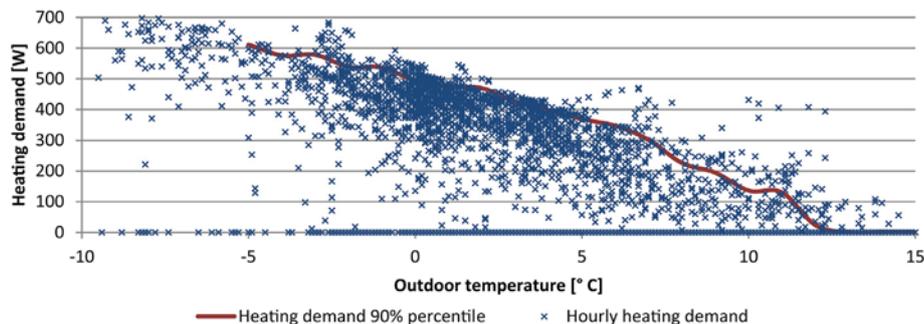


Fig. 3. Hourly heating demands and 90th percentile of the heating demands in the dining room of House 1.

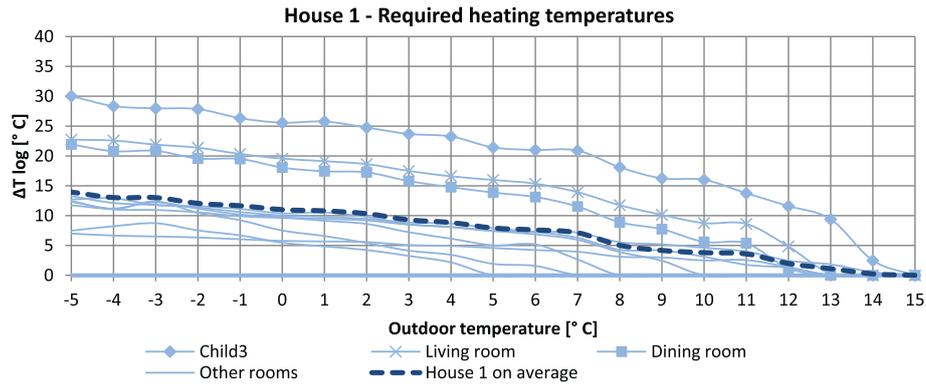


Fig. 4. Graph of required heating temperatures at varying outdoor temperatures – Case-House 1.

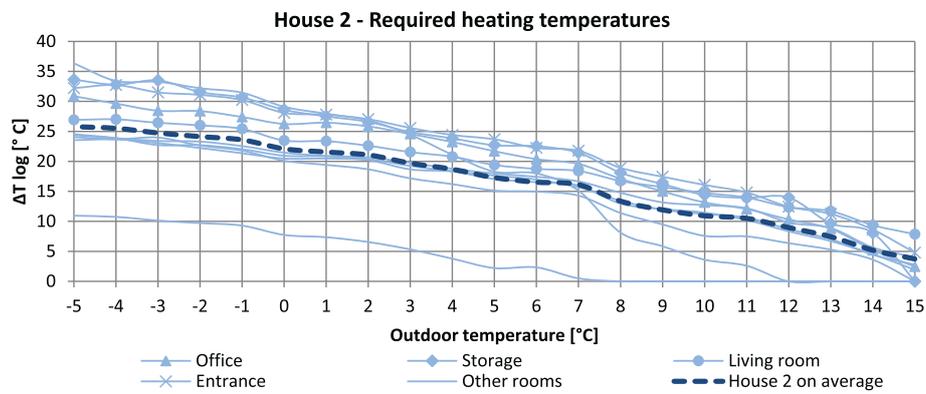


Fig. 5. Graph of required heating temperatures at varying outdoor temperatures – Case-House 2.

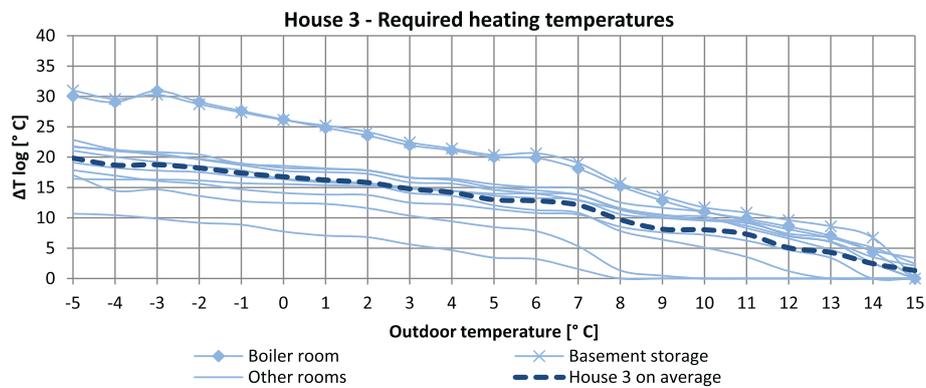


Fig. 6. Graph of required heating temperatures at varying outdoor temperatures – Case-House 3.

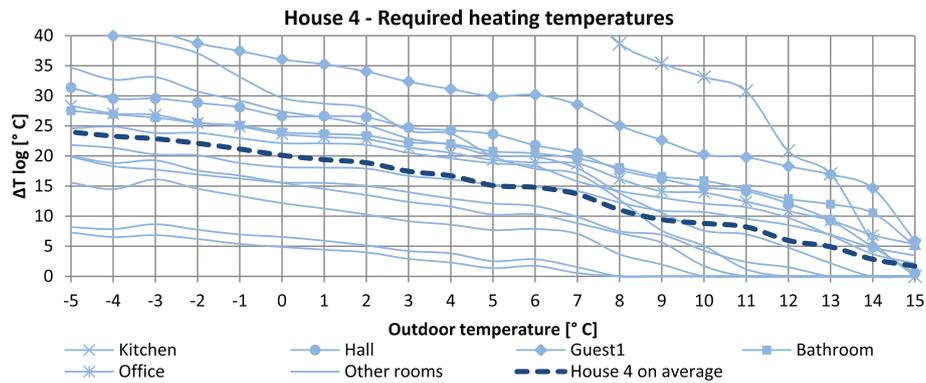


Fig. 7. Graph of required heating temperatures at varying outdoor temperatures – Case-House 4.

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
$\Delta T \log$ [° C]	33.0	25.5	22.4	18.0	14.4	13.2	11.8

radiators that require a 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.

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 Figs. 4–7 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 m². 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

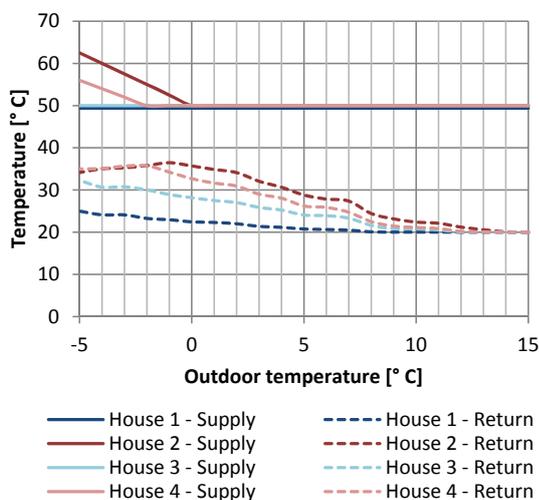


Fig. 8. Suggested supply temperature curves and corresponding return temperatures in the case-houses according to the required average LMTDs.

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 the 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 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 Figs. 4–7 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

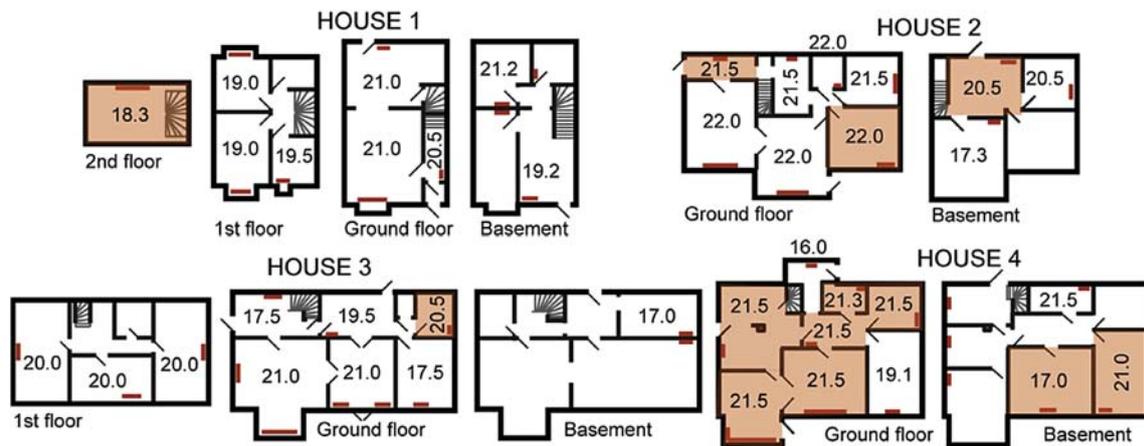


Fig. 9. Indoor temperature set-points and marking of rooms where indoor temperatures were occasionally found to be more than approximately 0.5 °C below set-point temperature.

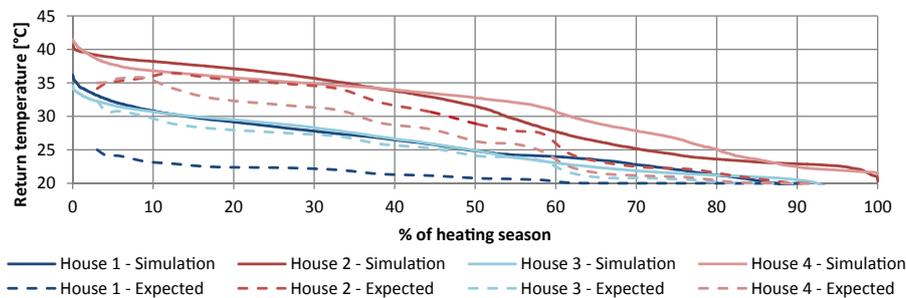


Fig. 10. Expected and simulated heating system return temperatures in the case-houses during the heating season when supply temperatures are based on the supply temperature strategy in Fig. 8.

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/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.

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 m² 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

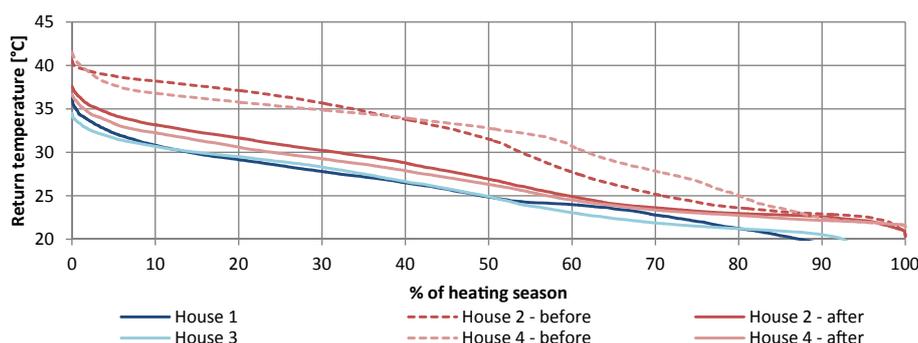


Fig. 11. Heating system return temperatures in the case-houses before and after replacing critical radiators.

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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Corrigendum

Corrigendum to ‘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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The authors regret that there was a mistake in the calculations of the logarithmic mean temperature differences given in Table 6 of the paper. The correct table should be:

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}	32.7	25.5	21.6	18.2	15.4	14.0	12.4

The authors would like to apologise for any inconvenience caused.

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V



Experience from a practical test of low-temperature district heating for space heating in five Danish single-family houses from the 1930s



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ABSTRACT

The efficiency of district heating systems is greatly affected by network supply and return temperatures. However, the opportunities to lower the temperatures and thereby increase network efficiency are restricted by customer installations. Very little is known about the customer installations, because heating system operation is only rarely monitored in detail. In this study, we therefore investigated the operation of the heating systems in five houses. The study had two aims: first to investigate how much of the heating season the houses could be heated with supply temperatures as low as 55 °C, and second to investigate whether occupant behaviour and heating system malfunctions caused unnecessarily high return temperatures. The results showed that all the houses were compatible with low-temperature supply, and in two of the houses return temperatures were even as low as the preferred 25–30 °C. Two main causes were found for unnecessarily high return temperatures in the remaining houses: a few radiators were found to be too small, and thermostatic radiator valves did not always ensure proper water mass flow. In conclusion, if these errors were corrected, the study indicates that it would be possible to heat the investigated houses with district heating temperatures of 55/30 °C.

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1. Introduction

Proper heating system control has recently begun to attract attention as important for current attempts to reduce energy consumption in buildings. In areas provided by district heating, poor heating system control not only increases energy consumption inside the building, but can also lead to lower efficiency in the total energy system if it leads to higher district heating supply and return temperatures. Higher heating system temperatures have two implications for the district heating system: less efficient heat production and less efficient heat distribution. Firstly, the efficiency of most heat producing units decreases when operating temperatures are high. Low-temperature operation is therefore preferable for condensing boilers, heat pumps, and solar thermal heating systems [1]. Secondly, high operating temperatures have a negative impact on heat distribution efficiency, because high temperatures lead to greater heat losses from the piping network. A recent study suggests that overall heat loss could be reduced by 35% for an existing pipe network and as much as 75% for a new optimized network, if

annual average supply and return temperatures can be reduced from 80/40 °C to 55/30 °C [2]. So, proper heating system control can lead to large savings in the energy system, especially in a country like Denmark, where more than 60% of homes are already heated by district heating [3] and district heating is expected to expand in the future [4]. Furthermore, proper heating system control is a prerequisite for the introduction of efficient low-temperature district heating, which is foreseen to play an important role in the future renewable energy system [5].

If proper heating system control is obtained, the heating system temperatures can be lowered according to the size of the heating elements and the heat demand of the building. Redesigning the entire existing heating system is costly, and therefore not a first option. However, recent research has indicated that most current radiators are large enough for existing buildings to be heated efficiently with low-temperature heating [6,7]. Simulations by Brand & Svendsen and Wang et al. show that existing radiator systems can be used for low-temperature heating when just a few renovation measures are carried out [8,9]. Jangsten et al. and Averfalk et al. measured the overall radiator supply and return temperatures in Swedish and Swiss apartment buildings, and showed that some existing buildings could be operated with very low temperatures [10,11]. The studies additionally showed big differences in

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operation temperatures for the investigated buildings, which could indicate that there is a large potential to improve heating system control and move towards 4th generation district heating, even for the current building stock.

Errors in the heating system control can be found already in the district heating substation or occur later in the internal heating system installations. Recent research suggests that there are errors in as much as 74% of district heating substations [12]. By use of automatic meter readings it is however possible to identify faults that may appear continuously [13] or even to improve the heat load patterns of the customers in order to improve the overall performance of the district heating system [14]. However, as illustrated by Petersson & Werner [15], the internal heating system installations also play a major part in obtaining the lowest possible temperatures. Poor hydraulic balancing, incorrect valve sizes, and poor thermal length of heat exchangers are identified as typical errors in the internal heating system installations.

There may be three main reasons for the mentioned errors in the internal heating systems. Firstly, heating systems are often designed to cope with extreme weather conditions, which often means that the heating system is not optimally designed for the actual operating conditions. This can be especially problematic for the hydraulics in the heating system if the actual operation requires a water mass flow that differs greatly from the design mass flow. Secondly, a proper commissioning process is very rarely carried out in Denmark, which means that, if the heating system is not working as planned, errors and malfunctions will not necessarily be identified and corrected. Lastly, heating installations and building constructions may be gradually updated and modified, to a point where there is no longer an apparent relation between the design of the heating system and the heat demand of the building. The result is a mismatch between design and operation of the heating systems, as has been identified in several recent studies [11,16–18].

Recent studies have suggested that hydraulic balancing of the heating system and the use of thermostatic radiator valves (TRVs) provide good solutions to improve heating system control despite of the design issues. Monetti et al. showed that applying TRVs in an old Italian multi-family building led to energy savings of 2–10% [19] while Ahern & Norton describes how application of TRVs, hydraulic balancing and proper pump setting can lead to energy savings of up to 19% [18]. Cholewa et al. showed that installation of TRVs and use of pre-settings can lead to energy savings of around 20% [20]. Trüschel showed how hydraulic balancing in three Swedish multi-family buildings could in some cases lead to energy savings, while other benefits included increased comfort or reduced heating system temperatures [21]. Similarly, Xu et al. used dynamic modelling to show that the application of TRVs can help reduce heat consumption and problems with overheating [22,23]. With regard to improving the heating system control, Tunzi showed how heating system temperatures can be optimized through proper TRV control [24]. Piana et al. showed how the lack of hydraulic balancing or severe part load operation can lead to extreme excess flow-rates of 300% and 212% respectively in some radiators [25]. The same tendency was found for floor heating systems, where Rhee et al. showed that use of TRVs and hydronic balancing is of great importance also for proper control of a hydronic floor heating system [26]. In conclusion, heating system performance can be greatly improved through improved control. Nevertheless, the solution is not bulletproof, and recent studies have also discussed the limitations of the current installations, and indicated that the stability and performance of TRVs can be easily compromised [27,28].

While current research has dealt with this area, the main part of current knowledge is based on simulations, and in general, the importance of the heating system temperatures are neglected in favour of energy savings. Only little information is available on

heating system temperatures inside buildings [11]. Furthermore, the measurements currently available are restricted to overall heating system temperatures, and do not indicate how the different parts of the heating system affect these overall temperatures. This study therefore provides new data on heating system temperatures in Danish single-family houses and reports novel and detailed investigations of how malfunctions that occur in buildings due to occupant behaviour or problems with specific in-house components can affect the potential to obtain low overall heating system temperatures. Such information is vital, if we are to identify the technical improvements that are needed to make existing heating systems work optimally and enable the use of low-temperature district heating.

This study had two main purposes: firstly, to make an investigation of the practical possibility of heating existing single-family houses with low-temperature heating, i.e. with a supply temperature of about 55 °C, and secondly, to identify and describe occupant behaviour and heating system malfunctions which may make it difficult to achieve lower district heating temperatures. The investigations were performed by monitoring the operation of the heating systems in five single-family houses and testing how the heating systems responded to lower supply temperatures. This paper includes discussion on how the heating system problems identified can be solved to enable existing houses to be heated with low-temperature heating.

2. Method

2.1. Description of the houses

This research was based on a case study of five single-family houses from the 1930s. The houses are illustrated in Fig. 1. The houses are all naturally vented and airtightness of the houses was not measured, but may be assumed to be around 0.5 h⁻¹, which is the minimum ventilation rate required in the Danish building code and corresponds well with averages found for older dwellings [29].



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

The U-values of external walls, roofs, and windows are estimated to be approx. $0.78 \text{ W/m}^2 \text{ K}$, $0.15\text{--}0.37 \text{ W/m}^2 \text{ K}$, and $1.5\text{--}2.8 \text{ W/m}^2 \text{ K}$ respectively. These values are based on a Danish catalogue of standard constructions, and U-values include thermal bridges [30]. Table 1 presents key information on the houses and their constructions. The heating systems in the houses consist of hydraulic radiators – the most common type of heating system in existing Danish single-family houses. The radiators are located as shown in the floor plans of the houses and a description of the types of radiator and their estimated heating power at the temperature set $90/70/20^\circ\text{C}$ is given in Table 2. Additional electric floor heating is installed in the first-floor bathroom of House 1 and in both bathrooms of House 3. The houses represent different architectural styles, and they differ in types of occupant and in heated floor area.

Heating is provided to the houses from a newly established district heating system, and the heat is delivered via a district heating substation. The substation was developed for low-temperature operation and has been tested and described in recent research [31,32]. A sketch of the substation can be seen in Fig. 2. Domestic hot water for each house is prepared through a direct heat exchanger, which reduces the risk of legionella, even when supply temperatures are reduced to 50°C . Space heating is provided through a separate heat exchanger. The space-heating supply temperature is weather-compensated, so the supply temperature varies with outdoor temperature depending on the insulation level of each house. The water mass flow in the heating system is governed by a small pump with automatic proportional control and individual thermostatic radiator valves.

2.2. Measurements and monitoring

Measurement equipment was installed in the houses at the beginning of the heating season 2015–2016 to investigate how the operation of the heating system affected the heating of the houses with low-temperature district heating. All temperatures were measured using equipment connected to a wireless network, which made it possible to supervise the operation of the heating system in real time. Three different types of temperatures were measured:

- radiator return temperatures (T_r)
- indoor temperatures (T_i)
- overall space heating (SH) and district heating (DH) temperatures

Radiator return temperatures, overall space heating temperature, and indoor temperatures were measured by use of Brunata FuturaComfort + loggers [33] that are approved according to European norms DS/EN ISO 9001 [34] and DS/EN 834 [35]. The loggers have an accuracy of $\pm 0.5^\circ\text{C}$ according to the manufacturer. Additionally space heating and district heating temperatures were

measured by use of the Danfoss ECL Comfort 310 controller [36] with pt1000 ESMC temperature sensors [37].

Return temperatures from all operating radiators in each house were measured on an hourly basis to identify where errors or malfunctions occurred in the heating systems. Every logger was equipped with a probe mounted on the outside of the return pipe of the individual radiator. The probes and pipes were covered with insulation and tape, as illustrated in Fig. 3, to reduce the effect of the surrounding air temperature. A comparison between the temperatures measured using this method and temperatures measured using a laser thermometer showed that the method underestimates return temperatures by $2.4\text{--}5.4^\circ\text{C}$ on average, so these measurements were not entirely precise, but they made it possible to evaluate the operation of the heating system and identify radiators with high return temperatures.

The indoor temperatures in the rooms of the houses were measured to evaluate the thermal comfort. The measurements were taken using the same type of loggers as the radiator return temperatures, except that they were equipped with an internal probe to measure the surrounding air temperature. The loggers were generally placed on furniture near internal walls at heights between $0.5 \text{ m}\text{--}2.0 \text{ m}$. The maximum room height was 2.75 m . These locations ensured a reasonable estimate of the average room air temperature; earlier studies have shown that the vertical temperature gradient under these conditions is no more than 0.3°C [38,39]. The indoor temperature measurements gave an indication of the set-points of the thermostatic radiator valves and made it possible to evaluate the relationship between indoor temperature requirements and the operation of the heating system.

Measurements of the outdoor temperature and the supply and return temperatures in the space heating and district heating system were carried out every 15 min in four of the houses. In House 2 it was regrettably not possible to make these measurements, since the occupants did not agree to put up this additional measurement equipment. The measurements were obtained from the heating system controller unit (see Fig. 2). Due to logger failures and connection problems, measurements are not available for the entire heating season. Nevertheless, comparison of these measurements with the radiator return temperatures made it possible to investigate the effect that each individual radiator had on the overall operation of the heating system.

The measurements were all instant temperature measurements, so they do not take water mass flow into account. Average temperatures calculated based on the measurements were therefore time-weighted averages and not volume-weighted. This type of measurement will give a realistic picture of the operation of the heating system when the water flow in the heating system is more or less steady. This was generally found to be the case for the measurements presented, but the proviso should be kept in mind before drawing conclusions from the results.

Table 1

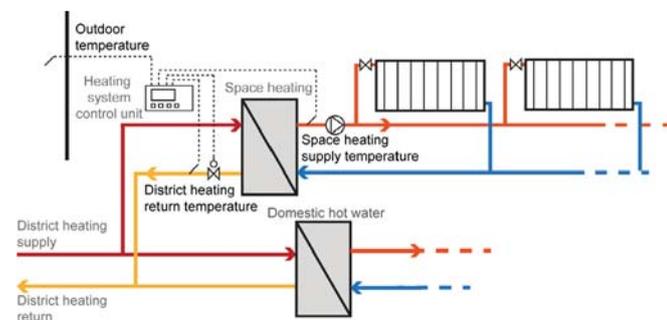
Key data for the houses investigated. All areas are based on external measurements as is the custom in Denmark.

House:	1	2	3	4	5
No. of occupants	1–5	2	2	2	2
Floor area/ basement area	$150 \text{ m}^2/48 \text{ m}^2$	$165 \text{ m}^2/69 \text{ m}^2$	$320 \text{ m}^2/118 \text{ m}^2$	$241 \text{ m}^2/118 \text{ m}^2$	$202 \text{ m}^2/107 \text{ m}^2$
Heated basement	48 m^2	55 m^2	47 m^2	110 m^2	45 m^2
External walls	Cavity brick wall with cavity wall insulation ($U = 0.78 \text{ W/m}^2 \text{ K}$)				
Basement floor/ walls	20 cm concrete towards ground ($U = 0.48 \text{ W/m}^2 \text{ K}$)/30 cm concrete ($U = 1.1 \text{ W/m}^2 \text{ K}$)				
Roof insulation	20 cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)	10 cm insulation ($U = 0.37 \text{ W/m}^2 \text{ K}$)	25 cm insulation ($U = 0.15 \text{ W/m}^2 \text{ K}$)	20 cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)	20 cm insulation ($U = 0.2 \text{ W/m}^2 \text{ K}$)
Windows main floor/basement	2-pane energy glazing ($U = 1.5\text{--}1.6 \text{ W/m}^2 \text{ K}$)			double glazing/1 pane ($U = 2.3/4.3 \text{ W/m}^2 \text{ K}$)	Mix of 2-pane energy glazing and 2-pane windows ($U = 1.5\text{--}2.7 \text{ W/m}^2 \text{ K}$)

Table 2

Description of types of radiator (plane, panel, column, or convector) and heating power (90/70/20 °C) in the rooms of the houses.

	HOUSE 1	HOUSE 2	HOUSE 3	HOUSE 4	HOUSE 5
Living room	Panel – 2203 W	Column – 3234 W	Panel – 6164 W	Panel – 2278 W	Column – 4054 W
Dining room	Column – 1830 W	Column – 2904 W	Panel – 4231 W	Panel – 4235 W	Column – 2976 W
Kitchen		Panel – 444 W	Panel – 1974 W	Panel – 865 W	Plane – 776 W
Bedroom	Column – 1830 W	Panel – 1511 W	Panel – 1705 W	Panel – 2535 W	Column – 2849 W
Child	Column – 1677 W		Panel – 2569 W		Column – 1382 W
Child2	Column – 1525 W		Panel – 2136 W		Column – 2849 W
Child3	Convactor – 1973 W				
Bathroom		Plane – 553 W	Panel – 1058 W	Panel – 886 W	Column – 1290 W
Office		Panel – 1705 W	Panel – 2569 W	Column – 1340 W	Column – 1808 W
Entrance	Convactor – 520 W	Panel – 1295 W	Panel – 1705 W	Panel – 585 W	
Hall				Column – 852 W	Column – 2027 W
Boiler room	Panel – 1490 W	Panel – 1295 W	Panel – 1511 W	Panel – 1364 W	
Laundry				Panel – 1364 W	Panel – 5345 W
Storage room	Panel – 2116 W	Panel – 1295 W	Column – 2470 W	Panel – 1364 W	Panel – 1562 W
Guest room		Panel – 1727 W		Panel – 1574 W	
Guest room2				Panel – 2578 W	
Bathroom2	Panel – 1058 W			Panel – 866 W	
Shed	Panel – 553 W				

**Fig. 2.** Layout of low-temperature district heating substation with indirect connection.**Fig. 3.** Equipment setup for the measurement of return temperatures from radiators.

2.3. Occupant contact

The occupants in the houses were regularly asked about their satisfaction with the space heating, and they were given the option to contact the researchers on phone or e-mail if they experienced any problems or discomfort. Therefore part of the heating system issues were identified through measurements, whereas part of them were identified when occupants took contact to ask about

implications with thermal comfort. An example of the latter was, that some occupants contacted the authors as they felt cold in the beginning of the heating season. This was found to be due to the fact that valves were stuck, and the problem was quickly fixed to ensure the thermal comfort. If a high return temperature from one radiator was noticed in the measurements on the other hand, the researchers took contact to the occupants to ask about the specific circumstances for the given radiators. This would for example lead to the specification that a radiator thermostat had been turned up, to removed moisture from a basement room, or because occupants felt a cold draft from the entrance door. In this way occupant contact helped ensure that thermal comfort was maintained during the measurement period, and classify problematic conditions that might not have been identified through measurements.

3. Results

The following sections present the results from the measurements in the single-family houses investigated. The first section reports the overall heating system supply and return temperatures measured in the houses. The second section describes the errors and malfunctions in the heating system design and control that were identified through the measurements, and how these affected the resulting return temperatures.

3.1. Heating system supply and return temperatures

Fig. 4 shows the outdoor temperature and space-heating supply and return temperatures measured in Houses 1, 3, 4, and 5 from October 2015 to March 2016. The measurements are not available for House 2, since the occupants did not agree to put up additional loggers, and due to logger failures, measurements are not available for the entire period. The space heating supply temperatures measured correspond well with the targets of low-temperature district heating, being generally below 55–60 °C, but increasing in cold periods. No supply temperature optimization was carried out during the study, so it may be possible to reduce the supply temperature further. The return temperatures correspond to the preferred 25–30 °C in two of the houses. In general, these results indicate that low-temperature district heating can be used for space heating in existing single-family houses, but that measures will be needed in some houses to achieve low average return temperatures.

The overall return temperature is a product of the individual

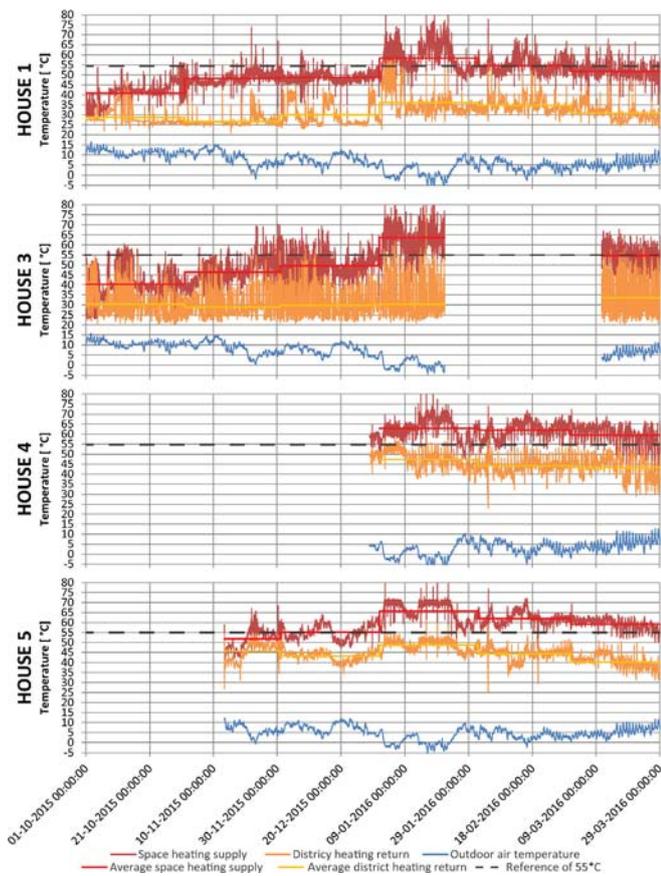


Fig. 4. Heating system temperatures in Houses 1, 3, 4, and 5.

radiator return temperatures in the houses. Average radiator return temperatures and space heating return temperatures from 1st September 2015 to 1st April 2016 are illustrated in Fig. 5. It should be kept in mind that these temperatures only provide an indication of the radiator return temperatures due to the uncertainties of the measurement method and the limitations of time-averaged values that do not take water mass flow into account. The measurements show that only a few radiators were unable to achieve a low return temperature, but that these had a large impact on the overall return temperature. For example in House 2 the overall space heating return temperature was measured to around 37 °C even though only three out of 10 radiators had a return temperature above 32 °C. This indicates that overall the heating systems may be compatible with low return temperatures, but that local problems must be resolved to achieve an overall low return temperature.

3.2. Heating system malfunctions and errors

Local problems in the heating systems that caused some radiators to have high return temperatures were investigated in detail. The analysis was based on a combination of measurements, occupant contact, and visits to the houses. The problems identified in the houses were grouped into three categories that are described and documented in the following sections:

1. Problems with thermostatic radiator valves
2. Problems regarding occupant behaviour
3. Problems with heating system design

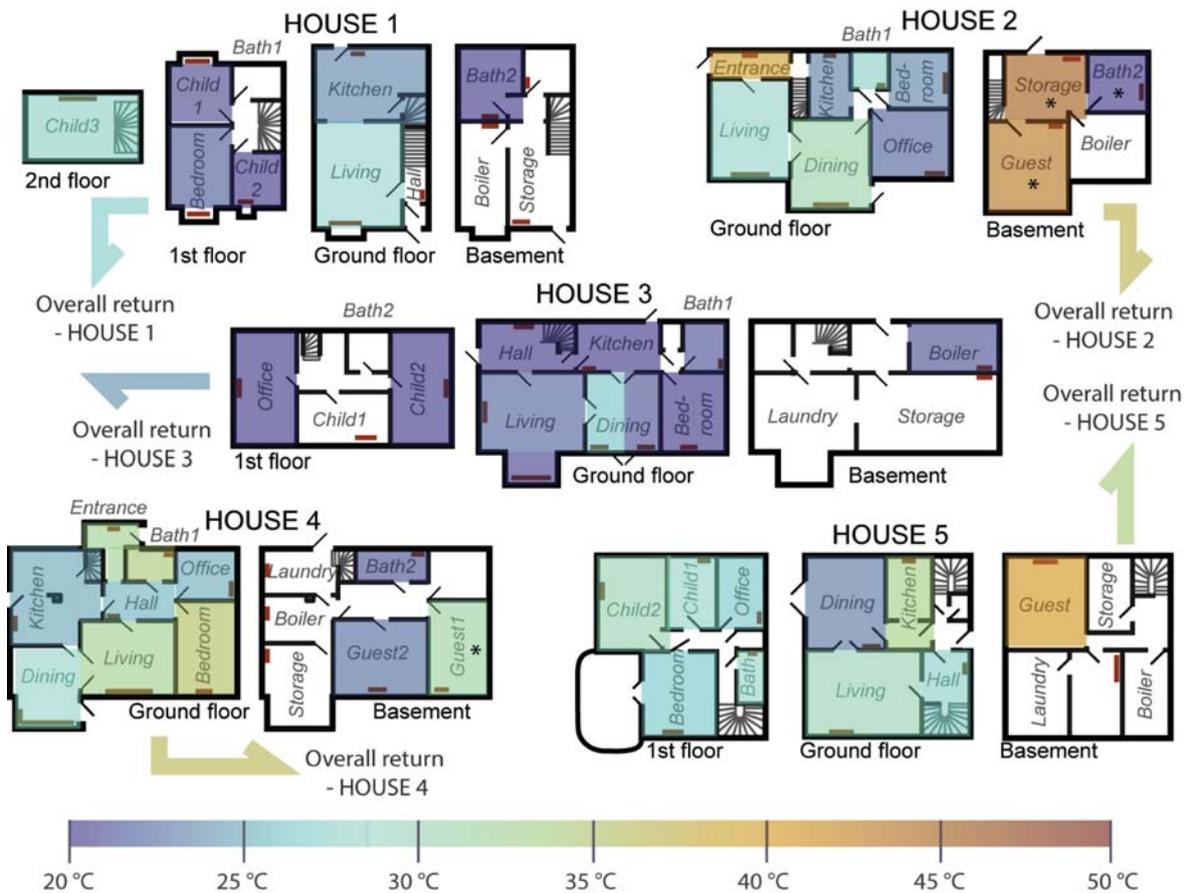
3.2.1. Thermostatic radiator valves

In some of the houses, the occupants found themselves feeling cold when outdoor temperatures dropped at the beginning of October. The problem was found to be that thermostatic valves had become stuck in a closed position, which was quickly corrected by helping occupants to loosen the valves. However, we also found that the remounting of the thermostats afterwards was not always carried out correctly. The incorrect mounting led to a high return temperature and therefore to inefficient heating system operation. An example is shown in Fig. 6 where return temperature in two rooms of House 1 were seen to increase to 33–37 °C and afterwards drop to 20 °C due to incorrect mounting of the thermostat and the correction of this. In some cases, the incorrect mounting was discovered by the occupants due to the resulting poor thermal comfort, but in other cases it was only revealed through the analysis of the measurements. This shows that this type of problem may occur without being noticed. Incorrect mounting was identified for both existing mechanical valves and for new electronic valves.

Shortly after the beginning of the heating season, measurements revealed that many of the thermostatic valves were worn or out-of-date in several of the houses, making the operation of the heating system inefficient. Many of the valves kept sticking or did not regulate the indoor temperature properly, and only some of the thermostatic valves in House 2 could be pre-set. This meant that the thermostatic valves in the remaining houses gave no opportunity to limit the mass flow through the radiators. Occupant behaviour, open windows, or malfunctions in one valve could therefore have a large effect on the return temperature of the overall heating system.

One general problem was found to be that occupants did not fully understand the functioning of the thermostatic radiator valves. Mechanical thermostatic radiator valves in Denmark are usually equipped with numbering from 1 to 5, leading to the common belief that a high set-point means that the radiator will deliver more heat. While this is in some ways true, it does not always work as intended. Higher numbers mean that the thermostat seeks to maintain a higher indoor temperature set-point. If a set-point of 5 is chosen, this will typically cause the thermostatic valve to seek to achieve an indoor temperature of 25 °C. Most radiators are not designed to deliver such high indoor temperatures, so this will result in a constantly open valve, ultimately causing high return temperatures and occasionally overheating. Fig. 7 shows two examples of changes in radiator return temperatures and indoor temperatures in rooms where the set-point of the radiator valve was reduced. As seen in the figure, the reduction of the thermostat set-point from 5 to 4 or 4 to 3 lead to a return temperature reduction of approximately 10 °C. The big difference is in the return temperatures, not the indoor temperatures achieved.

Another reoccurring problem in several of the houses investigated was that the thermostatic valves did not ensure the optimal balance of the water mass flow through the radiators. For rooms with more than one radiator or rooms that were connected through open doors, this meant that it was common that one radiator provided most of the heating in both cases, as illustrated in Fig. 8. The figure shows how radiators in the same or adjacent rooms, have return temperatures that differ by 15–20 °C for long periods. Here too, we found that a small change in thermostat set-point could have a large effect on the return temperature. Since the occupants are not provided with feedback on the operation of the radiators, this problem was mostly noticed through the measurements. Occupants would therefore be unlikely to react to the problem. And even if they did, they would not always find it easy to adjust the set-points and achieve a good balance.



*Temperature averages for shorter periods due to logger failure and technical problems

Fig. 5. Time-averaged radiator return temperatures in the houses from 1st September 2015 to 1st April 2016.

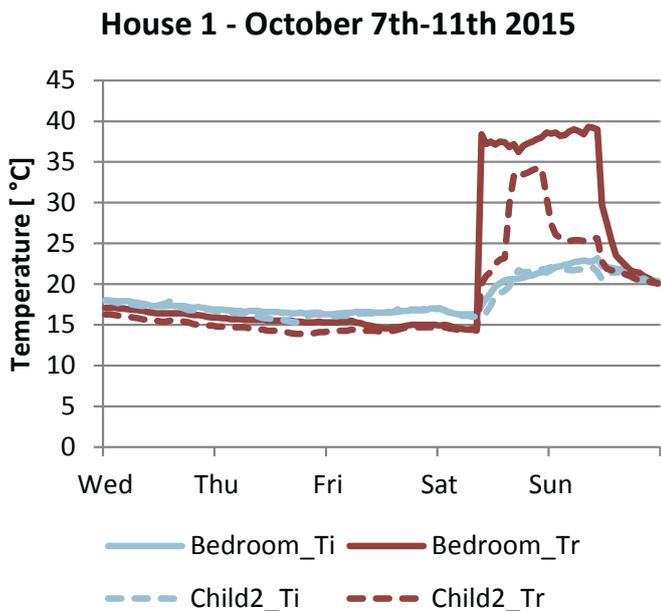


Fig. 6. Low indoor temperature (Ti) due to stuck valves and high return temperature (Tr) due to wrongly mounted thermostats.

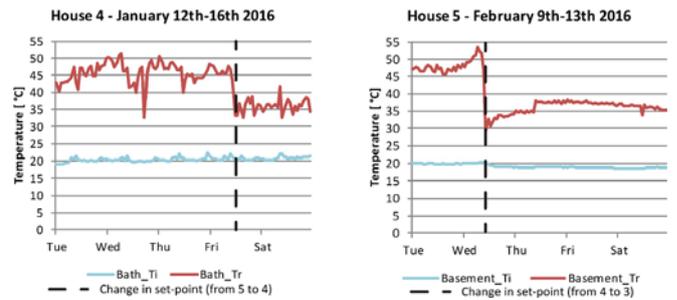


Fig. 7. Examples of return temperatures (Tr) and indoor temperatures (Ti) measured in rooms where the thermostatic valve was set on 5 and adjusted to 4 (left) or set on 4 and adjusted to 3 (right).

3.2.2. Occupant behaviour

Occupants were generally found to have very different preferences on indoor temperature, with great impact on the heating system return temperatures. Where indoor temperatures were high, the radiator return temperatures were also often high. Conversely, where indoor temperatures were low, the heating system return temperature was generally lower. The relationship between indoor temperatures and radiator return temperatures depends on the dimensions of the radiators in the houses. Most of the radiators installed in the houses investigated were found to be unsuited to providing indoor temperatures of 23 °C or higher from

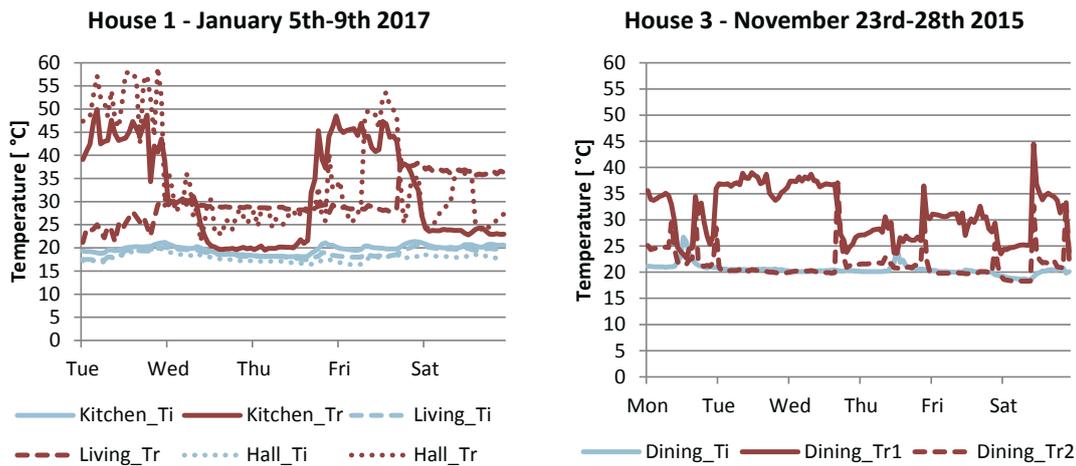


Fig. 8. Examples of poor water mass flow balance between radiators in connected rooms. Left: three radiators in adjacent rooms that emit very different amounts of heat. Right: two radiators in the same room – only one seems to provide the heat.

low-temperature heating. Fig. 9 shows an example of the difference between the radiator return temperatures measured in a room with a low indoor temperature and a room with a high indoor temperature.

The occupants in the houses investigated chose different indoor temperature set-points in the various rooms of their house – for example, the temperature set-point in living areas was often higher than that in bedrooms. In this situation, it would be best to keep doors between thermal zones closed, because open doors will cause radiators in warmer zones to partly heat the colder rooms. Nevertheless, keeping doors open can be a matter of preference, as was seen in House 2, where most doors were kept open, and the door to the basement was actually removed, due to the cat living in the house. Keeping doors open not only causes increased energy consumption due to indoor temperatures in some rooms being higher than necessary, but it may also lead to high heating system return temperatures because radiators are heating several rooms.

The indoor temperature set-points chosen are often a question of thermal preferences; however, we also found it was affected by a number of other factors. One example was that several occupants turned up the set-point of the thermostatic radiator valves during cold winter periods, even though maintaining the set-points should ensure the same indoor air temperature. This phenomenon can be easily explained because cold surfaces can lead to reduced

operative indoor temperatures. Similar problems could arise in buildings with poor air tightness, where drafts could cause occupants to feel cold. Another example seen in some houses was that set-points were increased in some basement rooms in an attempt to remove moisture. These types of behaviour led to higher radiator return temperatures, especially where occupants chose a set-point of 5.

The energy-saving intentions of the occupants were also found to have a large effect on the chosen strategy for indoor temperature set-points. Examples were the use of night set-back systems and reduced indoor temperature set-points in rooms that were not in use. While there is always debate on whether reducing indoor temperatures for short periods can achieve energy savings, it is generally not desirable in small buildings connected to district heating systems. This is because the re-heating of rooms causes a peak in the heat demand, which leads to high return temperatures and requires larger dimensions of district heating pipes. Moreover, the periodical lowering of indoor temperatures typically decreases the thermal comfort of occupants. Fig. 10 shows an example from House 3, where it can be seen how the overall space heating return temperature increases to 35–40 °C, due to continuous re-adjustment of thermostat set-points, and thereby peaks in the return temperatures of the living room, bedroom, and office.

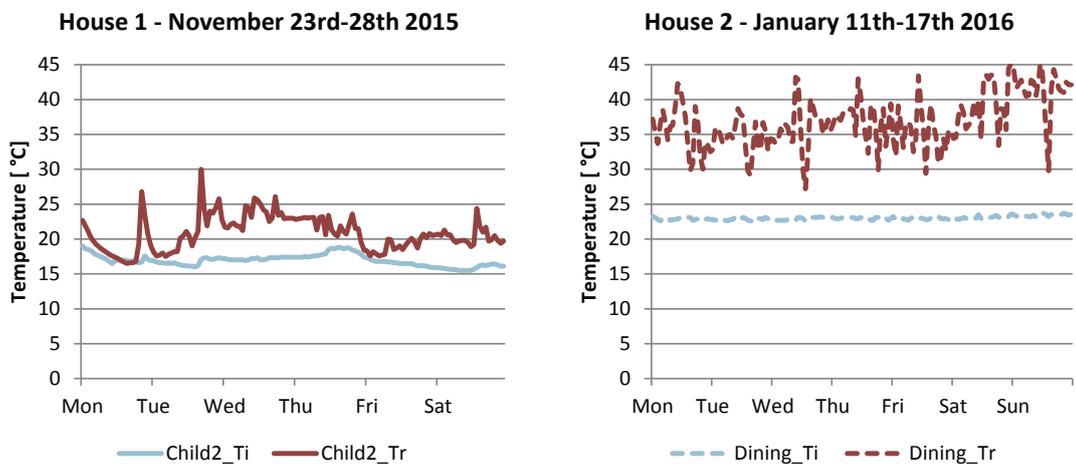


Fig. 9. Example of radiator return temperatures (Tr) in a room with a low indoor temperature (Ti) (left) and in a room with a high indoor temperature (right).

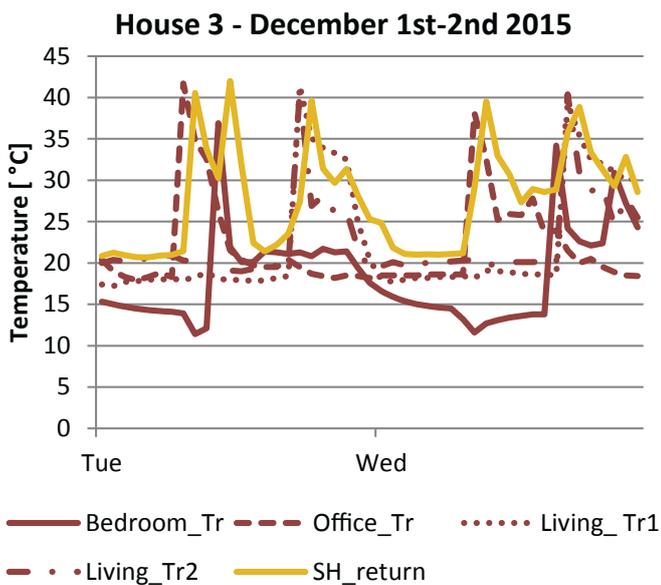


Fig. 10. Example of how radiator return temperatures (Tr) and the overall space-heating return temperature (SH_return) is affected by changing the set-points of thermostatic valves.

3.2.3. Heating system design

On our first visits to the case houses, a number of problems in the heating system design were identified that were expected to play an important role for the heating system performance. This was the case in House 4, where the radiator in one bathroom was built into a cabinet, and in the dining room of House 5, where a radiator was placed inside a concealer. While these solutions may be aesthetic, they reduce the heat emissions from the radiators and therefore often reduce thermal comfort and heating system efficiency. In the case of House 4, the cabinet made it impossible to loosen the thermostatic valve, which led to it being stuck in an open position. This problem was resolved by removing the front of the cabinet and loosening the valve, which resulted in a 25 °C reduction

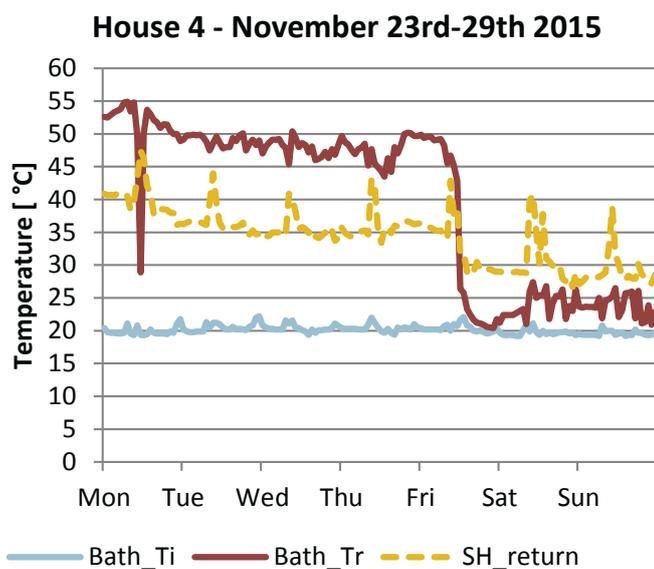


Fig. 11. Drop in radiator return temperature (Tr) and overall space heating return temperature (SH_return) after removing cabinet door and loosening radiator valve in the bathroom of House 4.

in the radiator return temperature, as shown in Fig. 11, and a reduction in the overall return temperature of approximately 5 °C. The concealer in House 5 was a problem because the thermostat was inside the concealer, where the air was generally warmer than in the dining room. This led the valve to reduce the heating output, before the set-point was met in the room, and the radiator in the living room ended up partly heating the dining room as well.

In a few rooms in the houses, the radiators were found to be too small to satisfy even the basic thermal requirements of the occupants while still delivering a low radiator return temperature. This was the case where a radiator had been removed when two rooms were combined into one, when a radiator was installed in formerly unheated basement rooms, or where a room was heated by a convector, which made it difficult to supply the necessary heating with low return temperatures. Such implications can therefore be categorized as heating system design errors that mainly occur due to changes in the use of the dwellings. Fig. 12 shows an example from House 1 where a radiator has a high return temperature of almost 40 °C, even when maintaining an indoor temperature below 20 °C.

4. Discussion

This study indicates that the existing single-family houses investigated may very well be heated with low supply temperatures, but not all of the existing heating systems are able to ensure a low return temperature. In some houses, local heating system problems need to be corrected to achieve return temperatures of 25–30 °C. This result is in line with recent studies of heating system temperatures in Multi-family dwellings in Sweden and Switzerland [10,11]. Similarly recent case studies of low-temperature district heating in Denmark has shown, that while supply temperatures can be lowered greatly, return temperatures are not always as low as expected [32,40].

The causes for high return temperatures were investigated by measuring the radiator return temperatures, using loggers that were not very accurate, and tended to underestimate the measured temperatures. Despite of this underestimation, high return

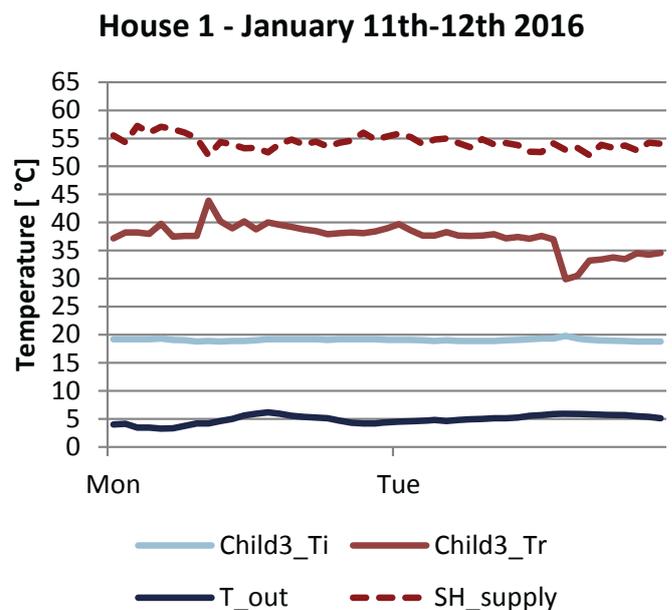


Fig. 12. Example of a convector with high return temperature (Tr), even when indoor temperature (Ti) is below 20 °C, supply temperature is around 55 °C, and outdoor temperature is around 5 °C.

temperatures of above 40 °C were still measured in the heating systems, and the measurements were still useful for comparison of radiator return temperatures and identification of large changes in return temperatures. Nevertheless, it should be kept in mind, that the measured radiator return temperatures might be up to 5 °C lower than the actual temperatures. The local problems that led to high return temperatures were found to be mostly due to inefficient thermostatic radiator valves, inefficient occupant behaviour, and errors in heating system design. Correcting these types of errors may very well be possible without investing in a completely new heating system, but it would require the replacement of some heating system components and preferably further development of current thermostat design. This result is generally in line with previous research, that has shown how hydraulic balancing, proper pump settings, and installation of well-functioning TRVs can help improve the heating system operation of existing buildings and thereby lower the energy consumption for heating [18–20]. Only this study, adds to the reasoning that improved heating system operation is also important to obtain low district heating return temperatures, as also showed in a case study by Trüschel [21], and thereby enable the introduction of low-temperature district heating.

One major problem was found to be excessive flow through individual radiators, caused by either poor radiator thermostat functionality or unintentional occupant behaviour. One solution to this problem could be to control the water mass flow to some extent, so that an individual radiator would not affect the entire heating system to a large degree. This might be achieved if new pre-settable radiator valves were installed. The result is in line with previous studies showing that TRVs are not necessarily suited to avoid excessive water mass flow [23] and that the installation of pre-set valves can limit excess water mass flows through radiators in an apartment building from a maximum of 300% to a maximum of 87% [25]. Installing new valves may also help ensure a smoother valve opening, which would also improve thermal comfort and lower the energy consumption. The solution is cheap and could be carried out as part of the general heating system maintenance over the years to come. However, it requires proper manual setting of the mass flow limitation, which can be difficult to ensure, as also referred through interviews in Ref. [11].

Another problem was due to limited user understanding of thermostat set-points and maintenance, as also reported in earlier studies [11,16]. This type of problem may be diminished by the introduction of electronic radiator valves, where the set-point is based on a temperature scale and the valve is automatically exercised to prevent it from sticking. However, the study found that even electronic valves had difficulty in ensuring low return temperatures, for example in cases where several radiators were heating the same room. It would therefore be good if current thermostat design could be further improved to include return temperature optimization. This functionality could help ensure that water mass flow is not only optimized for thermal comfort, but also with regard to return temperature. It would then be possible to prevent excessive water mass flows, imbalances between radiators, and unintentional occupant behaviour. This type of solution would also help avoid the high return temperatures and heat demand peaks associated with night set-back systems. Users would be able to stick to their desired set-back patterns and save energy, without causing increased energy consumption in the district heating network, by accepting a slower re-heating period started earlier in the night.

The main concern of the district heating company is to ensure proper thermal comfort for the customers. All the rooms in the connected houses should therefore be heated in accordance with occupant preferences, even when supply and return temperatures

are lower. The study showed that in some houses this might require slight modification of the heating system. Larger heating surfaces should be installed where radiators are found to be unable to ensure thermal comfort and still deliver a low return temperature. This may be especially relevant in living areas, where a high indoor temperature is often preferred. Additionally, it may be relevant when the use of rooms have changed, and a basement room is suddenly heated or a radiator has been removed to combine two rooms. Occupants should be free to choose whatever aesthetic solution they prefer, including radiator concealers for example. In this case, thermal comfort and low return temperature should be ensured by installing remote temperature sensors (or perhaps by designing more aesthetic radiators). Finally, the study found that heating systems were often operated at high temperatures to compensate for discomfort from cold surfaces, drafts, or excessive moisture content. General energy saving and indoor climate measures, such as improving ventilation, reducing air leakages, and adding extra insulation in external walls and windows, are therefore important for ensuring the proper operation of low-temperature heating. Such measures can be taken as appropriate over the years to come and help to meet the goals of reduced energy consumption in buildings. Indeed, many occupants may find it more inviting to invest in private energy savings and improved indoor climate, rather than a new radiator.

Investigations in this study regarded the heating systems of five single-family houses. These small heating systems may be quite different, than the heating systems in large multi-family dwellings, that are generally the most prevalent type of dwellings in dense cities supplied by district heating. However, the results of this study suggest, that the main problems in heating systems concern flow problems in radiator valves, occupant behaviour, and errors in heating system design. These types of problems could be expected to be even worse in multi-family dwellings. First of all, multi-family dwellings include a larger heating system and therefore it may be more complex to ensure proper flow through all radiator valves and obtain proper hydraulic balance. Secondly, multi-family dwellings consist of many different occupants, that may have very different habits and preferences. Consequently, as this study shows that inefficient control of one radiator may be problematic for a single-family house, it is likely that the inefficient control habits of one occupant could affect the overall heating system operation in the multi-family dwelling. Lastly, one learning from this study was, that it can be difficult to communicate with occupants and ensure that the correct measures are taken to improve heating system control. If this is difficult for a single-family house, it can be expected to be even more complicated in a multi-family dwelling, where different occupants need to agree on control strategies and central heating system improvements. Additionally, the individual occupants may not feel obliged to improve the overall heating system efficiency of the building, as they may feel less responsible for the overall energy consumption of the building and may not get proper feed-back on energy behaviour through current billing systems. As a conclusion, the results of this study suggest that there is a high likelihood, that the operation of heating systems in old multi-family dwellings can be improved drastically if design and operational errors were corrected. This aspect should however be investigated further.

5. Conclusions

In this study, we monitored the operation of the heating system in five Danish single-family houses from the 1930s. We found that all the houses could be successfully heated with low supply temperatures. Two of the houses were also able to ensure low return temperatures, while the remaining three houses showed higher return temperatures than the preferred 25–30 °C. Measurements

of individual radiator return temperatures were performed in order to evaluate how the operation of the individual radiators affected the overall heating system return temperature. Although these measurements did not have high accuracy, they proved useful to show large differences between radiator return temperatures and show how for example changes in thermostat set-points could cause large variations in the radiator return temperature. The heating system monitoring revealed two main barriers to achieving lower district heating return temperatures: lacking radiator heating power in the rooms of some houses, and a general problem of imperfect balancing and control of thermostatic radiator valves. To prepare all such houses for low-temperature district heating, two measures are therefore suggested. Firstly, under-dimensioned radiators should be replaced with radiators with a heating area large enough to ensure the thermal comfort of occupants. This is especially important in living areas, where thermal comfort is a major concern. Secondly, critical thermostatic radiator valves should be replaced. The most robust solution would be for a new electronic thermostatic valve to be developed that would optimize water mass flow with regard to both thermal comfort and optimal return temperature. In conclusion, the study indicates that the existing single-family houses investigated can certainly be heated with low-temperature district heating, though some of the houses have local heating system problems that must be fixed to ensure the preferred low return temperatures.

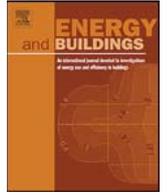
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Case study of low-temperature heating in an existing single-family house—A test of methods for simulation of heating system temperatures



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ABSTRACT

Low-temperature heating provides an efficient way of heating our buildings. To obtain a high efficiency it is important that the heating systems in the buildings are operated with both low supply and return temperatures. This study set out to investigate how typical assumptions in the modelling of heat emissions from existing hydraulic radiators affects the heating system return temperatures calculated in a building simulation model. An existing single family house with hydraulic radiators was modelled in the simulation program IDA-ICE. Simulations were performed with various levels of detail and the calculated indoor temperatures and radiator return temperatures were compared to temperatures measured in the case house. The results showed that the detail of the simulation model has a large influence on the results obtained. The estimated return temperatures from the radiators varied by up to 16 °C depending on the assumptions made in the simulation model. The results indicated that a detailed building simulation model can provide a good estimate of the actual heating system operation, provided that actual radiators and realistic indoor temperatures are taken into account in the model.

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1. Introduction

More than 25% of the final energy consumption in the EU is attributed to households [1]. The households are thereby the sector with the second largest final energy consumption in the EU, which makes the sector a central focus area for energy consumption reductions. One way of reducing the energy consumption of households in cold climates is to improve the efficiency of the heating systems. Low-temperature heating provides one promising solution to how this may be done. By reducing the heating system temperatures it is possible to increase the efficiency of heat production from solar collectors, heat pumps, and condensing boilers. Furthermore the heat loss from the distribution systems inside both new and existing buildings is reduced [2,3]. The highest heating system efficiencies are obtained when both supply and return temperatures are as low as possible. Recent research has therefore described the benefits of using heating system supply and return temperatures as low as 50 °C/20 °C [4]. However while the supply temperature is often controlled according to a weather compensation curve, the return temperature is highly dependent on the

design and operation of the heating system. This study therefore set out to test methods for evaluation of the possibility to obtain a low return temperature in heating systems with supply temperatures of 55 °C or lower.

Recent studies have shown how new houses can be designed with a low-temperature heating system supplied by either low-temperature district heating [5], a heat pump [6], or a boiler [2]. Less focus has been put on the heating systems in existing houses. This is despite the fact that the existing buildings form the larger part of the building mass. In Denmark most existing houses are heated by hydraulic radiator systems that were dimensioned according to design temperatures such as 90 °C/70 °C or 70 °C/40 °C. If these houses are to be heated by supply and return temperatures of 55 °C/25 °C or lower, it may be necessary to evaluate whether the heating system is suited for this type of low-temperature operation. A reduction of the heating system supply temperature might lead to poor thermal comfort and high heating system return temperatures in case the existing radiators in the houses are too small. This could in turn lead to poor heating system efficiency.

Recent studies that have investigated the use of radiator systems for low-temperature heating in existing buildings include [7–11]. These studies investigated the heat supply and heat demand in certain case study buildings by applying numerical analysis [9,10] or by using building simulation programs [7–9,11]. These types of anal-

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Nomenclature

T_s	Supply temperature
T_r	Return temperature
T_i	Indoor temperature
P	Heat flux emitted from the water [W]
q_m	Water mass flow rate [kg/s]
C_{water}	Specific heat of water [J/kg °C]
K	Power law coefficient depending on radiator height and width [W/m °C]
l	Length of the radiator [m]
n	Radiator exponent [–]
Φ_0	Design heating power at the standard test conditions [W]
Φ	Heating power at the operating temperatures [W]
ΔT_0	Mean temperature difference between radiator and surroundings in the standard test conditions [°C]
ΔT	Mean temperature difference between radiator and surroundings at the operating temperatures [°C]
ΔT_{arit}	Arithmetic mean temperature difference
ΔT_{log}	Logarithmic mean temperature difference

ysis require that assumptions are made about the design heating power of current radiators and about the applicability of parameters and equations describing heat emissions from the radiators. For example, the estimation of the design heating power of the current radiators in the building investigated might be based on calculations of the design heat loss of the building and the design heating system temperatures [7,8,10,11]. Heat emissions from the radiators might be calculated using either arithmetic or logarithmic mean temperature differences, and by applying specified or standard radiator exponents. Another major assumption is that indoor temperatures can be based on standard set-points of 20 °C or 22 °C [7,8,10].

Very little is known about the consequences of applying these assumptions. Therefore it is difficult to make reasonable assumptions and take into account any inaccuracies that might derive from such assumptions. This is important because the existing radiator sizes, may not correspond to the radiator sizes expected from the estimated design heat loss of the buildings [12]. Nor is it fully accurate to calculate the heat emission from the existing radiators using standard parameters and equations that have not been adjusted to the properties of low-temperature heating [13]. Lastly, indoor temperatures have a large effect on the heat emissions of a low-temperature heating system. Therefore accurate indoor temperatures may play a significant role for the validity of the results.



1.1. Objective

This paper set out to investigate the significance of the assumptions applied in simulations dealing with low-temperature radiator heating. The results from the study provide new knowledge on how dynamic simulations and measurements can be performed in order to obtain realistic results from evaluations of low-temperature heating systems – knowledge which may increase the accuracy of future studies in this area of research.

2. Method

The investigations presented in this paper were based on a case study of a Danish single-family house. The house was modelled in the commercial simulation tool IDA ICE and a number of simulations were performed to test how different assumptions affected the simulation results. The simulation results were evaluated with regard to indoor temperatures and heating system supply and return temperatures, and the calculated values were compared to temperatures measured in the house. The pros and cons of the investigated methods for simulation of low-temperature heating in existing buildings were discussed, and a suggestion was given for how to perform future studies on this topic.

3. Case study & simulation model

The case study was based on a typical Danish red-brick house from the 1950s. The original part of the house consists of approximately 100 m² of living area and a 70 m² basement (of which 18 m² is currently heated). In 1992, a two-storey extension was added to the house with 43 m² on the ground floor and 27 m² on the first floor. The house was modelled in the building simulation tool IDA ICE. The building construction was studied during a visit to the house and otherwise determined on the basis of drawing material and standard constructions at the time the house was built [14]. A picture of the case study house and the simulation model are shown in Fig. 1.

Three occupants live in the house and they were considered to be at home most of the time, because two are retired and the third often studies at home. Electrical equipment was identified during the visit to the house, and all internal heat gains were modelled using specified schedules. The average internal heat gains from equipment, light and occupants in the schedules were 5.2 W per m² heated floor area. This corresponds well with the average of 5 W/m² that is usually applied for Danish energy calculations [15]. The occupants were assumed to have a standard hot water consumption of 41 L hot water per person per day [16], and the house was assumed to be naturally ventilated by a fixed air flow of 0.3 l/s per m² heated floor area. Real weather data from northern Zealand, Denmark, was obtained from the Danish Metrological Institute and



Fig. 1. Picture of the case study house (left) and model of the case study house in IDA-ICE (right).



Fig. 2. Floorplan of the case-study house showing the ground floor (top left), the basement (bottom), and the first floor (top right).

applied in the simulation model. The outdoor temperatures in the period were between 4 and 11 °C and the sky was overcast.

Assumptions about non-heated spaces such as basements often cause significant uncertainty in simulation programs, so we chose to include the basement in the simulation model [17]. However, the main part of the basement has no heating devices and therefore no temperature set point, so its inclusion only serves the purpose of including the heat loss through the basement constructions. The house is heated by a new condensing natural gas boiler with weather compensation. Heat losses from pipes, hot water tank and boiler, which are all located in the non-heated basement, were estimated to be constant 435 W based on standard values from [14] and measurements of pipe lengths and insulation thicknesses.

All the radiators in the house were included in the simulation model. The radiators were modelled with well-functioning P-thermostats with a 2 °C dead band. This corresponds to the actual radiator valves in the house, except for the valves on the radiators in bathroom 1 and in the parents' bedroom that are both manual valves. The radiator in the parents' bedroom is always off, and was therefore also turned off in the simulation model. There was no mass flow control on the radiators in the house and the flow is therefore alone controlled by the thermostatic valves. However a theoretical maximum mass flow rate of 0.1 kg/s was assumed for each radiator in the model.

To ensure that the simulation model could be used to provide a reliable result, the natural gas consumption was measured during a 6-days measurement period, and compared to the heat consumption calculated by the simulation model during the same period. The natural gas consumption was read from the gas meter as 62.23 m³, which was estimated to correspond to a total heat demand of 646 kWh, based on a natural gas heating value of 11 kWh/Nm³ and a boiler efficiency of 106% [14]. The total heat demand calculated from the simulation model in IDA-ICE was found to be 689 kWh. This result was considered sufficiently close for the model to be applicable for the purposes of this investigation.

3.1. Simulation program

The case study was conducted by use of the commercially available dynamic building simulation program IDA ICE (version 4.6.1). IDA ICE has been validated according to several current standards

and can be used to perform advanced simulations of building energy consumption and indoor climate in individual building zones [18,19]. The program provides a predefined water radiator unit that can be used for simulation of heat emissions in building zones. The heat emitted from the radiator is calculated according to the heat balance on the water side and the air side of the radiator as given in Equation (1) and Equation (2) respectively.

$$P = q_m \times C_{water} \times (T_s - T_r) \quad (1)$$

where P is the heat flux emitted from the water [W], q_m is the water mass flow rate [kg/s], C_{water} is the specific heat of water [J/kg °C], T_s is the supply temperature, T_r is the return temperature

$$P = K \times l \times \Delta T_{log}^n \quad (2)$$

where K is a power law coefficient depending on radiator height and width [W/m °C], l is the length of the radiator [m], n is the radiator exponent [–]

The radiator element can be customized by user input on the geometry, the radiator exponent, and the design heating power of the radiator. Based on these inputs the program calculates the power law coefficient of the radiator and the maximum mass flow rate through the radiator according to the equations above. For simplicity the program allows the user to model the radiator elements without the piping system. In this case pumping power, pressure losses and hydraulic imbalances are not taken into account in the simulation, and the supply temperature at each radiator corresponds to the boiler supply temperature. The piping system was not included in the simulation model of the case study house, which makes it possible to discuss how this simplification affects the simulation results.

The indoor air temperatures calculated by the simulation program are average air temperatures for each zone. This means that the air in each zone is assumed to be perfectly mixed and no temperature gradients are taken into account. This is a common assumption in numerical studies and node-based simulation programs however it should be kept in mind when evaluating the simulation results.

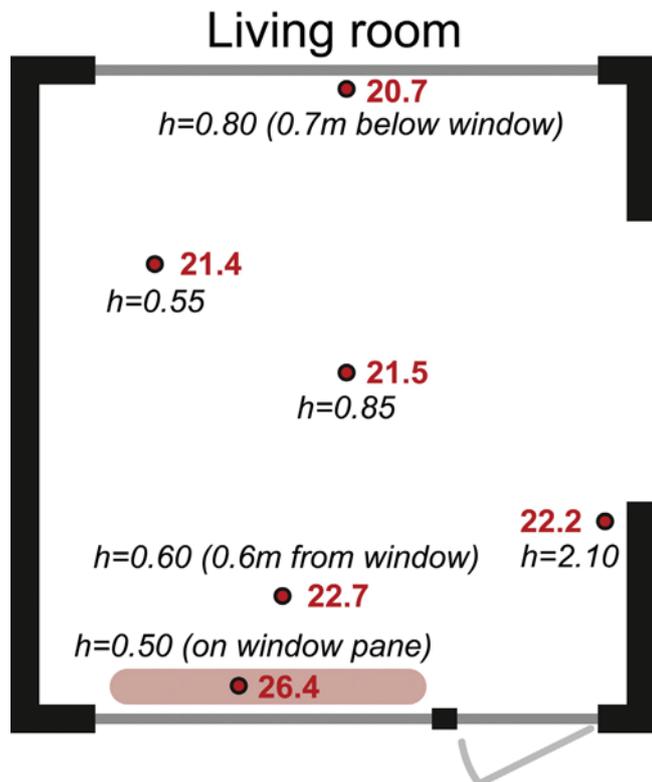


Fig. 3. Indoor temperatures measured at six different locations in the living room.

4. Temperature measurements

The indoor temperatures, radiator return temperatures, and boiler temperatures in the case house were measured during a 6-day measurement period in November 2014. The outdoor temperatures in the period were between 4 and 11 °C. The measurements provided useful inputs for the simulation model and made it possible to compare the simulation results to the actual conditions in the case house. The temperatures were measured every 10 min and the logger equipment had an accuracy of ± 0.35 °C, according to the manufacturer.

4.1. Indoor temperature measurements

The indoor temperature was measured in each room of the case house. The locations of the temperature loggers are marked on the floorplan in Fig. 2. The loggers were often located on furniture in one end of the room, as it was not possible to place the loggers in the middle of the rooms.

A small test was carried out to investigate the influence of the logger location on the measured indoor temperature. The indoor temperature was measured at six different locations in the living room, as seen in Fig. 3. As seen from the figure, it can be expected that there is a significant vertical and horizontal temperature gradient in some of the rooms. Temperatures that were measured in one end of the room were found to differ from the temperature measured in the middle of the room by up to 1.2 °C. The temperature gradient was mainly assumed to play a significant role in rooms with a large volume, such as the living room, or rooms where there are not radiators below all windows, such as in the Dining room/Kitchen, the TV room, the Entrance and Bath1.



Fig. 4. Pictures of the measurement setup. The pictures illustrate the mounting of the temperature probe to the outlet pipe of the radiator.

4.2. Return temperature measurements

The heating system temperatures were measured using temperature loggers equipped with temperature probes. The temperature probes were attached to the outlet pipes of the various radiators and covered with insulation to measure an approximate temperature of the return water. Additional loggers were connected to the supply and return pipes at the natural gas boiler. Pictures showing the measurement equipment and setup can be seen in Fig. 4.

The accuracy of the measurement method was evaluated through two tests. In the first test, the temperature of a radiator pipe was measured with three different loggers at the same time, in order to evaluate the inaccuracy due to the probe location under the insulation. Secondly, the temperatures measured with the illustrated logger setup were compared to temperatures measured with a laser pointer. The tests showed that the difference between the temperatures measured by three different loggers connected to the same pipe was up to approximately 2 °C. Furthermore the difference between the temperatures measured with the given measurement setup and those measured with a laser pointer were 0.4–4.2 °C. The measurement method was therefore assumed to have an inaccuracy of up to approximately 6 °C. This means that the measurements could not be used for a validation of the simulation models. Instead they were used to provide an indication of the actual heating system temperatures in the case house.

5. Simulation assumptions

In order to investigate the significance of typical assumptions applied in simulations dealing with low-temperature radiator heating, a number of simulations were performed based on various calculation assumptions. Typical assumptions that were investigated in the study can be divided in the following three categories:

- 1 Method chosen for calculation of heat emissions from radiators.
- 2 Method chosen for estimation of the design heating power of existing radiators.
- 3 Indoor temperature set-points applied in the simulations.

The theory behind the calculation of heat emissions from radiators and estimation of design heating power of existing radiators is described in the next sections. Furthermore the simulation assumptions that were investigated in the study are described in detail.

5.1. Calculation of heat emissions

The heat emitted from a given radiator is usually defined by test measurements and stated by the manufacturer in product catalogues. The tests are carried out for a number of standard mean temperature differences and using a fixed water mass flow rate. In the current standard, EN 442-2 [20], the tests are carried out with a water mass flow rate corresponding to the temperatures 75/65/20 °C for supply, return and air temperature respectively. In practice the operating temperatures differ from the test temperatures and therefore so does the water mass flow rate. The actual heat emitted from a radiator can be calculated using Equation (3) based on the mean temperature difference (MTD) between radiator and surroundings.

$$\phi = \left(\frac{\Delta T}{\Delta T_0} \right)^n \times \phi_0 \quad (3)$$

where ϕ_0 is the design heating power at the standard test conditions [W], ϕ is the heating power at the operating temperatures [W], ΔT_0 is the MTD between radiator and surroundings in the standard test conditions [°C], ΔT is the MTD between radiator and surroundings at the operating temperatures [°C], n is the radiator exponent [–]

The mean temperature difference is the difference between the temperature of the radiator and the temperature of the air. The temperature difference is the driver of the heat emissions and is therefore an important factor in the calculation of the heating power. The temperature difference is based on a mean radiator temperature, since radiators are usually warm at the top and colder near the bottom. One way of calculating the temperature difference between the mean radiator temperature and the air temperature (T_i) is by using the arithmetic mean temperature difference. The arithmetic mean temperature difference is described in EN 442-2 and calculated in accordance with Equation (4).

$$\text{Arithmetic mean temperature difference} = \Delta T_{\text{arit}} = \frac{T_s + T_r}{2} - T_i \quad (4)$$

However, the arithmetic mean temperature difference does not provide a precise estimation of the mean radiator temperature if there is a large difference between the supply and the return temperature. This is due to the fact that the temperature distribution over the radiator surface is not linear. A more precise method is to use the logarithmic mean temperature difference, which is calculated in accordance with Eq. (5).

$$\text{Logarithmic mean temperature difference} = \Delta T_{\text{log}} = \frac{T_s - T_r}{\ln \left(\frac{T_s - T_i}{T_r - T_i} \right)} \quad (5)$$

5.1.1. Radiator exponent

The relation between the mean temperature difference and the heat output of the radiator is described by the radiator exponent. This exponent is important since the relationship between the two is non-linear. The radiator exponent can be derived by testing the radiator at different temperature sets and using Eq. (3) to determine the exponent that describes the relation between the measured heat outputs. The exact radiator exponent differs slightly for different types and sizes of radiators. Typical radiators with a height above 0.4 m have a radiator exponent of approximately 1.3, which is an applicable assumption for standard situations. However, according to recent findings it may not be applicable to use

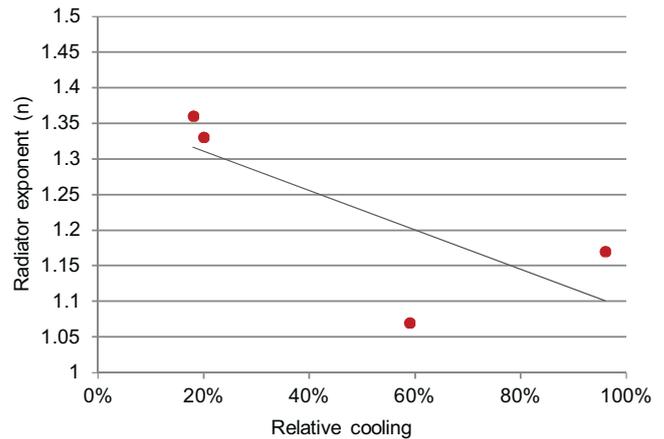


Fig. 5. Relationship between relative cooling and radiator exponent for a Type 22 radiator [13].

the radiator exponent found during standard test conditions to calculate heat emissions in special cases like low-temperature heating [13]. Instead the radiator exponent should be varied depending on the relative cooling of the radiator. This is due to the fact that the nature of the heat emissions change when the mass flow rate and the turbulence of the water in the radiator changes. The relative cooling of a radiator with certain operating temperatures can be calculated using Equation (6).

$$\text{Relative cooling} = \frac{T_s - T_r}{T_s - T_i} \quad (6)$$

The relationship between the relative cooling of a plate or a column radiator and the radiator exponent can be assumed to approximate the curve shown in Fig. 5, as found by [13]. The given curve can be assumed to apply for typical radiators with a height above 400 mm. However it must be underlined that the curve does not apply for convector type radiators with a height below 400 mm, where the radiator exponent was found to increase with increasing relative cooling.

This means that, for a Type 22 radiator operated with temperatures of 55/25/20 °C, the relative cooling is 86% and the accurate radiator exponent describing the heat emitted from the radiator is closer to $n=1.15$, than the standard $n=1.3$. This study evaluated which effect the accuracy of the radiator exponent and the choice of method for calculation of the MTD had on the simulation results. Three different simulations were performed using either the logarithmic MTD or the arithmetic MTD and either a radiator exponent of 1.3 or an exact radiator exponent to calculate the heat emissions from the radiators. The exact radiator exponent was estimated by use of Fig. 5 based on a calculation of the relative cooling of each radiator according to the measured supply and return temperatures.

5.2. Design heating power of existing radiators

When investigating the potential to heat an existing building with lower temperatures it is necessary to estimate the heating power of the existing heating elements. The most accurate procedure for estimating the design heating power of the radiators in an existing building is to visit the specific building and identify the actual radiator types and sizes. However it is not always possible to get access to the building. In that case the design heating power of the existing radiators can be estimated based on construction drawings of the house or calculations of the design heat loss in the house. In this study we tested three different methods for estimat-

Table 1
Radiator types and sizes in the case study house with estimated design heating power of each radiator.

Location	Height [m]	Depth [m]	Length [m]	No. of columns	Type	Design heating power, Φ_0 at 90/70/20 °C [W]
Living room	0.35	0.25	2.0	50	Column	4230
Dining room	0.55	0.14	0.78	20		1530
Bathroom 1	0.6	0.14	0.42	11		900
Parents' bedroom	0.55	0.14	0.78	20		1530
Office	0.55	0.14	0.78	20		1530
Blue room	0.55	0.14	0.78	20		1530
Entrance	0.4	0.1	1.2	–	Plate (Type 22–2 plates and 2 convector panels)	1930
Bedroom 4	0.6	0.1	0.8	–		1870
Bedroom 3	0.6	0.1	1.0	–		2330
Bedroom 2	0.6	0.1	1.0	–		2330
Bedroom 1	0.6	0.1	1.0	–		2330
Bathroom 2	0.6	0.1	0.3	–		700
Basement	0.66	0.1	0.78	–		1970

ing the design heating power of the radiators in the case house and investigated how each method affected the simulation results.

5.2.1. Actual radiator sizes

For the first method the radiators in the case house were characterized and measured during a visit to the house. The design heating power of each radiator was estimated using an Excel program based on empirical data from tests of typical Danish radiators. The program was acquired from the Danish Technological Institute. According to tests performed by the Danish Technological Institute, the general accuracy of the program was $\pm 5\%$, though in a few cases, the inaccuracy of the program was as much as 10–15%.

The radiators in the case house are listed in Table 1. The design heating power of the radiators is given for the temperature set 90/70/20 °C which was the standard design temperature set in Denmark in the mid-1900s.

5.2.2. Construction drawings

The second method was based on an estimation of the design heating power of the radiators by use of the construction drawings of the house. This is only possible if adequate drawings including the original radiators are available. This method includes the risk that old radiators have been replaced with newer models, or that some old radiators have been removed altogether, if large internal refurbishments have been carried out such as walls being knocked down to combine a number of rooms into one.

The drawings of the case house included all of the radiators that were in the house today, apart from the radiator in the basement. Furthermore the drawings included two extra plate radiators in the dining room, because this room used to be three separate rooms. When the heating power of the extra radiators were included, while the heating power of the radiator in the basement was removed, the total design heating power in the house was reduced by 1100 W.

5.2.3. Calculation of design heat loss

The third method was to estimate the design heating power of the existing radiators based on calculations of the design heat loss of the building. In this case, the radiators are assumed to be dimen-

sioned to cover the design heat loss of each room at given design temperatures. However, it may be difficult to identify realistic design temperatures for old radiator systems, because commonly applied temperatures have differed both over time and depending on the original heating source of the house. For houses heated with natural gas, it was customary in Denmark to use design temperatures of 90/70 °C. By 1990, the design temperatures had changed to 80/60 °C and, around 1995, the design temperatures were lowered even further to 62.5/47.5 °C [21]. In district heating areas, the design temperatures are determined by the district heating company and may therefore vary around the country. For many years, it has been common to use a design temperature set of 70/40 °C for radiators in buildings supplied by district heating. This design temperature set was also included in the building code in 1995 [22]. This method therefore includes in-built inaccuracy due to assumption about design temperatures. Furthermore, the method assumes that current practices can be used to estimate the design heat loss used for dimensioning of radiators even in houses constructed many years ago. This may also cause some bias because the procedures for the calculation of heat loss changed many times during the 1900s. Earlier, it may also have been custom that radiators in small houses were dimensioned by a blacksmith using a rule-of-thumb approach resulting in general over-dimensioning.

The design heat loss for all rooms in the case house were calculated in accordance with Danish design conditions using an indoor temperature set point of 20 °C, an outdoor temperature of –12 °C, and without any heat gains. The design heating power of the radiators was estimated for two different sets of design temperatures. In the first calculations the design heating power was calculated for a design temperature set of 90/70 °C in the old part of the house and 80/60 °C in the new part of the house, according to the age of the two building parts. In the second calculation, the radiators were dimensioned for a design temperature set of 70/40 °C. This meant that the design heating power of the radiators in the second calculation was larger than that in the first calculation, because larger radiator dimensions are required to cover the same heat loss with a lower temperature set.

Table 2
Design heating power in the house calculated using 4 different methods.

Scenario	Total design heating power at temperatures 90/70/20 °C [kW]			
	Old part	New part	Basement	Total
Design heating power based on actual radiator sizes	11.24	11.49	1.97	24.70
Design heating power based on radiators included in drawings of the case house	12.11	11.49	0	23.60
Design heating power based on design heat loss and design temperatures of 90/70 °C in the old part of the house and 80/60 °C in the new part of the house	9.05	5.50	0	14.55
Design heating power based on design heat loss and design temperatures of 70/40 °C	19.65	9.38	0	29.03

Table 3
Scenarios for the calculation of return temperatures investigated in the simulation model.

Scenario	Category	Radiator exponent (n)	Mean temperature difference	Indoor temperature set-point	Method for design heating power
A1	Calculation of heat emissions	According to measurements	Logarithmic	According to measurements	Actual radiators
A2		n = 1.3	Logarithmic	According to measurements	Actual radiators
A3		n = 1.3	Arithmetic	According to measurements	Actual radiators
A4		n = 1.3	Logarithmic	20 °C	Actual radiators
B1	Estimation of design heating power	n = 1.3	Logarithmic	According to measurements	Drawings
B2		n = 1.3	Logarithmic	According to measurements	Design heat loss (90/70 and 80/60)
B3		n = 1.3	Logarithmic	According to measurements	Design heat loss (70/40)

Table 2 shows a summary of the design heating power of the radiators in the house for the different calculation methods at a design temperature set of 90/70/20 °C.

5.3. Indoor temperatures

The indoor temperature set-point is an important input for studies on low-temperature heating. This is due to the fact that the heat demand in a given room and the heat emitted from a radiator is largely dependent on the indoor temperature. This study investigated how assumptions on the indoor temperature set-point affected the analysis of a low-temperature heating system. First a simulation was performed where the indoor temperature set-point in all rooms was given as 20 °C corresponding to the indoor temperature required in the Danish Building Code. Secondly a simulation was performed where indoor temperature set-points in the house were based on actual measured indoor temperatures.

5.4. Scenarios

The simulation model in IDA-ICE was all together used to investigate 7 different scenarios for how to simulate low-temperature heating in the case study house. The scenarios represented different variations on how to calculate the heat emissions from the radiators, how to estimate the design heating power of existing radiators, and how to estimate the indoor temperature set-points. The scenarios were split in two categories: Category A deals with different methods for calculation of heat emissions, while Category B deals with different methods for estimation of design heating power. The scenarios are summarized in Table 3.

The results from the simulations were evaluated from two different aspects. First the indoor temperatures measured in the case house were compared to the operative indoor temperature calculated by the simulation scenario A1. This scenario was expected to be the scenario that was closest to the actual situation in the house. The aim of the comparison was to evaluate how well the simu-

lation model with the given assumptions was found to resemble reality. Secondly the calculated heating system temperatures in all simulation scenarios were compared to the actual heating system temperatures measured in the house. The aim of this comparison was to evaluate how different assumptions affect the calculation of heating system temperatures. The heating system supply temperature was based on the actual supply temperature measured in the case house, and this temperature was the same in all models. The evaluation therefore focused on the return temperatures from each radiator in the case house and from the overall heating system.

6. Results and discussion

6.1. Calculated indoor temperatures

Fig. 6 shows the measured indoor temperatures in the case house along with the calculated average indoor air temperatures according to Scenario A1.

The figure shows that the calculated indoor temperatures in the living room, the dining room, the basement, and bath1 were lower than the measured indoor temperatures. This indicates that the heating powers of the radiators included in these rooms of simulation model, are too small to maintain the measured indoor temperature. However the uncertainties in the estimation of the radiator heating power are not expected to be the main reason for the difference between the calculated and the measured indoor temperatures in these rooms. Since the temperature difference is mainly found in large rooms where the logger location can be expected to cause the measured temperature to be higher than the average, it is expected that the difference can be explained by the uncertainties in the indoor temperature measurements. The results therefore highlight that the uncertainty of indoor temperature measurements and the simplification of the indoor temperature calculations, must be kept in mind when the results from node-based simulation tools are evaluated.

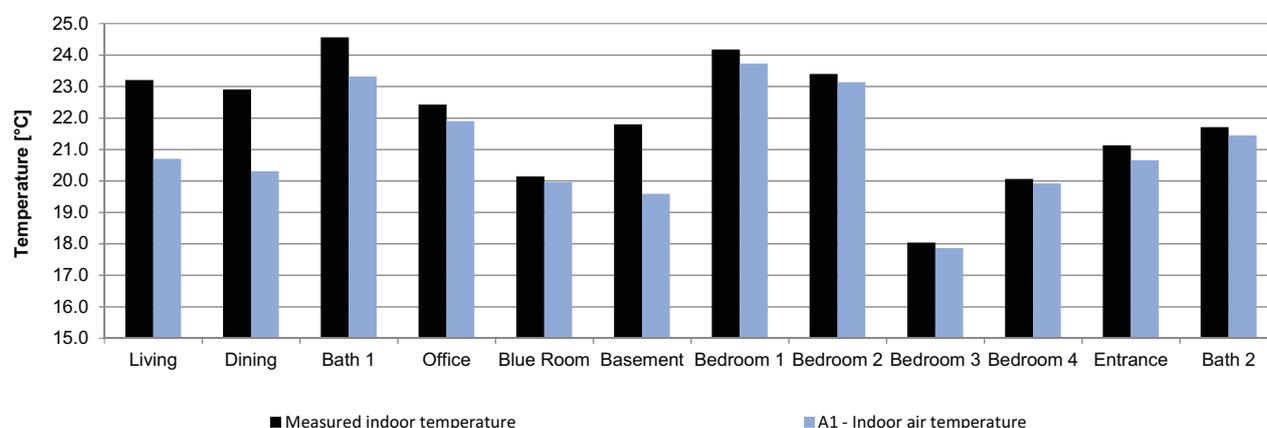


Fig. 6. Measured temperatures in the rooms of the case house compared to calculated average indoor temperatures according to Scenario A1.

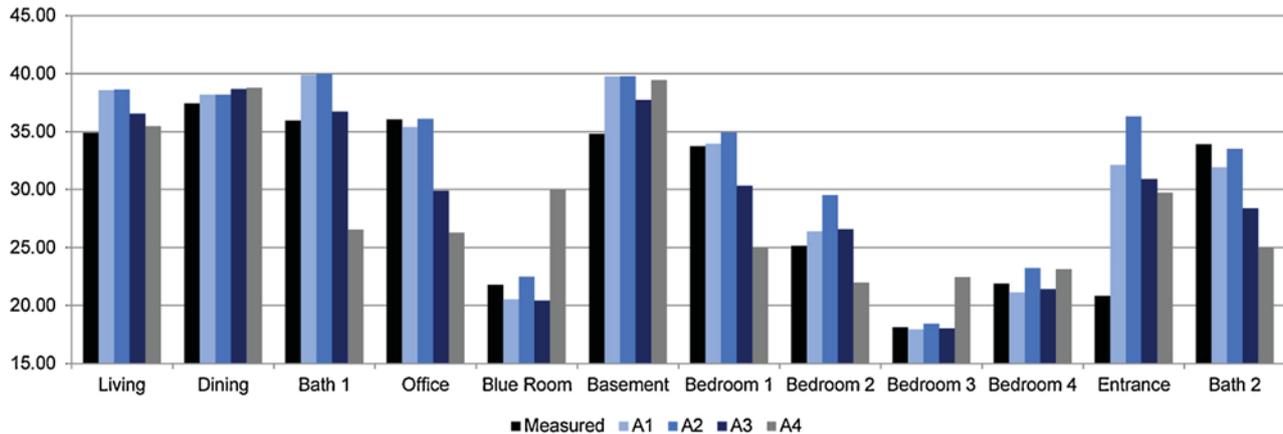


Fig. 7. Return temperatures from all radiators in the case house as measured and calculated from Scenarios A1–A4.

6.2. Calculated return temperatures

6.2.1. Scenario A

The calculated average return temperatures from the radiators in the case house according to Scenario A1–A4 are shown in Fig. 7 alongside the average measured return temperatures.

As seen from the figure the scenarios A1 and A2 provided almost similar results and showed a good correspondence with the measured temperatures. The return temperature from the radiator in the entrance was the only temperature that the scenarios failed to provide a reasonable estimation of. However the return temperature from this radiator was not accurately estimated by any of the scenarios, which was found to be due to fact that the thermostatic valve on this radiator was almost closed, thereby causing the entrance to be partly heated by radiators in adjacent rooms. This indicates that the detailed simulation model can provide reasonable calculations of the radiator return temperatures, but it cannot be used to estimate return temperatures in cases where occupant behaviour causes this type of malfunction. The maximum deviations between the calculated and the measured return temperatures in Scenarios A1 and A2 were approximately 4–5 °C, if the radiator in the entrance is not taken into account. The largest deviations were found on the return temperatures from the radiators in the living room, the basement, and bath1. These radiators were found to have a high calculated mass flow rate and therefore the deviation may partly be caused by the high maximum mass flow that was assumed in the model. Furthermore part of the difference may be explained by measurement inaccuracies as the

mounting of the temperature probe on the radiator pipes may cause the measured temperatures to be lower than the actual return temperatures. The difference could also be explained by the fact that the piping system and the heat losses from the pipes were not included in the simulation model. However the results indicate that the simulation model can be used to provide reasonable estimates of the heating system temperature despite of this simplification.

The return temperatures estimated in Scenario A3 where the arithmetic MTD was used did not differ significantly from the temperatures estimated in Scenarios A1 and A2. The main difference in the calculated return temperatures was found for the radiators in the office, bedroom1, and bath2. Scenario A3 estimated the return temperatures from these radiators to be up to 6 °C lower than the measured temperatures and the temperatures estimated in scenario A1 and A2.

Generally it was found that the use of the standard radiator exponent in Scenario A2 resulted in slightly higher calculated return temperatures than those from Scenario A1. Scenario A3 that was based on calculations with the arithmetic mean temperature difference resulted in slightly lower calculated return temperatures. While Scenario A2 thereby provided results that were on the safe side, Scenario A3 slightly overestimated the heating power of the radiators.

The return temperatures calculated in Scenario A4 showed the largest deviations from the return temperatures calculated in the remaining scenarios and from the measured return temperatures. The method was found to underestimate the return temperatures by 8–9 °C in rooms such as the office, bath1, and bedroom1, where

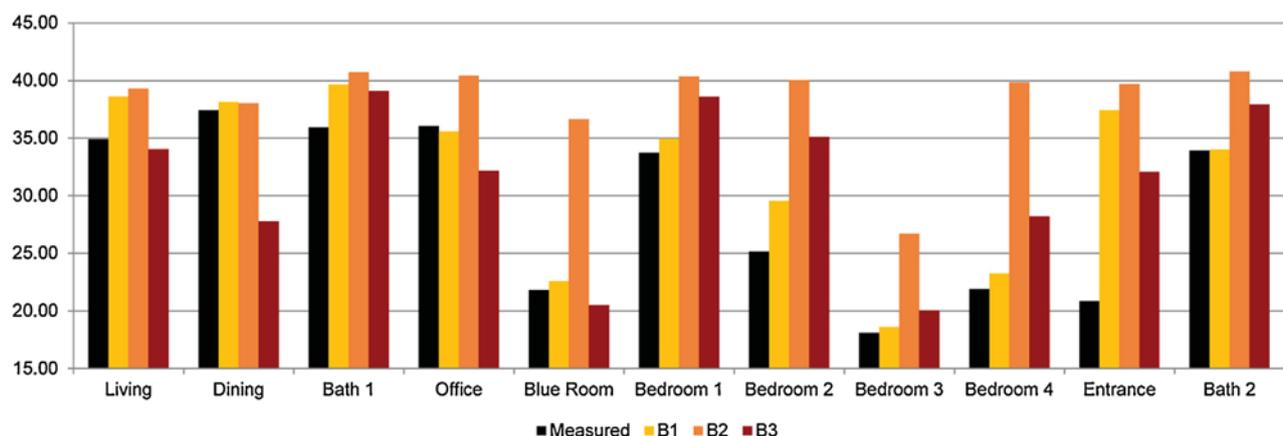


Fig. 8. Return temperatures from all radiators in the case study house as measured and calculated from Scenarios B1–B3.

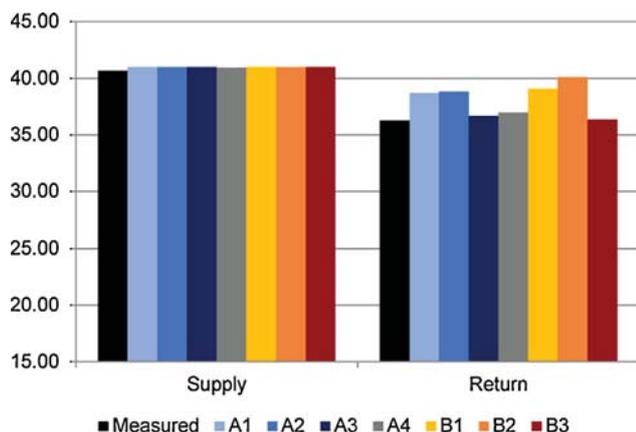


Fig. 9. Average boiler return temperature measured and calculated from the scenarios.

the measured indoor temperature set-points were high. Also the return temperatures were over-estimated in rooms where the measured indoor temperature set-points were below 20 °C. The indoor temperature set-points were thereby seen to have a large effect on the accuracy of the calculated return temperatures. The effect might be especially visible in this study, as the rooms of the case house were found to have very different indoor temperature set-points ranging between 18 and 24 °C. The simulation performed in Scenario A4 may therefore not be useful to estimate actual radiator return temperatures. However it could be useful to identify the most substantial problems with a high radiator return temperature, as seen for the radiators in the living room, the dining room, and the basement.

6.2.2. Scenario B

Fig. 8 shows the calculated average return temperatures from the radiators in the case house according to Scenario B1–B3 along with the measured average return temperatures. The basement radiator was not included in these simulations as the basement was not planned to be heated at the time of construction.

The results from Scenario B1 showed only minor deviations in the calculated return temperatures compared to Scenario A1. This was due to the fact that the extra radiators that were included in the drawings of the case house were not big enough to influence the calculated return temperatures.

The return temperatures calculated in both scenarios B2 and B3 were found to differ greatly from the measured temperatures and the return temperatures estimated in the remaining scenarios. The use of high design temperatures in Scenario B2 was found to cause an overestimation of the return temperatures from the radiators in the new part of the house. Similarly the use of design temperatures of 70/40 °C in Scenario B3 caused an underestimation of the return temperatures from the radiators in the old part of the house. The differences between the calculated return temperatures and the measured return temperatures in the scenarios were found to be up to approximately 18 °C and 10 °C respectively. These methods were therefore not found to be suited to calculate accurate heating system return temperatures. While Scenario B2 provided results that were on the safe side, Scenario B3 on the other hand was found to over-estimate the heating power in the house.

6.3. Heating system temperatures

The average measured boiler temperatures in the case house are seen in Fig. 9 along with the boiler temperatures calculated in all scenarios. As seen from the figure the calculated boiler return temperatures were all between 36 °C and 40 °C. All of the Scenarios

were thereby seen to provide reasonable estimates of the overall boiler return temperature. The high return temperatures and high water mass flow rates that were calculated in some of the radiators in the investigated case study house may however be part of the reason for the small difference. In that case the assumptions on maximum water mass flow in the radiators may have a significant influence on this result. Even though all the Scenarios were found to provide a reasonable estimate of the boiler return temperature, it does therefore not mean that all the Scenarios represent suitable calculation methods. This is underlined by the differences in the calculated return temperatures from the individual radiators.

7. Conclusions

This study showed that the detail level and assumptions included in a simulation model have a large impact on the simulation results of studies on low-temperature heating in existing buildings. The calculated radiator return temperatures were found to differ by up to 16 °C depending on the model assumptions. Furthermore the difference between the calculated and the measured return temperatures were found to be up to 18 °C in some cases. However the results of the study indicated that a simulation model can be used to provide reasonable estimates of the heating system temperatures if actual radiator sizes and reasonable indoor temperature set-points are included in the model.

The study showed that it is complex to estimate and model actual indoor temperatures and temperature set-points. At the same time these inputs were found to have a large effect on the calculated return temperatures in the simulation model. A simulation based on a standard indoor temperature of 20 °C was not found to provide a good estimation of the heating system temperatures. The method could be used to identify radiators that are likely to cause a high return temperature, but it did not provide a good estimate of the actual return temperatures from the radiators. It can be useful to base the simulation model on measured indoor temperatures, however the uncertainties related to this type of measurements should be kept in mind.

The case study showed that it was necessary to include the actual radiator sizes in the simulation in order to obtain accurate results. Estimating the radiator sizes based on calculations of design heat loss was found to cause the calculated heating system temperatures to differ greatly from the measured temperatures. The use of simplified standard methods for calculation of the heat emissions from the radiators was not found to cause significant differences in the calculated heating system temperatures.

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VII

Using information from electronic heat cost allocators to identify heating system malfunctions

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Abstract

Proper heating system operation in buildings is a vital area for the realization of low-temperature district heating with supply and return temperatures of 55 °C and 25 °C respectively. But the operating area of the district heating companies usually only extends to the substations at the entry of the buildings, and very little is known about the actual use and distribution of heat inside the buildings. This paper describes one possible method for district heating companies or building technicians to monitor heating system operations, and thereby identify heating system malfunctions, inside apartment buildings. The method uses data from existing electronic heat cost allocators to locate radiators with high return temperatures. The method was tested by comparing data from heat cost allocators with detailed measurements of radiator return temperatures in an apartment building in Frederiksberg, Denmark. The investigations indicate that data from the heat cost allocators can be used to identify radiators with continuously high return temperatures, and thereby locate severe problems with e.g. hydraulic balancing in heating systems. However, the method needs further development and tests to ensure the accurate identification of the various heating system malfunctions and their effect on overall heating system efficiency.

Keywords: *Low-temperature district heating; Hydraulic radiators; Commissioning; Automatic fault detection*

1 Introduction

Energy efficiency improvements in space-heating installations have become a major focus area in the attempt to reduce CO₂ emissions and fossil fuel dependency. While the energy renovation of a building envelope is often a costly affair, the improvement of heating system installations can often provide energy savings with a small investment and a short pay-back time [1,2]. The energy consumption of a heating system can be reduced by installing thermostatic radiator valves and carrying out hydraulic balancing [1–4], or by influencing occupant behaviour, e.g. through the use of heat cost allocators [5,6]. A well-functioning heating system can also lead to additional energy savings, especially in areas heated by district heating, because the heating system temperatures are lower [7,8]. The benefits of this include reduced heat loss in district heating pipes, increased efficiency of heat production from boilers with flue gas condensation, reduced electricity for pumps, and increased hydraulic capacity in the pipe network. In European countries, where efficient district heating can play a considerable role in the future European energy system [9–11], monitoring and improving space-heating operations is therefore becoming increasingly important.

To ensure the efficient operation of heating systems, both the central heating substations and the terminal elements must be operated properly. Fault detection and the improved operation of central heating substations

have been investigated for example by Zinko, Gadd, and Yliniem [8,12,13]. Using wireless substation energy meters, it is possible for district heating suppliers to monitor the operation of individual substations and provide fast fault-detection in district heating substations as well as feedback on heating operation efficiency [14]. Furthermore, data on the central heating substation can often be easily accessed and analysed by service managers, which means that changes or improvements in substation control are often relatively cheap, as visualized by Petersson & Werner [7]. Studies have shown that there are faults in the operation of up to 75% of substations [15], and problems in a customer's heating substation are the main cause of high return temperatures [7]. However, the operation of the internal building installations is also important. According to Zinko et al. [8], faults in the space-heating system can account for up to 60% of identified faults in heating installations, and estimates show that the optimization of the internal heating installations would reduce return temperatures by about 7 °C [7], leading to a total annual return temperature of 30 °C when both central and internal heating installations are working properly.

Overall heating consumption can be monitored closely, but very little is known about the heating distribution inside buildings or the actual operation of typical heating systems [16]. Studies by Jangsten et al. [17] and Averfalk et al. [16] have reported on overall space-heating temperatures in apartment buildings to illustrate typical operation temperatures in secondary systems. A series of Swedish reports have focused on practical studies of how the replacement of thermostatic valves and carrying out of hydraulic balancing in the space-heating systems of existing apartment buildings can help reduce return temperatures [18,19]. Furthermore, previous work by the present authors has addressed the possibility of identifying problematic terminal elements in heating systems that contribute significantly to high return temperatures [20]. However, the current knowledge of heating system operation referenced is generally limited to case-specific studies. The main reason for this is that the investigations mentioned above required detailed analysis of the individual buildings and access to all the individual apartments to be able to perform hydraulic balancing, for example. This is both costly and time-consuming.

The excessive amount of measurement equipment needed to monitor heating system operation in detail is a major barrier to efficient fault detection in space-heating systems [21]. On the other hand, many heating systems are equipped with substantial amounts of measurement equipment to meet the requirements for fair distribution of heat costs, in accordance with the energy efficiency directive from 2012 [22,23]. In this paper, we therefore propose, and describe an empirical investigation of, a method of using data from electronic heat cost allocators for fault detection in space-heating systems in apartment buildings. If fault detection in heating systems can be carried out with data from already available heat cost allocators, this would enable building managers to optimize heating system operation without installing any additional expensive equipment.

The use of data from heat cost allocators for the estimation of heating output and heating system temperatures is associated with some uncertainty. One major uncertainty lies in the fact that the calculation of heat emissions from a radiator depends on its estimated nominal heat output. The nominal heat output of a radiator can be estimated using rough calculation procedures that can involve inaccuracies of up to 13.5%, as described in detail by Arpino et al. [24]. Furthermore, the installation conditions of the radiator have a large impact on the actual heat output of the radiator, which means that the actual heat output can differ greatly from the estimated value.

For example, several sources state that the heat output from a radiator connected with a bottom-bottom opposite-end solution can be as much as 12% less than a top-bottom opposite-end connection [24,25]. The distance between the radiator and the floor or a window pane can lead to additional reductions of as much as 10% in the heat output [26]. Even bigger impacts are seen when a radiator is partially covered or placed behind a concealer or cabinet, which can reduce the heat output by 10–25% [24,26]. Beck et al. [27] found that painting the wall behind a radiator black can increase the heat output by as much as 20%, whereas Beck et al. [28] report that metallic paint on the radiator can decrease the heat output by as much as 10%. They also showed that fouling of a PKII radiator can reduce its actual heat output by as much as 20% due to reduced convection, while increased convection due to forced air flows can dramatically increase the heat output from a radiator [29–32]. Further uncertainty is added by the inaccuracies of the equations applied to calculate heat output from radiators in operation conditions differing from the standard test conditions, as explained for example by Goettling [25], Paulsen & Rosenberg [33,34], and Ploskić [29]. Moreover, Dell’Isola et al. [22] and Celenza et al. [35] show that the inaccuracy of heat emission measurements based on a single heat cost allocation device can be more than 9-10%. So although heating system monitoring using data from heat cost allocators would be cheap, it would also be associated with considerable uncertainty.

In this paper, we not only describe the foundations for a method that would enable the identification of heating system malfunctions based on data from electronic heat cost allocators, but we also make a rough investigation of the uncertainty related to the method. The method proposed can provide new insights into actual heating system operation and provide a powerful and cheap tool for heating system monitoring and automatic fault detection. A new tool like this could play an important role in the effort to reduce energy consumption in buildings and enable the use of low-temperature heating.

2 Method

The study consists of three parts. Firstly, we describe the theory and the method used to calculate individual radiator return temperatures based on data from electronic heat cost allocators. The radiator return temperatures provide an indication of the efficiency of the heating system because high radiator return temperatures indicate a high water mass flow and thus a potential malfunction that can lead to a high overall heating system return temperature. Secondly, we introduce the measurements and calculations conducted to validate the method through a case study in an apartment building in Frederiksberg, Denmark. Finally, we report how we investigated the uncertainty of the method by analysing how sensitive the calculated radiator return temperatures were to changes in the input parameters.

2.1 Heat emissions from radiators

A basic introduction to heat emissions from radiators is essential to understand the principle of heat cost allocators. The heat emitted from a radiator to the room air results from the temperature difference between the radiator surface and the air. Typically, the heat emitted from a radiator is described by Eq. (1) and Eq. (2), as for instance explained in detail by Goettling [25]. Eq. (1) is used to calculate the heat released from the water circulating in the radiator, and Eq. (2) is used to calculate the heat emitted from the radiator to the air. Due to the conservation of energy, they should provide equal results.

$$Q = m c (T_s - T_r), \quad (1)$$

where m is the water mass flow; c is the specific heat capacity of water; T_s is the supply temperature to the radiator; and T_r is the return temperature from the radiator.

$$Q = A U (T_m - T_o), \quad (2)$$

where A is the surface area of the radiator; U is the heat transfer coefficient of the radiator; T_m is the mean radiator temperature; and T_o is the air temperature.

One major problem with Eq. (2) is the estimation of the mean radiator temperature, since the radiator temperature varies across the radiator surface. To get around this problem, the equations can be integrated to calculate the heat emitted from a small section of the radiator, over the area dA and with a change in water temperature of dT , as illustrated in Fig. 1. This method assumes a one-dimensional flow of hot water from the top of the radiator to the bottom. While this is often reasonable, heat flows in a horizontal direction also occur to some degree, but these are neglected in this approach.

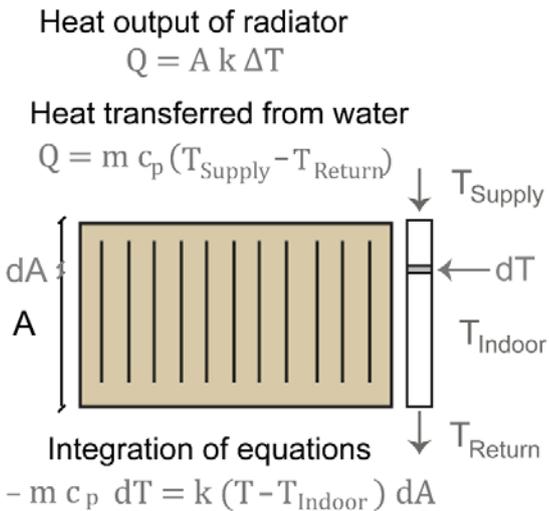


Fig. 1. Illustration of a one-dimensional model of a radiator for calculation of heat output over a given area dA

The result of the integration is that the heat emitted from a radiator over the whole area A can be described by using the logarithmic mean temperature difference, as given in Eq. (3):

$$Q = A U \Delta T, \quad (3)$$

where ΔT is the logarithmic mean temperature difference calculated by $(T_s - T_r) / \text{LN}((T_s - T_o) / (T_r - T_o))$.

In this equation, the heat transfer coefficient, U , can be tricky to determine because it varies over the height of the radiator. The heat output of a typical radiator consists of 10–40% radiation, while the rest is natural convection [25]. Since the thermal boundary conditions for both radiation and convection change over the height of the radiator, so does the heat output, as also illustrated by Ploskić [36]. However, empirical studies show that the relationship between the heating power of the radiator and the mean radiator temperature can be described by a power law equation, as shown in Eq. (4). In this way, the term $A U$ can be replaced by a constant K_Q . Both K_Q and the radiator exponent n can be derived by measuring the heat output of the radiator at different supply and return temperatures.

$$Q = K_Q (\Delta T)^n, \quad (4)$$

where K_Q is a parameter describing the heat output of the radiator; n is the radiator exponent, which normally takes values between 1.1 and 1.4 – most typically around 1.3: and ΔT is the logarithmic mean temperature difference.

Instead of using the factor K_Q , radiator manufacturers often test their radiators at nominal temperatures, and provide the nominal heating power measured in these standardized test conditions [37]. In this case, the equation can be modified to calculate the heat output from the same radiator at a different set of temperatures, as shown in Eq. (5).

$$Q = Q_n \left(\frac{\Delta T}{\Delta T_n} \right)^n, \quad (5)$$

where Q_n is the nominal heat output of the radiator at the test temperatures and ΔT_n is the logarithmic mean temperature difference at the test temperatures.

The way this equation is derived means that it serves merely as an approximation to estimate heat emissions and temperature distributions in a radiator. A more accurate equation that can be used to estimate the temperature distribution across a radiator was suggested by Glück [38] and is shown in Eq. (6).

$$-m c dT = \frac{K_Q}{A} (T - T_a)^n dA, \quad (6)$$

This equation can be integrated analytically, leading to the relationship between heating system temperatures, water mass flow, and radiator heat output given in Eq. (7), where the radiator exponent n should be between 1.2 and 1.33 [39].

$$(T_r - T_a)^{(1-n)} - (T_s - T_a)^{(1-n)} = (n - 1) \frac{K_Q}{m c}, \quad (7)$$

From this equation, a model for the calculation of the radiator surface temperature at a given height of the radiator can be derived. The model is shown in Eq. (8) and is also referred in the European standard EN 384 [39,40]. This method turns out to be more accurate with regard to estimating the temperature distribution across the radiator, which is highly relevant when it comes to the use of heat cost allocators. It should be noted that the height refers to the thermal height and not the physical height. The difference between the two arises due

to the fact that the actual flow through the radiator is not one-dimensional. As described by Paulsen [39], the thermal height can differ from the physical height by as much as 10% and is usually slightly higher than the physical height in the case of a panel radiator, while it is slightly lower in the case of a column radiator.

$$T_m = \left((T_s - T_a)^{(1-n)} + \left(1 - \frac{h}{H}\right)^{(n-1)} \cdot \left(\frac{KQ}{mc}\right)^{\frac{1}{(1-n)}} \right) + T_a, \quad (8)$$

where T_m is the radiator surface temperature at height h ; h is the thermal height at which the surface temperature is measured; and H is the total height of the radiator.

The equation can be further rearranged if we isolate the mass flow, mc , and assume that this will be the same both at the height, h , and at the outlet of the radiator. When we want to calculate the radiator return temperature (the temperature at height $h = 0$), we can therefore replace the term for the mass flow, mc , with an equation based on the excess radiator temperature, $T_m - T_a$, at some other height of the radiator, h_m . The calculation is shown in Eq. (9).

$$T_r = \frac{(T_m - T_a)^{(1-n)} - \frac{h_m}{H}(T_s - T_a)^{(1-n)}}{\left(1 - \frac{h_m}{H}\right)^{\frac{1}{1-n}}} + T_a, \quad (9)$$

where $T_m - T_a$ is the excess radiator temperature measured by the heat cost allocator at the thermal height h_m

As shown by Paulsen [39], the equations presented provide rather accurate estimates of heat output and radiator surface temperatures under test conditions where all input parameters are well-known and the heat output of the given radiator can be modelled depending on the flow. For conditions with very small flows, it may be difficult to provide accurate results, because the radiator might only be warm at the very top, which is not reflected by the surface temperature measured lower on the radiator. Nevertheless, such situations are not relevant to this study, because the main aim is to identify situations with high mass flows and high return temperatures.

2.2 Electronic heat cost allocators

Electronic heat cost allocators provide the possibility of distributing the total heating bill in a multifamily building in accordance with the actual heat consumption of each household. An electronic heat cost allocator is mounted on each heating body or terminal element to monitor the heat emitted from each heating source and make it possible to estimate the share of the heat used in each apartment as a percentage of the total heating.

The electronic heat cost allocators considered in this study were two-sensor devices that estimate the heat emissions from a radiator based on measurements of both the radiator surface temperature and the air temperature in the room. The heat cost allocators are tested and approved in accordance with the European norm EN 834 [40]. The heat cost allocator calculates the units of heat emitted from the radiator every 2 minutes by applying the instantaneously measured temperatures to Eq. (10), which can be viewed as a modified version of Eq. (4). To be able to use this equation, the heat cost allocator company estimates the nominal heating power of the radiator, for example, on the basis of old product catalogues. Furthermore, both the radiator exponent and the constant k are chosen as to ensure the best fit between the measured and calculated heat output for

the given type of heat cost allocator. These values therefore vary for different types of heat cost allocators. The units of heat emitted are summed for a given time-period, as shown in Eq. (11), before the information is transmitted via wireless connection.

$$R = Q_n k (T_m - T_a)^{n, meter}, \quad (10)$$

where R is the units of heat emitted; Q_n is the nominal heating power of the given radiator; k is a constant describing the relationship between the units of heat counted, the temperatures measured, and the heat output of the radiator; T_m is the radiator temperature measured by one sensor in the heat cost allocator; T_a is the air temperature measured by the second sensor in the heat cost allocator; and $n, meter$ is the radiator exponent for the given heat cost allocator.

$$R_x = \sum_x^0 Q_i, \quad (11)$$

where R_x is the heat emissions summarized over x minutes.

The constant k is estimated based on the basic heat count of the heat cost allocator R_B , which is the counted units of heat in certain basic temperature conditions, ΔT_B . These values were derived through tests, and the relationship between the values is shown in Eq. (12). The values are thus specific to the given heat cost allocator and the specific radiator.

$$R_B = Q_n k (\Delta T_B)^{n, meter}, \quad (12)$$

where R_B is the units of heat counted in the basic conditions and ΔT_B is the logarithmic mean temperature difference at the basic temperatures.

By relating the basic heat count of the radiator to the actual heat count measured for each time-period, we can calculate the excess temperature of a given radiator at a given time. The relationship between the two can be described by using Eq. (13), which can be viewed as a modified version of Eq. (5). Please note that this equation applies the effective radiator exponent n_2 . This exponent is applied to make up for the fact that the built-in sensor that measures the indoor air temperature is often affected by its close proximity to the heating sources, as Goettling also points out [25]. This can be compensated for by adding approximately 0.1 to the radiator exponent programmed in the heat cost allocator. If the heat cost allocator is connected to a remote air temperature sensor, however, the effective radiator exponent is equal to the radiator exponent coded in the given allocator ($n_2 = n, meter$).

$$T_m - T_a = (T_{mB} - T_{aB}) \left(\frac{R}{R_B} \right)^{\frac{1}{n_2}}, \quad (13)$$

where T_{mB} is the radiator temperature measured by the heat cost allocator in the basic conditions; T_{aB} is the air temperature measured by the heat cost allocator in the basic conditions; and n_2 is the effective radiator exponent.

All heat cost allocators should be certified in accordance with the European norm EN 834. The norm describes a number of specifications that heat cost allocators must meet, and these should be mentioned here. The first specification is the so-called “start of counting” value, which ensures that heating consumption is registered even in situations with small demands. The heat cost allocators we used account for heating consumption that occurs when the temperature difference between the sensors is as low as 3 °C. Temperature differences lower than this do not lead to high radiator return temperatures and high water mass flow rates, so this was sufficient for our purposes. Another specification is the counting rate when there is thermal impact, which is relevant if the air temperature measured is biased, e.g. when the heat cost allocator is covered or affected by direct sunlight. If such an event causes the indoor air temperature measured to increase suddenly, the heat cost allocator will switch to function as a one-sensor device where the indoor air temperature is assumed to be 20 °C.

2.3 Case study

The method proposed was investigated in a case study of an apartment building from 1905 located in Frederiksberg, Denmark. The building consists of eight apartments, each of approximately 160 m². The apartments are distributed over four floors including the attic space. Fig. 2 shows the floor plan of the case building. The construction consists of uninsulated brick walls, a concrete basement, and a tile roof with a low insulation level. Windows range from old single-pane windows to energy-efficient 2-pane glazing windows with gas filling. The building is equipped with a hydraulic radiator heating system connected to a central district heating substation located in the basement. While some occupants have installed modern panel radiators under the windows, others still rely on the original column radiators that are often located near internal walls. The location of the original radiators is indicated by the black oblongs in the floor plan in Fig. 2.

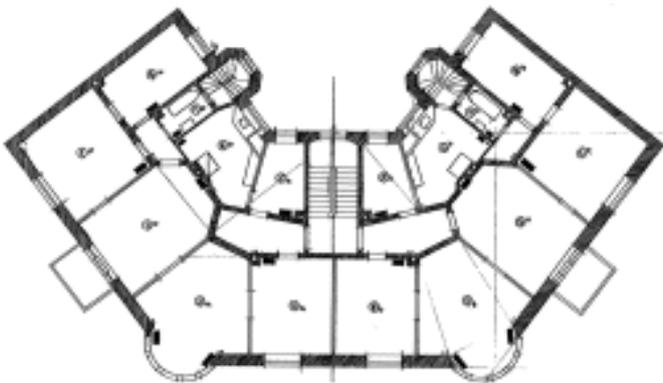


Fig. 2. Illustration of the floor plan in the case study apartment building

Eight radiators that represent different cases were investigated in this paper. Information about the radiators is shown in Table 1.

For these eight radiators, the heat emissions in units were collected from the heat cost allocator devices with an accuracy of 1 decimal place, approximately every 2–3 hours. The time interval varied slightly due to transmission problems on some occasions and was therefore quite a lot longer than 2 hours in some periods. From the measured units of heat emitted by each radiator, the radiator return temperatures were calculated, as described in Table 2.

Table 1. Description of the radiators analysed in the study

No.	Type	Size L x D x H [mm]	Average measured indoor temp. [°C]	Heating power [W] at 90/70/20
1	Plan	300 x 40 x 500	22.4	369
2	Panel	1100 x 57 x 545	18.4	1386
3	Column	12 elm x 220 x 1000	17.3	2441
4	Panel	1200 x 102 x 600	21.6	2592
5	Panel	1200 x 57 x 545	21.0	1512
6	Plan	1500 x 40 x 600	21.2	1845
7	Column	10 elm x 215 x 1000	20.1	1858
8	Column	16 elm x 215 x 1000	21.2	2973

Table 2. Description of the procedure followed for the calculation of return temperatures from each of the eight radiators

Step	Description	Parameters and assumptions
1	<p>The basic counting rate (R_B) was calculated for each radiator (Eq. (12))</p> $R_B = Q_n k (\Delta T_B)^{n_{meter}}$	<ul style="list-style-type: none"> • The Q_n of each radiator is shown in Table 1 and estimated by the heat cost allocation company • The constant k is known to the heat cost allocation company and is specific for the type of allocator • Brunata allocators are tested for a basic logarithmic mean temperature difference of 34.67 °C • Brunata allocators are coded with $n_{meter} = 1.33$
2	<p>The excess radiator temperature ($T_m - T_a$) for each radiator was calculated by using the counted units of heat per hour (R) for each x-minute time-period (Eq. (13)):</p> $T_m - T_a = (T_{mB} - T_{aB}) (R/R_B)^{1/n_2}$	<ul style="list-style-type: none"> • The excess temperature in the basic conditions ($T_{mB} - T_{aB}$) was (57 °C – 20 °C) for the Brunata allocators • Since Brunata heat cost allocators are compact two-sensor devices, the effective radiator exponent n_2 was assumed to be 1.43
3	<p>The calculated average excess radiator temperature ($T_m - T_a$) was added to Eq. (9) in order to calculate the radiator return temperature</p> $T_r = (((T_m - T_a)^{1-n} - (h_m/H)(T_s - T_a)^{1-n}) / (1 - h_m/H))^{1/(1-n)} + T_a$	<ul style="list-style-type: none"> • All heat cost allocators were located at a relative physical height h/H of 2/3 of the radiator height. The relative thermal height of the heat cost allocators h_m/H was therefore assumed to be 0.67 for column radiators and 10% higher (0.737) for panel radiators. • The supply temperature to the radiator (T_s) was assumed to be 60 °C. This was based on the temperature from the central heating substation, which averaged 60 °C, though in some periods it varied by as much as 10 °C • Indoor air temperature (T_a) in all rooms was assumed to be 21 °C • The radiator exponent (n) of all radiators was assumed to be 1.3

It should be noted that the time interval between transmissions of data collected and the number of decimal places included in the transmitted data were important parameters in the case study. Fig. 3 shows how the calculated return temperature varies in relation to the heating consumption of a small and a large radiator when the heating consumption is given with a resolution of 1 decimal place and data is transmitted once every two hours. As the figure shows, the limited number of decimal places in the current data may have had a small impact for large radiators where the variation in return temperature for a 0.1 unit variation was around 3 °C in the worst case. For a small radiator, however, a 0.1 unit variation can result in a difference of more than 10 °C in the calculated return temperature. To achieve the most reliable results, data must be transmitted frequently and should be given with the largest resolution possible. Frequent transmission of data is also important because Eq. (13) provides a time-weighted radiator temperature due to the nature of Eq. (11). This will make it difficult to identify heating system malfunctions that occur for limited periods of time, if the interval between the data transmissions becomes too long.

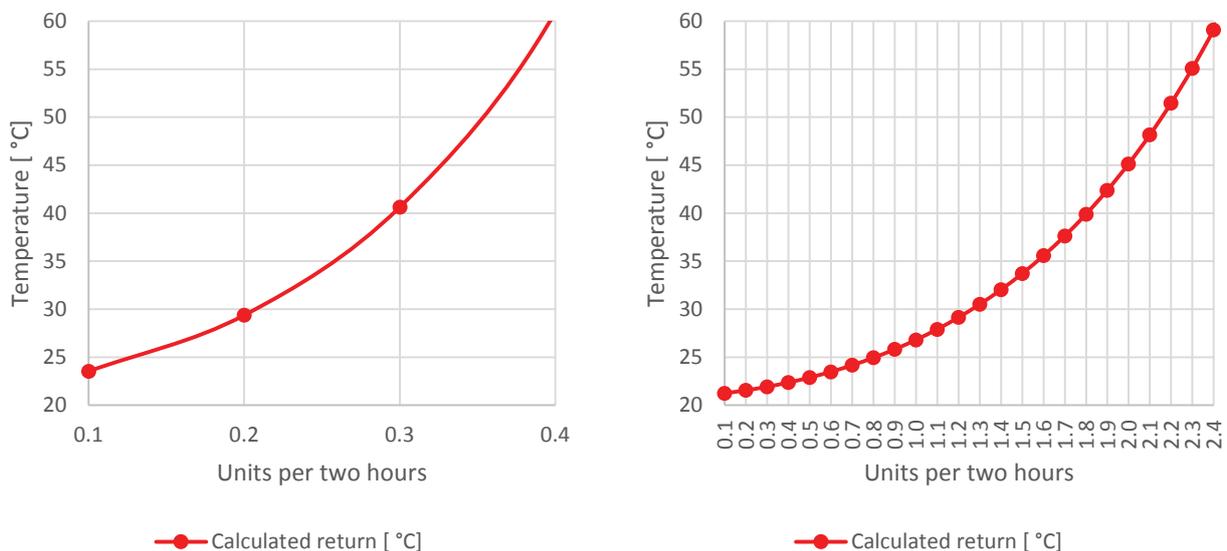


Fig. 3. The effect of the number of decimal places in the transmitted units of the calculated return temperatures for a small radiator (Radiator 1, left) and a large radiator (Radiator 8, right)

In addition to collecting the data from the heat cost allocators on the eight radiators, we also carried out two other types of measurement to investigate the accuracy of our proposed method:

- Radiator return temperatures were measured from all 8 radiators
- Indoor air temperatures were measured in the rooms where the radiators are located

Both measurements were conducted with Brunata Futura temperature loggers, which are identical to the heat cost allocators [41]. The loggers measuring radiator return temperatures were equipped with probes mounted on the radiator return pipes with a strip. It should be noted that this method will tend to underestimate the actual water temperature, because the temperature measurement is carried out on the outside of the pipe and the temperature probe will also be affected by the indoor air temperature. However, it was not possible to insert

measurement devices in the space-heating pipes. The indoor air temperature loggers were located on furniture at heights between 0.4m and 1.8m to provide an estimate of the indoor temperature in the operational zone. According to the manufacturer, the general logger accuracy is ± 0.5 °C. These measurements were carried out on an hourly basis, and transmitted via the same wireless network as used for the heat cost allocators.

All the data were collected over an approximately two-week measurement period in November 2016.

2.4 Investigation of uncertainty

Three main parameters were considered to be subject to some uncertainty and have major importance for the results. These were the estimated nominal heating output of the radiators, the assumed supply temperature to the radiators, and the assumed indoor air temperature in the rooms. The uncertainty of our proposed method was investigated by analysing how sensitive the resulting calculated radiator return temperatures were to changes in these input parameters. This investigation was carried out by showing the relationship between the measured units of heat and the calculated return temperature for Radiator 5, when the numerical value of the three input parameters were varied as shown in Table 3.

Table 3. Changes in input parameters for sensitivity analysis

Parameter	Low estimate	Assumed value	High estimate
Nominal heating power, Q_n	-10%	1512 W	+10%
Supply temperature, T_s	55 °C	60 °C	65 °C
Indoor air temperature, T_i	18 °C	21 °C	24 °C

3 Results and discussion

3.1 Comparison of measurements

Fig. 4 shows the comparison of the radiator return temperatures measured on the return pipe and calculated based on data from the heat cost allocators for Radiators 1 and 2. These radiators represent cases where there seems to be a mismatch between the calculated and measured values, either for a short time-period (Fig. 4, left), or for a longer time-period (Fig. 4, right). One possible explanation for these types of mismatch is that the temperature measured on the radiator return pipe did not always relate to the water flow through the radiator. Instead it was sometimes affected by high water temperatures in a nearby riser, which had a tendency to flow back into the radiators due to high flow situations, so that, in some cases, the radiator surface was cold although the temperature measured on the return pipe was high. This explanation is supported by the fact that sometimes the same unexplained high return temperatures were measured for several radiators connected to the same riser. An upside to this issue is that it underlines the possibility of using the proposed method to indicate the presence of short-circuits in the heating system: if the overall heating system temperature is high, and the calculations based on the heat cost allocators do not show problems in any of the radiators, there might be a short-circuit somewhere else in the heating system.

Some of the differences between the measured and calculated return temperatures shown in Fig. 4 may also be explained by the combination of frequent changes in radiator temperatures and a long time interval between two measurements from the heat cost allocator. This might explain the difference seen at the beginning of the measurement period for Radiator 2 (right). Frequent changes in temperature could occur due to a malfunctioning radiator valve, high pressure and hydraulic imbalance in the heating system, or sudden changes in the heat balance due to e.g. sunlight, changes in temperature set-point, or the opening of windows. Since the data from the heat cost allocators are summed over the given time-period, these peaks can be averaged out, resulting in a generally low radiator return temperature. Lastly, the measurements in Fig. 4 may also be an example of the fact that the proposed method is prone to some uncertainty that can make it difficult to identify all the problem radiators. For example, the proposed method might be unable to estimate a high return temperature if part of the radiator is clogged, if there is air in the radiator, or in cases where the heat cost allocator is no longer properly connected to the radiator surface for some reason. Moreover, it may not be possible to obtain accurate results if for some reason the actual radiator exponent and heat output for a radiator differs greatly from the estimate, and the method can be very inaccurate for radiators such as long convectors, where the water mass flow is horizontal rather than vertical.

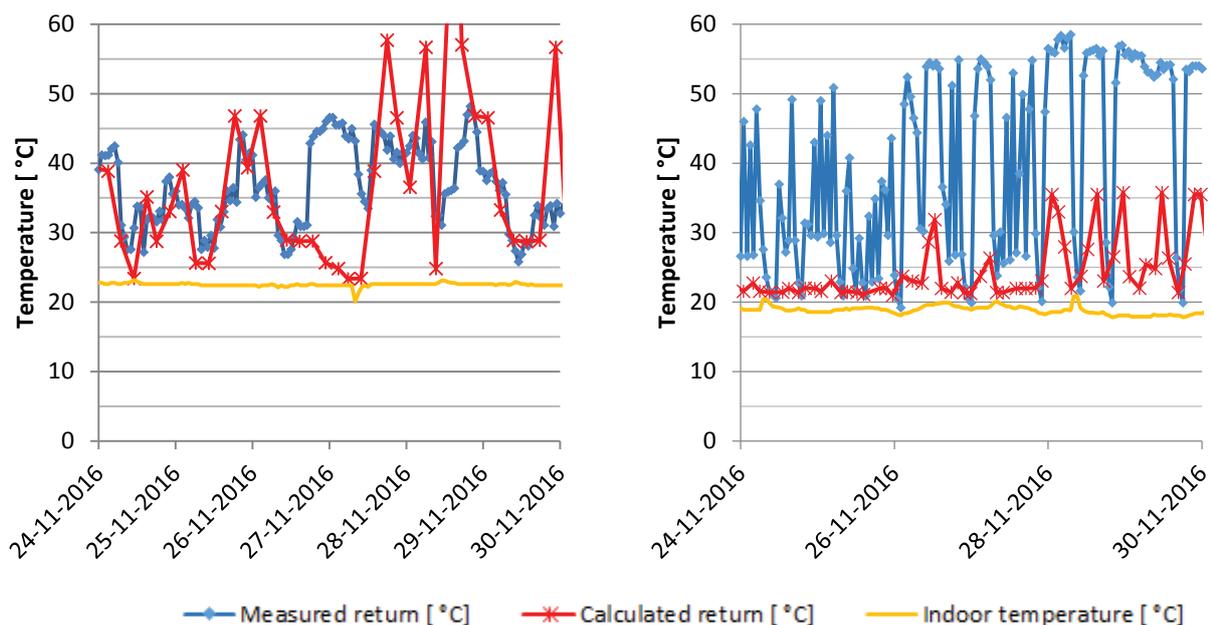


Fig. 4. Comparison of the calculated and measured return temperatures for Radiators 1 (left) and 2 (right) showing cases with poor correspondence

Fig. 5 shows the comparison between the measured and calculated return temperatures for Radiators 3 and 4. These radiators show examples of working conditions that might be difficult to monitor using the proposed method, due to the frequent fluctuations in temperatures. For Radiator 3 (left), an additional problematic condition is the indoor air temperature, which is almost 4 °C below the assumed 21 °C, which might partly explain why the calculated return temperature is often higher than the measured return temperature. The figure shows

that the proposed method can capture some of the changes in temperature, although not all peaks show with the same magnitude. However, the pattern of the calculated return temperatures would reveal that there might be some special conditions causing sudden peaks in the return temperature, which could be problematic for the hydraulic balance of the heating system or cause a high overall return temperature in the heating system. These peaks could occur due to the use of temperature set-back in some rooms.

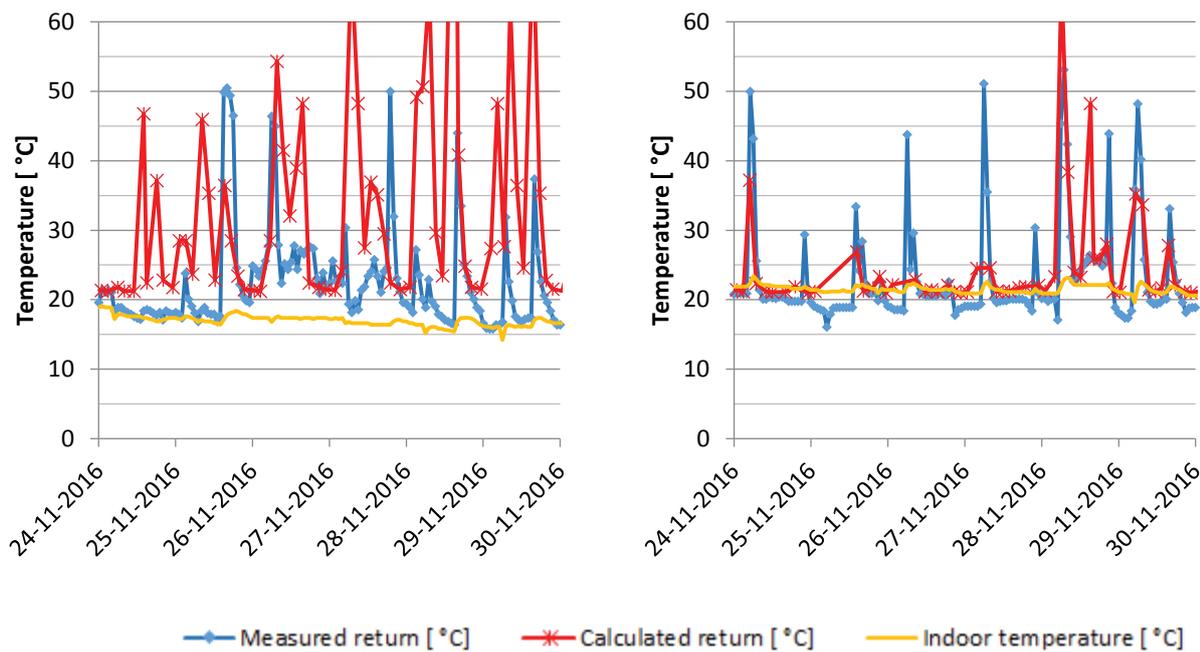


Fig. 5. Comparison of the calculated and measured return temperatures for Radiators 3 (left) and 4 (right) showing cases with difficult conditions

Fig. 6 shows the comparison between the measured and calculated return temperatures for Radiators 5 (left) and 6 (right). The figure shows examples where the radiators have steady operation conditions for long periods of time, and where the proposed method provides a clear picture of the heating system operation. As the figure shows, the proposed method was able to identify the major malfunction that led to a continuously high return temperature from Radiator 5 (left), which occurred because the thermostat was not mounted properly on the radiator valve. Furthermore, as Fig. 6 (right) shows, the method was also able to identify several cases where the radiators worked well and ensured a low radiator return temperature.

In many cases, the calculated radiator return temperatures corresponded well with the measured temperatures, as Fig. 7 shows, where the method proves able to illustrate the variation in the return temperature over time for Radiators 7 and 8. The proposed method was thereby found to provide a useful tool in many cases for an overview of the actual operation of the heating system and the use of each individual radiator. However, as shown in the figure, the exact temperatures do not match completely, and there is often a difference of up to 5 °C between the calculated and the measured return temperatures.

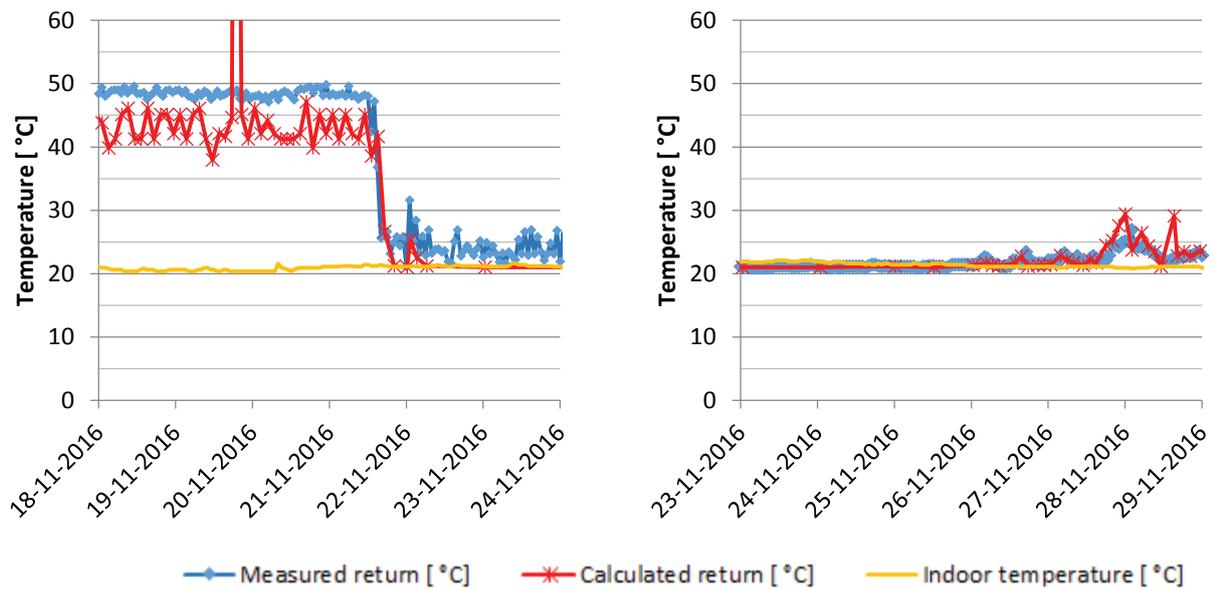


Fig. 6. Comparison of the calculated and measured return temperatures for Radiators 5 (left) and 6 (right) showing cases with good correspondence

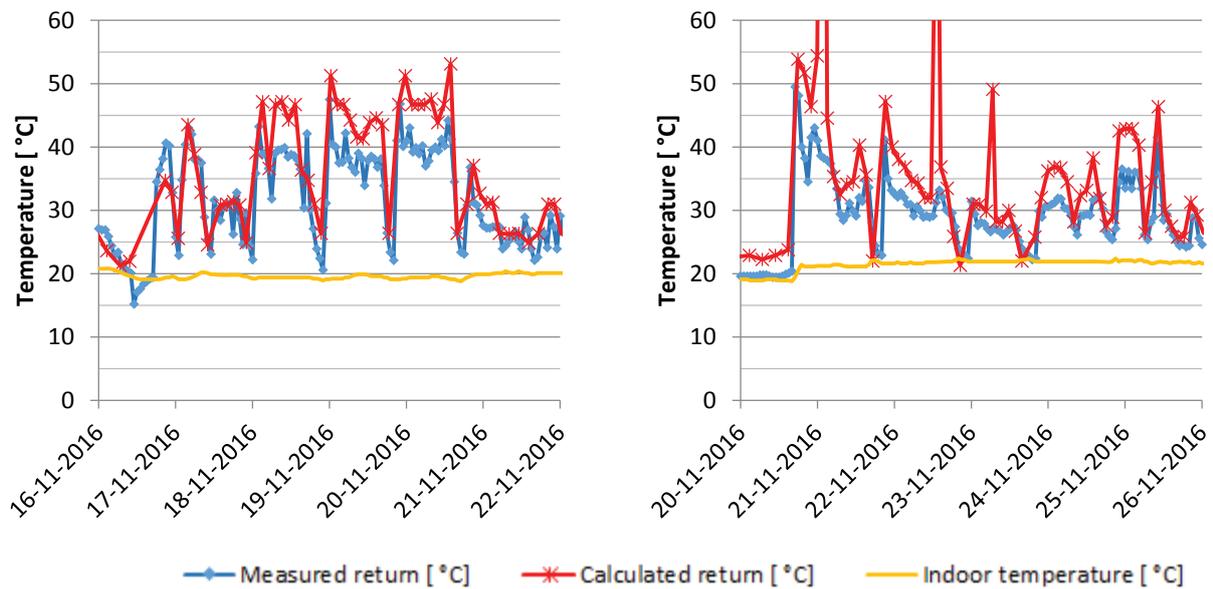


Fig. 7. Comparison of the calculated and measured return temperatures for Radiators 7 and 8 showing cases with good correspondence

The results indicate that the current method makes it possible to get a good indication of how the heating system is operating and identify some of the radiators that are poorly controlled. However, the differences between

measured and calculated return temperatures for some radiators, such as Radiators 1 and 2 in Fig. 4, the method needs further testing and development to ensure that it will succeed in identifying all the problem radiators.

3.2 Measurement uncertainty

Fig. 8 shows the relationship between the number of units of heat registered in a time-period of two hours and the calculated return temperature when the nominal heating power of the radiator is varied by $\pm 10\%$ (based on an example from Radiator 3). As the figure shows, the calculated return temperature is very sensitive to changes in the nominal heating power, especially for high return temperatures, which is the main focus of the proposed method. The calculated return temperature can vary by more than $7\text{ }^{\circ}\text{C}$ for a change in the estimated nominal heating power of the radiator of $\pm 10\%$.

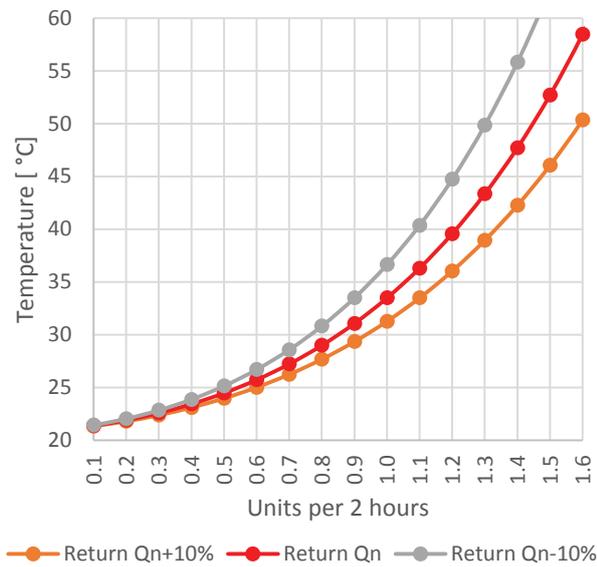


Fig. 8. Relationship between the units of heat counted and the calculated return temperature with a variation of $\pm 10\%$ in the nominal heating power (example from Radiator 3)

Fig. 9 and Fig. 10 show how the assumed supply temperature and indoor air temperature affect the calculated radiator return temperature. As the figures show, a $5\text{ }^{\circ}\text{C}$ variation in the supply temperature results in a change in the estimated return temperature of more than $10\text{ }^{\circ}\text{C}$ in the worst cases, while a $3\text{ }^{\circ}\text{C}$ variation in the assumed indoor air temperature results in a difference of as much as $7\text{ }^{\circ}\text{C}$ in the estimated return temperature.

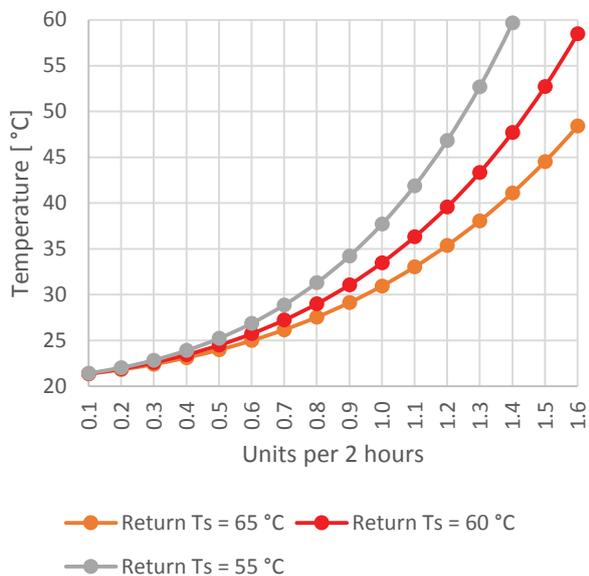


Fig. 9. Relationship between the units of heat counted and the calculated return temperature with a variation of ± 5 °C in the supply temperature (example from Radiator 3)

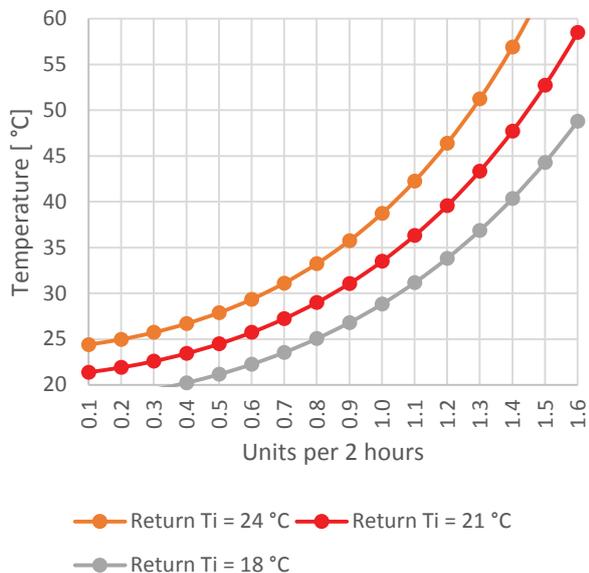


Fig. 10. Relationship between the units of heat counted and the calculated return temperature with a variation of ± 3 °C in the indoor air temperature (example from Radiator 3)

The analysis of uncertainty shows that the estimation of the nominal radiator heating power and assumptions made with regard to indoor air temperature and heating system supply temperature have a large impact on the calculated radiator return temperatures. To achieve the best possible results, these uncertainties need to be

reduced through the further development of the method. Firstly, the uncertainty related to the assumed heating system supply temperature can be greatly reduced by measuring the supply temperature on the heating system riser closest to the radiators. These extra measurements would increase the accuracy of the proposed method at very little extra cost. Secondly, the uncertainty with regard to the indoor air temperature could be reduced if the actual sensor measurements could be transmitted along with the calculated units of heat emitted. This would also reduce the uncertainties related to the backtracing of the radiator surface temperature by using the equations presented.

But even with these measures it would not be possible to remove the uncertainties completely, and it is especially difficult to get around the uncertainty in the estimation of the radiator heat output. Instead, the monitoring system could be adjusted to the individual buildings, through the continuous use of the measurements and the detection of faults. For example, one might adjust the calculations for a given radiator if the method estimates a continuously high return temperature that is not identified in the subsequent service checks.

4 Conclusions

The current study presents a first investigation of the possibility of using data from heat cost allocators to monitor heating system operations and identify malfunctions in the operation of radiators. The results indicate that it is possible to provide an indication of faults in specific radiators that lead to high return temperatures and excessive mass flow. The proposed method might also provide new insights into the operation of radiators, because it makes it possible to visualize the changes in heating system temperatures over time. However, the results are very sensitive to assumptions and inputs to the calculations, and in our research we also identified cases where the calculated radiator temperatures did not correspond to those expected. So the basic methods described in this paper need further testing and development. Nevertheless, the proposed method could have a huge potential for improving heating system efficiency, which is crucial if we are to reduce energy consumption in buildings and enable the use of low-temperature heating. Furthermore, the method could be developed to provide automatic fault detection in heating systems or be applied to identify the radiators that contribute most to the overall heating system return temperature.

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VIII

The costs and benefits of preparing existing Danish buildings for low-temperature district heating

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Abstract

This paper aims to provide an overview of the costs and benefits of preparing existing space heating systems for low-temperature district heating. The costs were estimated on the basis of previous work carried out on the topic, which included the evaluation of current heating element dimensions, current heating system control, and the methods available to identify and correct heating system malfunctions. The costs identified were compared with the savings achieved in the energy system if low-temperature district heating is implemented and the savings achieved by the district heating customers investing in improved heating system control. The investigations resulted in simple pay-back times of 1.2–4.3 years from an energy system perspective and 0.2–9.4 years for the individual district heating customer. The current study thus indicates that it is economically feasible to invest in improved heating system control to enable a reduction in the district heating return temperatures.

Keywords: 4th generation district heating; space heating; radiators; heating system control; low-temperature heating

1. Introduction

Low-temperature district heating is a promising solution for energy efficiency improvements in the future heating sector. This is because the efficiency of many renewable heat sources, such as heat pumps, solar heating, geothermal heating, and biomass boilers with flue gas condensation, is greatly increased if temperatures are lowered [1]. Furthermore, a reduction in district heating temperatures will reduce the heat losses from the district heating network. For these reasons low-temperature district heating can potentially play an important role in the future European energy system [2].

Low-temperature district heating can be implemented in new areas with low-energy buildings [3–6], or through a transition to lower temperatures in a current system with existing buildings [5–9]. Since existing buildings make up the majority of the building stock, the main challenge is to reduce the temperatures in the existing networks. In this case, it is necessary to reduce both supply and return temperatures equally, to meet the hydraulic limitations of the existing district heating pipes. Focus should therefore be put on a reduction in the return temperature as well as a reduction in the supply temperature.

A reduction of the district heating return temperatures would be beneficial even today. The current energy system is largely based on condensing biomass or gas boilers and waste incineration, and a reduction in the district heating return temperature makes it possible to extract a greater amount of heat from these energy plants [10]. Moreover, a reduction in return temperatures also reduces the heat losses from network pipes and increases the capacity of the network, which can allow expansion to new customers or reduce pumping costs [11]. The savings achieved from a reduced return temperature differ greatly depending on the heat

source in question [12] and can be determined in many different ways, taking into account for example the possibility of expanding the district heating network to new customers or avoiding the replacement of the current pipes [11]. Frederiksen & Werner [10] present an illustration of the savings expected in 27 Swedish district heating companies, showing average savings in the order of EUR 0.15 per MWh °C, but ranging everywhere from EUR 0.03 to 0.38 per MWh °C.

When the return temperature has been reduced, it is possible to reduce the supply temperature by a corresponding amount. This is especially important in the long run, where heat pumps and solar heating are expected to deliver a larger amount of heating. If the district heating temperatures can be reduced from 80 °C/45 °C to 55 °C/25 °C, the COP of a heat pump based on industrial waste can increase from 4.2 to 7.1. Similarly the cost of solar thermal will decrease by around 30% due to the increased efficiency of solar panels [13]. The optimal temperature level in a district heating network therefore depends on the available heat sources, and they can be further affected by other individual parameters, such as the heat loads in the system and the age of the existing district heating pipes [14]. On this note, Ommen et al. [15] recommended optimal supply temperatures in the Copenhagen area of around 65–70 °C, while other studies have shown that ultra-low-temperature district heating can be a feasible solution in small district heating networks with a low heat density [16]. On a general level, however, Lund et al. [17] showed the feasibility of reducing Danish district heating supply and return temperatures to an average of 55 °C/25 °C, and current estimates show that, if such a temperature reduction is implemented in the Danish district heating systems, this will generate an annual saving of EUR 10 per MWh of district heating produced [13].

To a large extent, the reduction in both supply and return temperatures is dependent on the components installed in the buildings. For example, current heating systems were designed for supply and return temperatures as high as 90 °C/70 °C [18,19], and it must be ensured that these heating systems can cover the heat demand of the buildings at lower temperatures, before the district heating supply temperature is reduced. The district heating return temperature is generally dependent on the design and control of the in-house installations [14,20], and if the in-house installations do not work properly, this can easily lead to higher district heating return temperatures than necessary. Again, this can make it difficult to reduce the supply temperature, because there must be a certain cooling of the district heating water for the right amount of heat to be delivered within the hydraulic capacities of the district heating pipes. To be able to implement low-temperature district heating, it is therefore necessary to prepare the heating installations in existing buildings for low-temperature heating. In this paper, we aim to estimate the costs of this preparation by combining the results of previous findings on this topic. This is necessary because the costs consist of many different strands that should all be taken into consideration. Through the summaries provided in this paper it is thereby possible to combine these strands to provide a new overview of the overall feasibility of improving existing space heating systems to implement low-temperature district heating.

1.1 Aim of study

The aim of this study was to evaluate the cost of the improvements needed to enable current space heating systems in existing buildings to make the transition to low-temperature district heating by 2050. The evaluation was carried out by combining and discussing the results of four years of research carried out on Danish heating systems. These results consist of an evaluation of the dimensions of current heating elements, an investigation of the need for improvements in heating system control, and an investigation of the tools available to carry out the transition towards lower temperatures. In this paper, we combined these results

to draw conclusions about the cost of preparing existing buildings for low-temperature space heating. The economic feasibility of improving the space heating systems was evaluated both from the perspective of the district heating customer and from the perspective of the overall energy system in order to provide input to the evaluation of the feasibility of implementing low-temperature district heating in existing building areas.

2. Input to economic analysis

Three different aspects of the space heating systems of existing buildings were evaluated through reference to earlier publications in order to assess the improvements needed to prepare existing buildings for low-temperature space heating:

1. Dimensions of current heating elements
2. Control of current heating systems
3. Methods to support the transition

The following three sections refer to the studies that were included in the evaluation of each of these aspects and describe the overall results that were used as input to the economic evaluation.

2.1 Dimensions of current heating elements

The potential for heating a building with low-temperature district heating generally depends on the relationship between the heat output of the heating elements installed and the heat loss of the building. We therefore investigated the heating system dimensions and heat demand in a number of Danish houses in order to estimate the potential for reducing the heating system temperatures [19,21–23]. In these studies, we investigated the heating system dimensions in existing buildings with regard to the design conditions. This made it possible to provide a simple reference for the heating system dimensions and compare heating systems installed in a large number of buildings irrespective of the original design heating system temperatures and the individual energy renovations carried out. Design conditions in Denmark are described in DS 418 [24] and are based on a design outdoor temperature of $-12\text{ }^{\circ}\text{C}$, and a design indoor temperature of $20\text{ }^{\circ}\text{C}$. No heat gains are included when the heat losses from the building are calculated. Design heating system supply and return temperatures have varied throughout the 1900s, from $90\text{ }^{\circ}\text{C}/70\text{ }^{\circ}\text{C}$ at the beginning of the 1900s, to $70\text{ }^{\circ}\text{C}/40\text{ }^{\circ}\text{C}$ in recent building regulations, and $60\text{ }^{\circ}\text{C}/40\text{ }^{\circ}\text{C}$ in the current building regulations [19].

In these studies, the relationship between the heat output of the heating elements and the heat loss of the buildings in the design conditions was given by a factor, which was denoted the radiator factor, and defined as follows: *the radiator factor describes the relationship between the design heat output of the heating elements with supply and return temperatures of $70\text{ }^{\circ}\text{C}/40\text{ }^{\circ}\text{C}$ and the current design heat loss of the building.*

Fig. 1 summarizes the results on radiator dimensions in existing houses [19,21–23]. The blue bar represents the radiator factors estimated for Danish single-family houses in different stages of energy renovation, as described in our theoretical study [19]. The lower limit of the bar represents a situation where the only energy renovations included are the installation of thermo-windows in houses from before 1950 and a minimum insulation level of 50 mm under all the roofs of the houses. The upper limit of the bar represents a case where all windows have been replaced with new double-glazing low-energy windows, all roof constructions

included 100–200mm of insulation, and all cavity walls and floors over unheated basements were equipped with 60mm and 100mm insulation respectively. The boxes and whiskers represent the results of an analysis of 1645 Danish houses [23]. The box marks the range of the radiator factors in 25–75% of the houses analysed, while the top and bottom whiskers represent the top 5% and bottom 5% of radiator factors respectively. Finally, the red crosses indicate the radiator factors of houses in specific case studies [21,22].

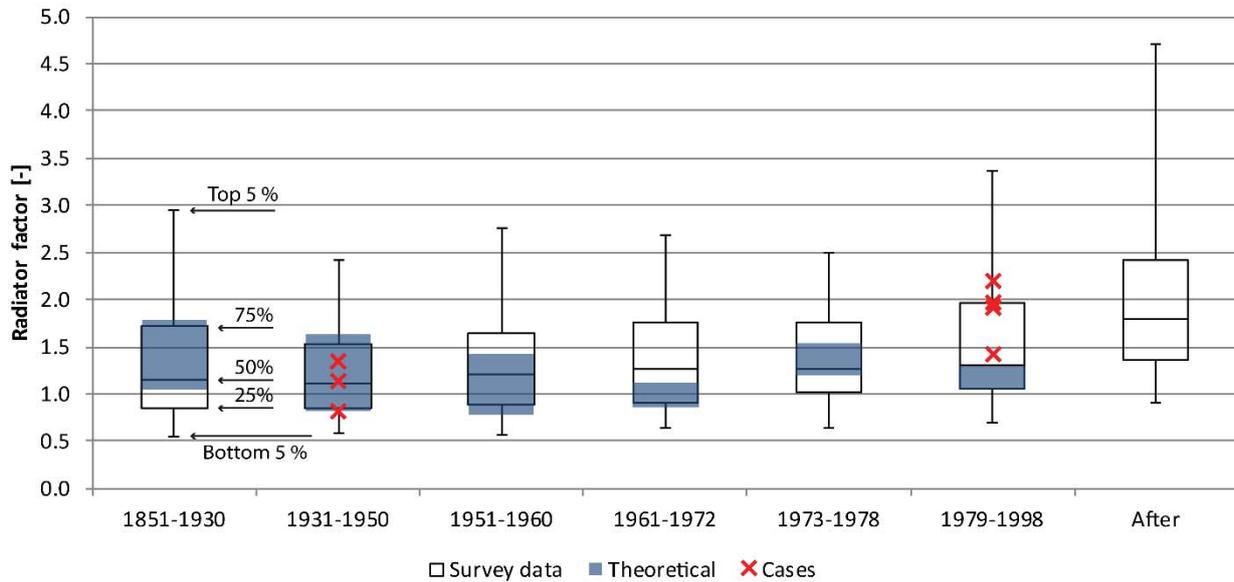


Fig. 1. Radiator factors of houses investigated in four studies on heating system dimensions [19,21–23]

The figure shows that the majority of existing heating systems are over-dimensioned relative to the current heat loss of the buildings with heating system temperatures of 70 °C/40 °C, because most heating systems have a radiator factor above 1.0. The blue bars show that the radiator factors will generally be between 1.2–1.7 if existing houses are assumed to go through reasonable energy renovations in the years between now and 2050. This was also found in the investigation of the 1645 Danish houses, where it was estimated that only 8% of existing houses will have heating systems with a radiator factor below 1.0 if the buildings are renovated to have a maximum design heat demand of 60 W/m², which corresponds to a heat demand of approximately 125 kWh/m² per year [23]. If the heating system is dimensioned properly in accordance with the design temperatures of 70 °C/40 °C, it is possible to use much lower temperatures during most of the year, because heat gains reduce the demand for additional heating, and actual outdoor temperatures are generally far above –12 °C [19,23]. However, even if some heating systems have a radiator factor below one, this will not necessarily cause great problems, because it will mainly lead to increased return temperatures from these houses. Furthermore, even when the heating elements in a building have an average radiator factor below one, this does not mean that all the radiators need to be replaced to bring the heating system up to date. The studies estimated that, to ensure that the preferred occupant comfort is maintained while heating system temperatures are kept low, it is only relevant to replace up to 40% of the radiators in houses with under-dimensioned heating systems [21].

These findings indicate that it is not necessary to invest a large amount of money in the replacement of existing heating elements to prepare existing heating systems for low-temperature district heating in 2050. This result is supported by several other studies that have shown that components in existing heating systems

are often over-dimensioned [7,25–28], so that it may only be necessary to replace a few radiators in the 8% of buildings that it is estimated will still have under-dimensioned heating systems even when energy renovations have been carried out in the years to come. In these buildings, it is therefore assumed that 40% of the radiators will be critical and need to be replaced. This means that only some 3% of existing radiators will need to be replaced.

2.2 Heating system control

The evaluation of the need to improve current heating system design and control to ensure that existing heating systems can operate properly with low-temperature supply was conducted with reference to three studies [21,22,29]. These studies investigated the heating system control and design in nine existing Danish single-family houses through measurements of the overall heating system supply and return temperatures, with more detailed measurements of the return temperatures from radiators in some of the houses. The overall heating system measurements revealed that heating system temperatures were already low in six of the houses investigated [22,29]. Fig. 2 shows the heating system temperatures measured in two of these houses, which were successfully heated with average heating system supply and return temperatures as low as 45 °C/30 °C. These houses therefore had no need for improved heating system control to be able to provide the necessary space heating with low-temperature district heating.

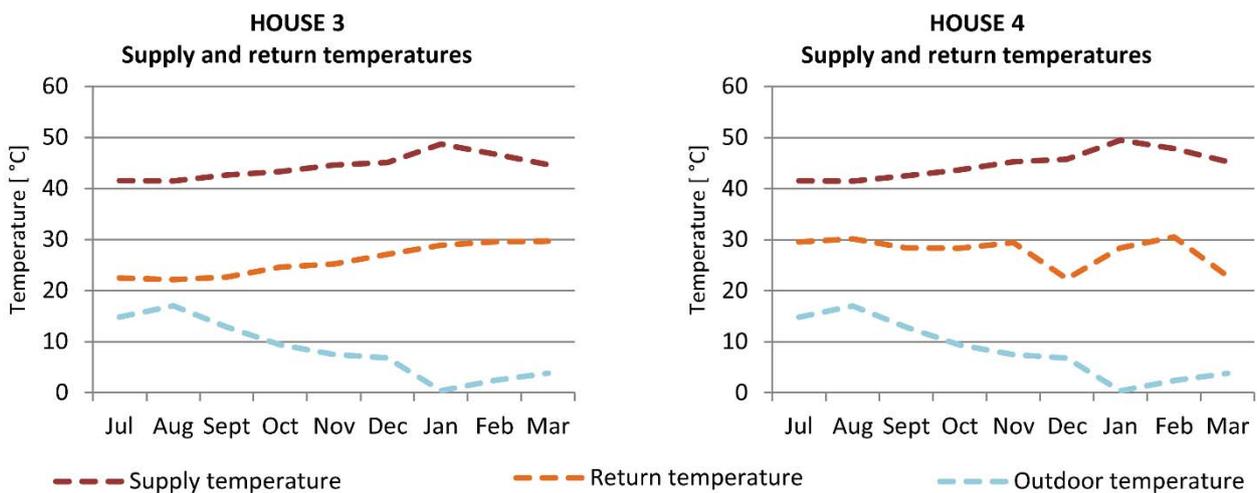


Fig. 2. Heating system temperatures measured in two single-family houses from the 1980s [22]

In the remaining three houses, we found that heating system design and control was a barrier to reducing heating system temperatures. The radiator return temperatures indicated that it was mainly the high return temperatures of just a few radiators that caused the high overall heating system return temperature [29]. The result is illustrated in Fig. 3, which shows the average measurements of heating system return temperatures in two of the houses investigated. The colour codes indicate whether the average measured return temperatures are high (red) or low (blue), which shows that three radiators in House 2 have high radiator return temperatures that seem to contribute greatly to the high overall return temperature.

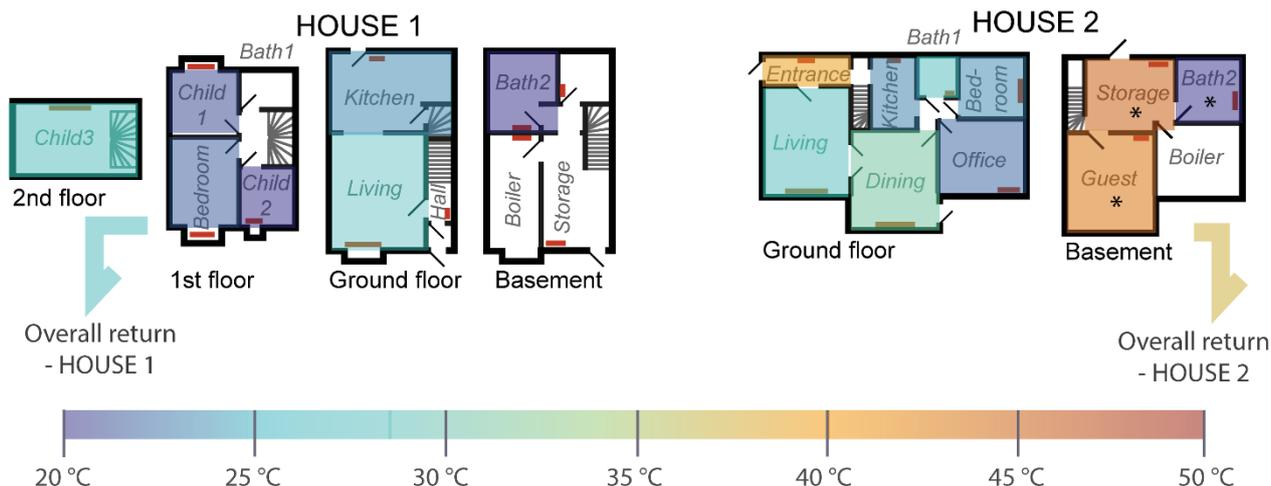


Fig. 3. Measured return temperatures in radiators and overall heating system in two houses from the 1930s [29]

The results indicate that the main problem with current heating system control is poor hydraulic control in the heating systems, which leads to excess water flows and high return temperatures in some radiators. These problems may be due to the relationship between pump operation, radiator valves, and control of thermostats. Other studies have similarly shown how these control components can have a large influence on both heating system temperatures, occupant thermal comfort, and energy consumption for heating [30–32]. Where issues with high return temperatures are identified, therefore, the main action required to ensure proper heating system control in existing buildings seems to be improving the hydraulic control of the heating system.

There are various tools available to improve heating system control. First the right pump should be installed, and thermostats should be installed to control the water mass flow through each heating element. For the thermostat to work properly, the correct valve needs to be installed. However, since it can be difficult to ensure efficient and robust correction of heating system faults using available components, we further suggested the development of two new tools to improve heating system control. The first suggestion was the development of a new electronic thermostat with an added return temperature sensor. The thermostat should be able to limit the water mass flow through the valve based on both the indoor temperature set-point and a maximum radiator return temperature. This would prevent unnecessary excess water mass flows through the radiator. The second suggestion was the development of a new pump control system that would ensure that the pressure in the heating system matches the actual heat load situation in the building. This would avoid high pressure leading to extreme excess water flows through some heating system components. These two components were evaluated as potential alternative tools for improving heating system control in the future.

Based on the results, we estimated that, while all buildings would benefit from an improved pump control system to ensure the robust operation of the heating system, a further 40% of existing buildings need improved heating system control to ensure low district heating return temperatures. This is a rather high estimate considering the results, in which improved heating system control was only needed for some of the heating elements in 3 out of 9 houses. However, we chose 40% in an attempt to make a realistic worst-case estimate, which allows for situations that may occur in other types of buildings than those included in this study.

2.3 Ways to support the transition

Malfunctions occur continuously in heating installations, and occupants do not always notice or make efforts to correct them. It is, therefore, necessary for technicians to monitor the operation of district heating substations and heating systems to provide this service and ensure continuous efficient operation. We investigated ways of providing such service in two studies: a case study of a method used by the Danish district heating company in Middelfart [6] and the evaluation of a new method of monitoring heating system operation in apartment buildings [33]. Both methods provided promising results.

The first investigation was based on an evaluation of work carried out by Middelfart district heating, where a service technician was hired to monitor data from customer substations transmitted at frequent intervals through a wireless connection. Customers with high return temperatures and customers with sudden changes in their heating consumption were contacted by the service technician, who made the customer aware of the issue and offered a service check of the heating installations. The service technician solved any problems identified in relation to the settings of the current installations and advised that a plumber should fix problems identified in relation to inadequate installations. The method is quite well-known and has been applied by several district heating companies. In Middelfart, the method was combined with the identification and elimination of unnecessary by-passes in the district heating network and the implementation of automatic temperature optimization in the district heating system. As shown in Fig. 4, these actions had a large impact on the temperatures in the district heating system.

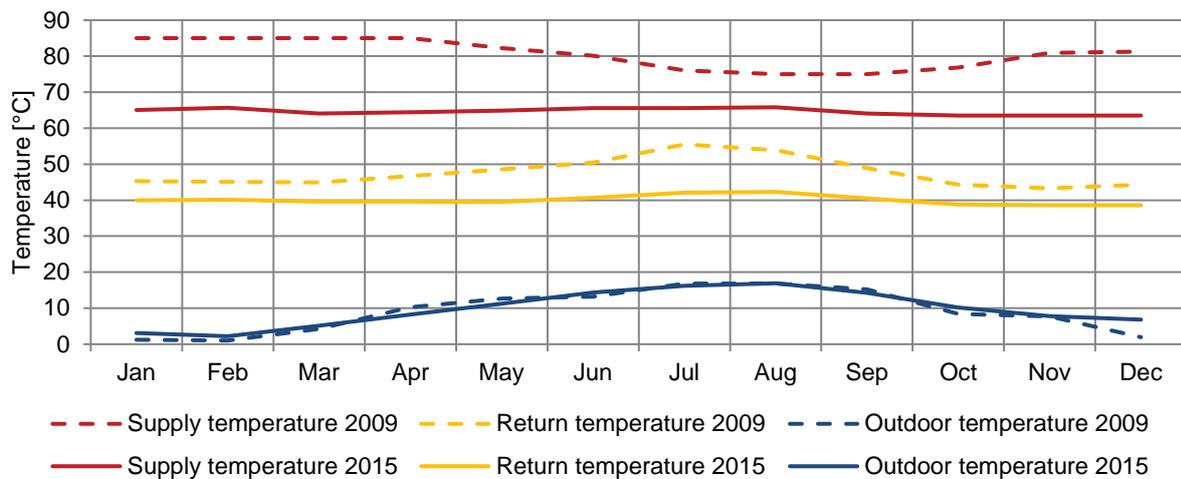


Fig. 4. Temperatures measured in the district heating network in Middelfart in 2009 and 2015 [6]

The second method is for heating systems in apartment buildings and is only in the development phase. A lot of malfunctions can occur in the operation of an internal heating system, but they are especially difficult to identify in apartment buildings, where it is difficult to monitor heating system operation in individual apartments with their individual occupants. A method was therefore suggested for monitoring heating system operation by using data from the heat cost allocators usually installed on all heating elements to meet the new Energy Efficiency Directive [34]. The method shows that information about the number of consumed units registered for each heating element can be used to estimate the return temperature of the heating element and thereby evaluate whether the return temperature is so high that it indicates a malfunction in the heating system control [33]. Data from electronic heat cost allocators are transmitted via wireless

connections at frequent intervals and the method requires very little additional equipment, which means it is inexpensive. The results from our evaluation were promising, so we assume the method can be further developed to provide a tool for identifying malfunctions in the operation of the terminal elements of a heating system. This type of monitoring should be combined with manual inspections of the heating systems aimed at identifying and eliminating hydraulic short-circuits in the internal building installations.

Both these tools would be inexpensive and require very few man-hours to apply once the heating system control system has been brought up to date. Furthermore, even though these tools are essential for the implementation of low-temperature district heating, their cost should not be attributed to the implementation of lower district heating temperatures, but rather to the general cost of maintenance that is relevant for any kind of heat source. We anticipate that the motivation to maintain the heating system will come from the desire to maintain the thermal comfort consumers want and avoid excessive energy consumption costs. Therefore, the cost of maintenance is not included in the analysis and neither is the economic savings that might be achieved due to improved thermal comfort of customers and reduced energy consumption in the individual buildings.

3. Costs

We carried out an economic analysis of the feasibility of implementing low-temperature district heating based on the actions identified as necessary to bring heating systems up to date. The analysis was carried out both from the perspective of the district heating customer and from the perspective of the overall energy system, as described in the following.

3.1 Overall framework

We assumed that the transition in the temperature levels in the district heating networks and the improvements in building installations will take place over a long time-frame between now and 2050. In such a lengthy time period, many of the installations will be replaced at the end of their lifetimes, so that in these cases at least the improvements will incur very little extra expenditure. Furthermore, there will also be improvements in the insulation level of the district heating network and energy savings in the building stock.

The analysis starts from the temperatures defined for 4th generation district heating in Denmark [13], which means that we assumed that by 2050 the average annual energy-weighted district heating temperatures will be reduced from the current 80 °C/45 °C to 55 °C/25 °C.

The costs of improved heating system control were based on a standard definition of a single-family house and an apartment building as shown in Table 1. The single-family house is assumed to have an annual heat consumption for space heating of 15 MWh and the heated floor area is assumed to be 150 m² with ten radiators. The apartment building is assumed to have an annual heat consumption for space heating of 183 MWh with 130 radiators in a total heated area of 2000 m². The heat loss in the district heating network is assumed to be 19% [13], so the heat production required to satisfy these heat demands is assumed to be 17.9 MWh and 217.8 MWh respectively.

Table 1. Definition of standard building typologies

	Heat demand [kWh/m ²]	Heat demand [MWh/year]	Heat demand incl. heat loss [MWh/year]	Heated floor area [m ²]	Number of radiators [no.]
Single-family house	100	15	17.9	150	10
Apartment building	91.5	183	217.8	2000	130

3.2 Costs of improving heating system control

The costs of the various actions identified in the study were estimated based on a combination of communication with sector representatives and data on average prices from Danish construction projects given in Molio price data [35]. The total cost of each action consists of the cost of materials and of the working hours that would be spent on the installation of the component, as shown in Table 2. The cost of one working hour was assumed to be EUR 70. For the two new products that we suggested should be developed, the costs were estimated as follows: we assumed that the new return temperature thermostat would be priced only slightly higher than current electronic thermostats and that the improved pump control could be implemented by a craftsman with 3 hours of work in a single-family house and 8 hours of work in an apartment building. All prices include VAT.

Table 2. Costs of various improvements to heating system control

	Single-family house			Apartment building		
	Work [hours]	Cost of materials [EUR]	Total [EUR]	Work [hours]	Cost of materials [EUR]	Total [EUR]
Pump	2	200	340	4	530	810
Radiator valve	0.5	30	65	0.25	30	47.5
Radiator	1.5	400	505	1.2	400	484
Improved pump control	3	-	210	8	-	560
Return temperature thermostat	0.15	48	58.5	0.15	48	58.5

To make it possible to compare the costs with the savings in the district heating system, we converted them to a cost per MWh of heat production with reference to the standard buildings defined in Table 2. For example, the cost of installing new valves in an apartment building was calculated by multiplying the cost of a new valve by the number of valves in the standard apartment building and dividing this number by the total heat demand in the building:

$$\frac{47.5 \text{ Euro/valve} \cdot 130 \text{ valves}}{217.8 \text{ MWh}} = 28.4 \text{ Euro/MWh}$$

The cost of each action in EUR/MWh is shown in Table 3.

Table 3. Costs of various improvements to heating system control per MWh of heat produced

Costs EUR/MWh	Single-family house	Apartment building
Pump	19.0	3.7
Radiator valve	36.4	28.4
Radiator	282.9	288.9
Improved pump control	11.8	2.6
Return temperature thermostat	32.8	34.9

Most of the actions for heating system improvements lead to benefits additional to the reduced district heating temperatures. These benefits include both energy savings and fewer occupant complaints, which could add up to savings in the order of 15% of the energy consumption or EUR 1300 per year due to less time spent on complaints, as Trüschel points out [30]. Another benefit is reduced electricity consumption from the installation of new energy-efficient pumps. This can add up to an annual saving of EUR 50 in a Danish single-family house where the cost of electricity is about EUR 0.26 per kWh and a 40W pump is replaced by a new 5W pump. Furthermore, the increased comfort of occupants is also an additional benefit that can be difficult to quantify, like the reduction in complaints. These types of savings were not included in the analysis, but we assume that they will provide an incentive for the general maintenance and improvement of current heating system control, which will therefore reduce the number of improvements needed for the introduction of low-temperature district heating.

3.3 Costs and benefits for the district heating consumer

Some customers especially need to improve their heating installations to make it possible to reduce the district heating supply and return temperatures. We compared the investment for these improvements with the savings that these customers will receive when they reduce their return temperatures if their local district heating company is one of several in Denmark which have introduced return temperature tariffs. Two examples of such temperature tariffs were included in the current analysis – one introduced in the Copenhagen area and the other in Høje Taastrup, just west of Copenhagen. In Copenhagen the customer pays an extra tariff if the average annual cooling of the district heating water is less than 27 °C, while they receive a discount if it is more than 37 °C. With an average annual supply temperature of 80 °C, these temperatures correspond to average annual return temperatures of 53 °C and 43 °C respectively. Both tariff and discount are rated at EUR 0.72 per °C per MWh heat consumed. In Høje Taastrup, the consumers receive a discount or have to pay a tariff if their average annual return temperature is below or above 46 °C, respectively. Both tariff and discount are rated at EUR 1.28 per °C per MWh heat consumed. The tariffs are based on the expected savings in the district heating systems due to the return temperature reductions. These savings include reduced heat losses, increased energy efficiency in heat production, and the benefit of additional capacity in the pipe network, which makes it possible to connect new customers to the existing pipe networks or reduce the costs of new pipes to increase the hydraulic capacity. Nevertheless, the tariff schemes are designed to balance themselves out, so that the tariffs paid by customers with high return temperatures equal the discounts received by those that have low return temperatures.

Two different customer cases were investigated. The first case was a single-family house with an average annual return temperature of 40 °C, which needs to be reduced to 25 °C. The savings and bonus achieved

from the reduction in return temperatures would amount to EUR 162 per year or EUR 288 per year, depending on whether the house is located in Copenhagen or in Høje Taastrup. The second case was an apartment building with an average annual return temperature of 53 °C, which needs to be reduced to 25 °C. The savings and bonus achieved in this case would amount to EUR 2372 per year or EUR 6559 per year, depending on whether the apartment building is located in Copenhagen or Høje Taastrup. Due to the structure of the tariff in Copenhagen, the apartment building in Copenhagen only receives a discount on the temperature reduction from 43 °C to 25 °C.

We investigated four different hypothetical solutions for the problems leading to high return temperatures, based on the review of the design and control of current heating systems presented in section 2. The solutions are listed in Table 4, where the cost of each solution is given according to the prices in Table 2.

Table 4. Four hypothetical solutions to reduce heating system return temperatures and the cost of these solutions

	Single-family house [EUR]	Apartment building [EUR]
Pump, new radiator valves	990	6985
Pump, improved pump control	550	1370
Pump, improved pump control, return temperature thermostats	1135	8975
Replacement of 30% of radiators	1515	20246

We calculated the simple pay-back time in years for each of the solutions by dividing the investment cost by the annual savings from the reduction in return temperature, as illustrated in Fig. 5.

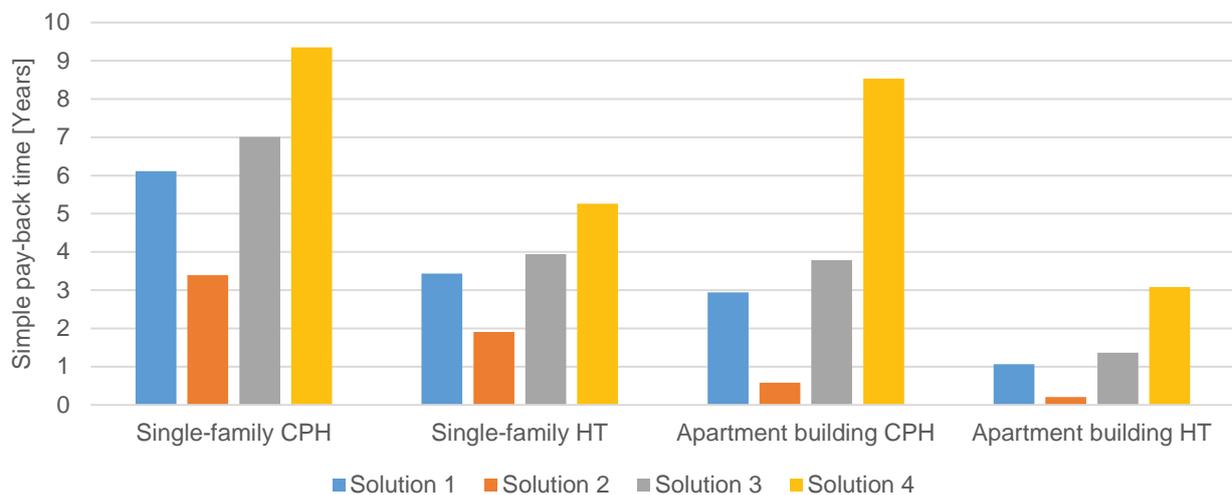


Fig. 5. Simple pay-back time for customers' investments in improved heating system control in Copenhagen (CPH) and Høje Taastrup (HT).

As the figure shows, the customers generally have a very low pay-back time for their investments in improved heating system control. It is clear that the pay-back time is shorter in Høje Taastrup than in Copenhagen, and pay-back times are also shorter, the higher the original return temperature. So the scenario with the shortest pay-back time is the apartment building with a 53 °C return temperature located in Høje Taastrup. Replacement of radiators is the solution with the longest pay-back time, and all other solutions have pay-

back times of less than 7 years. The resulting pay-back times are generally similar to those presented for hydraulic balancing by Trüschel in [30], which were between 1.5 years and 6.5 years. The scenarios are also well in line with the costs for improved heating system control in northern Germany [31]. These costs were estimated to be in the range of EUR 2–7 per m², while the current costs range from EUR 0.7–10.1 per m², but generally also cover a wider scale of improvements. The results also highlight the fact that if improved pump control can be carried out at the estimated low cost and have as big an impact on heating system temperatures as indicated in ongoing research, this solution is very cost-efficient, even where it needs to be combined with new valves or thermostats.

3.4 Costs and benefits in the district heating system

The savings achieved in the energy system if low-temperature district heating is implemented by 2050 are estimated to be EUR 10 per MWh [13]. We estimated the costs of improving the heating systems in existing buildings to enable this temperature reduction on the basis of the findings in section 2, where it was estimated that 3% of radiators need to be replaced, a new pump control system should be implemented in all buildings, and 40% of buildings would require additional improvements in heating system control. These improvements were assumed to consist of the installation of a new pump, and the installation of either new radiator valves or new thermostats that include a return temperature sensor. However, since the analysis of heating system control was based on the current situation of the buildings, this scenario is considered to describe a worst-case situation. By 2050, it is expected that some improvements in the heating systems will be carried out in connection with the general maintenance of the heating systems and the end of the lifetimes of current heating system components. Furthermore, it is expected that some heating system improvements will be carried out to improve occupant comfort, ensure energy savings, or reduce the number of complaints, as described earlier. So a second and more realistic scenario for what will need to be done to improve heating system control assumed that 3% of radiators will have been replaced, a new pump will have been installed in all buildings, but that new improved pump control will still be needed, and new radiator valves and new thermostats with a return temperature sensor will be needed on only 10% and 20% of existing radiators respectively. The scenarios are summarized in Table 5.

Table 5. Implementation of solutions in the existing building stock in the two scenarios

Action	Scenario 1 [% of buildings]	Scenario 2 [% of buildings]
Improved pump control	100%	100%
Return temperature thermostat	20%	20%
New pump	40%	-
New radiator valve	20%	10%
Radiator	3%	-

Based on the need to implement these solutions in current heating systems and the costs given in Table 4, the total cost of improving buildings for low-temperature district heating was calculated in EUR/MWh. This cost was compared with the annual savings of EUR 10 per MWh with the simple pay-back time in the heating system illustrated in Fig. 6. It should be noted that the costs only cover the space heating system, and that additional investments are expected to be necessary in the domestic hot water system. The upper line

represents the simple pay-back time for single-family houses and the lower line is the simple pay-back time for apartment buildings.

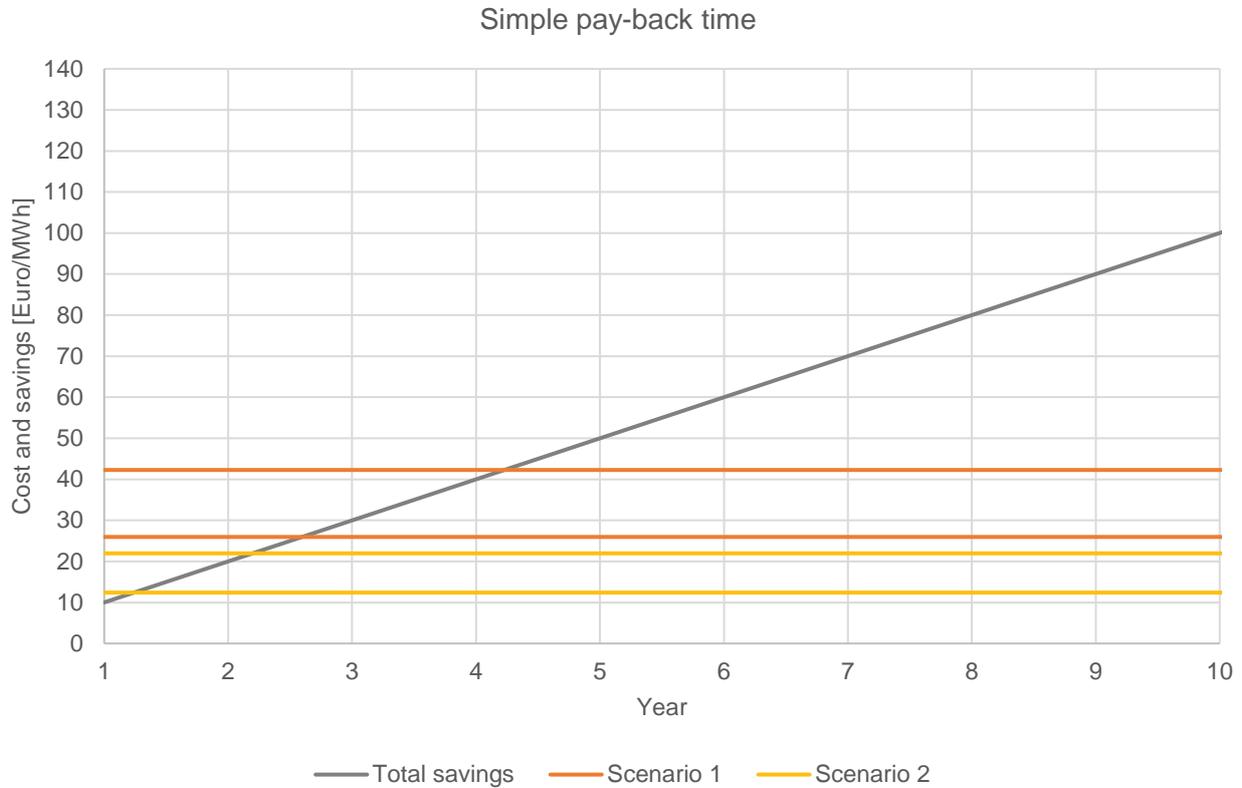


Fig. 6. Simple pay-back time for preparing existing space heating systems for low-temperature district heating.

As the figure shows, it is generally very feasible to implement 4th generation district heating with its benefits compared to the cost of the improvements that will be necessary in current heating systems. The simple pay-back time on the investments in the heating systems is approximately four years in the worst-case scenario, while it is less than two years in the best-case scenario.

4. Uncertainties

The current results provide an indication of the feasibility of preparing existing space heating systems for low-temperature district heating. However, the estimated costs include a great deal of uncertainty. The main uncertainty arises from the fact that the estimated costs are not based on actual demonstration projects, which means it has still not been verified whether the suggested actions can help reduce current return temperatures to the expected 25 °C. Another uncertainty arises because prices for proposed future components are difficult to estimate. Finally, the studies were mainly concerned with single-family houses. However, although the findings have not yet been published, a study of an apartment building was also carried out and generally supports the current findings [36]. Nevertheless, more research is needed to verify that the situation in existing apartment buildings is similar to that presented in the studies referred to. Overall, these uncertainties and assumptions mean that the cost of improved heating system control may be higher than has been estimated in this study. On the other hand, the savings could also be a lot bigger,

because this study did not include additional savings that are likely to derive from improved heating system control. These include both energy savings and fewer occupant complaints, which may add up to savings in the order of 15% of the energy consumption or EUR 1300 per year due to less time being spent on complaints, as Trüschel points out [30]. Furthermore, when a new pump is installed, this will typically lead to considerable savings in electricity, which can be in the order of EUR 50 in a Danish single-family house with electricity costs around EUR 0.26 per kWh if a 40W pump is replaced by a new 5W pump. All in all, we therefore believe that the current analysis provides a reasonable estimate of the feasibility of preparing existing buildings for low-temperature district heating, within the limits of the information available on the topic. This is further verified by the fact that the conclusions of the current study are in line with the findings of other recent studies on the topic [30,31].

5. Conclusion

This study made an estimate of the costs and benefits of preparing heating systems in existing buildings for low-temperature district heating, on the basis of a summary of recent research in the area. The results indicate that it is feasible to invest in improved heating system control to make it possible to reduce district heating temperatures. The estimated investments needed were found to have simple pay-back times of between 0.2 years and 9.4 years for the individual customer and between 1.3 years and 4.2 years when the total energy system is considered. The savings for the district heating customer were based on the use of return temperature tariff schemes currently used in Denmark, and the results therefore highlight the importance of implementing such schemes in order to provide an economic incentive for customers to invest in improved heating system control. Only in this way will it be possible to realize the transition to low-temperature district heating and thus reduce the general cost of producing energy. So this study shows that there is good reason to continue work on ways to prepare existing buildings for low-temperature district heating. This work could include the development of new efficient tools for improved heating system control and for facilitating the correction of current heating system malfunctions, so as to ensure the continuous robust operation of heating systems.

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Low-temperature district heating can increase the efficiency of our energy system greatly. In this study, we therefore investigated the possibility of providing existing buildings with space heating from low-temperature district heating. First, we analysed the heat output of existing radiators in typical dwellings. Second, we investigated if heating system control and design provide barriers to lower the heating system temperatures. Last, we evaluated a number of methods and tools to improve the heating system operation and lower the district heating temperatures.

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