

## Article

# Impact of Domestic Hot Water Systems on District Heating Temperatures

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**Abstract:** When buildings become more energy effective, the temperature levels of district heating systems need to be lower to decrease the losses from the distribution system and to keep district heating a competitive alternative on the heating market. For this reason, buildings that are refurbished need to be adapted to suit low-temperature district heating. The aim of this paper is to examine whether four different energy refurbishment packages (ERPs) can be used for lowering the temperature need of a multi-family buildings space heating and domestic hot water (DHW) system as well as to analyse the impact of the DHW circulation system on the return temperature. The results show that for all ERPs examined in this study, the space heating supply temperature agreed well with the temperature levels of a low-temperature district heating system. The results show that the temperature need of the DHW system will determine the supply temperature of the district heating system. In addition, the amount of days with heating demand decreases for all ERPs, which further increases the influence of the DHW system on the district heating system. In conclusion, the DHW system needs to be improved to enable the temperature levels of a low-temperature district heating system.

**Keywords:** district heating; energy efficient refurbishment; building simulation; low-temperature heating; domestic hot water

## 1. Introduction

The housing and service sector represents almost 40% of the total energy use in Sweden [1]. The main source of this energy use is district heating, electricity and bio fuels. In 2016, 57% of the energy used for heating buildings in Sweden was district heating and 26% was electricity [2]. The largest proportion of electricity is used for heat pumps and less is used for other technical solutions. Even though the use of fossil fuels is relatively low in this sector in Sweden, improved energy efficiency of buildings and their energy systems are important to reach political goals of a resource efficient society as well as to decrease the environmental and climate impact of our lifestyle [3]. Energy refurbishment is one way to decrease the specific energy use in buildings according to several studies, for example [4–7]. Improved energy efficiency in buildings also increases the possibility to use low-temperature heating systems due to the decreased heating load. Regardless, for supplying heat to a building, low-temperature heating systems bring several advantages, including both energy and exergy savings as well as reduced environmental impact, primarily due to lower CO<sub>2</sub>-emissions. Low-temperature heating systems combined with district heating increases the possibilities to also lower the temperatures in the district heating system. Decreased return temperatures in district heating systems has proven to be one way to increase the electricity production in combined heat and power plants, and decreased supply temperatures might result in

higher efficiency of flue gas condensation equipment [8]. Another major advantage of lowered system temperatures in the district heating network is the reduced distribution losses to the environment. Future district heating systems may have significantly lower supply and return temperatures than today's systems, and several studies have been made in this area which are often referred to as the fourth generation of district heating systems [8–11]. For buildings using heat pumps for space heating and domestic hot water (DHW), lowering the heat system temperatures is an effective way to increase the heat pump efficiency and thereby also decrease the levels of carbon dioxide emissions due to decreased electricity use [12,13].

Several studies point out the importance of decreasing the system temperatures in future district heating systems to continue to be a competitive alternative in the heating market [8,14]. This will be particularly important when buildings become more energy effective and the losses from the district heating systems will otherwise be unreasonably large compared to the delivered heat. The temperature levels of future district heating systems have been discussed in several papers. Lund et al. [9] performed a comparison with the third generation and the fourth generation district heating systems with the simulation model Energy PLAN. In this study, the annual average supply and return temperatures for the district heating system at the district heating plant is 55 and 25 °C, respectively. The grid losses are assumed to be 19%. Lund et al. [15] compared low-temperature district heating (55/25 °C) to ultra-low temperature district heating with electric boosting (45/25 °C) and to ultra-low temperature district heating with heat pump boosting (35/20 °C). Their findings show that the low-temperature solution (55/25 °C) has the lowest costs. Østergaard and Svendsen [16] studied the consequences of supplying Danish single family houses from the 1980s with ultra-low temperature district heating (average temperature level 44/31 °C), finding that this is possible for the main part of the year without compromising the thermal comfort. In the study, electrical boosting was used to achieve adequate DHW temperature. Yang and Svendsen [17] compared a real case ultra-low temperature district heating system in Denmark with low-temperature and medium temperature district heating systems from an energy, exergy and economic perspective. Their findings show that the low-temperature district heating system has the best performance in energy and exergy efficiency, followed by the ultra-low temperature district heating system. From an economic perspective the ultra-low district heating system had the lowest annual expense, followed by the low-temperature district heating system and the most expensive medium-temperature district heating system. Harrestrup and Svendsen [18] investigated changes in heat load profiles of two Danish building blocks when implementing energy saving refurbishment measures and low-temperature district heating. Their findings show that the supply temperature of 55 °C in the low-temperature district heating system might need to be increased during the coldest season to maintain an acceptable indoor climate. The return temperature of the system is generally higher with lower level of refurbishments implemented.

Swedish multi-family buildings normally have a central heating system consisting of either a district heating substation, a heat pump or some kind of bio fuel boiler, all with a hydronic distribution system to provide the apartments with space heating. Recently built or refurbished buildings might as well have systems for heat recovery such as mechanical ventilation with heat recovery (MVHR) or exhaust air heat pumps (EAHP), often combined with district heating. The space heating systems are centrally managed and can only be affected to a limited extent by the residents. Several studies of multi-family buildings refurbished with energy savings as a goal has been made where large reductions in energy use for space heating is achieved [19,20]. There are different technical solutions that can be used for heat distribution in low-temperature hydronic heating systems where radiators and floor-heating, or a combination of both, are the most common in Sweden. Several studies points out the possibilities of using existing radiators in buildings with decreased supply temperature [16,21]. Intentional over-dimensioning of radiators has been a practice for a long time and the unused capacity can in many cases be used to decrease the system temperatures even in a building that is not additionally insulated or in any other way has improved its energy performance. Another case is if a building has undergone energy-saving refurbishment, then the radiators will automatically be over-dimensioned due to the decreased heating

demand of the building. Østergaard and Svendsen [22] also examined the possibilities to decrease supply and return temperatures of space heating systems by replacing only critical radiators. They found that the supply/return temperatures could be reduced to 50/27 °C in the studied buildings.

The use of DHW on the other hand, tends to be less influenced by the refurbishment and new technical solutions, even though the use of DHW in theory could be reduced due to the installation of water saving faucets [23]. Previous studies of DHW use before and after refurbishment shows that it is mainly the inhabitant behavior that is of crucial extent to the results [24]. When the space heating demand is reduced and the DHW demand remains the same, the DHW will naturally constitute a larger proportion of the total energy use of the building. According to Swedish building regulations [25], the temperature level of the DHW should not decrease below 50 °C in any part of the DHW system, primarily because of the risk for developing unhealthy levels of *Legionella* bacteria. This temperature level varies between countries, and in Denmark for example, 45 °C is required [26]. *Legionella* bacteria are known to cause Legionnaires' disease if the aerosol of contaminated water is inhaled, and new outbreaks are reported constantly [27]. Apart from the temperature requirement, there is also a time limit for the maximum time it may take for the hot water to reach the tapping point. In order to meet the requirements, the DHW systems in multi-family buildings in Sweden generally have a circulation line to keep hot water available near all taps. Lowering the district heating system temperatures requires alternative solutions to handle the problem with *Legionella* and have been studied in several papers. Different types of temperature boosting, restricted system volume and sterilization has been studied, for example by Yang et al. [28], whom also studied decentralized substations with heat pump boosting of the DHW [29]. Averfalk and Werner studied apartment substations in multi-family buildings as a possibility to lower the return temperatures to the district heating system, also with the aspect to eliminate the risk of *Legionella* infections [30]. Circulation systems for DHW are also associated with large heat losses. A long-term study by Cholewa et al. [31] found that the heat losses from hot water circulation in 12 different multi-family buildings in Poland varied between 56.7% and 70.5%. Another study made by Bøhm [32] showed that the losses from the circulation system were 23% to 70% in the studied apartment buildings, which also resulted in reduced cooling of the district heating water. When it is possible to heat a building with supply temperatures of 50 °C or below the losses from the hot water circulation inevitably becomes a heating source in the building with unnecessary high temperatures.

The objective of this paper is to assess and discuss the connection between low-temperature district heating systems, energy efficient buildings and the requirements and installation of DHW preparation in a multi-family building in Sweden. By the use of simulated data from a building model, four different energy refurbishment packages (ERPs) are analysed with respect to the temperature levels of the space heating system, the DHW system and the district heating system. The aim of this paper is to examine whether the studied ERPs can be used for lowering the temperature need of the buildings space heating and DHW system as well as to analyse the impact of the DHW circulation system on the return temperature.

## 2. Materials and Methods

Simulations of a multi-family building was used to examine the relation between the district heating system temperatures and the temperatures of the heating system in the building. The technical installations are further described in Section 2.2. The simulations were also used to analyse to what extent the DHW system in the building influences the district heating return temperature after extensive building refurbishment. The building model used in the simulations was constructed by Gustafsson et al. [5] in the software TRNSYS 17 [33], and the results of the simulations has also been used in another study by Lidberg et al. [34]. The model and the data used to construct it, as well as the output data from the simulations, is in detail described in previous papers [5,34]. The case study building, and the ERPs are further described below.

## 2.1. Case Study Building

The model is based on a case study building that is situated in the city of Borlänge, 25 km North-West of Stockholm, Sweden. The building is a three-story slab blocks multi-family building with the long sides oriented to east and west. The house has 36 apartments and a total heated area of 3900 m<sup>2</sup>. This building type is common in Sweden for buildings constructed during the Swedish Million Homes Programme period 1965–1974 [35]. The building is supplied with district heating for space heating and DHW via a single stage parallel substation and the ventilation system consists of mechanical exhaust air fan. There are supply air vents above windows and centrally placed exhaust air fans. The total energy use for the building before refurbishment was approximately 130 kWh/(m<sup>2</sup> y) according to measurements of the building owner. The case study building is situated in the area Tjärna Ängar in Borlänge, and is also investigated in another research project [36]. The buildings in the area are very similar to one another and three of them has been renovated with the ERPs studied in this paper.

## 2.2. The Energy Refurbishment Packages

Four ERPs were simulated with the same improvements of the building envelope and with water saving faucets, but with different solutions in the ventilation and heating systems. The ERPs consisted of one with MVHR, one with more efficient exhaust fans, and two with EAHP. One EAHP package includes a heat pump that only provides heat to the space heating system. The other EAHP includes a heat pump that provides both space heating and DHW. Earlier studies have shown that both MVHR and EAHP can be used to reduce the use of district heating and also to decrease the use of primary energy and CO<sub>2</sub>-emissions [4,5,34,37], while less extensive refurbishment can be less costly and also less disturbing to the residents.

The district heating supply temperature was set to be 78 °C for outdoor temperatures of 0 °C and above. For lower outdoor temperatures, the district heating supply temperature was increased by 1 °C for each degree below 0 °C. The radiator panels were designed for a distribution temperature of 55 °C for winter conditions in the reference case, and the same design is used for all cases. The room temperature was set to 22 °C in the living zones and the radiator panels in stairwells was sized to keep 18–19 °C room temperature during these conditions. The DHW system was set to keep a constant temperature of 50 °C for both tapping and circulation. The same scheme for use of DHW was used in all simulations. The installation of water saving faucets in all ERPs is assumed to decrease the use of DHW from 38 L/(p·day) to 28 L/(p·day) at 45 °C.

ERP A includes MVHR, with a specific fan power of 1.50 W/L s and a thermal efficiency of 85%. ERP B includes more energy efficient exhaust fans with a specific fan power of 0.45 W/L s, half of what is used in the reference case. ERP C and D both includes an EAHP, Thermia Mega XL [38], with variable speed compressor. ERP C and D has the same technical installation for space heating where the heat pump is installed in serial before the district heating substation to provide as low inlet temperature as possible to the heat pump and thereby minimize the electricity use of the compressor. With a restricted heat output from the heat pump of 30 kW, the heat pump supplies part of the heat load for space heating with a backup consisting of district heating. ERP D was set to primarily produce space heating but was enabled to produce DHW when the capacity exceeded the space heating load. The heat pump settings for the DHW preparation was to keep 1/3 of the DHW tank at 40 °C, while the remaining part of the DHW demand and circulation was produced with district heating. In addition, half of the radiator panels in the living zones in ERP B, C and D are replaced with ventilation radiators, which in earlier studies has been found to enable lowering of heat system temperatures [39,40]. With ventilation radiators, the natural convection is increased since the inlet air is forced to pass through the radiator because of the pressure difference between indoors and outdoors created by the exhaust ventilation system, and also due to the placement of the inlet air vent. Properties of the reference case and the energy refurbishment packages are further described in Table 1 and supplementary details of the building model and the simulations can be found in [5,34].

**Table 1.** Description of the building reference case and the different energy refurbishment packages (ERPs) [34].

ERP	Heating	DHW	Ventilation	Radiators	U-Value, W/(m <sup>2</sup> K)			DHW Demand, L/(p-day), 45 °C
					Walls	Roof	Windows	
Ref.	DH	DH	Exhaust	Panel	0.34	0.24	3.15	38
A	DH	DH	MVHR	Panel	0.23	0.11	1.52	28
B	DH	DH	Exhaust	Ventilation	0.23	0.11	1.52	28
C	DH + EAHP	DH	Exhaust	Ventilation	0.23	0.11	1.52	28
D	DH + EAHP	DH + EAHP	Exhaust	Ventilation	0.23	0.11	1.52	28

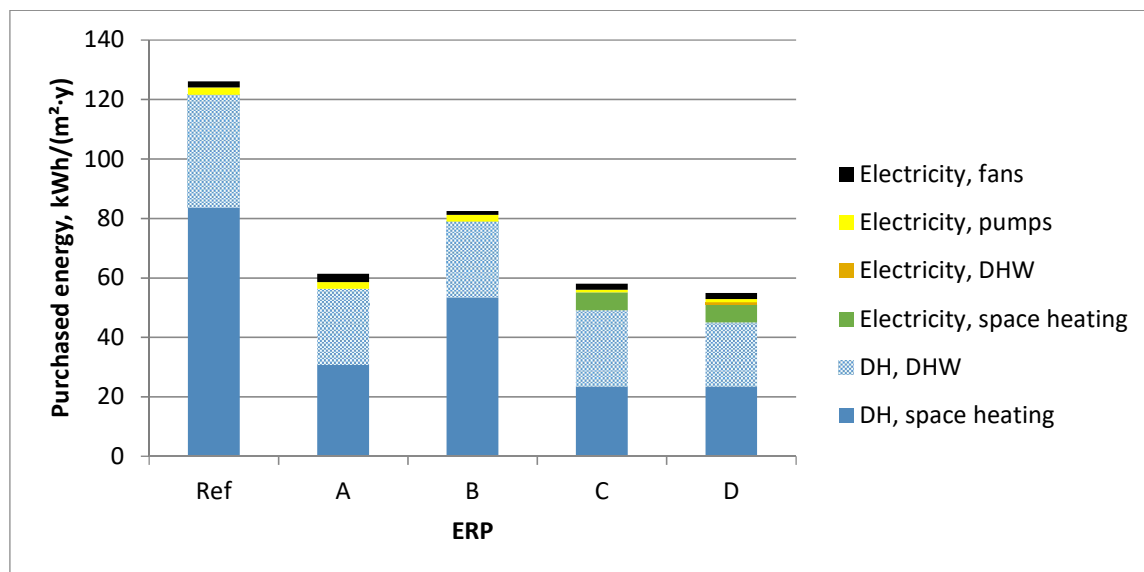
### 2.3. Performance Gap and Limitations

This study is performed with a Swedish multi-family building as a case study. The results are therefore representative for Swedish circumstances but are assessed to be useful as indicators for multi-family buildings with similar prerequisites situated elsewhere. As the study is performed with simulated data, there are always uncertainties in the compliance between the model and the simulation compared with the real existing building and the local preconditions on site. This is also known as the performance gap and has been further studied by for example Danielski [41] and De Wilde [42]. There are several reasons why a performance gap might occur. Allard et al. [43] studied different types of performance gaps, pointing out flaws or deviations from the intended design, uncertainties in the evaluations methods (simulations and measurements on site), unintended operation of the building or unexpected user behavior. As the intention with this study is to evaluate how these energy efficient refurbishment packages tend to be suitable for low temperature district heating or not, and not to conform the exact performance of the building, the simulated data is assumed to give sufficient precision in this case.

### 3. Results

The annual energy use for the reference case and each ERP is presented in Figure 1 and the relative changes compared to the reference case are described below. This part of the results has also been presented in an earlier paper [34]. ERP A reduces the use of purchased district heating with 54% and increases the use of electricity with 11%. ERP B reduces the use of district heating with 35% and the electricity use with 23%. This is the only ERP with decreased electricity use. ERP C reduces the use of purchased district heating with 60% and increases the use of electricity with 96%. ERP D reduces the use of purchased district heating with 63% and increases the use of electricity with 117%. The share of district heating to space heating and to DHW for each case are presented in Table 2. The energy use for space heating and the heating system temperatures for ERP C and ERP D are similar. ERP A, B and D were selected to be implemented in the real case study buildings in the Tjärna Ängar area in Borlänge, Sweden, wherefore from this point, only the results from ERP A, B and D will be presented.

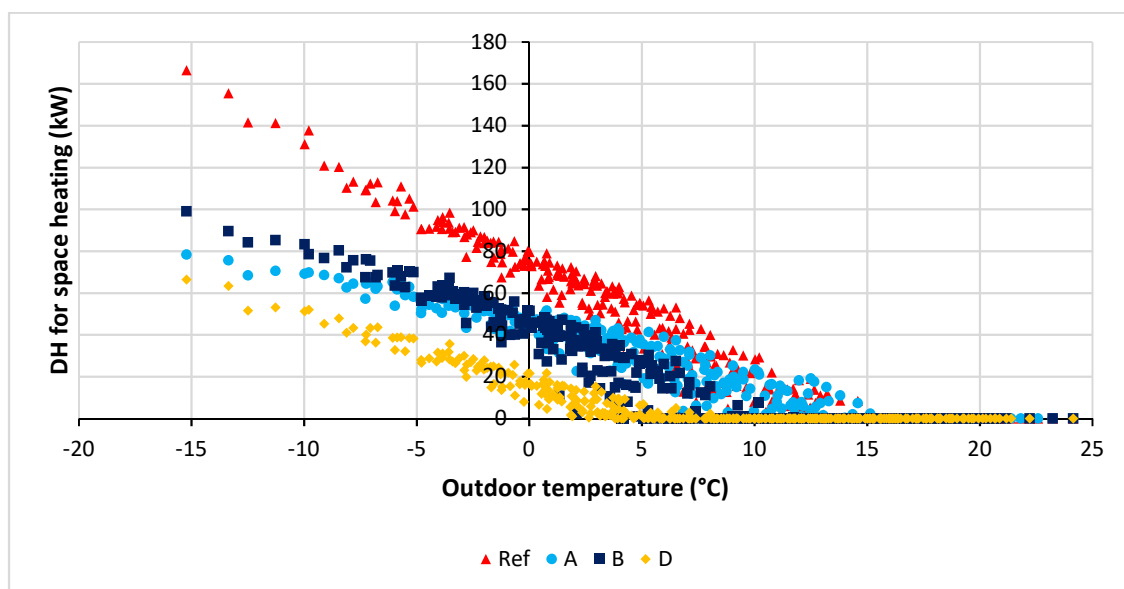
Figures 2 and 3 show the diurnal mean power of purchased district heating, for space heating only, for the reference case (Ref.) and the ERPs (A, B and D). The values are sorted by the outdoor temperature, starting with the coldest day to the left in both figures. In Figure 2, the diurnal mean power is compared to the outdoor temperature. The figure shows a reduced district heating space heating power requirement for all refurbishment cases. In Figure 3, the diurnal mean power for each day is shown, starting with the coldest day to the left. This figure clearly illustrates how the need for peak load during the coldest days of the year has decreased for all ERPs. In addition to the reduced district heating use for space heating these figures also show the profiles of the district heating use and the need for peak power in relation to the energy demand over time can be read out. ERP B and D have a more distinct need of peak power during the coldest days than ERP A. The profile of ERP A is flatter, and therefore the use of district heating is more even and robust when it comes to fluctuations in outdoor temperature.



**Figure 1.** The annual use of electricity and district heating for each case. This figure is also presented in an earlier paper [34].

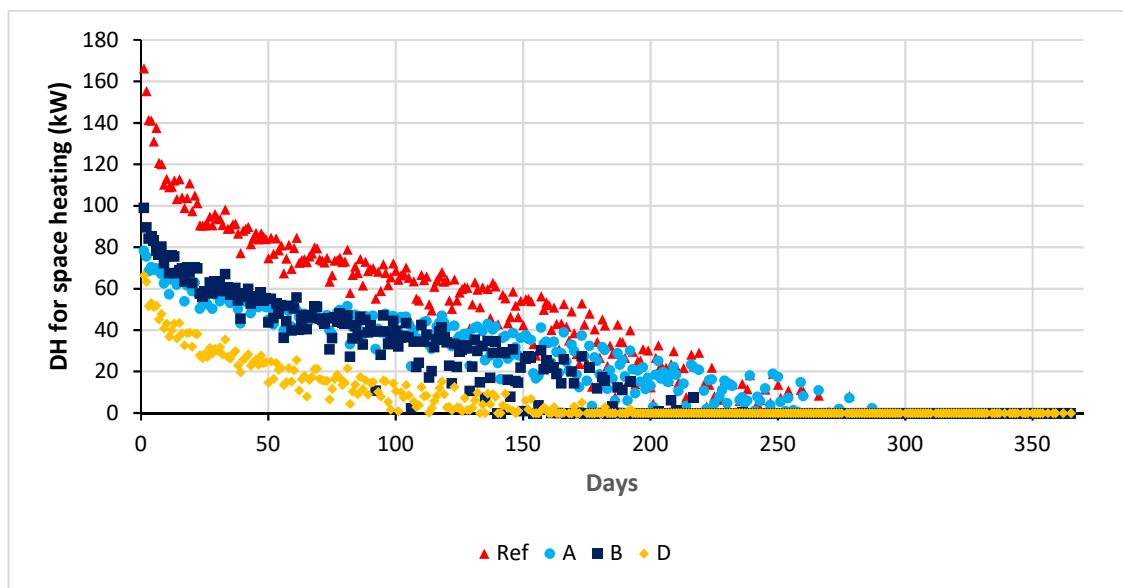
**Table 2.** The share of district heating used for space heating and for DHW.

District Heating Use	Ref.	A	B	C	D
For space heating (kWh/m² y)	84 (69%)	31 (55%)	53 (68%)	23 (48%)	24 (52%)
For DHW (kWh/y)	38 (31%)	26 (45%)	26 (32%)	26 (52%)	21 (48%)



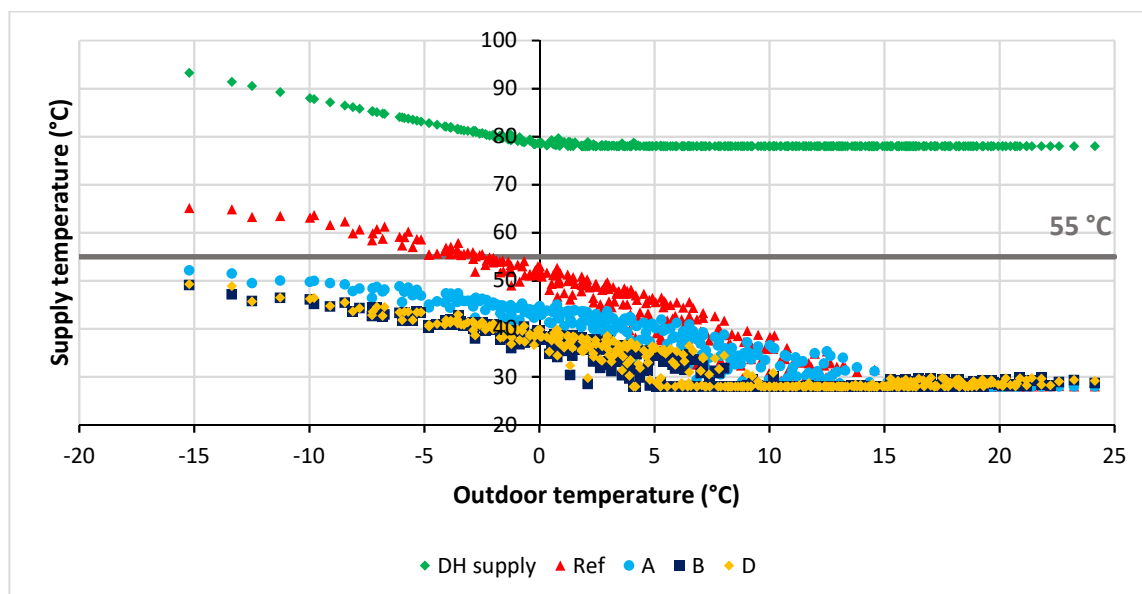
**Figure 2.** Diurnal mean power of the purchased district heating for space heating during one year compared to the outdoor temperature.



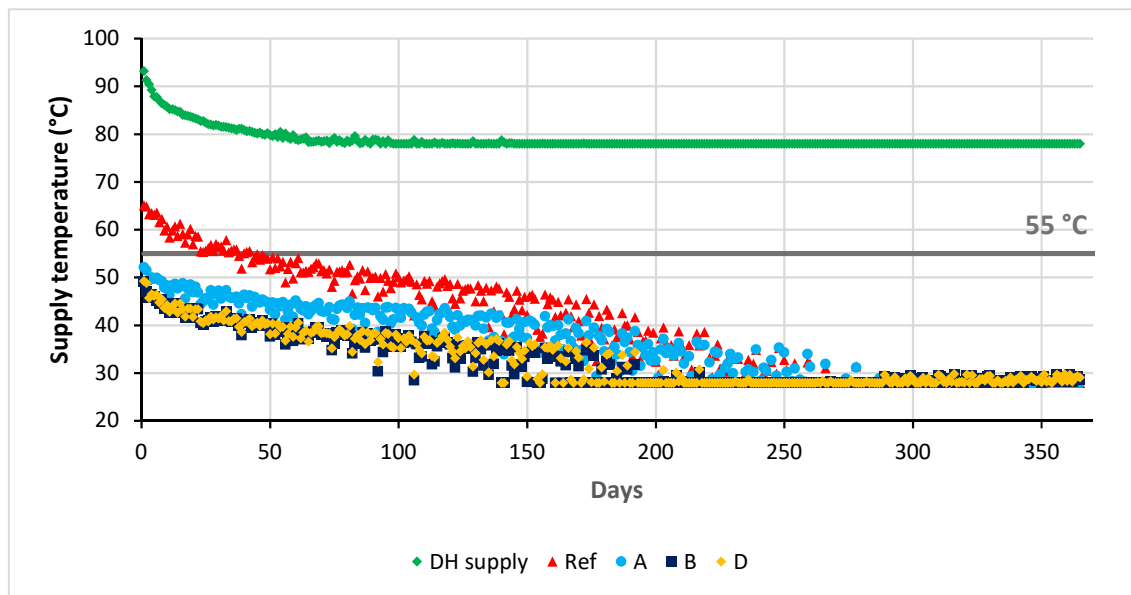


**Figure 3.** Diurnal mean power of the purchased district heating for space heating for each day for one year. The values are sorted with the coldest outdoor temperature to the left.

Figures 4 and 5 show the supply temperature from the district heating system to the building (the district heating supply temperature) together with the internal supply temperatures for the space heating system (space heating supply temperature) for the reference case and the ERPs. The values are sorted by outdoor temperature with the coldest day to the left. The space heating supply temperature is considerably lower for all ERPs compared to the reference case. ERP A has a slightly higher supply temperature than the other cases. This is the result of the ventilation radiators, which is simulated in ERP B and D, but not ERP A. The line at 55 °C temperature marks the same level of supply temperature from the heating source used for simulations of a low-temperature district heating system (fourth generation district heating system) by Lund et al. [9]. It is worth noting that the heat losses from the district heating distribution system is not included here.



**Figure 4.** The diurnal mean supply temperature from the district heating system to the building along with the diurnal mean supply temperatures in the space heating system in the building for the reference case and the ERPs compared to the outdoor temperature.

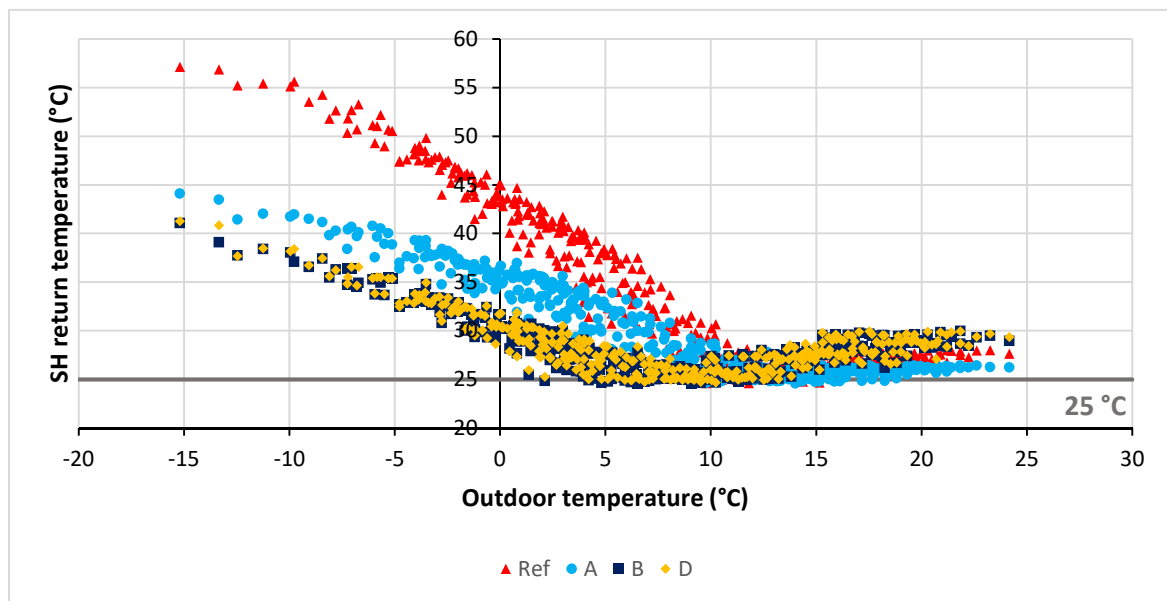


**Figure 5.** The diurnal mean supply temperature from the district heating system, to the building along with the diurnal mean supply temperatures in the space heating system in the building for the reference case and the ERPs for each day for one year. The values are sorted with the coldest day to the left.

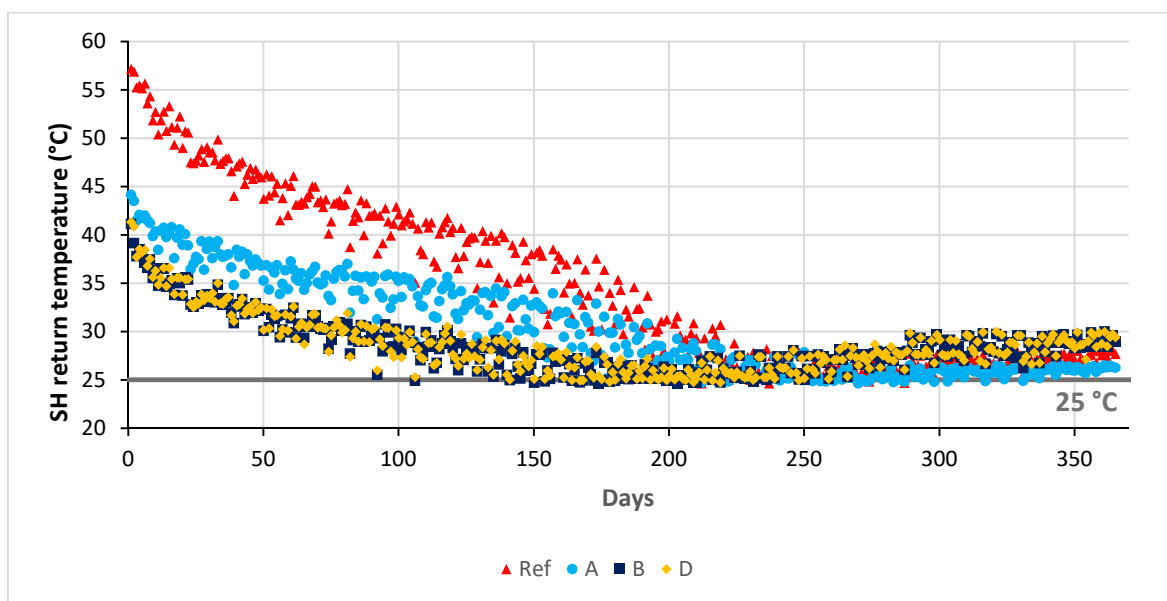
Figures 6 and 7 show the return temperature from the space heating system in the building for the reference case and the ERPs. The space heating return temperature is lower for all ERPs compared to the reference case. ERP A has a slightly higher return temperature than the other cases. This is the result of the ventilation radiators, which is simulated in ERP B and D, but not ERP A. In addition to the space heating return temperature, the DHW circulation also influences the return temperature to the district heating system, which is shown in Figures 8 and 9. This explains the temperature difference between Figures 6 and 8, and also between Figures 7 and 9. The district heating return temperature is almost constantly around 40 °C for all ERPs, unlike the reference case where the district heating return temperature is higher during the cold season of the year. This is explained from the district heating use, where space heating is relatively small in percentage for all ERPs but the reference case and the percentage of the DHW use and circulation is therefore larger. During summertime when no space heating is needed, the district heating return temperature is similar for both the reference case and all the ERPs. As long as the same technical solution is used for DHW, the return temperature is unlikely to go below the values in Figure 8. The line at 25 °C temperature marks the same level of return temperature to the heating source used for simulations of a low-temperature district heating system (fourth generation district heating system) by Lund et al. [9]. The heat losses from the district heating distribution system is not included.

The district heating return temperature does not reach the return temperature level of 25 °C at all. The space heating return temperature primarily reaches these values during the warmer time of the year. Note that when the average outdoor temperature is warmer than 15 °C, the space heating system will no longer be in operation. During the coldest part of the year it is clear that the systems including ventilation radiators (ERP B and D) brings a lower return temperature, which conforms the lower supply temperatures in Figures 4 and 5. The space heating supply temperature has decreased for all ERPs compared to the reference case, and constantly stay below 55 °C for all. The space heating return temperature has also decreased significantly compared to the reference case. Nevertheless, the result show that the return temperature only stays below 25 °C 14% of the time for ERP A, 10% for ERP B, and 7% for ERP D.

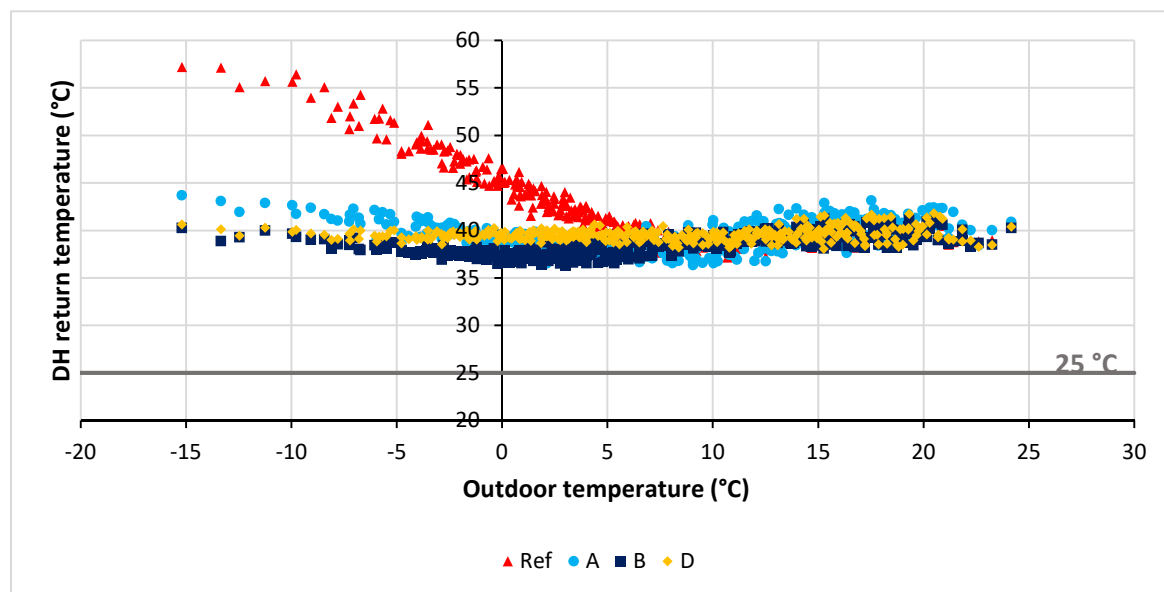




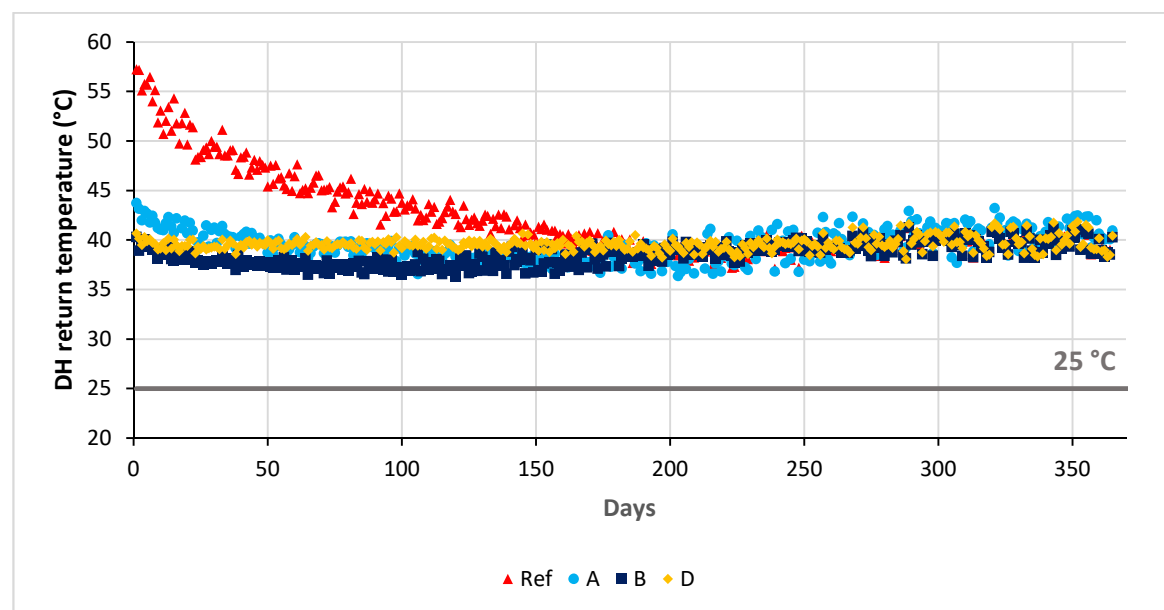
**Figure 6.** The diurnal mean return temperature from the space heating system in the building for the reference case and the ERPs compared to the outdoor temperature.



**Figure 7.** The diurnal mean return temperature from the space heating system in the building for the reference case and the ERPs for each day for one year. The values are sorted with the coldest day to the left.



**Figure 8.** The diurnal mean return temperature from the building to the district heating system for the reference case and the ERPs compared to the outdoor temperature.



**Figure 9.** The diurnal mean return temperature from the building to the district heating system for the reference case and the ERPs for each day for one year. The values are sorted with the coldest day to the left.

#### 4. Discussion

The results of this study show that the examined ERPs are suitable for lowering the temperatures of the space heating system in the studied building. All ERPs result in decreased supply and return temperatures for the space heating system, where ERP B and D lowers the temperatures the most because of the installation of ventilation radiators.

The return temperature from the building to the district heating system is considerably influenced by the DHW circulation, which increases the return temperature significantly. The share of district heating used for space heating and DHW respectively has impact on the return temperature to the district heating system. In this case, the district heating use for both space heating and DHW is decreased, the largest proportion is saved on space heating wherefore the parts are changed from

case to case. As a consequence, a larger share of DHW entails an increased influence of the DHW system on the return temperature of the district heating system. For all ERPs, the influence of the DHW temperature is larger than the influence of the space heating temperature, wherefore the return temperature to the district heating system is similar for all ERPs. For all ERPs the space heating supply temperature stays below 55 °C constantly, compared to the reference case where the space heating supply temperature increased above 55 °C for about 50 days/year or for outdoor temperatures of about −2 °C or colder. The conclusion of this is that for all ERPs, the space heating supply temperature is no longer determining for the district heating supply temperature. Instead, it will be the temperature level of the DHW that determines what district heating supply temperature that is required. In addition, the amount of days with heating demand decreases for all ERPs. The lowest demand of district heating for space heating occurs for ERP D where part of the heat demand is covered by the EAHP. Compared to the reference case, the amount of days with heat demand from district heating has decreased with approximately 100–150 days, as seen in Figure 3. In reference to the outdoor temperature, this means that there is no heat demand from district heating from 5 °C outdoor temperature compared to 15 °C for the reference case, as seen in Figure 2.

The ERPs that are presented in this study represent common strategies for refurbishment projects in Sweden with the aim to reduce the total use of energy for the building. The ERPs contained extensive measures including both building envelope improvement as well as renewed technical installations with significantly better energy performance. Nevertheless, there is a limit to what is possible in order to improve the buildings energy performance in terms of reducing the energy use for space heating. When this limit is reached, the DHW system is what remains that still can be influenced if further improvement of the energy performance is wanted. Water saving faucets can to some extent reduce the use of DHW use, but since the use of DHW is highly dependent on the behavior of the residents in the building, it is hard to influence. The DHW circulation has major impact on the district heating return temperature in the simulations with ERPs. To be able to lower the return temperatures to the levels of low-temperature district heating systems (55/25 °C), the DHW circulation system needs to be improved. The ERPs presented in this study might be suitable for refurbishment of multi-family buildings to a level that is suitable for low-temperature district heating, if complemented with improvement of or another technical solution for the DHW system. The supply temperature is lowered to an extent that matches the temperature levels of low-temperature district heating. Still, the return temperature needs to be lowered both for the space heating system and with concern to the DHW circulation. DHW preparation can be solved with alternative methods that might increase the use of electricity. For example, electrical boosting with heat pumps can be used to increase the temperature of the DHW if the supply temperature of district heating system is too low.

To some extent, the type of district heating system concerned by the refurbishment might determine the best way to handle the DHW problem. District heating systems can differ greatly in terms of heat sources and also in the amount of electricity produced within the system (CHP). Hypothetically, the temperature levels of district heating systems may vary as well, resulting in that a suitable solution for the DHW systems might vary. This research area needs to be further investigated.

## 5. Conclusions

For all ERPs examined in this study, the space heating supply temperature stays below 55 °C constantly. A conclusion of this is that all ERPs have the potential to make the simulated building suitable for low-temperature district heating. As a result of the lowered space heating supply temperature, the temperature need of the DHW system will determine the level of the supply temperature of the district heating system. In addition, the amount of days with heating demand decreases for all ERPs, which further increases the influence of the DHW system on the district heating system. The DHW system needs to be improved to enable the temperature levels of a low-temperature district heating system. This study points out the necessity of further research and investigations to find sustainable

solutions for DHW systems connected to low-temperature district heating systems. Another important conclusion is that the local prerequisites of the district heating system needs to be considered.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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