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Aftercooling concept: An innovative substation ready for 4th generation district heating networks

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ABSTRACT

The transition toward greener district heating (DH) systems is supported by the low-temperature operation of building heating systems. In addition to reducing the DH supply temperature it is necessary to parallelly decrease the DH return temperature. A common bottleneck in lowering DH return temperatures are multi-apartment buildings operating with domestic hot water (DHW) circulation loops. The most common substation design in existing systems heat the DHW circulation using the DHW heat exchanger (HEX). However, as the DHW circulation return temperature is high and the DHW circulation energy demand is relatively high as well, it often results in high DH return temperatures from the building. To address this challenge, this study investigated an innovative design for future-proof DHW substations for large multi-apartment buildings. In the new design, the DHW and DHW circulation loop are decoupled, each utilizing a dedicated HEX for its specific purpose. This new design enables aftercooling the high DH return temperature from the DHW circulation by channeling all, or part, of the return water through the space heating HEX. For the building case examples presented in this study, the DH return temperature reduction potentials are in the range of 5.4 °C–8.3 °C for the 4G temperature profiles.

1. Introduction

1.1. Background

The European Union has set the ambitious goal to phase out fossil fuels and reach climate neutrality by 2050 [1]. The strategy has been recently updated with the "*Fit for 55 package*" revising the short-term targets and aiming for a net greenhouse emissions cut of 55% by 2030 [2]. Buildings represent a central part of the decarbonization transition as they account for 40% of European energy consumption, where more than 75% is still generated from fossil fuels [3]. In particular, DH networks are considered a strategic asset for dense urban areas to sustain the green transition due to the high degree of flexibility and capacity to integrate renewable energy sources, as well as to enable affordable heating of buildings [4]. While it is dominant in Nordic countries and is present in Eastern Europe as part of the legacy from the Soviet Union, DH is now gaining momentum in new emerging markets such as Germany, the Netherlands, the United Kingdom, and Belgium, among others, due to the recent volatility of natural gas prices, that exposed European citizens to the risks of fuel poverty and unsecured energy supply.

The DH industry's current developments focus on identifying innovative technological solutions to support distribution networks operating at lower temperatures. The vision is to operate the systems with supply and return temperatures of 55 and 25 °C without compromising the end-user's comfort requirements from space heating (SH) and domestic hot water (DHW) systems, according to the 4th Generation District Heating (4GDH) definition [5]. According to Eurostat [6], almost 80% of the energy consumption in European households is linked to SH and DHW demand; therefore, the heating sector is crucial for decarbonizing the energy system [7]. A common misunderstanding when considering the transition from 3GDH to 4GDH is associating the idea that renovating the existing building stock is a prerequisite to delivering the expected indoor comfort with low-temperature DH. However, It has been documented that existing buildings of different years of construction [8–11] can be heated with temperatures lower than 55 °C for the majority of the SH season, which implies that DH operators can operate the networks for the most part of the year with low temperatures and only need to increase the temperatures during very cold outdoor temperatures. This is possible due to the generally conservative designs of radiators and heating elements [12,13] and by securing optimal control

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Abbreviations

3GDH	3rd generation district heating
4GDH	4th generation district heating
DH	District heating
DHW	Domestic hot water
HDD	Heating degree day
HEX	Heat exchanger
SH	Space heating
TRV	Thermostatic radiator valve

and operation of the SH systems [14–17]. In limited cases, there could be a necessity to replace some critical radiators in some rooms [18] or invest in new components such as thermostatic radiator valves (TRVs), balancing valves or new pumps [18,20]. Still, refurbishing the entire SH system is seldom necessary and should be the last option to consider [7]. Future renovations of the building stock will further reduce the supply temperature requirements, as shown in Ref. [18].

The current share of DHW energy for tapping and DHW circulation energy consumption typically ranges from 10 to 30% of the total DH consumption in buildings [7,19], although the consumption of DHW has been increasing in the last few years [20,21]. As the share of new and energy-renovated buildings increases, the share of DHW is expected to increase to 40–50% of the total DH consumption [7,22,23]. Hence in the future, the preparation of DHW will be the limiting factor for the minimization of the operating temperatures in DH networks [24].

The DHW regulations always require a high supply temperature to comply with the standard of comfort and hygiene of DHW to avoid the proliferation of Legionella bacteria. In Denmark [25] DHW must be delivered with a minimum temperature of 50 °C, although 45 °C during peak situations is allowed. Depending on specific national standards, in DHW installations with storage tanks, the water temperature has to be maintained in the range of 55–65 °C [7,26]. From the regulations, it is clear that in multi-apartment buildings with central DHW preparation, either with storage tanks or HEXs, it is required to maintain the DHW circulation loop at a minimum of 50 °C at all times. This prevents Legionella bacteria proliferation, reduces water consumption, and increases comfort, as waiting times are minimized. A side effect of maintaining the DHW circulation temperature at a minimum of 50 °C is that the flow weighted DH return temperature from the DHW service, tapping and circulation, will be high, especially when the DHW tapping amount is low. The circulation heat losses can range from a minor to a significant share of the combined DHW and DHW circulation consumption. According to Refs. [7,27] the DHW circulation in commercial and multi-apartment buildings can account for up to 80% and 65% of the DHW service heat demand respectively. Thus, large buildings with DHW circulation loops will be critical for realizing low return temperatures in future 4GDH systems. This highlights the importance of developing new substations for DHW systems that can secure DHW comfort and hygiene with low supply temperatures while ensuring a good cooling of the return temperature in the DH networks.

1.2. Aim

This study aims to investigate a novel DHW substation design that can secure low-temperature operation in multi-apartment buildings with DHW circulation loops connected to DH networks. The work evaluated, qualitatively and quantitatively, the capacity to safely deliver DHW while securing safe DHW circulation temperature and a reduction of the building level DH return temperature. Eight different Danish building case studies, with different shares of DHW consumption, DHW circulation loss, and SH consumption, were assessed and compared with typical DHW substation designs and different operating temperatures.

1.3. Further literature

It is a prioritized topic to investigate innovative solutions to secure comfort and hygiene in DHW systems with DHW circulation loops in large buildings. Benakopoulos et al. [28] studied and theoretically compared several substation designs to assess the readiness to achieve low-temperature operations in DHW systems. The reduction of the supply temperature down to 55 °C and the ratio between the circulation heat losses and DHW consumption are critical factors in achieving low return temperatures. Due to more stringent energy consumption requirements in buildings, circulation heat losses have been central in the analysis [20,29]. Kempe et al. [30] reported based on several buildings that DHW circulation losses in a multi-apartment building are in the range of 5–8 kWh/m^2·year (heated floor area) in Sweden, increasing up to 25 kWh/m^2·year in some cases [30]. In newly built or renovated buildings, the DHW circulation heat losses rarely drop below 5 kWh/m^2·year [31]. Also, in the most common DHW substation designs, either with HEX or storage tanks in parallel to SH systems, even during DHW draw-offs the cold water is always mixed on the secondary side with the return temperatures from the circulation flow at ~50 °C. This high inlet temperature of the secondary side prevents obtaining low DH return temperatures.

An alternative DHW substation design is the two-stage connection, where the cold water is firstly pre-heated by cascading the primary return temperature from the SH systems in an additional path of the DHW HEX. This configuration has the advantage of further decreasing the primary return temperature and was extensively used in Sweden [32]. However, the gradual reduction of the operating temperature in DH systems erodes the capacity to reduce the DH return temperature. Hence, the simple DHW parallel design has been prioritized in recent years because the effective reduction of the DH return temperatures did not justify the additional path of the DHW heat exchanger needed [33].

New solutions have been investigated by integrating boosting units, using electricity, in DHW substations to secure comfort and hygiene. Østergaard and Andersen investigated the impact of a booster heat pump for DHW preparation to the potential reduction of the operating temperatures in the network and increase of COP of central heat pumps [34]. Yang et al. [35–37] investigated several DHW configurations with booster units able to secure DHW with low and ultra-low supply temperatures in DH networks. Similarly, a heat booster was investigated for a substation connected to an ultra-low temperature DH with supply temperature in the range of 35–45 °C [38]. The substation had a heat pump coupled to a hot water storage tank installed on the primary side and a booster heat pump for circulation. This solution allowed demand management and load shifting according to electricity price variation, due to increased flexibility secured by the tank. Nevertheless, the solution was cost-competitive only under special conditions when compared to low-temperature DH solutions and the feasibility required a restructure of the current energy price. Thorsen et al. [39] tested a booster heat pump to cover the circulation heat losses in a DHW substation with a storage tank in a multifamily building in Denmark. It was documented that with a high flow temperature (65–90 °C) in the local DH network, it was possible to reduce the DH return temperature from 47.2 °C to 21.5 °C for the DHW service. Although the substation required electricity for the booster heat pump, the results were also economically attractive due to the typical *motivation tariffs* applied by Danish DH operators that secure discounted energy prices if the end-users can lower their average operating temperature [40–43]. As part of the study in Refs. [44,45], an alternative design was proposed for DHW substations, decoupling the DHW preparation from re-heating the DHW circulation by having two separated HEXs in parallel. Despite the promising initial results, the authors recommended a more in-depth investigation to assess the real potential of the concept that represents the core of this article.

1.4. Novelty statement

The aftercooling concept is an innovative DH substation for large multi-apartment buildings where the DHW preparation and reheating of the circulation flows are decoupled and obtained in two separate HEXs connected in parallel. The primary return temperature flow from the circulation HEX is further cooled by the SH system before returning to the DH network. The originality of the aftercooling substation lies in the potential to safely deliver sanitary water with DH flow temperatures as low as 55–60 °C, fulfilling the *Legionella* control requirements and achieving low DH return temperatures at the same time. This complies with 4GDH requirements and, unlike previous studies, does not involve the integration of any electrical boosting units.

2. Method

The general concept of cascading heat exchange for DH substations is well-known and has been applied for decades in DH systems. The benefit of the traditional two-stage system diminishes as the building stock becomes more efficient and has lower temperature requirements. However, a more energy-efficient building stock opens for an alternative DHW circulation application design, where the return temperature from the DHW systems is cascaded and aftercooled in the SH HEX. In this analysis, the three main applications are benchmarked against each other based on the return temperature level in multi-apartment buildings. As the parallel application is the most common DHW substation, it is presented as the reference case in this study.

A wide range of buildings, temperatures, and annual heat demands were assessed to evaluate the potential benefits of the cascading applications compared to the reference parallel case. This was expressed as flow-weighted DH return temperature reduction potentials in a generalized form for four DH and SH operating temperature profiles. The return temperature reduction potential was chosen as a basis for the evaluation because it can be used to assess the economic benefits of the solutions, for DH utilities via improved heat generation efficiencies [46] or for building owners via economic savings from DH return temperature bonuses or penalty tariffs [42,47]. In the following the methods and applied boundary conditions are explained.

2.1. Thermal demands

As the intention is to provide a generalized approach for evaluating the benefits of the considered application, simulated heat demands were applied for SH, and DHW service. The interconnected impact on the DH return temperature was analyzed by varying the ratio between the services. The variations were achieved by maintaining the yearly DHW energy demand constant while varying the yearly SH, and DHW circulation demand. The different services, and how they were quantified, are presented below.

2.1.1. Energy for DHW

The end-users draw thermal energy from the DH system heating up the cold water to the desired DHW temperature, which is set to 55 °C in this analysis, via a HEX. Due to variations in the cold-water temperature and end-user consumption patterns, a seasonal profile was applied. Those variations are based on measurements performed in multi-apartment buildings. The DHW tapping profile in multi-apartment buildings is typically characterized by high activity during the morning and afternoon/evening and sporadic low-flow tapping at other times, resulting in the DHW system operating in idle mode most of the time. For this analysis, the DHW consumption is applied evenly during a period of 6 h per day and no DHW tapping for the remaining 18 h per day. Although the DHW tapping profiles vary dynamically, the average daily consumption and accumulated tapping duration are relatively constant around the year, as shown in Refs. [33,45,48].

2.1.2. Energy for DHW circulation

For ensuring hygienic DHW supply in multi-apartment buildings with central DHW preparation, a DHW circulation is required all year around. The legal requirements for DHW circulation in Denmark state a minimum temperature of 50 °C at any place. A common approach is to operate the DHW circulation with 55 °C supply temperature and 50 °C return temperature.

2.1.3. Energy for SH

The SH demand is estimated based on the standard climate profile for Denmark with a base Heating Degree Day (HDD) temperature of 17 °C [49,50], which indicates the temperature where the SH demand ends, $T_{no\ demand}$. The non-heating periods are determined based on the following principle.

The heating season starts once the estimated diurnal temperature is below $T_{no\ demand}$ for three consecutive days. The season ends once the estimated diurnal temperature is above $T_{no\ demand}$ for three consecutive days. The mean diurnal temperature is estimated based on Eq (1).

$$T_{day} = \frac{T_{7:00} + T_{13:00} + 2 * T_{17:00}}{4} \quad \text{Eq. 1}$$

The SH demand during the heating season is estimated based on Eq (2).

$$Q_{SH}(t) = Q_{design\ SH} * \left(T_{outdoor}(t) - T_{design}\right) / \left(T_{no\ demand} - T_{design}\right) \quad \text{Eq. 2}$$

Where Q_{design} is the heat demand at design condition [W/m^2], $T_{outdoor}$, is the outdoor temperature, T_{design} is the outdoor temperature at design condition and $T_{no\ demand}$ is the temperature when no SH is required.

By varying Q_{design} heat demand profiles for different building efficiency levels can be generated. By varying $T_{no\ demand}$ the duration and intensity of the heat demand per heating degree can be diversified.

2.2. District heating and building space heating installation operating temperature profiles

Under the assumption of automatic controlled and operated installations, the energy demands are the result of the building envelope and the indoor temperature. The return temperature from the services fulfilling these demands results from the applied DH supply temperature and the building SH and DHW installation. In this analysis, the considered operating conditions are the following.

a) 4GDH supplying buildings with underfloor heating
b) 4GDH supplying buildings with radiators
c) 3GDH supplying buildings with underfloor heating
d) 3GDH supplying buildings with radiators

The DH supply temperature and the building SH installation operating temperatures for the cases above are defined as a function of the outdoor air temperature, shown together with the results in Figs. 5–8.

2.3. Heat exchanger model and dimensioning methods

For the HEX operation considered in this analysis, the following conditions enable the utilization of simplified static HEX models.

i. During most of the operation, the flow in the HEX will be turbulent
ii. For the applied temperature range the water media properties are relatively constant
iii. The applied HEXs are symmetric, which means similar heat transfer coefficients (k) for primary and secondary side at a given flow
iv. HEX model error will have a similar impact on all considered applications.

Based on this, the HEX model can be represented by:

$$UA = \frac{1}{k\left(\frac{1}{Q_p^{0.7}} + \frac{1}{Q_s^{0.7}}\right)} \qquad \text{Eq. 3}$$

Where U is the heat transfer coefficient, A is the heat transfer area, Q_p and Q_s are the respective primary and secondary flow through the HEX and k is a constant related to the convective heat transfer for a specific HEX. $1/k$ can be interpreted as a proxy representing the thermal length of the HEX.

Based on the UA value, the transferred heat is calculated by:

$$P = UA * \Delta T_{LMTD} \qquad \text{Eq. 4}$$

Where P is the capacity and $\Delta\ T_{LMTD}$ is the logarithmic mean temperature difference between the primary and secondary side of the HEX [51].

As HEXs are dimensioned for fulfilling a design condition, where the power, operating temperatures and flows are known the appropriate size is applied for each calculation case by varying the thermal length of the HEX, $1/k$.

2.4. Presentation of the considered DHW applications

The analysis compares three types of DH substation applications: a standard parallel SH and DHW application, a traditional two-stage application, and the new DHW aftercooling application. The thermal comfort for the end-users is identical for the considered applications, as the operating parameters of the services are identical, independent on the application.

2.4.1. Reference case: parallel SH and DHW application

As presented in Fig. 1, the first HEX provides the DHW service, tapping and circulation, and a second HEX, in parallel, provides the SH service. The application is simple, widely used, and has the lowest demand for components and control. The calculations for the parallel application are straightforward since all secondary flows and inlet temperatures to the HEXs are known. Based on the DH side return temperatures from the HEXs, the combined flow-weighted DH return temperature is calculated.

The SH supply temperature was assumed to vary according to the outdoor temperature, based on the principle of weather compensation, whereas the DHW to secure the specific temperature of 55 °C. The DHW circulation was assumed to be maintained at a return temperature of 50 °C to the substation.

2.4.2. Two-stage application (pre-heating of cold water/after cooling the primary heating return flow)

For the two-stage application, the HEX for the DHW service is divided into two sections, allowing the reduction of the primary heating return flow by preheating the cold water of the DHW as illustrated in Fig. 2. The demand for control is similar to the parallel application, although an extra HEX section is required. Also for the two-stage principle, the secondary flows and all inlet temperatures to the HEXs or sections are known, except one. The unknown is the secondary side inlet to the DHW HEX second section, corresponding to the DHW circulation inlet location. An iteration routine is applied to solve this. The HEX sizing for DHW is based on two HEXs as applied in the parallel application coupled in series. This HEX type is typically realized as a two-path HEX with 6 ports as shown in the figure below.

The SH supply temperature is based on the outdoor temperature, similar to the parallel concept. The DH return flow from the SH HEX is led to the middle part of the DHW HEX for pre-heating the cold inlet water, and hereby cool the DH return from the SH service, before being heated by DH to the DHW set temperature of 55 °C. The DHW circulation maintains a return temperature of 50 °C, similar to the parallel concept.

2.4.3. New application: after cooling of DHW circulation

The aftercooling application requires a separate HEX dedicated to the heating of the DHW circulation flow and coupled in parallel to the DHW HEX as presented in Fig. 3. The primary return temperature is then aftercooled by the SH via the SH HEX. As in the two-stage application, the secondary flows and inlet temperatures to the HEXs are known. Rule-based control is applied to divert the DHW circulation primary return flow to the SH HEX and DH return, by maximizing the flow to the SH HEX, respecting the aimed SH flow temperature, and a minimum dT of 5 °C between the primary side inlet temperature and the secondary side SH flow temperature. The HEX sizing for SH and DHW is similar to the parallel application.

The SH supply temperature is based on the outdoor temperature and the DHW at a specific temperature of 55 °C, similar to the parallel concept. The DHW circulation maintains a return temperature of 50 °C, similar to the parallel concept, but via the separate HEX, where the DH return is aftercooled in the SH HEX to the extent possible.

2.5. Return temperature analysis for the different applications

The annual return temperature from the application depends on the energy consumption of the DHW and SH services provided by the application, the DH supply temperature, and the applied HEXs. As the energy ratios, and thus capacity requirements of the DHW, SH, and DHW

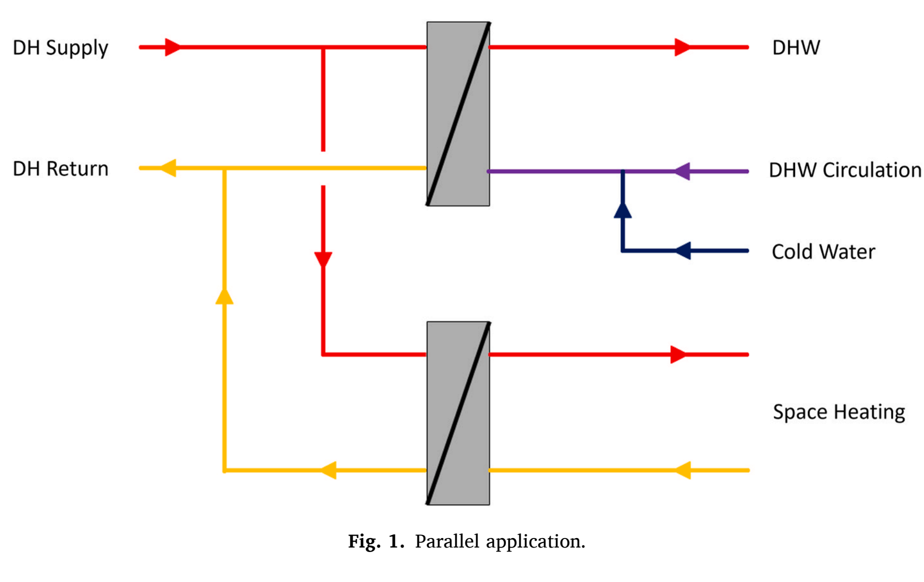

Fig. 1. Parallel application.

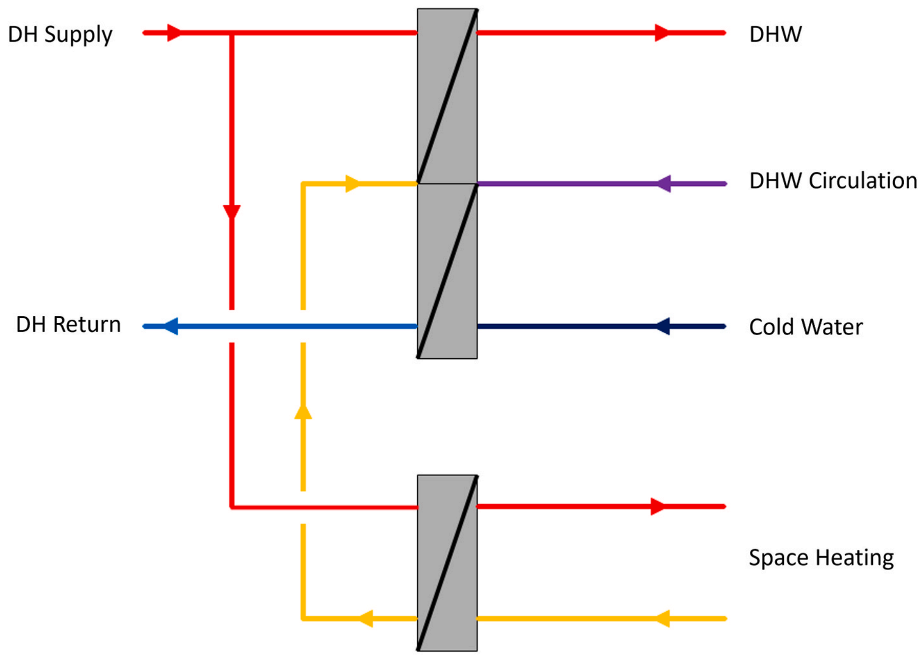

Fig. 2. Two-stage application.

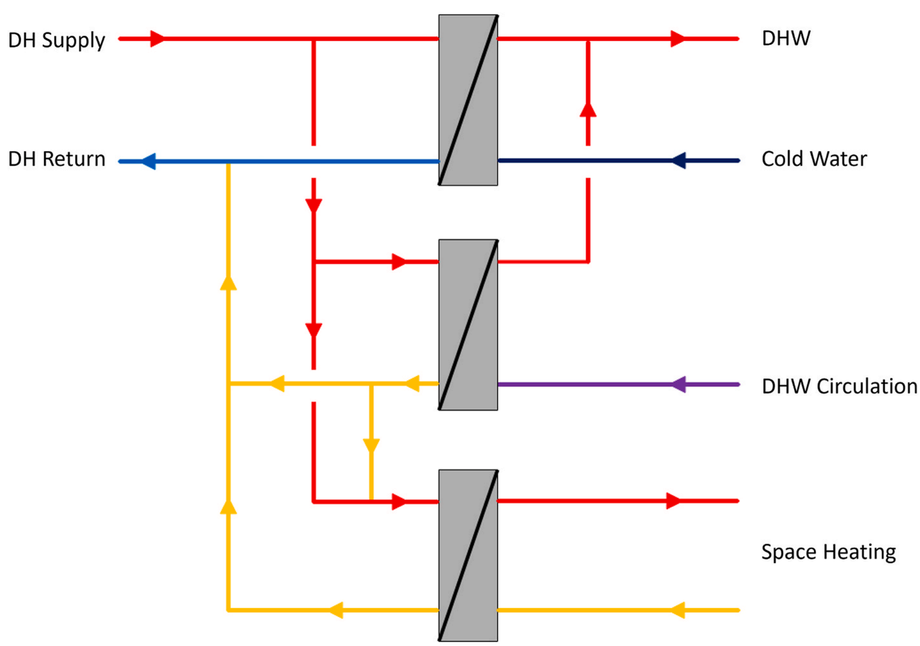

Fig. 3. Aftercooling application.

circulation were varied, the HEX was dimensioned accordingly. In this way, the applied HEX dimensioning is adapted to the scenario-specific energy demands. Once the flow and return temperatures have been estimated for each service, the common flow-weighted DH return temperature is calculated.

To compare the return temperature from the different applications over a wide range of demands, two dimensionless parameters, R_1 and R_2 were introduced. R_1 is the ratio of the DHW demand, E_{DHW}, to the SH demand, E_{SH}, Eq (5), and R_2 is the ratio of the DHW circulation demand, E_{circ}, to both DHW and DHW circulation demands, Eq (6).

$$R_1 = \frac{E_{DHW}}{E_{SH}} \quad \text{Eq. 5}$$

$$R_2 = \frac{E_{DHW}}{E_{DHW} + E_{circ}} \quad \text{Eq. 6}$$

These parameters were used in the analysis to evaluate the potential reduction in flow-weighted DH return temperatures. The comparison was made between the traditional two-stage approach and the innovative aftercooling application in relation to the reference parallel application. This assessment took into consideration both radiator and floor heating installations, adhering to the temperature requirements of 3GDH and 4GDH.

3. Building case examples

The investigation focused on eight existing Danish multi-apartment buildings as summarised in Table 1. This provides an overview of typical Danish multi-apartment buildings of different ages and energy renovation levels and it defines the R_1 and R_2 envelope in focus for the analysis. The data includes the actual measurements of the energy meters. Also, the two energy-related dimensionless parameters presented in section 2.5.1 are shown in the last two columns. By varying these ratios it is possible to assess the performances of the different substations for each specific building in wider operating conditions.

The low SH energy consumption of DK#1 is related to the stringent requirements of recent building codes, whereas the relatively low SH consumption for DK# 4-5-6 is related to the energy renovation level of these buildings. Instead, the low DHW consumption of DK #2 is associated with the presence of elderly people living in the apartments. These case studies are marked on the contour plots in the result chapter to indicate the potential DH return temperature reduction for the eight buildings.

4. Results

The main results presented in this paper compared the different substations based on their potential to reduce the annual DH return temperature. However, to provide an insight on the variation of the DH return temperature reduction over the year, an example is shown in Fig. 4. The solid red curve shows the DH return temperature for the reference parallel concept, whereas the dashed red curve shows the DH return temperature for the aftercooling concept. Outside of the heating season, week 23–37, no aftercooling via the SH circuit is possible, due to the absence of SH demand. Anyhow, still a few degrees return temperature reduction can be seen, and this is due to the added HEX area for the DHW circulation, compared to the parallel concept. During the remaining year aftercooling is possible. The largest absolute DH return temperature reduction potential occurs when the heating system goes from absorbing the full part of the DH return flow from the DHW circulation HEX to a reduced part, and vice versa. Those two situations can be seen in weeks 19 and 41. Before week 19, and going backward, and after week 41, the SH demand is increasing. Thus, the influence of the SH return temperature becomes dominant, and the DH return temperature reduction decreases.

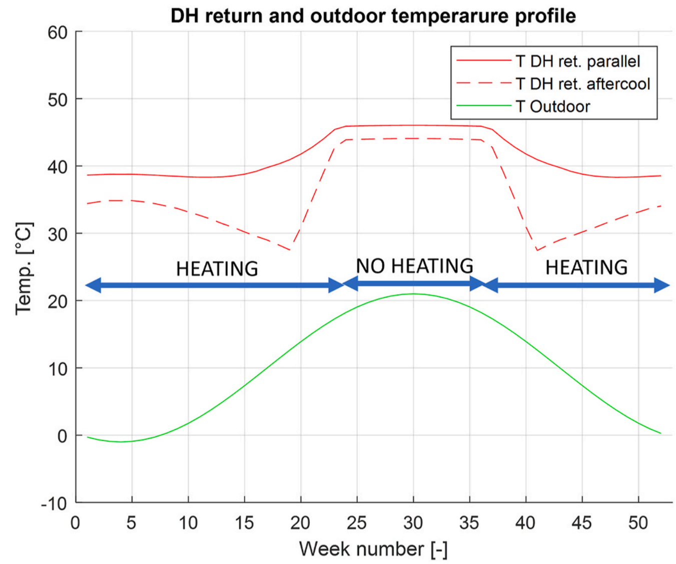

Fig. 4. Generalized example of the yearly DH return temperature variation.

In the following, the yearly DH return temperature reductions for the compared applications are shown, together with the applied temperature profiles. The dimensionless parameters, R_1 and R_2, are the axis or input parameters, whereas the flow-weighted yearly return temperature reduction potential can be read out of the contour lines of the plots. In this way, the results are presented for a wide range of R_1 and R_2 parameter combinations. By presenting the results as contour plots, it is simple to estimate the impact a change in the ratio of the services have on the return temperature reduction potential. The specific examples of the eight buildings presented in chapter 3 are marked in the graphs to give an example on the potential of existing buildings.

Table 1
Energy consumption for the services for 8 multi-apartment buildings and dimensionless energy parameters R_1 and R_2. The building symbol is the marker in the results figures.

Building ID /Symbol	Year	Location	Renovation level	Yearly DHW pr flat	Circ. Energy pr flat	Yearly SH pr flat	Nr. Flats	R_1	R_2
[−]	[Year]	[−]	None/moderate/deep	[kWh/y/apt]	[kWh/y/apt]	[kWh/y/apt]	[−]	[−]	[−]
DK#1/ x	2015	Copenhagen	None	1273	1234	2500	22	0.51	0.49
DK#2/ o	1951	Kolding	Moderate	354	1156	7300	31	0.05	0.77
DK#3/ o	1953	Kolding	Moderate	747	1156	6250	47	0.12	0.61
DK#4/ +	1967	Hillerød	Deep	1633	1012	4374	42	0.37	0.38
DK#5/ +	1967	Hillerød	Deep	1674	1012	4390	30	0.38	0.38
DK#6/ ◊	1973	Sønderborg	Deep	1200	1694	4594	45	0.26	0.59
DK#7/ *	1943	Viborg	Moderate	800	1205	3610	24	0.22	0.60
DK#8/ *	1944	Viborg	Moderate	1100	1283	5122	28	0.21	0.54

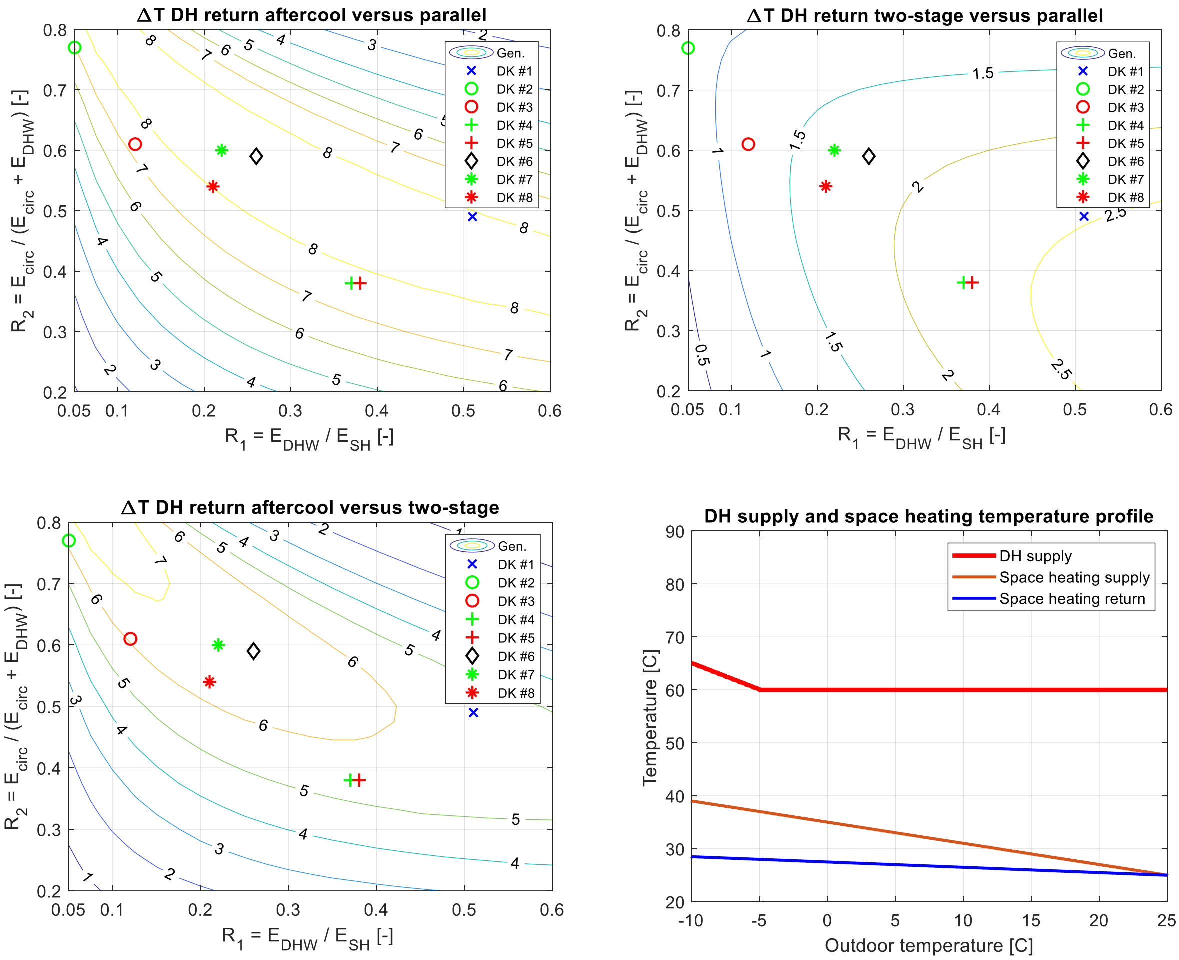

Fig. 5. DH return temperature reduction potential for the 4G-UFH scenarios.

4.1. 4GDH – underfloor heating

In this scenario, the aftercooling principle had the highest DH return temperature reduction potential, both compared to the reference parallel principle and the two-stage principle. This was due to the low-temperature profile of the 4G-UFH. A low return temperature from the SH circuit enables a high potential for aftercooling. At the same time, a low supply temperature to the SH is also beneficial, as the primary return from the DHW circulation HEX will have only a limited effect on the mixed primary inlet temperature to the SH HEX. Based on the eight-building cases envelope the aftercooling principle had a reduction potential of 7–8.3 °C compared to the parallel principle and is 5.4–6.7 °C better than the alternative two-stage system. Further the potential of the two-stage system is more sensitive to the R_1 variation of the buildings, compared to the aftercooling principle, which is the finding for all scenarios.

4.2. 4GDH – radiator heating

The SH supply temperature assumed in this scenario was increased to address the higher temperature requirements of radiators compared to UFH. Consequently, the return temperature from the radiator circuit was slightly higher compared to the previous UFH case, as observed in Fig. 6. It was found that the aftercooling substation has a potential of 5.4–6.7 °C, compared to the parallel principle and is 4.1–5.1 °C better than the alternative two-stage system. The SH supply temperature was increased, but since it was for most of the year still quite lower compared to the DH supply temperature, the effect on the DH return temperature was limited.

4.3. 3GDH – underfloor heating

In this scenario, it was assumed higher DH supply temperature in line to common 3GDH networks operations, as presented in Fig. 7. The results highlighted that the aftercooling principle had a reduced potential, due to the increased SH circuit return temperature, compared to the scenario with 4GDH. This was quantified in a potential reduction of 4.2–7.7 °C compared to the reference parallel principle and is 2.4–4.1 °C better than the alternative two-stage system.

4.4. 3GDH – radiator heating

Compared to the scenario presented in Section 4.3, the SH supply temperature was further increased to fulfil the radiators temperature requirements. The aftercooling principle highlighted a reduced potential, due to the higher SH supply and return temperature. The aftercooling principle showed a reduction potential of 3.0–5.8 °C compared to the parallel principle, and still 1.2–2.5 °C better than the alternative two-stage system.

4.5. Discussions

The innovative design of the aftercooling system aims to reduce the DH return temperature by minimizing the high return temperature from the DHW circulation in a standard parallel DHW substation. This is accomplished by using two HEXs to separate cold water heating from circulation and then cascading the circulation flow to the primary side in the SH system for further cooling. Figs. 5–8 emphasize that the lower the SH return temperature, the higher the aftercooling potential. While the

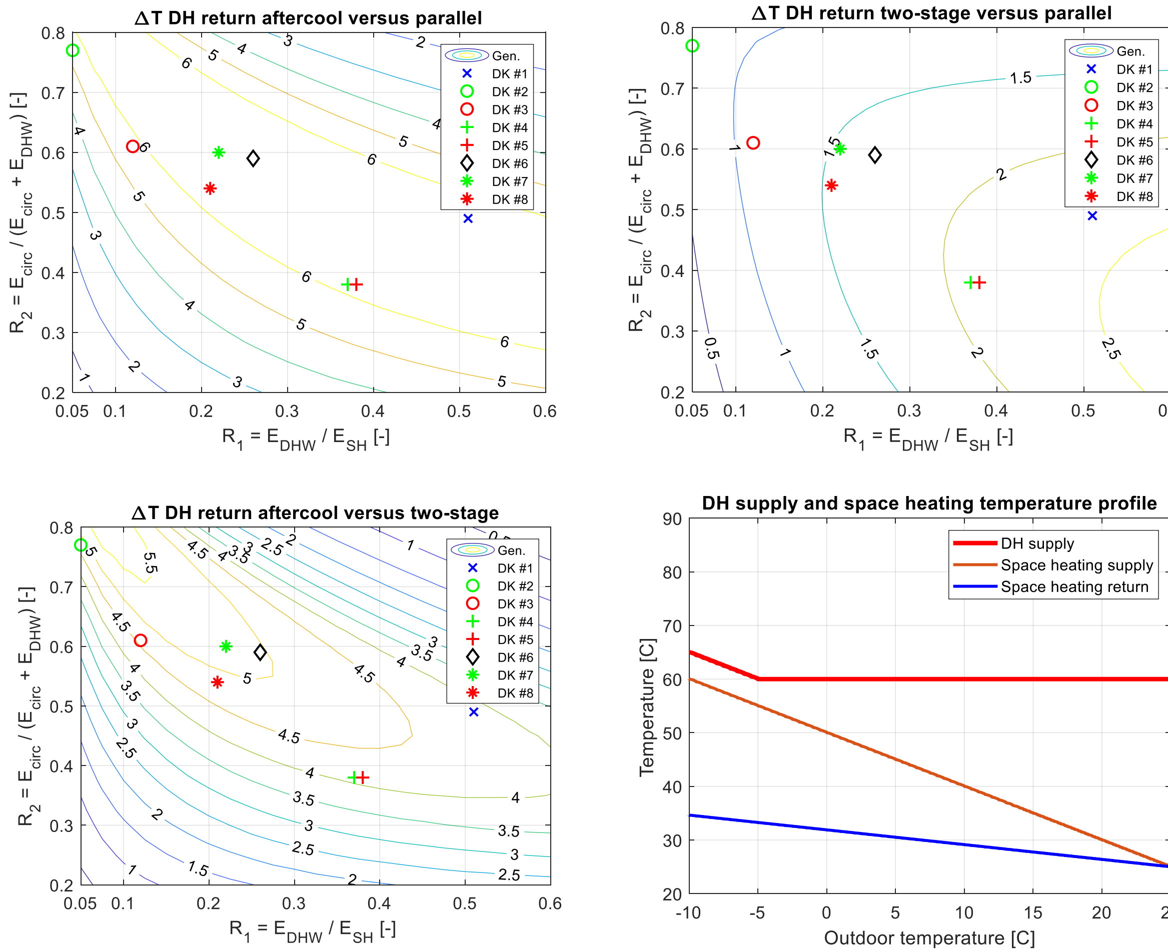

Fig. 6. DH return temperature reduction potential for the 4G-RAD scenarios.

UFH exhibited a greater potential, the proposed concept can still effectively lower DH return temperatures even with existing radiators. This is significant, considering radiators are the predominant SH element used in Europe. To ensure this, as a pre-requisite, it is important that existing radiators are properly operated and controlled to maintain low operating temperatures, as documented in numerous studies [7–10,18,42]. Hence, the analysis is not applicable to uncontrolled radiators. Deviation of the emitters' temperature profiles will affect the results. For instance, higher operating temperatures in the SH systems will erode the capacity to reduce the overall DH return temperature. On the contrary, lower operating temperatures will positively impact the DH return temperatures.

The analysis also evaluated the implications of the dimensionless parameters R_1 and R_2 for the aftercooling application. Adjusting their ratios changed the share of SH and DHW service, tapping and circulation, in the investigated cases. This facilitated a broader analysis and interpretation of the results, contextualizing them within the eight building cases that were employed to evaluate the concept's potential. Low energy demand for DHW circulation and SH showed a diminished capability to reduce the DH return temperature. This highlights the high potential of the proposed system, even for buildings with a high thermal mass that aligns with 4GDH requirements. For countries where the heating season length is similar to Danish conditions, and the space heating systems are operated under 3rd or 4th generation temperature profiles, the results will be representative. In case the heating season is shorter, the potential will be reduced.

In contrast, the two-stage substation's ability to reduce the DH return temperature diminishes with decreasing operating temperature. Its primary function is to preheat DHW using the return from SH installation — a solid approach since the SH return temperature will always be higher than the incoming cold water. But while the aftercooling method is active throughout the SH season, the two-stage method operates only during DHW preparation. This leads to an increasing potential in relation to the DHW to SH demand ratio, R_1. However, this potential decreases as the proportion of DHW circulation to the total DHW service demand, R_2, increases. Even though this concept was popular in Sweden, the DHW parallel design was preferred in recent years. This is because the effective reduction of the DH return temperatures did not justify the additional path, components, and costs of the DHW heat exchanger [33].

During the non-heating season, the primary return temperature flow from the DHW circulation HEX cannot be aftercooled by the HE system as depicted in Fig. 4. Yet, the annual average reduction potential remains promising, suggesting it is a viable solution for renovating substations in multi-apartment buildings that have circulation systems. An alternative design might incorporate booster heat pumps to compensate for circulation losses, as explored in Refs. [39,44,45]. This design ensures low return temperatures even in the non-heating season but comes with increased capital and operational costs - due to the electricity consumption of the heat pumps. Such costs could be offset if DH operators provide incentive-based tariffs to consumers, a practice largely seen in Denmark and Sweden [7,40]. However, this may not be relevant in other DH markets. Future studies should demonstrate the viability of the concept in the field, assess the economic viability of the aftercooling substation across various DH markets, contrasting it with other innovative designs that leverage electricity to enhance DHW, tailored to specific national standards. In case the motivation tariffs to consumers may not be part of the heat price structure, the savings need to be linked

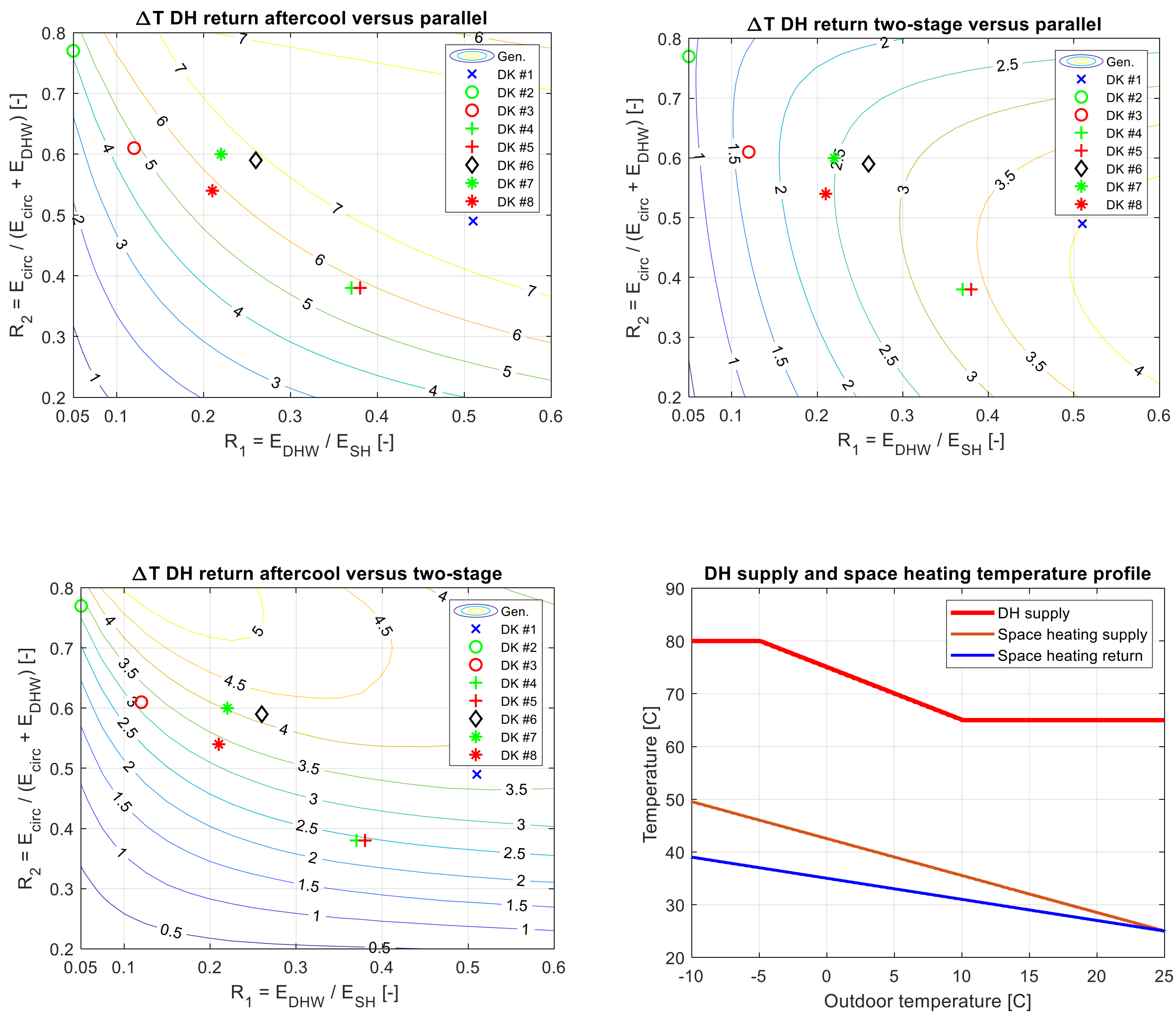

Fig. 7. DH return temperature reduction potential for the 3G-UFH scenario.

to improved heat generation efficiencies, increased networks' hydraulic capacity and minimized thermal distribution losses.

5. Conclusions

The innovative feature of the aftercooling design is its capacity to reduce the return temperature of the DH system. This reduction is made possible by mitigating the high return temperature associated with DHW circulation in standard parallel DH substations. The proposed design employs two distinct HEXs: one for heating cold water and the other for the DHW circulation flow. Subsequently, the primary flow from the DHW circulation HEX undergoes additional cascading cooling via the SH HEX. The investigation yielded comprehensive insights into the potential temperature reduction of both the conventional two-stage application and the novel aftercooling design, relative to the parallel layout.

The analysis revealed that the aftercooling substation significantly lowered the yearly DH return temperature in existing multi-apartment buildings, with a potential temperature reduction of 1.2–6.7 °C when compared to the two-stage application and 3.0–8.3 °C when compared to the parallel application. These findings underscore the improved performance of the proposed concept over the two-stage application, making it a reliable strategy for upgrading existing substations in multi-apartment buildings with circulation systems.

Additionally, the results suggest that the relevance of the aftercooling application increases as buildings transition to greater energy efficiency. These efficient structures not only necessitate lower supply temperatures but also result in reduced SH return temperatures. As a result, the proposed aftercooling design stands out as a future-proof solution. It not only aligns with 4GDH requirements but also guarantees occupant comfort while concurrently lowering the operating DH temperature across the networks. Specific for the 4GDH operating conditions, the analysis revealed a potential temperature reduction of 4.1–6.7 °C when compared to the two-stage application and 5.4–8.3 °C when compared to the parallel application. The pre-requisite is that the emitters are correctly operated and controlled. Unnecessarily high operating temperatures will affect the potential to reduce the overall DH return temperature with the aftercooling substation.

Future research will deepen into the business model of the proposed design, comparing it with other alternatives in the DH market, both with and without an incentive-based heat tariff structure. For systems that do not employ incentive schemes, the main advantage of reducing the return temperature translates into savings for utility companies. These savings will correspond to improved heat generation efficiencies, increased hydraulic capacity in DH networks, and minimized thermal distribution losses.

CRediT authorship contribution statement

Jan Eric Thorsen: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Oddgeir Gudmundsson:** Writing – review & editing, Writing – original draft, Visualization, Software,

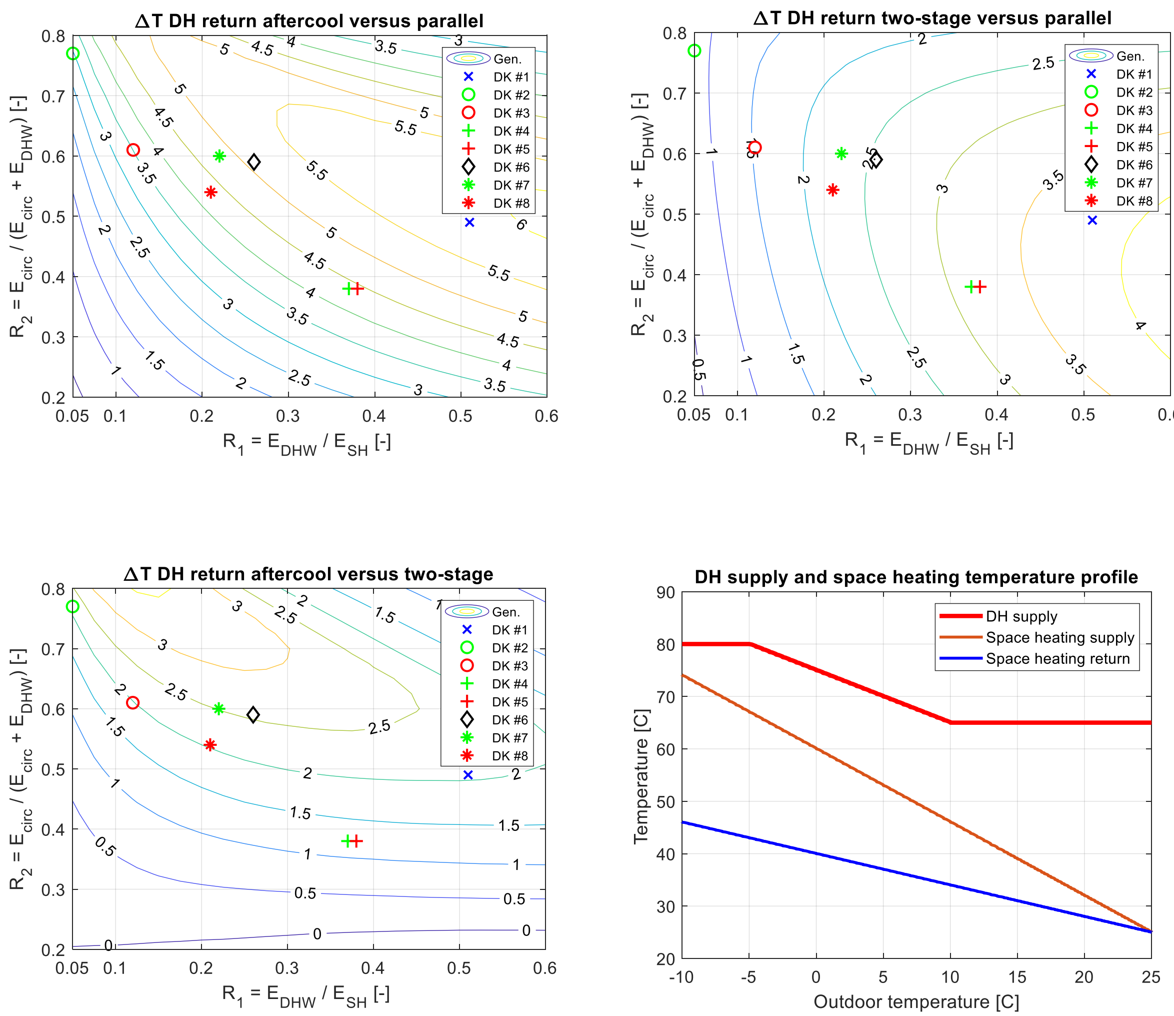

Fig. 8. DH return temperature reduction potential for the 3G-RAD scenario.

Methodology, Formal analysis, Data curation, Conceptualization. **Michele Tunzi:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization. **Torben Esbensen:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

Data will be made available on request.

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