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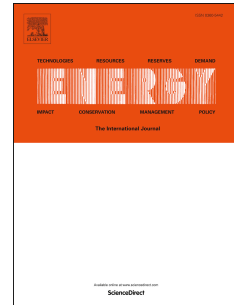
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Credits

Roles of the authors in writing the paper “What does a well-functioning heating system look like? Investigation of ten Danish buildings that utilize district heating efficiently “

Dorte Skaarup Østergaard: Conceptualization, Methodology, Investigation, Writing – original draft

Michele Tunzi: Investigation, Writing – review & editing

Svend Svendsen: Supervision, Project administration, Writing – review & editing

What does a well-functioning heating system look like? Investigation of ten Danish buildings that utilize district heating efficiently

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Conflicts of interest: None

Abstract:

In order to reach targeted 4th generation district heating temperatures around 55 °C supply and 25 °C return, it is necessary to ensure that heating installations inside buildings are designed and operated properly. In this study we investigated the best-case of current design and operation of building installations with the aim of identifying whether there is a gap between current best-case examples and future temperature targets. The study included 7 single-family dwellings and 3 apartment buildings, that were selected based on their low district heating return temperature. Data from the building substations showed that single-family dwellings obtained return temperatures in the range from 25-30 °C while the apartment buildings had return temperatures in the range of 30-40 °C. This indicates that there is a gap between the best functioning heating installations in apartment buildings today, and the targeted district heating return temperatures of 25-30 °C in future 4th generation district heating networks. District heating return temperatures in the range of 30-40 °C could however be the initial ambition for the existing buildings all around Europe that are expected to be connected to new district heating systems in the near future.

Keywords: Low-temperature district heating, 4th generation district heating, District heating substations, low return temperatures, space heating, domestic hot water,

1 Introduction

In order to reduce the effects of climate change during the next century, our energy system needs to change drastically within the next 30 years. For the building sector, this means that a large amount of work is to be done in order to integrate renewable energy sources, reduce energy demands, and ensure efficient utilization of energy. In EU one technology that may support this transition and these goals, is district heating [1,2]. District heating provides the option to ensure cost-efficient integration of many renewable heat sources and waste heat [3]. Additionally, the concept of 4th generation district heating demonstrates how district heating temperatures in future networks can be lowered in order to obtain a highly efficient energy system [3–5]. The main benefits of lower district heating temperatures is increased efficiency in heat production from heat pumps and increased heat output from renewable heat sources such as solar heating and geothermal heat. If heating system temperatures can be lowered in all parts of the system chain, from heat production to heating systems inside buildings, district heating poses a promising technology for a low carbon future. As new district heating systems are expected to be constructed in many European cities during the coming decades, it is therefore strictly necessary that we make sure that they are designed properly in order to meet the aims of the lowest possible system temperatures.

In this paper we focus on the last part of this chain – how do we make sure that district heating is utilized efficiently inside the buildings? In this context, a key indication of efficient utilization of district heating is low district heating return temperatures. When district heating return temperatures are as low as possible, it leads to benefits such as larger capacity in the district heating network, applicability of smaller pipe dimensions, better utilization of many renewable heat sources, reduced pumping costs, and smaller pipe heat losses [6,7]. A reduction in the district heating return temperature can also serve as a step on the way towards low-temperature district heating, since it enables a supply temperature reduction in existing district heating networks, while maintaining the same temperature difference between supply and return [8,9].

According to the definitions of 4th generation district heating, future district heating systems should strive to obtain annual average district heating temperatures as low as 55-60 °C supply and 25-30 °C return [3,4]. Several studies have proven how supply temperatures can be lowered in new built and existing building areas [10–12], and how district

heating substations can be designed to deliver sufficient comfort when district heating temperatures are lowered [13,14]. Low return temperatures have however proven difficult to obtain in practice. Pilot studies of low-temperature district heating have shown return temperatures around 40 °C and 35 °C in both existing and new built houses [12,15]. Studies of a number of existing apartment buildings in Sweden [16] and Switzerland [8] showed that even existing buildings may be operated with very low heating system temperatures. However, average return temperatures were only seldom as low as 30 °C. This was supported by a study by the authors investigating low-temperature district heating in five Danish single-family houses, where return temperatures as low as 25-30 °C were only obtained in two of the houses and it was seen that the operation of the heating systems was not very robust [17,18]. Recent studies have also highlighted how faults in district heating substations occur very often and lead to district heating temperatures higher than necessary [6,19,20]. Finally, Petersson and Werner [21] showed that heating system return temperatures as low as 30 °C should be achievable if heating installations are optimized and operated properly. Apart from a general focus on substation fault detection and correction, Helge and Werner [22] pointed to increased thermal lengths of heat exchangers and radiators, automated hydronic balancing of heating systems, and elimination of hot water tanks and hot water circulation, as key aspects of how to obtain these desired low district heating return temperatures.

These aims have also been the focus area of a large amount of current research, aiming on how to improve the heating system operation in buildings with high district heating return temperatures. Tunzi et al. [23], Benakopoulos et al. [24] and Oevelen & Salenbien [25] showed that it is possible to reduce current heating system temperatures in existing buildings greatly, if the heating system supply temperatures are optimized. Several studies have shown how either improved heating system control and hydraulic balancing [26–28], improved operation of domestic hot water installations [29–31], or energy renovations [32–34] can lead to both energy savings and lowered heating system operational temperatures. Furthermore, typical malfunctions in building installations for district heating and ways of eliminating malfunctions to improve the operation of district heating systems have been addressed in several recent studies [35,36]. While a large amount of current research has therefore focused on examples of buildings with poor performing heating systems, and how these might be improved, only few studies have focused on describing well-functioning heating systems.

In this study we therefore chose a new and different approach. Recognizing the fact that people are more likely to learn from the good examples than from the bad ones, we set out to make a description of some of the best examples of well-functioning heating systems connected to Danish district heating systems. In collaboration with four different Danish district heating companies, we made contact to ten customers who utilized district heating efficiently. Thereby, we had the chance to survey and investigate the buildings and heating systems of one single-family house, six row houses, and three apartment buildings, which had some of the lowest return temperatures in the included district heating systems.

The aim of the study was two-fold. First, we describe the efficiency and operation of some of the best current Danish well-functioning heating systems. The objective was to reflect on the gap between the operation of current well-functioning heating systems and the aim to obtain district heating return temperatures as low as 25-30 °C in future 4th generation district heating systems. Second, we describe building characteristics, occupant habits, and technical installations in the identified dwellings with well-functioning heating systems. The aim was to assess whether there is a relation between heating installation design or occupant habits and the efficiency of the heating system operation. The study thereby provides new knowledge on the status of best practice of heating systems in current buildings and the specific gaps that need to be filled in order to prepare existing buildings for low-temperature heating. The results of this study lead to important input on where to focus future research efforts, in order to ensure high efficiency of new district heating systems that are planned in existing building areas all around Europe in order to abate climate change.

2 Method

The study was conducted through a practical investigation of ten case buildings. In this section we first describe how these case buildings were selected. Second, we describe the method for data collection in each of the case buildings and lastly we show an example of the data collected for one of the buildings.

2.1 Selection of buildings with efficient utilization of district heating

Collaboration with four district heating companies in the Copenhagen area was established in order to identify buildings with efficient utilization of district heating. In this context, a building with efficient utilization of district heating was defined as a building where the lowest possible district heating return temperature was achieved. Focus was therefore

not put on the lowest possible heating consumption but rather on the possibility of the heating installations to utilize the largest possible amount of heat from the district heating water. In order to identify buildings with efficient utilization of district heating, we applied the following method. First, data from energy meters in all customer substations were extracted. Second, customers in buildings with the lowest return temperatures in the systems were identified and contacted. Ultimately, ten out of the approximately 30 customers we contacted, agreed to participate in the project.

The customers that agreed to participate in the project included the following building types:

- 1 detached single-family house
- 6 row-houses
- 3 multi-family buildings

The building types were dependent both on the typology of the collaborating district heating companies as well as they were a random result of the types of customers who happened to have the lowest return temperatures.

2.2 Data collection for description of well-functioning heating systems

The data collection and analyses consisted of four steps:

I. Graphs of obtained district heating supply and return temperatures

Before the buildings were analysed in detail, data was collected to verify the achieved supply and return temperatures in each of the houses. The data was collected from the energy meters that are installed in the substation of each building for billing purposes. The energy meters are wirelessly connected and therefore data can be extracted rather frequently. As far as possible, the data included monthly values of flow-weighted heat demand, supply temperature, and return temperature during a three year period. In some cases, it was not possible to get data for the whole three year period, and the graphs were then based on the available data.

II. Description of building characteristics and occupant habits

All relevant building information, such as original building drawings and energy labels were acquired. Based on this input along with a visit to all buildings, we identified key building characteristics such as age of the buildings and insulation levels of building components. An average building insulation level factor was calculated as an

average of the estimated construction U-values. Occupant habits were evaluated through a discussion with the occupants regarding their knowledge about the heating system and their typical behaviour in controlling and maintaining the heating installations. Based on the conversation we assessed the level of engagement and technical insights of the occupants on a five step range from 1-5, corresponding to a range from very high to very low. For apartment buildings the assessment was based on the engagement and knowledge of the service technician or manager responsible for the heating system operation and maintenance.

III. Heating installations were inspected and described in detail

During building visits, we first made a schematic drawing of each of the district heating substations. Substation control equipment and domestic hot water installations were noted in the drawings, and the settings and functionality of each of the substation elements was described. Second, we made a survey of the space heating system in the buildings. This included an inspection of the type of heating elements and the installed control components, such as thermostatic radiator valves and pre-settings.

IV. Evaluation of district heating consumption

We calculated the average district heating consumption of each of the buildings based on the measurement data. The calculations were based on the available measurement data, which typically included 2-3 years of heating consumption. The heating consumption was divided by the total heated floor area of the building, in order to arrive at a comparable figure for the district heating consumption in kWh/m² heated floor area. The area of heated basement rooms were included in the heated floor area.

3 Example of data collection for Building 1

In the following sections we provide an example of how data was collected for one of the case buildings. As it is not possible to show all the gathered information for all ten buildings in this paper, we refer to [9,37] for detailed information.

3.1 Data for Building 1

Figure 1 shows the data on monthly average values for district heating supply and return temperatures as well as total district heating consumption for Building 1 during the three year period from 2016 to 2018. The figure illustrates that Building 1 has succeeded in delivering district heating return temperatures as low as 25 °C all year long, even during summer time, when heating demands are low and mainly represent the need to heat domestic hot water.

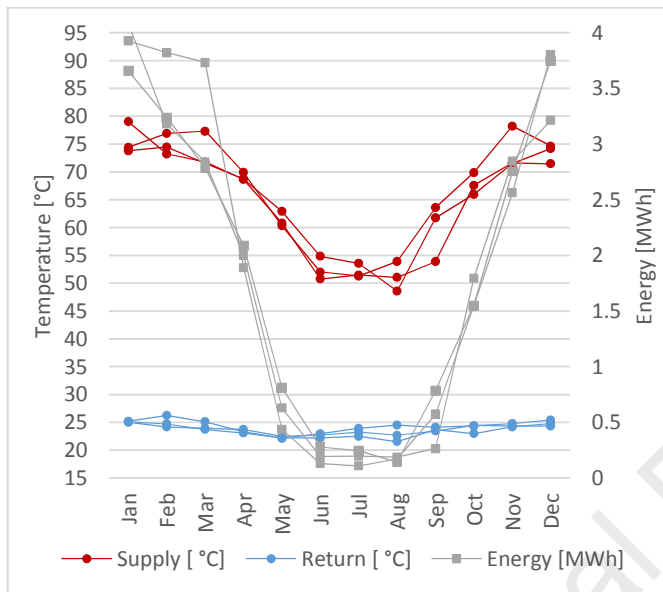


Figure 1 Monthly average values of district heating energy consumption, supply and return temperatures in Building 1.

3.2 Building characteristics and occupants

Building 1 is a single-family house that was constructed in 1928. The total heated floor area of the house is 229 m², which is distributed on three floors: basement, main floor, and first floor. It is a red brick house with a tile roof. The external walls are constructed as cavity brick walls and they have later been insulated with a blown in foam insulation. The roof was later renovated when the first floor was added to the house, and at this time, roof constructions were insulated with 100-200mm mineral wool. Windows are equipped with 2-pane energy glazing. Estimated U-values of these constructions are 0.78 W/m² K, 0.38 W/m² K, and 1.33 W/m² K respectively. The average insulation level of the building was thus estimated to be 0.83 W/m² K based on an average of the construction U-values.

The house is occupied by an elderly couple. They are both retired and they are therefore often present in the house. The husband is very engaged in the heating system control and maintenance. He has a keen interest in the operation of the

heating system and monitors the operation of the heating system on monthly basis. He has an extensive knowledge about the functionality of the district heating substation and the different technical components. The occupants are also very aware of the set-points on their thermostatic radiator valves. The occupants are therefore evaluated to have a very high engagement level.

3.3 Heating installations

The house is supplied with space heating through a direct connection, delivering heat to a two-pipe radiator system with 11 radiators. There is no controller and hence no local weather compensation of the heating system supply temperature or set-back of heating system temperatures. A differential pressure controller is mounted on the space heating supply and return pipes, ensuring the correct differential pressure across the space heating installations. All radiators are controlled by thermostatic radiator valves without pre-settings. Some radiators were additionally equipped with old return temperature thermostats, providing the option to limit the maximum return temperature from the radiator.

Domestic hot water is heated instantaneously in a plate heat exchanger and there was no domestic hot water circulation system in the house. The plate heat exchanger is controlled by a pressure regulator (PM regulator) that adjusts the flow of the district heating medium through the heat exchanger to ensure that proper domestic hot water comfort supply temperature is achieved during tapping. The heat exchanger is also equipped with a bypass valve that ensures continuous circulation of district heating through the service pipe to ensure that heat for preparation of domestic hot water is available instantly. The bypass valve is equipped with a return temperature thermostat. If the temperature of the district heating medium falls below the set-point, the valve therefore opens to circulate district heating through a bypass pipe. A radiator located in the boiler room was mounted on the return line from the domestic hot water system, thus providing the option to cool down the district heating water by-passing the domestic hot water heat exchanger in the summer.

A summary of key parameters of the installation is given in Table 1 and the layout of the heating installations is visualized in a standard Piping and Instrument Diagram (PI&D) seen in Figure 2. Please refer to [9,37] for details on the installations of all case buildings.

Table 1 Summary of key parameters of heating system installations in Building 1.

Space heating connection	Central heating control and weather compensation	Night set-back	Heating system type	Control of heating elements	Pre-settings on radiator valves	Domestic hot water installation	Domestic hot water circulation
Direct	No	No	Two-pipe Radiators	TRVs and some return-thermostats	No	Plate HX	No

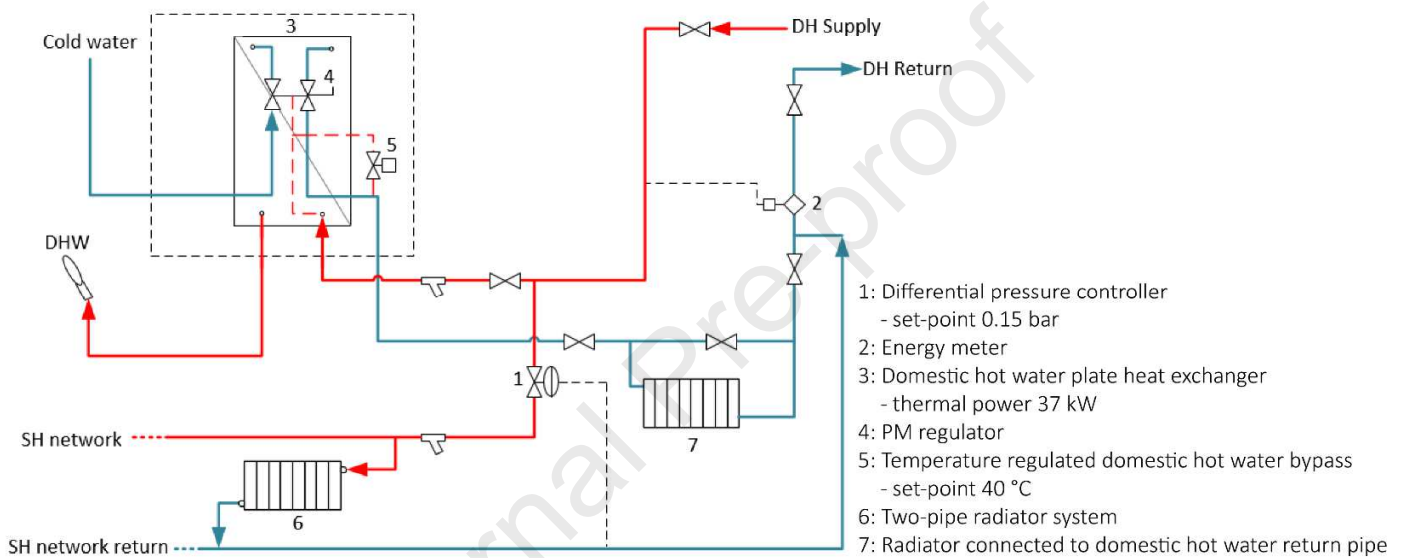


Figure 2 Piping and Instrument Diagram of the heating system layout in Building 1. Adapted from [37]

3.4 District heating consumption

The measured district heating consumption in the house is 20.4 MWh in 2016, 22.1 MWh in 2017, and 22.7 MWh in 2018, leading to an average annual district heating consumption in House 1 of 22.1 MWh. The total heated floor area of the house is 229 m² including the heated basement. This gives a district heating consumption of 96 kWh/m².

4 Results and discussion

As it is not possible to include the full list of data collected for each of the case buildings, this section provides an overview and comparison of the most important findings. Please refer to [9,37] for more details.

4.1 Data describing supply and return temperatures in buildings

Figure 3 shows the measured energy consumption and district heating supply and return temperatures for nine of the case buildings during a 2-3 year period from 2016-2019. Unfortunately it was not possible to get accurate monthly values for Building 4 which has therefore been excluded here. The first six buildings are single-family dwellings, while the last three are large apartment buildings.

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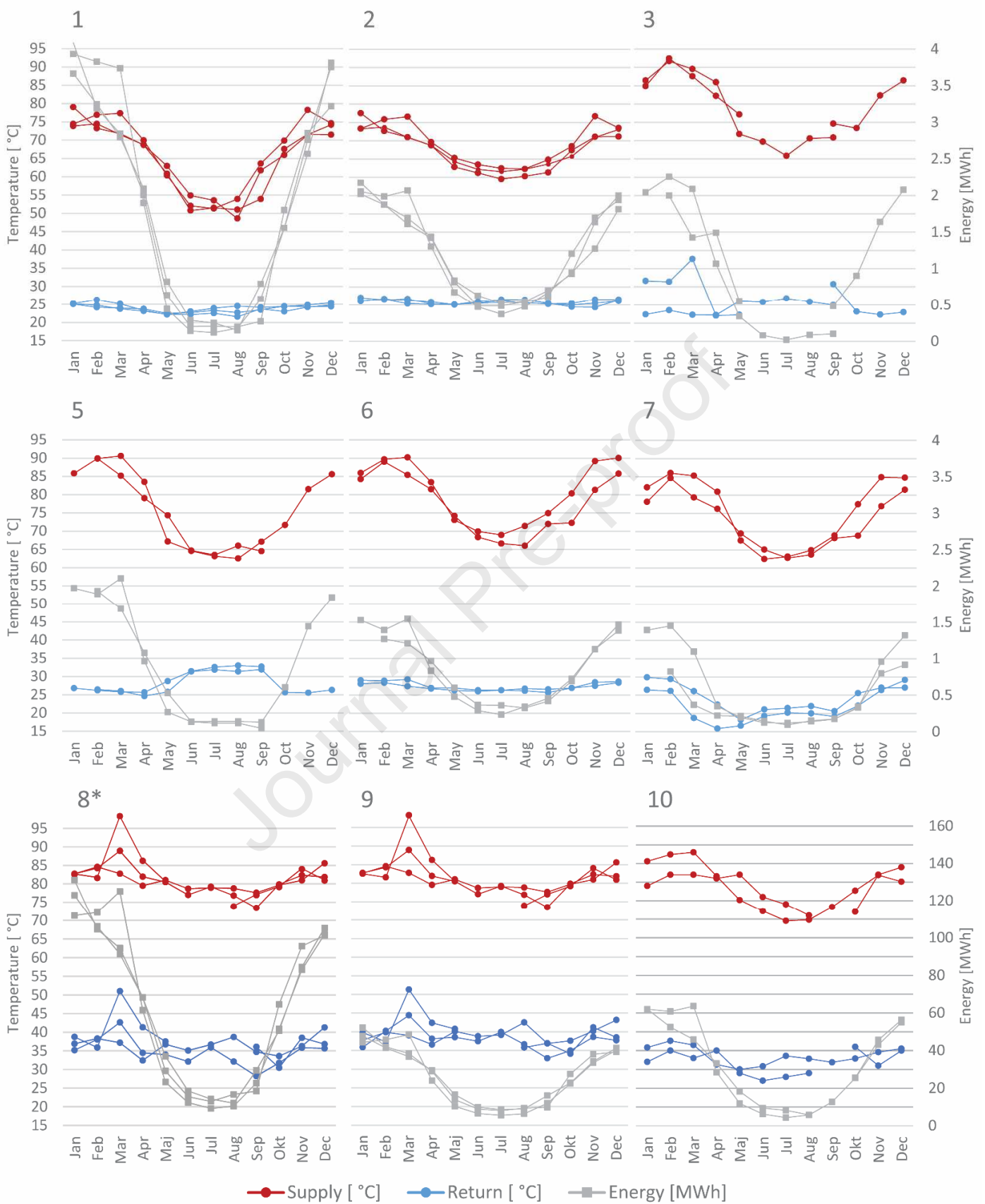


Figure 3. Measured energy consumption, supply, and return temperatures for 9 of the buildings in the study. *Due to measurement issues, the supply temperature in Building 8 is taken from Building 9 which is in the same area.

For the single-family dwellings, it is seen that district heating return temperatures are typically in the range between 25-30 °C all year. Buildings 1, 2, and 6 have almost constant return temperatures during the year, with almost no seasonal variation. In buildings 3 and 7 there is a variation in the return temperature, but it does not seem to be seasonal, while, in building 5, the district heating return temperature increases from approximately 25 °C to 30 °C during summer time. This indicates that all of the domestic hot water installations can provide very low district heating return temperatures even during the summer time when the heat demand is low. The variations in return temperatures in Building 3 and 7 occur due to the heating installations in the houses. Building 3 is heated by an air heating system, which is in some cases supplied with cold outdoor air, meaning that the district heating return temperature can potentially be almost as low as the outdoor temperature in the given month. This causes return temperatures to be very low during some winter months. In Building 7, water pipes are cast into the concrete ceilings, in order to use the ceilings as heating elements. This solution is also seen to be able to deliver a very low return temperature due to the large heating areas.

Buildings 8, 9, and 10 are all apartment buildings. As seen from the graphs the district heating return temperatures from these buildings are in the range from 30-40 °C, being around 35 °C on average. The lowest return temperature is obtained in building 10, which is the newest of the buildings, being from 2006. None of the buildings show any apparent seasonal variation in the district heating return temperatures, indicating that both space heating installation and domestic hot water installations deliver rather low return temperatures, even during the summer when heat demands are low.

4.2 Building characteristics and occupant behaviour

Figure 4 shows the construction year, the average construction U-value and the engagement level of the occupants or service manager in the buildings. The red bar indicates that the building is a detached single-family dwelling, while orange bars are row houses, and blue bars represent apartment buildings. As can be seen from the graphs, the buildings are from many different construction periods. Building 1, 8, and 9 are constructed around the 1930s. However both Building 8 and 9 were equipped with central heating systems much later, in 1994. All row houses were constructed in the same period around 1970, while Building 10 is the only newer building, constructed in 2006. The average construction U-values of the Buildings are generally around $1 \text{ W/m}^2 \text{ K}$, indicating that most buildings have reasonably insulated construction elements. Only two buildings have insulation levels that differ largely from the average. This is Building 9 which has much higher average U-value, due to the fact that only few energy renovation measures have been taken, and building 10 which is quite new and therefore has a lower average construction U-value. The buildings thereby show some variation in insulation level although they are generally reasonably insulated.

The engagement level of the occupants or service managers in the buildings also differ. In half of the buildings, it is found that the occupants or service managers have a very high engagement level and a high level of knowledge about the heating installations. This indicates that it may be more likely that heating installations are well-functioning in case the occupants or service manager has a high engagement level, which seems reasonable. On the other hand, the occupants or service managers in the other half of the houses only had a low or medium engagement level. They did not pay specific attention to the heating installations and generally controlled them according to old habits and general comfort requirements. A main conclusion is therefore, that the current results indicate that it is also possible to obtain low district heating return temperatures in buildings where occupants are less engaged.

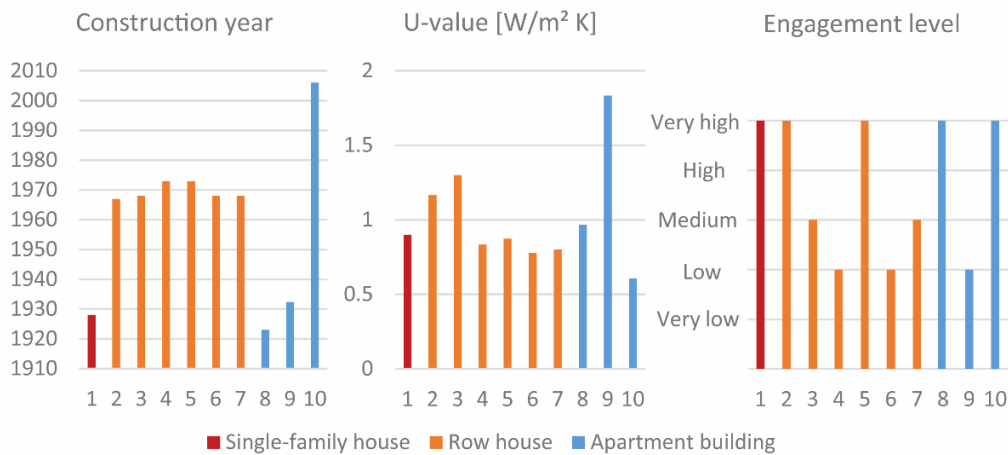


Figure 4. Construction year, average construction U-values and engagement level of occupants.

4.3 Heating installations

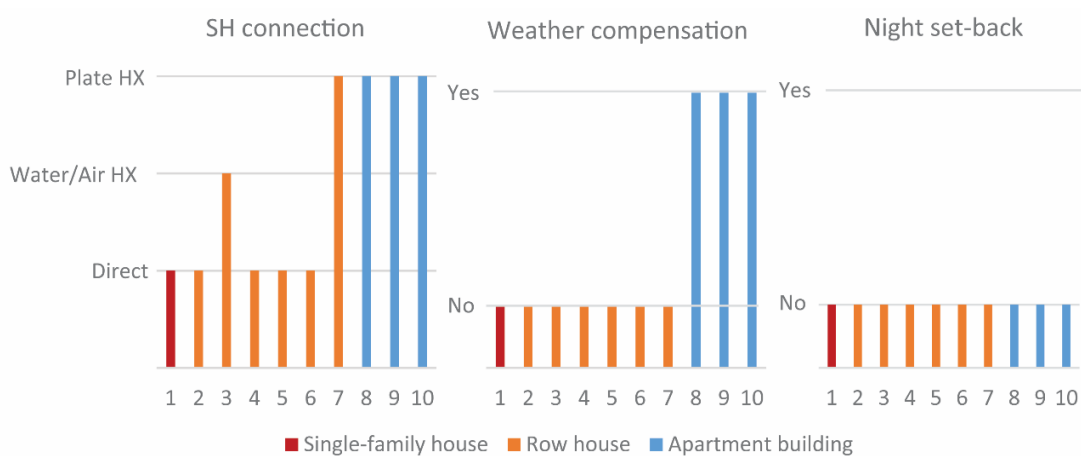
Space heating system

Figure 5 shows an overview of the space heating substations and the substation control in the case buildings. As can be seen there is a large variation in the space heating installations of the single-family houses (red and orange bars), while the space heating installations in the apartment buildings are very similar (blue bars).

Most of the single-family houses are equipped with direct district heating, with no special control systems. These are very simple heating installations that make it possible to obtain slightly lower district heating return temperatures, than in case of the indirect connection, because there is no heat degradation in a heat exchanger. All of the buildings are equipped with standard two pipe radiator systems, where the only special deviation is that floor heating has been added in the bathroom of Building 5. Building 3 is equipped with a water/air heat exchanger and heated by air heating, while Building 7 is equipped with a brand new district heating unit with a plate heat exchanger, and heated by a rather special ceiling heating system. None of the space heating systems in the single-family houses are controlled with a weather compensation unit and night set-back is not applied in any cases. The control of the heating elements in the single-family houses are on the other hand very different, ranging from manual valves on the ceiling heating system, to a central thermostat for the air heating system, and combinations of thermostatic radiator valves and return temperature radiator valves for the remaining houses. Only one of the houses has pre-settings in the radiator valves.

For the apartment building, the space heating installations are very similar. All buildings are equipped with a plate heat exchanger, all apply weather compensated supply temperature control in the space heating system, and none of them apply night set-backs in the heating system operation. They are all equipped with two-pipe radiator systems, however in buildings 8 and 10, additional floor heating circuits are connected to the space heating system, for the case of building 8 these installations have been made on individual basis whenever an apartment owner wanted this type of heating. In building 9 the radiator system is designed with reversed return to improve hydronic balancing. All of the radiators in the buildings are equipped with thermostats with pre-settings and floor heating circuits are controlled with return temperature valves. In this regard it should be noted, that all space heating systems are rather new, since the installations in Building 8 and 9 is from 1994, even though the buildings were constructed much earlier.

Even though all three apartment buildings have similar heating installations, this does not necessarily mean that the building installations that are presented in this study, are the only types of installations that can provide a low district heating return temperatures. This study only contains three apartment buildings, and the results do therefore not represent a complete overview of well-functioning installations. Other studies have shown that it is also possible to obtain low return temperatures in buildings with other types of installations, such as heat exchangers for domestic hot water preparation and space heating systems without pre-settings on radiator valves [24,31]. However, several studies underline that installation of balancing valves, pre-settings on radiator valves, and radiator thermostats in space heating systems can provide large benefits also in the form of energy savings and improved occupant comfort [27,38].



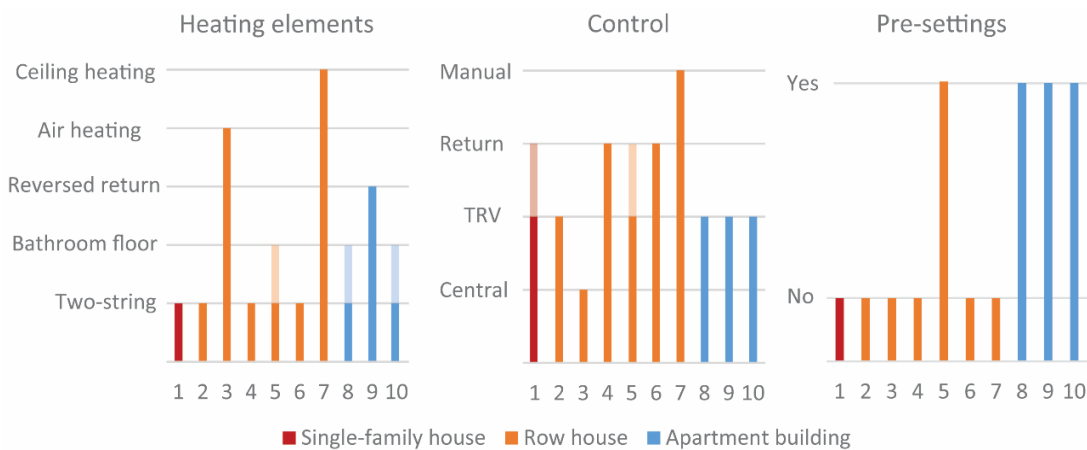


Figure 5. Overview of space heating installations and control.

Domestic hot water installations

Figure 6 provides an overview of the domestic hot water installations in the case buildings. As can be seen most of the single-family houses are equipped with plate heat exchangers for preparation of domestic hot water, while only one is equipped with a spiral heat exchanger and one has a storage tank. In this regard it should be noted, that the domestic hot water installations are in most cases separate installations and not part of a standard district heating substation. They are all designed properly according to provide a heat output of 37 kW or more at district heating temperatures 60/30 °C, domestic hot water supply temperature at 45°C, and a cold water temperature of 10 °C. None of the single-family dwellings have domestic hot water circulation systems. Furthermore, it should be noted, that in the row houses there is only a very small need for bypass in the domestic hot water installations to keep the service pipe warm, due to the fact that the district heating pipes are running through the basements of the row houses, causing the service pipe to be very short. In the detached single-family house, the issue with the domestic hot water by-pass has been solved by a special installation, where a radiator in the basement has been connected to the return pipe from the domestic hot water substation. This means that the water returning from the domestic hot water heat exchanger can be cooled down in the radiator, which will provide some heat to the basement during summer months. This layout is much in line with previous suggestions for improvements of domestic hot water installations for low-temperature district heating systems, where it has been suggested that by-pass flows from domestic hot water heat exchangers could be used to provide comfort heating in bathrooms during summer periods [39] These technical installations are quite specific, and their characteristics are well in line with the requirements for future 4th generation district heating described in [22]: no

circulation or storage of domestic hot water, and no need for bypass in the district heating system. This is essential for the low district heating return temperatures obtained during summer months.

All apartment buildings are equipped with a centrally located domestic hot water storage tank and domestic hot water circulation systems. These domestic hot water solutions deliver reasonably low return temperatures, which is illustrated by the measurement data from summer periods, showing return temperatures that are generally in the range 30-35 °C. It should be noted however, that the domestic hot water circulation temperatures have not been investigated in detail, and therefore it has not been verified whether the installations are operated with temperatures that meet the requirements for limitation of Legionella bacteria growth, which was seen to be an issue in another recent study. The return temperature from domestic hot water systems may be increasingly important for the district heating system in the future, as there may be a tendency for energy renovations to lower the space heating demands and required space heating temperatures, which causes heat demands for domestic hot water to make up a larger share of the total heating consumption, and therefore causes return temperatures from domestic hot water installations to be equally more dominating [40–42]. While new buildings can be designed with apartment substations as suggested in [22], it may be necessary to accept that existing apartment buildings, are operated with the existing installations for several decades. Both this study and other recent studies therefore indicate, that there is a need for further research in this field, if the return temperatures from existing domestic hot water installations in apartment buildings are to be lowered further than the 35-40 °C that have been identified for older buildings in this study, and that has also been estimated in another recent study [41]. Possible solutions that are currently investigated include the installation of small heat pumps for domestic hot water circulation heat losses or improved charging schedules for domestic hot water tanks [29,43,44]. However, increased return temperatures in summer periods may not be a crucial issue in district heating networks, as the capacity in the pipes should be plenty during summer months where heat demands are far from peak load situations. The main disadvantage may therefore be, the need to accept somewhat higher district return temperatures, which can cause slightly less efficient heat production from some renewable heat sources.

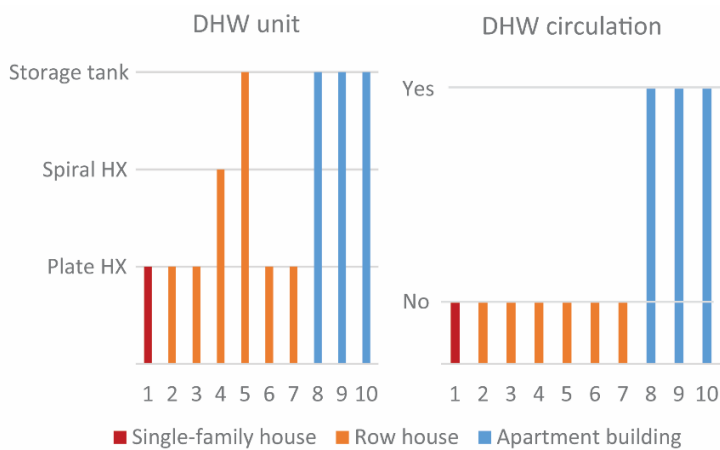


Figure 6. Overview of domestic hot water installations.

4.4 District heating demand

Figure 7 shows the average annual district heating consumption in the case buildings. As can be seen, the district heating consumption is in the range 43-119 kWh/m² for single-family dwellings and 85-127 kWh/m² for apartment buildings. A large part of the evaluated buildings thereby have heating consumptions that correspond rather well to the average district heating demands for Danish buildings [45], although four of the row houses show heating demands that are noteworthy below the average heating consumption of 110-120 kWh/m² that is identified for row houses constructed around 1970. The results indicate that buildings with efficient utilization of district heating do not necessarily need to have very low heat demands, although it may be an advantage as almost half of the surveyed houses have heat demands that are noteworthy lower than the average, and none of the surveyed buildings have very large heat demands. It should be noted in this regard, that the heat demands of row houses are related to a certain degree of uncertainty, due to the fact that heat losses may occur from neighboring houses with higher indoor temperatures, that thereby cover some of the actual heat demands. This also causes a small bias, since it is generally easier to obtain a low district heating return temperature if there is a large amount of heat gains from for example neighbours.

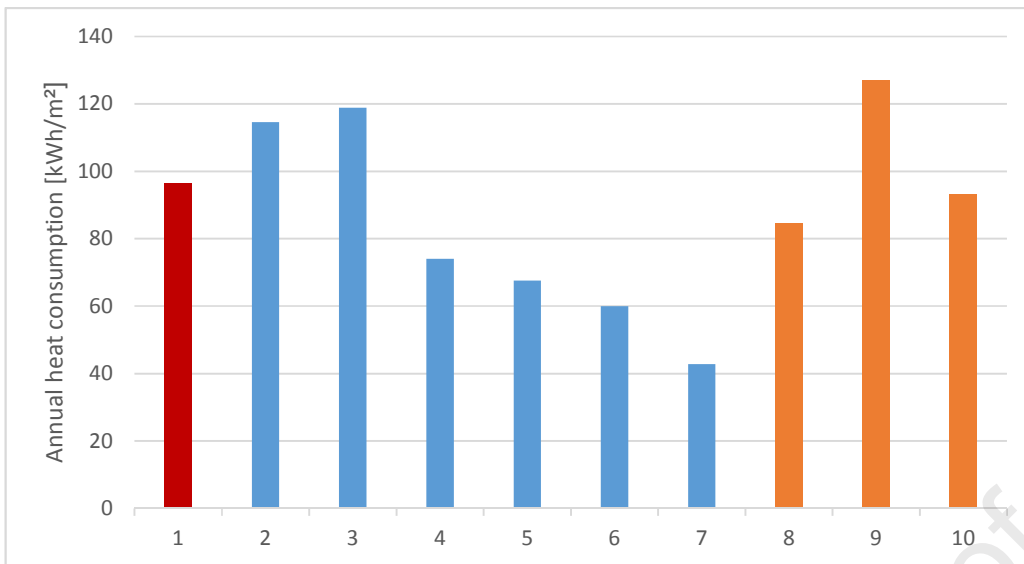


Figure 7. Annual average heating consumption in the case buildings.

4.5 Results in a broader perspective

Although the results presented in this paper deal with ten specific Danish buildings, the overall learning from these buildings can provide perspectives for future district heating installations and future research.

The surveyed buildings are equipped with typical district heating installations for both space heating and domestic hot water. The space heating connections are either direct or indirect and domestic hot water is prepared centrally in domestic hot water tanks or heat exchangers. These installations are common in both existing buildings and are also often the current standard for new installations [46]. It may however not always be possible to adjust current district heating networks and installations to match the layouts displayed in this project. For example, many efficient installations showcased in this paper were located in row-houses and consisted of direct space heating connection and a very short district heating service pipes, which may not be applicable for a single-family house in a high pressure district heating system. On the other hand, the results may provide inspiration for new district heating installations – could it be relevant to consider direct district heating connections and how can we make an effort to reduce the length of service pipes, if we aim to reduce the temperatures in future district heating systems? Additionally, some of the identified measures can be implemented also in existing buildings. For example, all included apartment buildings were equipped with string balancing valves and thermostatic valves with pre-settings, which can indicate that such solution helps reduce district heating return temperatures.

This study was not detailed enough to provide specific conclusions on how building installations should be designed in the future in order to ensure lower district heating temperatures. In future research it would be highly relevant to investigate more detailed data for well-functioning heating systems in order to understand how the systems are designed and operated in detail. Measurements could preferably include high resolution data for flows and temperatures, including those in the domestic hot water circulation systems. Furthermore, design data for the substation heat exchangers or domestic hot water tank sizes could be compared with the actual measured peak loads and typical part loads. These types of investigations would be beneficial in order to learn more about how to optimize the design of building installations in order to obtain low district heating temperatures in practice.

5 Conclusions

The study investigated the layout of the building installations and the district heating temperatures in ten Danish buildings that provided low district heating return temperatures. The study had two aims:

The first aim, was to describe the efficiency and operation of some of the current Danish well-functioning heating systems, in order to reflect on the gap between current well-functioning heating systems and the aim to obtain district heating return temperatures as low as 25-30 °C in future 4th generation district heating systems. In this regard, it was found that all seven single-family dwellings that were included in the study obtained very low district heating return temperatures in the range 25-30 °C, while the 3 apartment buildings had district heating return temperatures in the range 30-40 °C. This indicates that there is a gap between the best functioning heating installations in apartment buildings today, and the targeted district heating return temperatures of 25-30 °C in future 4th generation district heating networks.

The second aim, was to evaluate whether there is a relation between certain heating installation design or occupant habits, and the efficiency of the heating system operation. In this regard it was found that all seven single-family dwellings included in the study had a direct district heating connection to the space heating system. Although this does not mean that direct connections are a prerequisite to obtain low district heating return temperatures, it is in line with the fact that direct connections can provide slightly lower return temperatures as there are no degradation heat losses

from a heat exchanger. None of the houses had circulation of the domestic hot water inside the building, and six of them were row-houses with a very short service pipe, meaning that there was only little need for by-pass in the domestic hot water heat exchangers. Apart from this, the heating installations in the buildings were very different, showing that low return temperatures can be obtained in small buildings with many different types of heating elements and control. All of the three apartment buildings have very similar heating installations. The domestic hot water systems consist of storage tanks and all buildings have domestic hot water circulation systems. The space heating installations consist of two-pipe radiator systems that are equipped with balancing valves, pre-settings on radiator valves, and thermostats on all radiators. Central controllers are connected to regulate the space heating supply temperature according to a weather compensation strategy. None of either single-family dwellings or apartment buildings apply night set-back in the space heating systems. It should be noted that since this study only concerns ten specific buildings, the results should not be used to draw any conclusions concerning the general building mass. It is highly possible that there are other types of installations that also lead to low district heating return temperatures.

Another conclusion from the study is, that it does not require neither specifically low heating demands nor special engagement and high level of knowledge on heating system operation to obtain low district heating return temperatures. This means that if the technical installations are designed properly it should be possible to obtain low district heating return temperatures in many types of buildings irrespective of these parameters. Additionally it should be noted, that even though the surveyed apartment buildings did not obtain district heating return temperatures as low as 25-30 °C, they still demonstrated that typical building heating installations in existing apartment buildings can be brought to operate with return temperatures in the range 30-40 °C, which is still lower than what is found in many existing buildings. Such return temperatures should therefore be the goal for existing apartment buildings already today, and as seen in this study, these return temperatures can be obtained in many different types of buildings and it does not require deep renovation of the building envelope. This supports the general consensus that high district heating return temperatures may in many cases be reduced if the existing heating system installations are brought to operate properly.

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Highlights:

- *Single-family dwellings can obtain return temperatures in the range 25-30 °C*
- *In these, short service pipes and no circulation of DHW were typical*
- *Well-functioning apartment buildings had return temperatures in the range 30-40 °C*
- *Radiator systems were equipped with balancing valves, pre-settings, and thermostats*
- *There is a gap between current standards and future 4GDH requirements*

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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