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Low-temperature operation of heating systems to enable 4th generation district heating: A review

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A B S T R A C T

District heating networks increasingly rely on heat pumps, condensing biomass boilers, and excess heat in the transition to sustainable energy systems. Accordingly, district heating operators seek to reduce their networks' supply and return temperatures to maximise production efficiencies, minimise heat losses from distribution pipes and allow greater utilisation of renewable heat sources and excess heat. Experts have predicted that investing in solutions that reduce heating temperatures in buildings will yield a return on investment of 300% for district heating operators. Therefore, expecting incentives, building operators should identify methods to reduce supply and return temperatures to enable a rapid, widespread transition to low-temperature district heating. Ample research has investigated and documented the feasibility of low-temperature heating in buildings, and this paper presents the first comprehensive review. It synthesises available literature and adds new perspectives to help guide future implementation, research and development of low-temperature heating. The energy and temperature demands of various heating systems provides a background, leading to a review of typical malfunctions and their impacts. The article subsequently reviews the obtainable supply and return temperatures before and after renovating the building envelope and heating systems. It further identifies and summarises vital measures for decreasing heating system temperatures. Ultimately, the authors recommend minimising heating system temperatures using automatic balancing of space heating and ventilation systems, novel solutions for safe domestic hot water supply, and digitally-enabled performance monitoring and optimal control.

1. Introduction

District heating is essential for enabling energy flexibility, supplying from various heat sources and cost-effectively distributing heat to the end-users [1]. Traditional district heating networks utilise fossil fuel generation and heat recovery. In contrast, the modern approach utilises seasonal thermal storage [2–5], local excess heat [6–8], and renewable and decentralised energy sources [9,10]. This approach demands lower network operating temperatures to cost-effectively utilise these energy sources while reducing heat losses from the network.

Buildings play an essential role in district heating systems. A single building can determine the required supply temperature for a district heating network. Meanwhile, high return temperatures can harm the network's heat retention, hydraulic capacity and production efficiency. Lowering district heating temperatures requires designing and modifying building installations to satisfy heating demands with minimal temperatures. There is a need to update best practices for building installations, including longer thermal lengths of heat exchangers and radiators, solutions for automatic hydronic balancing in heating systems and solutions that reduce the need for domestic hot water (DHW) circulation and provide legionella safety [11].

A transition to the 4th Generation District Heating (4GDH) is underway, targeting average supply/return temperatures of 55–60 and 25–30 °C [12,13]. Defined broadly, 4GDH is a concept whereby smart thermal grids with low temperatures and structured incentives support the integration of low-temperature heat sources and renewable electricity generation. Reviews exist to support the performance of district energy networks [14] and district heating and cooling [15]. However, these have focussed on network performance and not the performance of heating installations that

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constrain the networks' potential operating temperatures. Proper operation of installations is critical for enabling low-temperature district heating, so there is a need to review the available literature and summarily guide future research and development.

This article reviews the current state of heating installations in existing buildings to broadly identify the required research and development for enabling low-temperature district heating. It introduces the typical temperature demands in buildings and the best-practice design of installations to deliver the necessary heat. It then provides state-of-the-art knowledge and methods towards reducing heating temperatures in existing buildings. It describes malfunctions in substations leading to high temperatures and methods to correct these malfunctions. It further describes the effect of energy renovation on low-temperature district heating and the available improvement measures to reduce district heating temperatures in existing building installations. Lastly, the article concludes on the gaps in current knowledge while providing recommendations for future research within this area. The scope of this review is on typical buildings (e.g. existing dwellings and office buildings) and does not include other heating applications (e.g. industrial).

2. The role of buildings in the district heating system

2.1. Temperature requirements and heat demand in buildings

Typical heat demands in dwellings and offices consist of space heating, domestic hot water (DHW), and ventilation heating. Fig. 1 presents an overview of typical temperatures to secure comfort and hygiene with space heating and DHW systems for current and future district heating systems. In recent years, researchers introduced the concept of 5th generation district heating (5GDH), which aims to operate networks with temperatures close to the ground temperature ('cold district heating'), deliver heating and cooling with the same infrastructure, and boost temperatures locally with heat pumps at each consumer [16,17]. Lund et al. [18] suggested that 5GDH should be 'a parallel development' to 4GDH and not be considered as the evolution of the 4GDH. Unless otherwise stated, this review article describes buildings connected to low-temperature district heating – or 4GDH – networks.

In most modern homes, occupants expect to obtain room temperatures in the range of 18–24 °C. Field studies in Northern Europe show that occupants often prefer 22 °C or more in living areas and roughly 24 °C in bathrooms [19,20]. In bedrooms, occupants often desire lower room temperatures of 18–20 °C while sleeping. In many cases, occupants turn off the radiators in bedrooms and sleep with the windows open.

The dimensioning of heating installations affects the necessary supply temperatures to provide thermal comfort. Older radiators typically used design temperatures of 90/70 °C [21,22] (indicating supply and return temperatures of 90 °C and 70 °C, respectively), which reduced their size and cost. New radiators use lower design temperatures, such as 55/35 °C or even 45/35 °C, enabling low-temperature heating in modern low-energy buildings [22–25]. Although radiators remain the most common heat emitters in Europe, floor heating is increasingly common in new buildings because of its pleasing comfort and aesthetics. Its large heat emitting surface enables design temperatures of 45/40 °C or less. Actual heat demand is typically far less than the design heat demand, calculated without internal heat gains at extremely low outdoor temperatures. As such, these heating systems can operate with much lower temperatures. It is common to operate space heating systems with supply temperatures of 30–70 °C for radiators and 30–40 °C for floor heating. Fig. 2 summarises the typical room temperatures and heating system design temperatures.

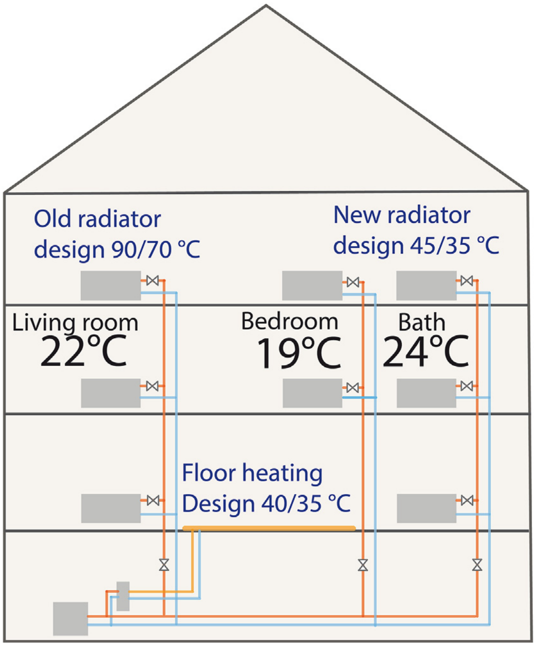

Fig. 2. Examples of temperature requirements for space heating installations.

Temperature requirements for DHW installations vary between countries [26], and therefore depend on national regulations. Generally, DHW temperatures around 45 °C at the kitchen tap and 40 °C in the shower are sufficient for comfort [27,28] as presented

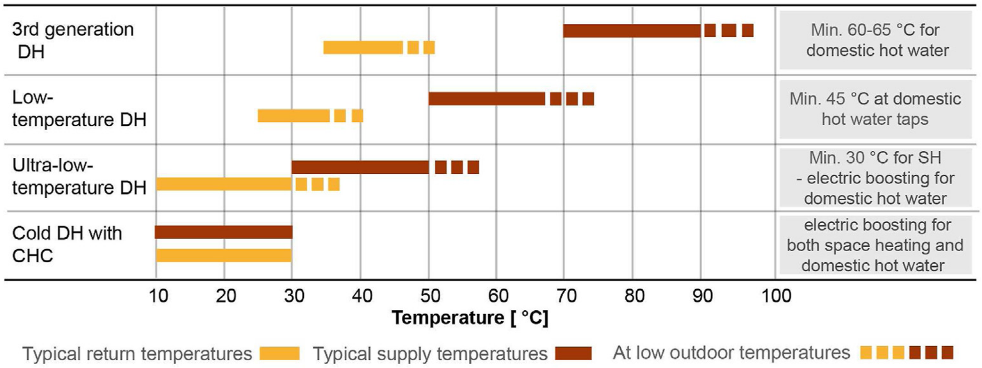

Fig. 1. Overview of typical temperature for space heating and DHW systems in current and future district heating systems.

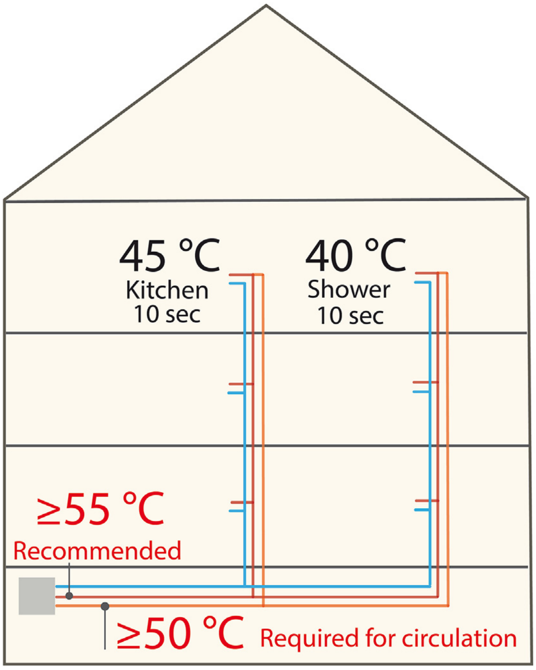

Fig. 3. *Examples of temperature requirements for DHW installations based on Danish legislation* [27,29].

in Fig. 3. Still, it is common to apply higher DHW temperatures to avoid Legionella bacteria growth, occurring at temperatures between 20 and 45 °C. Therefore, it is common to maintain 55–70 °C in DHW tanks and 50–60 °C in the DHW circulation system [26].

Surveys have demonstrated the strong relationship between DHW temperature and the risk of Legionella bacteria growth [30]. Surveys in Germany and Hungary found that maintaining DHW temperatures above 50–55 °C reduced the risk of high concentrations, while temperatures above 60 °C almost eliminated the bacteria [31–33].

German legislation relaxes the temperature requirements for DHW installations when using direct heat exchangers with a water volume of less than 3 L in the pipes [34]. However, recent research has suggested that low water volumes may not protect against legionella bacterial growth enough to loosen temperature requirements [31,35,36]. In a sample of small and large systems, DHW temperatures below 50 °C yielded high concentrations, while temperatures above 60 °C eliminated Legionella bacteria [31]. The risk of legionella growth was more prevalent in installations with DHW tanks than in those with heat exchangers, regardless of the water volume [31,32]. Similarly, others could not find a relationship between building size and legionella contamination [33]. These results highlighted that DHW temperatures affect Legionella contamination and that the drinking water supply introduces the bacteria [31,32].

It is common to have balanced mechanical ventilation in new and renovated dwellings, offices, and schools. In such cases, district heating may supply a heating coil to pre-heat the supply air and minimise cold draughts. The comfort temperature of the fresh air entering the building zones depends on the type of ventilation, the location of the air inlet, and the air velocity. The design minimum temperature of the supply air is typically around 16 °C [37], in which case, the space heating systems provide supplemental heat at the zone level to maintain comfort. The district heating temperatures required to deliver roughly 16 °C largely depend on the design of the heating coil. New ventilation heating coils have design temperatures of around 60/30 °C [38].

2.2. Share of heat demands

In cold climates, space heating represents the primary share of total heating consumption. In Denmark and Sweden, the demand for space heating in existing apartment buildings is around 60–70% of the total heat demand [39,40]. In schools and office buildings, where DHW consumption is typically minimal, space heating constitutes around 90% of the total heat demands [39]. Comparatively, the demand for space heating in new and renovated buildings is less due to energy-saving measures such as mechanical ventilation with heat recovery, high insulation levels, and low-energy windows. Meanwhile, DHW demands have been increasing, and few measures are available to reduce energy consumption for DHW preparation [39,41]. One effective measure is to install drain water heat recovery. It is typically applied vertically below shower drains and has provided heat recovery ranging from 29 to 75% in experimental tests [42,43]. The technology is well-established and straightforward, as the shower's cold-water supply pipe is coiled helically around a standard-size drain pipe. The drain water forms an annular film on the pipe walls, enhancing heat transfer but substantially limiting the efficiency when applied horizontally. The need for vertical orientation presents a barrier to widespread adoption, so there are efforts to develop efficient horizontal units [44,45]. Shower drains commonly discharge water at 30–38 °C [44], and showering represents more than 80% of DHW heat demand [46], which presents ample opportunity for savings. However, these devices have not seen widespread adoption or acceptance, so there is a strong need for promotion in the residential sector [47]. Therefore, in Northern Europe, the share of district heating consumption applied to DHW in new or energy-renovated multi-family buildings is likely to be in the range of 45–50% in the future [39,41,48]. Fig. 4 summarises the shares of heat typically used for space heating and DHW in three different building types in Denmark.

In new and renovated buildings, excessive supply air temperature set-points can increase the heat share from ventilation heating. However, the demand for air heating should be relatively small for well-functioning mechanical ventilation systems with efficient heat recovery, which pre-heats the ventilation air to comfortable temperatures without the air heating coil [37]. The exception is in freezing outdoor temperatures when the ventilation system partially bypasses heat recovery to elevate exhaust temperatures and avoid frost accumulation. Therefore, ventilation heating should not constitute a large share of the total heat demand in buildings,

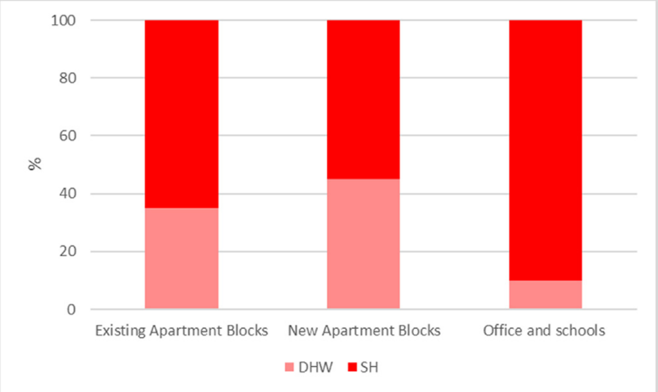

Fig. 4. Typical share of heat for DHW and space heating in three different building types in Denmark.

apart from situations without heat recovery or where freezing temperatures are ordinary.

Space heating installations significantly impact district heating temperatures in offices and existing residences, while DHW installations likely dominate this impact in new and renovated buildings. Therefore, DHW installations largely determine the necessary supply temperature and obtained district heating return temperatures in new residential areas [41]. The variable part of the district heating load will decrease with the space heating demands, while the daily heat demands for DHW will form a constant base load that is similar in both the winter and summer period [48].

2.3. Typical district heating substations

The typical layouts of heating installations vary significantly based on age, geographical location, national regulations, and other factors. This section provides an overview of the recommended designs for typical heating installations in buildings supplied by 3rd and 4th generation district heating networks to provide a base understanding of the impacts on the district heating temperatures.

2.3.1. Space heating systems

Space heating substations have either a central heat exchanger that transfers heat between the district heating network and the internal space heating system or a direct connection where the district heating network supplies hot water directly to the pipes of the internal spacing heating system. Fig. 5 shows typical layouts of these substations. As illustrated by the figure, the substation should have: (A) a controller that enables weather-compensated control to decrease heating system supply temperatures as outdoor temperatures increase and demands for heating decrease [49]; (B) temperature sensors in the outdoor air and on the supply pipe to realise weather-compensated control; (C) a valve that controls the supply of district heating to regulate the heating system supply temperatures according to the weather-compensated set-points; (D) possibly a differential pressure controller to ensure appropriate operating conditions for the control valve; and (E), if directly connected, a non-return valve to mix the space heating return water into the supply water to achieve the desired supply temperature set-point.

2.3.2. Domestic hot water systems

Most domestic hot water installations use an instantaneous heat exchanger or a buffer tank. In both cases, a heat exchanger physically separates the fresh drinking water from the district heating water.

Instantaneous heat exchangers heat DHW instantaneously when tapped, reducing the stored volume of DHW and the risk of Legionella growth. Conversely, they must satisfy the peak demand instantaneously, which requires larger heat exchangers and service pipes (i.e., the pipes connecting the district heating network to the building) in single-family houses or terraced houses [50]. In apartment buildings, occupants demand DHW at various times, diffusing the peak demand [51–53].

Buffer tanks store DHW locally, requiring careful consideration of Legionella growth. Tank solutions are best suited for facilities with simultaneous tappings (e.g. sports facilities) or cases needing substantial bypass flows to maintain high enough temperatures in the pipes (due to long service pipes or low space heating demands) [49]. Buffer tanks can reduce the peak heat demand due to a constant low charging rate, but they increase the heat loss from DHW installations.

Fig. 6 shows the layouts of the two DHW solutions. Each DHW substation includes a controller (A) that regulates the district heating flow through the control valve (C) to achieve the temperature set-point of the DHW. The temperature is measured on the DHW supply pipe or inside the tank (B) for a fast response. A differential pressure controller (D) can ensure stable operating conditions for the control valve despite the relatively large and varying pressure differences in the network. The DHW heat exchanger often includes a small bypass (E) to maintain sufficient temperatures in the district heating service pipe to avoid waiting for DHW, particularly in summer when there is no space heating demand. The bypass valve opens when the district heating supply temperature drops below 35–40 °C at the heat exchanger. The return flow from the DHW circulation often connects to the middle of the tank.

2.3.3. Balanced mechanical ventilation systems

In buildings with balanced mechanical ventilation, a district heating system can directly or indirectly supply heat via an air heating coil. An indirect connection hydraulically separates the district heating system from the air heating coil to avoid freezing in district heating pipes.

Fig. 7 shows a typical layout of an air heating coil when freezing outdoor temperatures require a partial bypass of heat recovery to maintain exhaust temperatures above 0 °C. The controller (A) varies the supply temperature to the heating coil to maintain the required air temperature, as measured in the supply air (B). The control valve

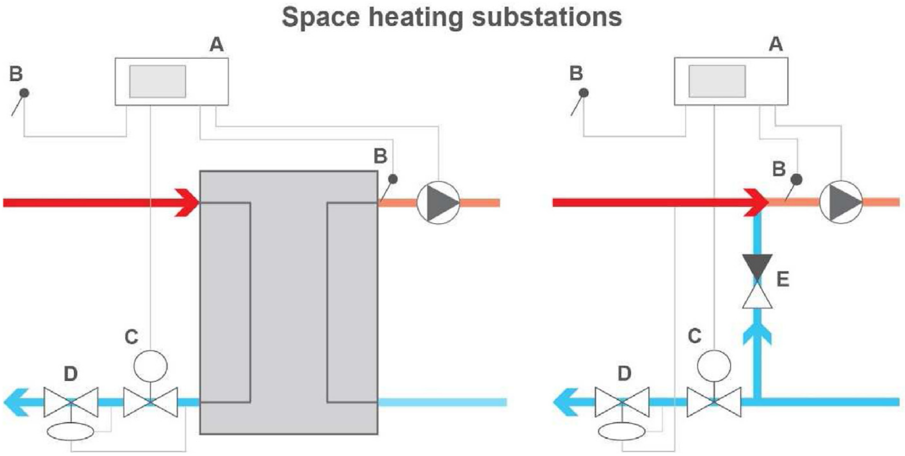

Fig. 5. Example of basic layout for an indirect (left) and a direct (right) space heating substation. (A) Controller (B) Temperature sensors (C) Actuator and control valve (D) Differential pressure controller (E) Non-return valve.

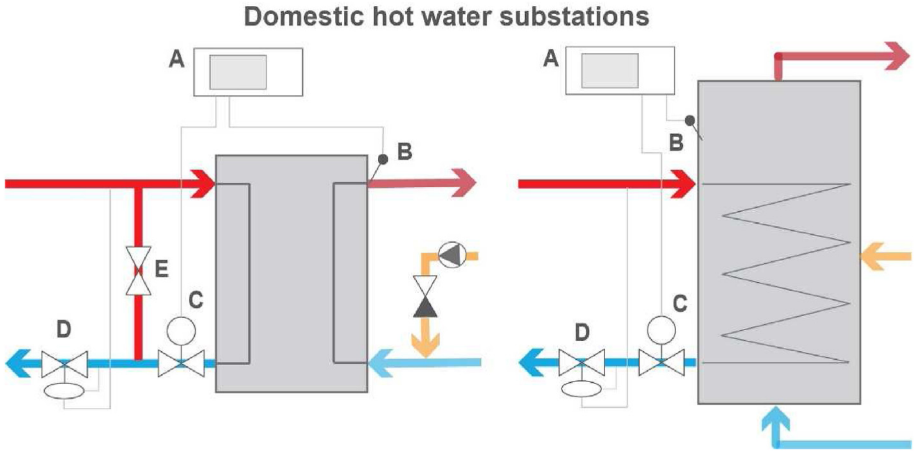

Fig. 6. Example of layout of a DHW heat exchanger (left) and a DHW storage tank (right). (A) Controller (B) Temperature sensor (C) Actuator and control valve (D) Differential pressure controller (E) Bypass valve.

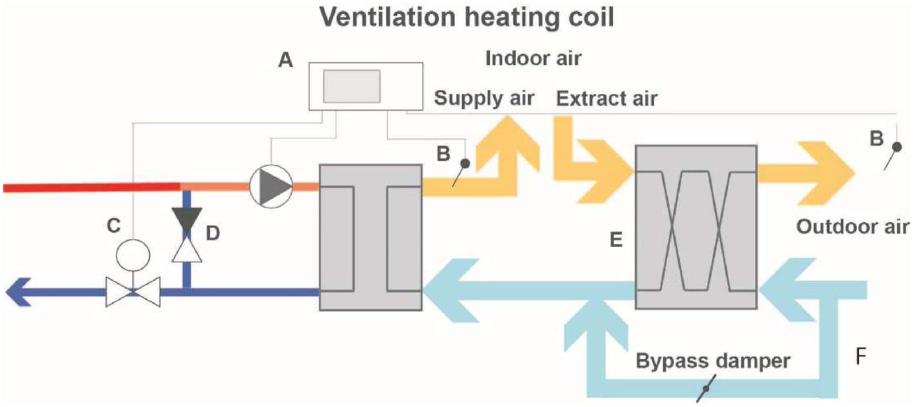

Fig. 7. A typical schematic from a ventilation controller in a building with variable heat recovery and a heating coil. (A) Controller (B) Temperature sensor (C) Control valve (D) Bypass valve (E) Heat recovery unit (F) Heat recovery bypass damper.

(C) governs the share of recirculated water in the mixing loop. If the air temperature is too low, the controller opens the valve to recirculate less return water into the supply. The heating coil is often downstream of the air-to-air heat exchanger (D). With highly efficient heat recovery, supply air temperatures are typically above the minimum threshold for thermal comfort without air heating. When operating ideally, the heating coil is only active when partially bypassing heat recovery through a bypass damper (E) to avoid frost accumulation. In rare cases, the flow through the heating coil is varied to maintain the required supply air temperature, which offers the potential of lower return temperatures but risks freezing in the pipes.

2.4. *Typical malfunctions in district heating substations*

The design and operation of heating systems and district heating substations affect the required supply temperatures and attainable return temperatures. The design temperatures in new buildings are relatively low, yet, in some cases, researchers have been unable to obtain lower return temperatures in newer buildings [54]. Potentially, malfunctions or errors during operation are causing these higher-than-expected return temperatures.

District heating substations often have malfunctions causing higher district heating temperatures [55–57], and many malfunctions are quickly and inexpensively fixable. Conducting on-site visits to problematic buildings helps identify and eliminate these malfunctions to obtain lower temperatures [56,58]. Several resources provide exhaustive lists of possible malfunctions [56,59,60], while others describe working routines for identifying errors [49,56].

A good starting point for identifying errors in district heating installations is to recognise common errors. Researchers surveyed over 246 Swedish district heating substations providing high return temperatures from 1992 to 2002 [61]. Almost 63% of the errors were due to faults and improper temperature set-points and regulation in components on the building side (as opposed to the network side).

The Danish district heating company supplying heat to greater Copenhagen published a similar list of errors [62]. Meanwhile, a study from 2019 reported on the typical faults experienced by 56 Swedish district heating companies [57]. The survey found that the faults most frequently occurred in heating system components or control valves and actuators, accounting for roughly 31% and 23% of substation faults, respectively. Controllers and incorrect set-points were less frequently perceived to cause faults. In contrast, leakages due to poor maintenance were a prominent issue, sometimes related to substandard gaskets and poor welding of heat exchangers.

Unnecessary bypasses, shunts and mixing valves can be present in space heating systems, DHW systems, and ventilation systems

[56,63,64] They often remain from heating with non-condensing fossil-fuel boilers requiring high flows and return temperatures to avoid corrosion of the heat exchangers. These unnecessary bypasses and valves are no longer necessary once connected to district heating networks. In some situations, district heating water circulates through inactive air heating coils, causing high flows and return temperatures. One should remove unnecessary bypasses, valves, or inactive air heating circuits and add mass-flow control to active air heating circuits.

Another typical error reported by Danish and Swedish district heating companies is unnecessarily high-temperature set-points, causing poor operation and excessive energy consumption [56,62,63]. The supply temperature set-points in heating systems should be less than the available temperature from district heating to avoid fully open valves causing excessive flows. For space heating systems specifically, the supply temperature set-points should vary according to outdoor temperatures to minimise the heat loss from distribution pipes while minimising the negative impacts from stuck-open thermostatic valves. In DHW systems, the temperature set-point should not substantially exceed the national requirements for Legionella prevention to avoid excessive circulation heat loss and lime precipitation. Lastly, excessive air heating can reduce zone temperature control and increase return temperatures from the heating coil. Therefore, the set-points temperatures for the supply air in ventilation systems should not exceed the desired room temperatures when using radiant systems to heat zones individually.

Broken components should always be replaced, whether it concerns controllers, control valves, or actuators. These are typically the main components in substation specifications, so they must function correctly. Several guidelines additionally stress the importance of proper sizing of control valves [49,65]. Oversized valves can lead to poor flow control in district heating networks, especially when there are errors in heating systems [62], leading to excessive flows in heat exchangers or DHW tanks and consequently high return temperatures. Issues caused by oversized control valves can, in the worst case, be resolved by replacing the valve or installing a pressure differential controller across the control valve [62]. To attain the best regulation, the supply temperature sensors for both the DHW and space heating should be in close contact with the supply pipes after the heat exchangers. When the space heating system is turned off (e.g., during summer), the flow on the district heating side of the heat exchanger should be closed manually. A lack of space heating flow could prevent the supply temperature set-point from being reached, so manually closing the district heating flow avoids unnecessary flows with high return temperatures.

Heat exchangers have not generally been a common source of problems [57,63], but fouling of heat exchangers and design errors occur in some cases [57,61,62]. Fouling of heat exchangers can often be identified by a temperature difference of more than 3–5 °C between the return temperatures on the network side and the building side in heat exchangers operating close to their design conditions [49,62,66].

3. Obtainable supply and return temperatures

3.1. Existing heating systems

There are lower bounds to attainable supply and return temperatures in ideally functioning heating systems. A well-functioning system can typically provide return temperatures of 25–35 °C. Several Danish cases provide empirical evidence of this, including small single-family dwellings with direct district heating connections [67], new single-family dwellings operating with supply/return temperatures of roughly 50/30 °C [68], and existing single-family dwellings with average supply/return temperatures around 55/30 °C [68] and 45/35 °C [69]. Several cases demonstrated low supply temperatures of 55–60 °C, but errors and malfunctions can easily cause return temperatures to be higher than expected [68,70,71].

Well-functioning, well-designed heating systems in multi-family dwellings can yield return temperatures of 30–35 °C [67,72,73]. In Sweden, 109 radiator heating systems, serving between 20 and 300 apartments each, had supply temperatures of 55 °C or below at outdoor temperatures of 5 °C, with return temperatures of roughly 25–40 °C [73]. In Switzerland, residential buildings used supply temperatures of 35–58 °C at outdoor temperatures of 5 °C but with relatively high return temperatures, as the water temperature through the radiators decreased by only 2–12 °C [74].

The temperatures obtained from a well-functioning DHW installation depends on their design and specifications. Minimum supply temperatures can range from 50 °C to 70 °C depending on the temperature requirements to avoid harmful Legionella growth [29,75]. District heating can supply temperatures below 50 °C if local electric boosting increases DHW temperatures [76–78].

Return temperatures from DHW installations can be as low as 25 °C for installations with instantaneous heat exchangers, short service pipes and no circulation of DHW. Return temperatures for DHW systems with buffer tanks and DHW circulation are often in the range of 40–45 °C [39]. As DHW represents an increasing share of the total heat demand in new and energy-renovated buildings, high return temperatures from DHW systems will have a more significant negative impact. As a result, district heating return temperatures in energy-renovated apartment buildings can be above 40 °C for much of the year [41].

The main cause of high return temperatures is DHW circulation. DHW systems typically maintain at least 50 °C in the circulation loop to avoid Legionella growth, so the return temperatures can rise to 50 °C when residents are not using DHW. In many cases, such high return temperatures dominate because the circulation heat losses constitute the major share of the total heat demand for DHW [39,41,48]. As Fig. 8 illustrates, the total heat consumption for DHW systems derives from two main aspects: the heat losses in the system and the heat consumed as DHW. The ‘DHW efficiency’ is the ratio of heat consumed as DHW relative to the total heat consumption for DHW – the remainder is heat loss. Existing Danish buildings have had measured DHW efficiencies of roughly 15% in office buildings, 33% in apartment buildings, and 48% in single-family houses [39]. However, 13 Danish apartment buildings were found to have relatively higher DHW efficiencies between 30 and

Fig. 8. Heat *losses in typical Danish DHW installations with circulation (based on* [39]*).*

77% [79]. Meanhile, while surveys from Poland found DHW efficiencies between 29.5% and 43.3% [80], and in China, various types of buildings and DHW systems had DHW efficiencies between 28.7% and 56.2% [81].

The DHW efficiency has a significant impact on the district heating return temperatures. Benakopoulos et al. presented an overview of the potential for low temperatures in different DHW systems [82], where reduced district heating supply temperatures increase the minimum ideal return temperatures. Therefore, it is essential to reduce the need for DHW circulation and ensure proper insulation of DHW circulation pipes to achieve a high degree of energy efficiency and reduce district heating return temperatures in the future.

3.2. After energy renovation of building envelopes

There is a common misbelief that heating elements are too small to allow low-temperature heating in existing buildings, but this is rarely valid. Studies have shown that, in up to 80% of Danish buildings, the radiators are large enough to accommodate the transition to low-temperature district heating [83]. Where the size of the radiators requires higher heating system temperatures during cold periods, energy renovations are likely to reduce this demand during the coming decades. Resultingly, most existing buildings will have sufficiently large heating elements for district heating supply temperatures below 55 °C for nearly the whole year [21,41,84].

Future energy renovations should result in oversized heating elements relative to the decreased heat demand, so the design and operation of heating systems should be according to lower temperatures regimes [85] A renovation that included new windows, thicker insulation of the building envelope, and a ventilation system with heat recovery reduced the total heat demand of a 1970s apartment building in Borlänge, Sweden, from 149 kWh/m^2 to 65 kWh/m^2. Therefore, the renovation made it possible to reduce the supply/return temperatures in the existing radiator system to 48/36 °C [86]. In Backa Röd, the total energy demand of a 1970s apartment building was reduced from 178 kWh/m^2 to 63 kWh/m^2 using similar energy renovation measures [87].

District heating can supply heating coils used for heating ventilation air. The primary purpose of a heating coil is to heat the incoming air to a minimum comfort temperature. In the Danish climate, ventilation heat losses are typically in the range of 35–40 kWh/m^2 per year, but up to 90% can be recovered from the exhaust air using a counterflow air-to-air heat exchanger [88]. This potential depends on the airtightness of the building envelope, as the outgoing air must pass through the heat exchanger to transfer heat to the supply air. Therefore, modern airtight buildings should be equipped with heat recovery ventilation to transfer heat from the outgoing air to the incoming air to reduce heat demand. In leaky existing buildings, heat recovery may be installed to reduce heat demand if accompanied by measures to improve airtightness. In five separate renovation projects of multi-family dwellings in Sweden and Estonia, the buildings received heat recovery ventilation and improvements to the building envelope, resulting in overall heat savings of 37%–71% [89].

3.3. After improvements to heating and ventilation systems

3.3.1. Improvements for space heating systems

As presented in Section 2.4, heating system malfunctions in buildings form a large share of faults experienced by Swedish district heating companies [57,61]. These errors are often related to the poor hydronic balancing of space heating systems or missing or broken radiator valves [57]. Faults in space heating systems range from simple faults and inefficient control settings to undersized heating elements or heat exchangers.

Heating systems can be operated with low flows and high temperature differences or with high flows and low temperature differences, where 'temperature difference' refers to the cooling of hot water from the entrance to the exit of the heating element [22]. A low-flow strategy enables the lowest possible return temperatures in ideally functioning heating systems. However, obtaining maximal temperature differences can be challenging when employing a low-flow strategy, as faults such as stuck-open valves and bypasses yield high return temperatures roughly similar to the supply temperatures. Conversely, a high-flow strategy yields slightly higher return temperatures in ideally functioning heating systems, but the strategy is more resilient to common faults by ensuring that the return temperature never surpasses the lower supply temperature [90]. The high-flow strategy can even reduce return temperatures in cases without proper hydronic balancing and flow control [91]. The slight temperature differences and guaranteed maximum return temperatures support the transition to low-temperature district heating while also reducing the heat losses from distribution pipes inside the building.

The simplest solution to improve the space-heating operation of an existing building is to modify its weather compensation curve, which adjusts the supply temperatures according to outdoor temperatures. Without further changes or investments to a heating system, the curve can be updated with lower supply temperatures to obtain high-flow operation with slight temperature differences. The update may initially require a simple tuning by the janitor or building service personnel [92]. The minimised supply temperatures motivate the occupants to use all available radiators to obtain their desired comfort level instead of inefficiently relying on too few radiators. In this scenario, if occupants cannot obtain their desired room temperatures unexpectedly, it indicates a local fault that demands repair or an instance of misuse that warrants added instruction. In a Swedish survey of multi-storey buildings, 8% of space heating systems had supply temperatures below 55 °C when it was −16 °C outdoors (the design temperature). Furthermore, 87% had supply temperatures below 55 °C at 0 °C [73], demonstrating the potential for low supply temperatures in existing buildings, even at cold outdoor temperatures.

Fig. 9 presents an example of a minimised weather compensation curve. The Danish multi-storey building was from the 1980s and had radiators designed for supply/return temperatures of 70/40 °C at an outdoor temperature of −12 °C. The yearly energy consumption for the space heating (from the central heat meter) was divided by the yearly number of heating degree hours to obtain a heat demand coefficient for the building. Knowing the capacity of the installed radiators, the authors calculated the necessary supply and return temperatures for part-load operation at each outdoor temperature. The resulting curve assumes that the heating system is well controlled and operated, and it illustrates the potential for lowering the supply and return temperature in such a building.

It can be helpful to the efficiency of district heating networks to avoid intermittent heating based on occupancy profiles or sleep schedules in well-insulated buildings [93], particularly in heavy buildings with high thermal inertia. Such buildings have relatively low heat loss and cool down slowly. Gadd and Werner have explained that, in such buildings, intermittent heating shifts the demand to the re-heating period rather than significantly reducing total heat consumption, which increases peak demand and yields higher return temperatures [94]. The higher return temperatures reduce the thermal capacity of the network, such that district heating operators need to compensate by increasing supply temperatures. Thus, periodic changes to room temperature set-points are only appropriate for poorly insulated buildings characterised

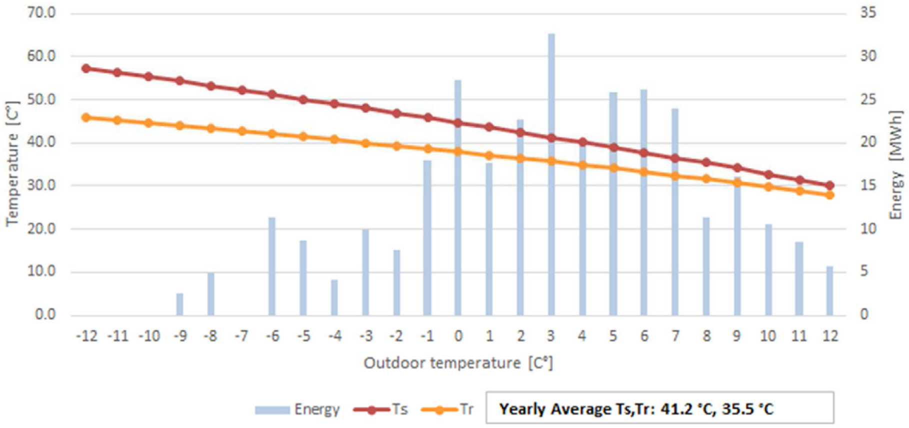

Fig. 9. Improved weather compensation curve for minimum supply temperatures in a Danish building with radiators designed for 70/40 °C.

by high heat demand when maximising the system efficiency in a district heating network.

Occupants often incorrectly misuse thermostatic valves as on-off or proportional controllers, where higher settings correspond to higher heat output from heating elements. Furthermore, occupants often use only a few radiators to heat their entire dwelling, leading to higher return temperatures [92]. A robust operation instead uses all radiators in heated zones and follows the general guideline to end-users: 'set the thermostatic valves to maintain the desired indoor temperature and do not alter it.'

Installing thermostatic valves and ensuring hydronic balance can also improve heating system operation, typically providing heat savings and short payback times [95]. Yet, only 24% and 43% of dwellings have thermostats in France and the United Kingdom, respectively [25], showing ample potential for improvement.

Installing string-balancing valves and radiator valves with proper pre-settings on all radiators helps maintain proper hydronic balance while limiting excessive water flows through individual heating elements. This limits the maximum flow through the valve, ensures the necessary flow distribution throughout a building, and provides the occupants with adequate control of their thermal comfort [49,95]. In several cases, proper hydronic balancing of space heating systems equipped with thermostats provided heat savings in the range 9–15% with a payback period of only 1–2 years [95,96]. However, savings typically depend on the condition of the system before making improvements. The installation of balancing valves can also reduce occupants' complaints and enable reduced heating system temperatures in cases with insufficient heating or high return temperatures in some zones [96]. Lastly, pre-settings appropriately limit the water flow through individual heating elements, which is vital for low-temperature operation, as it helps to limit the consequences of inappropriately operating thermostats as open/close valves or with intermittent temperature set-point schedules [97,98]. Otherwise, both misuses can cause extreme flows with high return temperatures during re-heating periods that significantly impact the overall heating system temperatures [99].

Automatic hydronic balancing has been perceived as an essential technical improvement to enable low-temperature district heating [11]. Manual balancing is typically performed by experts and therefore depends on the availability of the workforce to make adjustments both initially and after changes to the heating system [96]. Therefore, future industrial developments include new electronic thermostatic valves limiting the flows and return temperatures from radiators. This adapts to the changes in the heating systems' operation and secures automatic hydronic balancing in a cost-effective way. However, in the authors' opinion, the critical design recommendation is that these new devices must be robust against the end-users' tendencies to misuse these control elements because this represents one of the most impactful factors towards elevated temperatures in heating systems.

Generally, these first measures aim to reduce typical misoperation of existing heating systems, including unintentional bypass and poor control of water flows. They also aim to limit too high supply temperature set-points, which janitors often implement in response to comfort complaints rather than fixing distributed errors.

Invasive and expensive technical measures are rarely needed for low-temperature operation but can be applied to reduce heating system temperatures in existing buildings. These include installing new heat exchangers, replacing critical radiators, and replacing heating elements or complete heating systems. The latter is expensive, so it is only relevant for old single-pipe heating systems operating with high supply temperatures with radiators near internal walls. Replacement heat exchangers can be designed to ensure compatibility with lower supply and return temperatures, which is also relevant for replacing worn-out or leaky heat exchangers [57]. One may consider only increasing the radiator sizes in living rooms or bathrooms – where occupants often prefer higher comfort temperatures – if it enables a more significant reduction in overall heating system temperatures [100].

To summarise, current research shows that existing space heating systems can operate with low temperatures, and the following measures can reduce heating systems temperatures in existing buildings:

1. Optimise the weather compensation curve with minimised supply temperatures and high-flow operations.
2. Fix the faults in heating system operation, including harmful temperature settings and unnecessary bypasses.
3. If necessary, upgrade the heating systems by installing local control devices such as thermostatic radiator valves or string balancing valves or replacing heat exchangers, critical radiators, and heating systems at the end of their lifetimes or when is appropriate to ensure proper comfort and low operating temperatures.

3.3.2. *Improvements for domestic hot water systems*

In existing residential buildings, minimising the circulation heat losses is vital for reducing district heating return temperatures, as circulation losses represent a substantial share of the utilised heat for DHW. Adding insulation to the DHW pipes will reduce heat losses and save energy while potentially reducing district heating return temperatures [82]. In buildings operating with low-temperature space heating, it may be advantageous to directly reheat DHW circulation in an external heat exchanger and cascade its district heating flow to the space heating system to reduce its return temperature [82]. This concept relies on low-temperature space heating to cool the district heating flow for DHW circulation instead of relying on the fresh cold water flow into the tank, which may be insufficient at times.

Office buildings have low DHW demand typically, and taps are spread out spatially. In such cases, local electric heaters could prepare DHW instead of central preparation and circulation. In small single-family dwellings with short distances between the DHW heating unit and taps, there may not be a need for DHW circulation. Due to insufficient flows during the summer, removing the DHW circulation system can lead to cooling in the service pipes when using instantaneous heat exchangers instead of tanks. This may increase the need for bypass flows, harming return temperatures, especially in dwellings with long service pipes.

Other technical solutions to reduce district heating temperatures in DHW systems include reducing charging flows for DHW tanks and installing booster heat pumps or sterilisation systems. Fast-charging of DHW tanks often causes unnecessarily high peaks in demand with high return temperatures in the district heating system [68,101]. Implementing a flow-limiting control strategy can reduce peak demand and return temperatures. A demonstration case in Denmark reduced the peak demand for heating a DHW tank in a new apartment building from 70 to 80 kW to approximately 25 kW while reducing return temperatures by roughly 10 °C [101]. The solution involves updating the district heating flow controller to limit the charging flowrates to the tank while ensuring the potential for higher flowrates in periods with extraordinarily large DHW demand [102]. This was seen to be necessary for particular days of the year, such as December 31st when many occupants take showers simultaneously. One can obtain similar peak reductions in existing buildings, but it can be challenging to obtain similar return temperature reductions if the DHW circulation pipes are insulated insufficiently. The supply temperature in the network and the extent of circulation heat losses limit the potential to achieve low return temperatures from DHW tanks. As presented in Fig. 10, for high supply temperatures and low DHW efficiency (i.e. high circulation losses), DHW tanks cannot provide low return temperatures.

In situations that prioritise low district heating return temperatures and where relatively high circulation heat losses yield high return temperatures, a DHW circulation heat pump can reduce return temperatures. Such heat pumps use district heating water as a heat source, providing lower return temperatures. In a recent test, this solution reduced district heating return temperatures from approximately 45 °C to 20 °C, while the electrical energy represented a 15–20% share of the heat for DHW recirculation [103,104].

The use of decentralised heat exchangers for DHW – also referred to as ‘flat stations’ in apartment buildings – minimises circulation heat losses and the need for bypasses in DHW installations while reducing the risk of legionella growth even at lower ranges of district heating supply temperatures between 50 and 55 °C. Researchers have estimated that flat stations are not more expensive than standard DHW systems and could be a preferred solution for new and existing buildings [105]. A Danish case study reported the performance of flat stations in an existing building, where a two-pipe heating system replaced a one-pipe system [105]. The reduced length of distribution pipes provided roughly 8% heat savings while eliminating the central substation and its heat losses provided 10% savings. The most significant savings came from increasing occupant awareness and allowing individual optimization of heating supply temperatures, which yielded 12% savings for a total of 30%. The district heating return temperature decreased from 65 °C to 35 °C. A Danish case study similarly estimated that using flat stations could reduce heat losses up to 30% compared to traditional distribution systems for DHW and space heating [106]. Flat stations can provide an easy solution for energy metering, which makes distributing energy costs between apartments more feasible. When using flat stations, they should be accessible from the stairwell, and individual heat consumption and heating temperatures should be available for fault detection and diagnosis.

One should aim to reduce DHW temperatures in new and renovated buildings, where DHW represents a large share of the total heating consumption. Progressive technical solutions such as disinfection or small DHW volumes may help overcome the risk of Legionella and thereby enable a reduction in DHW temperatures below the current requirements. The flat-station concept – and new concepts for disinfection and electric boosting solutions – warrant further research to demonstrate safe operation concerning Legionella even with temperatures below the current regulatory minimums. A case study investigated how disinfection equipment

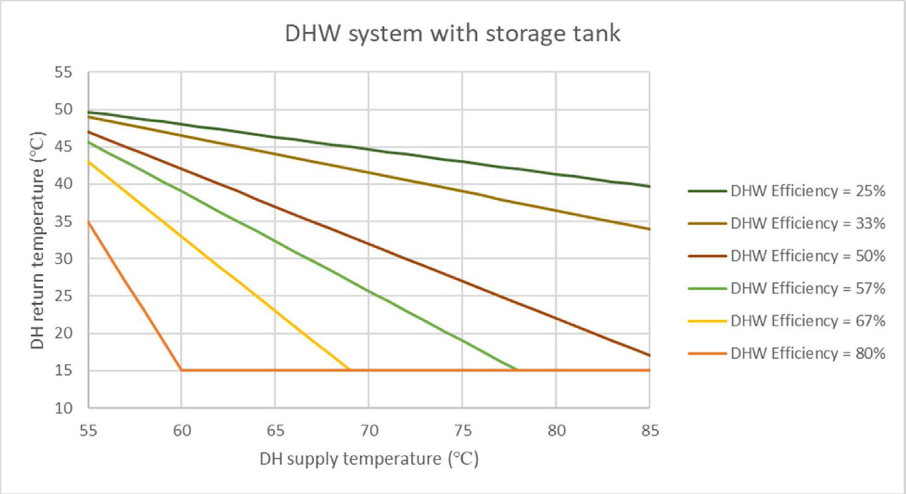

Fig. 10. Return *temperature as function of supply temperature and circulation heat losses from DHW tanks* [82].

installed in DHW systems could affect the heat losses inside buildings [107]. DHW circulation decreased from 55/51 °C to approximately 47/44 °C and reduced the heat loss by roughly 35%. Once demonstrated, these solutions could enable district heating supply temperatures corresponding to the required comfort temperatures of 40–45 °C. In such cases, district heating should directly cover the space heating demand without boosting temperatures. Many refer to this as ultra-low-temperature district heating. In places with low heat density, the combination of electric boosting (e.g., DHW heat pumps or in-line electric heaters) with district heating supply temperatures of 40–45 °C can provide an energy-efficient alternative to higher temperature district heating [28,108–110]. Electric boosting is rarely financially viable compared to low-temperature district heating due to the current high cost of electricity or components [108–113]. Still, a simple in-line electric heater combined with a micro hot-water tank may be favourable to a heat pump solution [114–116]. In such cases, the electrical fuses and local electrical grid must support the required peak electrical consumption [28].

To summarise, current research shows that the following measures reduce temperatures for DHW in existing buildings:

1. Minimise the circulation heat losses and insulate DHW installations properly.
2. Limit charging flowrates for DHW tanks based on actual tapping profiles to minimise peak loads and return temperatures.
3. Consider cascading the district heating flow for DHW circulation to a low-temperature space heating system.
4. Consider disinfection or electric boosting solutions such as heat pumps or direct electrical resistance.
5. Use flat stations and instantaneous DHW preparation when upgrading existing DHW installations.

For DHW solutions, Legionella is still a central concern. To obtain the most extensive benefits from the solutions mentioned above – such as disinfection, electric boosting and flat-stations – further research is needed to demonstrate safe operation with DHW supply temperatures as low as 45 °C.

3.3.3. *Improvements for ventilation systems*

Installing mechanical ventilation with heat recovery reduces heat demand and allows lower hot water supply temperatures for space heating. In Danish residences, it is possible to recover up to 90% of the ventilation heat loss (typically 35–40 kWh/m^2 per year) depending on the airtightness of the building envelope and other factors. One is the prevalence of sub-zero outdoor temperatures, which requires supplementary heating to minimise the risk of freezing inside the heat exchanger. Another is the balance of supply and exhaust airflows, as there should be a slight under-pressure to minimise heat loss due to wind and stack effects. The extent of this under-pressure depends on the airtightness of the building [117], so designers typically specify equal supply and exhaust airflow rates.

In existing buildings, installing mechanical ventilation with heat recovery is relatively costly, but it is cost-effective in airtight buildings. Researchers in Estonia simulated a complete renovation of a multi-family dwelling, including mechanical ventilation with heat recovery. The resulting energy-weighted average return temperature to the district heating network was 22 °C (27.4 °C for space heating; 17.2 °C for DHW). When they simulated a renovation package that instead recovered heat using an air-to-water heat pump with the evaporator in the exhaust air, the district heating return temperature increased by 10–15 °C [118].

After installing ventilation with heat recovery, the system may be prone to errors that increase the demand for space heating. Researchers and practitioners have observed errors that cause unnecessary bypasses of heat recovery, such as sensor faults or improper tuning [89,119] Ventilation airflows may not be configured correctly during commissioning, creating unintended imbalances between supply and exhaust airflows that increase the heat loss due to unwanted airflow through the building envelope. The cause may be measurement error when balancing airflows through air inlets and outlets or due to air leakage through ducts. From the estimated annual energy impact of the top 20 faults in commercial buildings in the USA, air-duct leakage accounted for 22.7%. Excessive airflow through the building envelope accounted for another 26.1%. Together, the two types of faults accounted for 25.8 TWh in annual energy losses [120]. Thus, building operators should implement functional performance testing at regular time intervals, if not continuously, to ensure proper operation of ventilation systems to minimise heat demand [121,122]. Narrowing the performance gap between expected and realised heat demand can enable lower supply and return temperatures in heating systems.

Ventilation inherently affects heat demand by replacing heated stale air with cold outdoor air during the heating season. Heat recovery reduces the demand for space heating, which helps enable low-temperature heating. Centralised ventilation systems have long ducts that can demand high pressures and may incur leakages. Decentralised ventilation provides an alternative by serving single apartments, floors or zones, limiting size and pressure requirements for ducting. Such units are more difficult to operate and maintain, so the authors recommended having service agreements and continuous performance monitoring using operational data (e.g. 'smart' ventilation, building management systems). The heat recovery efficiency of most decentralised ventilation systems exceeds 80%, so the supply air is within a comfortable range of the indoor air. Thus, the heating coil is only needed when the system partially bypasses heat recovery to maintain exhaust air temperatures above freezing. In temperate climates, it can make sense to use electric heating coils or none at all to avoid the costs and challenges of installing decentralised hydronic heating coils. Otherwise, a hydronic heating coil generally yields lower costs and primary energy consumption.

To summarise, the following measures can reduce ventilation heat loss and thereby permit lower heating temperatures in space heating systems:

1. Install mechanical ventilation with efficient heat recovery, and only operate the air heating coils during freezing conditions when bypassing heat recovery may be necessary to avoid accumulating frost.
2. Regularly perform functional performance testing to ensure balanced supply and exhaust ventilation rates and minimal duct leakage, as this helps to maximise heat recovery.
3. To overcome space constraints in existing dwellings in temperate climates, consider installing decentralised ventilation without hydronic heating coils, as the required heat recovery bypass is often minimal.

3.3.4. *Continuous commissioning of digitalized heating systems*

The ongoing digitalisation of demand-side systems provides a means to detect and diagnose faults in heating and ventilation systems, enabling new tools that can assist building operators with maintaining low system temperatures. There are many examples of using data from district heating substations to detect and diagnose faults related to high system temperatures [55,57,58,123–126]. However, far fewer examples use hydronic heating system data inside residential buildings, likely due to inaccessibility. The few documented examples have used data from heat pumps [127], digital heat meters [57,128], programmable room thermostats [99], and digital heat cost allocators [129]. As more of these data sources become available, one can expect to see more tools for continuous commissioning. Prior sections described methods to physically improve heating and ventilation systems and adjust their control set-points to achieve low-temperature operation. The authors expect to see advanced techniques – such as the Internet of Things (IoT), machine learning algorithms, dynamic thermal models and optimal control – applied to the described methods to fulfil their potential over the long term. Early examples of digitalisation enabling optimal control include smart radiator thermostats with return temperature limiters [130] and optimal fault-tolerant control of hydronic space heating systems using heat cost allocator data [92]. In the coming years, we expect to see similar digitally-enabled advances towards automatic hydronic balancing and temperature optimization.

4. Conclusions

For the transition to renewable-based district heating networks, it is essential to improve the operations of heating systems inside buildings, thereby securing comfort and hot water hygiene with lower temperatures. Current operating temperatures in district heating networks are much higher than necessary to fulfil national standards for Legionella-safe DHW and typical indoor comfort requirements for space heating.

A common misbelief is that old radiators, designed for higher temperatures and no heat gains, cannot be operated with lower temperatures. Research has documented that design requirements lead to oversizing heat emitters, allowing low-temperature space heating operation without compromising comfort.

Existing space heating systems can operate with supply temperatures in the range of 30–70 °C and return temperatures as low as 25–35 °C. Typically, supply temperatures below 55 °C are adequate to ensure the end-users' comfort for most of the year. Only during extreme outdoor temperatures, rarely occurring in regular operation, should these supply temperatures increase. Hence, optimising the weather compensation curve and minimising the supply temperature is an inexpensive and straightforward improvement in the operation of space heating systems.

Concerning DHW systems, the minimum supply temperatures can vary from 50 °C to 70 °C according to the specific type of installations and national requirements for Legionella safety. In well-operated systems, one should expect optimal return temperatures as low as 25 °C for DHW installations with instantaneous heat exchangers, no circulation of DHW and short service pipes. In comparison, one can expect an optimal return temperature of roughly 35 °C from a DHW installation with a tank and circulation.

Legionella growth is typically associated with poor design and operation of DHW installations. Disinfection and electricity use – with boosting units to increase DHW temperatures – are alternative treatment solutions. The preparation of DHW that complies with the national requirements for Legionella safety represents a crucial area of development in the transition towards low-temperature operation. This rate of development will set the limit for decreasing supply temperatures in district heating networks. DHW demand will represent the dominant share of the total heat demand in the future due to the expected energy renovation of buildings. Furthermore, developing new DHW installations and technical solutions to secure comfort and hygiene in sanitary water, without high temperatures and circulation heat losses, will be a prioritised area of investigation.

An assessment of substations and heating systems highlighted that malfunctions and faults are among the main barriers to implementing lower temperatures in district heating networks. Hence, identifying and fixing errors is vital in the years to come. The digitalisation of the demand side represents a breakthrough for improving building services. The possibility of securing automatic temperature control and hydronic balancing while monitoring the entire system opens up new hardware and software solutions to minimise manual building-service activities. These developments will empower district heating operators, janitors and building managers to pinpoint and correct faults in heating systems quickly and cost-efficiently to ensure the expected space heating comfort and DHW hygiene with minimal operating temperatures.

It is important to note that energy renovations are not a prerequisite for operating heating systems with lower temperatures and should be considered one of several parallel activities in the transition to low-temperature district heating. For instance, installing mechanical ventilation with heat recovery substantially reduces the heat demand and enables lower temperature operation of space heating systems in relatively airtight dwellings. In such cases, intermittent or continuous functional performance testing should maintain balanced airflows and maximise heat recovery. Digitalisation (or 'smart' ventilation) could cost-effectively enhance performance monitoring. When combining efficient heat recovery with air heating coils, the coil should only be used during freezing conditions, as efficient heat recovery is otherwise enough to maintain comfort. While not a prerequisite for low-temperature district heating, minimising ventilation heat loss significantly affects heat demand and the required supply temperatures.

The design and installation of new heating systems should follow future expectations for lower heating temperatures. Hence, there is a need to define new design standards for both space heating and DHW installations that envision low-temperature heating in the context of future renewable-based energy systems. Towards this aim, the key research areas for low-temperature heating in buildings will focus on:

1. The role of digitalisation to improve building services;
2. The development of new technical solutions for the Legionella-safe supply of hot water;
3. Automatic balancing of space heating (and ventilation) systems ensuring comfort with minimal operating temperatures.

Credit author statement

Dorte Skaarup Østergaard: Conceptualization, Methodology, Investigation, Writing and original draft. Kevin Michael Smith: Investigation, Writing and review & editing. Michele Tunzi: Investigation, Writing and review & editing. Svend Svendsen: Supervision, Conceptualization, Project administration, Writing and original draft.

Declaration of competing interest

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 review paper.

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