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Cost-Effective Heating Control Approaches by Demand Response and Peak Demand Limiting in an Educational Office Building with District Heating

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Abstract: This study examined three different approaches to reduce the heating cost while maintaining indoor thermal comfort at acceptable levels in an educational office building, including decentralized (DDRC) and centralized demand response control (CDRR) and limiting peak demand. The results showed that although all these approaches did not affect the indoor air temperature significantly, the DDRC method could adjust the heating set point to between 20–24.5 °C. The DDRC approach reached heating cost savings of up to 5% while controlling space heating temperature without sacrificing the thermal comfort. The CDRC of space heating had limited potential in heating cost savings (1.5%), while the indoor air temperature was in the acceptable range. Both the DDRC and CDRC alternatives can keep the thermal comfort at good levels during the occupied time. Depending on the district heating provider, applying peak demand limiting of 35% can not only achieve 13.6% maximum total annual district heating cost saving but also maintain the thermal comfort level, while applying that of 43% can further save 16.9% of the cost, but with sacrificing a little thermal comfort. This study shows that demand response on heating energy only benefited from the decentralized control alternative, and the district heating-based peak demand limiting has significant potential for saving heating costs.

Keywords: demand response; peak demand limiting; district heating; cost-effective heating control; educational office building

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1. Introduction

The building sector is a remarkable energy consumer and carbon emitter, responsible for around 35% of worldwide energy usage along with around 25% of the global carbon emissions [1]. Thus, buildings play a paramount role in assisting in environmental protection and global climate change improvement by minimizing their energy use and corresponding carbon emissions. Nowadays, the demand response (DR) approach in buildings has been broadly accepted to shave or shift peak hours of energy consumption to reduce energy costs and greenhouse gas emissions [2]. The strategy is to reschedule the use of patterns from higher energy-consumption or energy-price period(s) to a lower peak period [3]. While executing the DR control, both the thermal comfort and indoor air quality should be maintained at an acceptable level [4]. Building energy demand can be adjusted [5] by the multivariate set points of indoor air temperature within the buildings [6].

In addition, Hu et al. [7] claimed that dynamic energy pricing could be considered as the most efficient pricing pattern in the DR strategy.

The district heating (DH) system is widely used in many countries (e.g., China, Russian, Poland, and Germany) [8]. In addition, it is also broadly adopted in Finland, and almost half of the Finnish people live in buildings that are heated by DH [9]. Regarding the large number of DH-based buildings, there has been growth of interest and demand for DH-based DR approaches. For example, Kontu et al. [10] proposed a city-scale DR approach applied in the DH systems with three different sizes, while Sweetnam et al. [11] proposed a domestic DR management on all DH networks in England. In addition, Ala-Kotila et al. [12] conducted field tests on the DR application in the DH grid in student accommodations, while Yuan et al. [13] proposed and applied DH-based DR for the pools and pool space in a Finnish swimming hall. The above DR methods on DH can all decrease the total DH cost. Moreover, Eguiarte et al. [14] developed a domestic decision support tool based on domestic users on DR for reducing heating costs. To date, the research on the DR of DH is limited to the few papers mentioned above, but this research topic deserves more in-depth study.

In addition, the dynamic behavior of buildings heated by DH has been examined by some researchers as well as the effect of the heat load cut on costs [10]. For example, Dominkovic et al. [15] conducted a building-level simulation on the DH systems with thermal building mass for storage and optimized it with a linear optimization model. In addition, Dreau and Heiselberg [16] also studied the energy flexibility of residential buildings considering different heat storage solutions (e.g., short-term heat storage, battery, and hot water tank). Finally, all of them concluded that the peak load shaving was determined by the specific elements (e.g., the thermal mass, building envelope insulation condition, and climatic conditions, as well as acceptable indoor operating temperature range).

A small number of studies have investigated the impact of DR management on the entire energy system. For example, Difs et al. [17] proposed a local energy system with both the DH supplier and corresponding customers and analyzed the proposed system under the circumstances with three different energy conservation measures (e.g., attic insulation, heat load controls, and electricity savings). Romanchenko et al. [18] applied thermal energy storage in the DH systems and analyzed its heat-load-variation decrease level, and they also compared the storage performance between the hot water tank and building thermal inertia in terms of similar storage capacity. They finally found that the analyzed system can decrease the annual operating cost by 1% with building thermal inertia and by 2% with the thermal energy storage (TES) tank and the DH system. Cai et al. [19] studied energy flexibility, mainly DR, on the DH network for the project called Copenhagen Public Works (21 customer nodes) and obtained the energy cost savings (around 11%). Moreover, Guelpa et al. [20] proposed improving the DH system via DR management to reschedule the building thermal request profiles. They found that the proposed management method could decrease primary energy consumption by 0.4% annually with no additional investment costs. Vandermeulen et al. [21] did a comprehensive review on the different approaches to quantify energy flexibility and found that more advanced control strategies were required for system optimization. Therefore, according to the current knowledge on district-heated buildings, there have been no investigations to compare the cost-saving potentials of the decentralized DR, centralized DR, as well as peak demand limiting. Other than these, there are no more related studies about the impacts of DR management on the entire building energy system.

As mentioned above, there has been no study focused on the comparison between the decentralized DR, centralized DR, and peak demand limiting in district-heated buildings, which makes it a research gap in this topic. In addition, researchers have conducted a few studies on DR management of DH-based buildings with dynamic energy prices. The novelty of this paper is the presented comparison based on the dynamic energy prices for a large educational office building. Thus, three cost-effective heating control visions were examined, including (a) the decentralized DR control, (b) centralized DR control, and (c) limiting peak demand while maintaining indoor air thermal comfort.

2. Methodology

2.1. Structure of the Simulation Study

The IDA Indoor Climate and Energy (ICE) building simulation tool was used in this paper to model, simulate, and analyze the indoor temperature conditions, the behavior and cost of building energy consumption, and the heating control approaches. Figure 1 shows the formation of the heating control approaches including decentralized and centralized DR controls and peak demand limiting. As shown in Figure 1, the DR controls are formed by taking the indoor and outdoor air temperatures and the energy price changes of the DH grid.

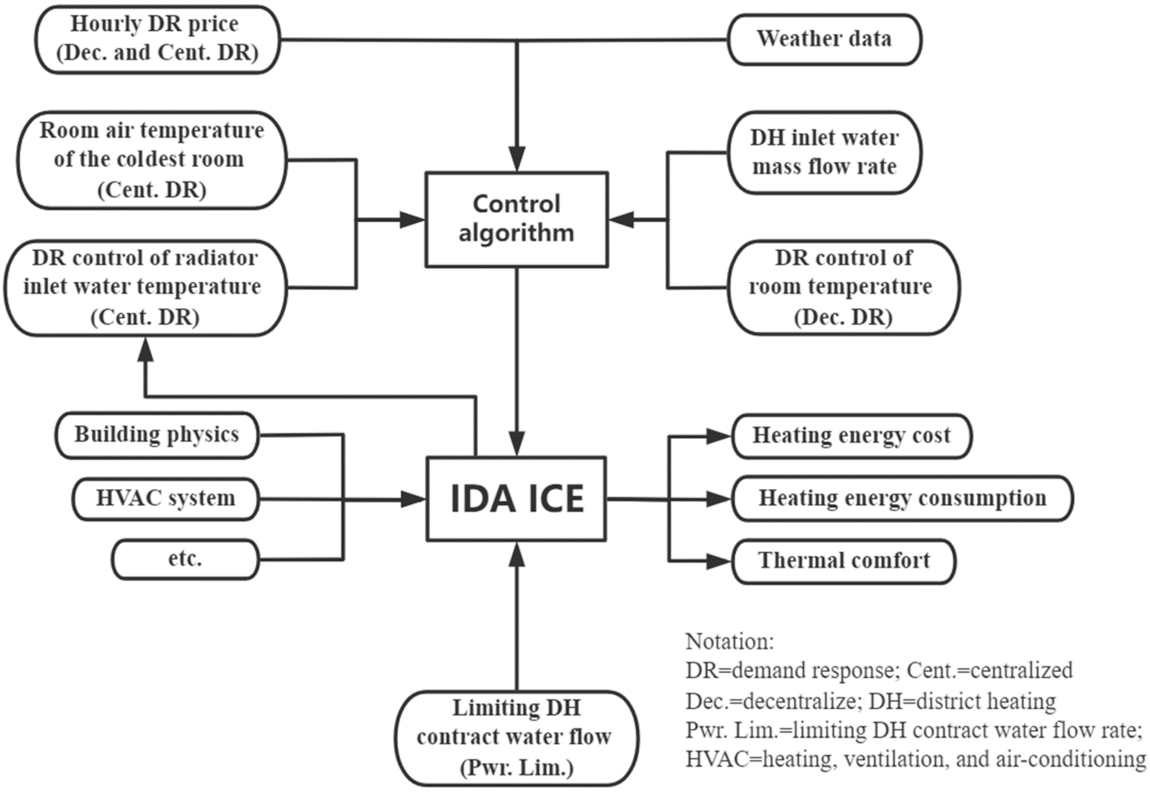

Figure 1. Simulation process principle for decentralized and centralized DR controls and peak demand limiting.

2.2. Hourly DH Price

The used DH price in this research points out that the price of a regular Finnish DH producer included not only the energy fees, but also the taxes, as well as the dynamic transfer fees. As seen in Figure 2, the hourly DH prices adopted in this paper were determined by a DH system comprised of a heat-only boiler and a combined heat and power (CHP) plant, and the detailed information could be found in Salo et al. [22]. The CHP plant can provide different types of energy, which can be used only for heat production consuming wood and peat. The heat output of the CHP plant can meet up to 50% of the peak heat demand per hour, and the rest is produced by the purely oil-fired heat boiler. The cheapest produced heat included the heat from CHP plant (supplying only heat or supplying both heat and power) and the heat-only boilers, which were elected hourly to meet the heat demand. The heat demand was calculated per hour under the circumstance of adopting the weather data from the Finnish Test Reference Year 2 (TRY) [23]. Moreover, the electricity costs also included the losses, risks, and profits, causing an increase of the marginal costs by 21%.

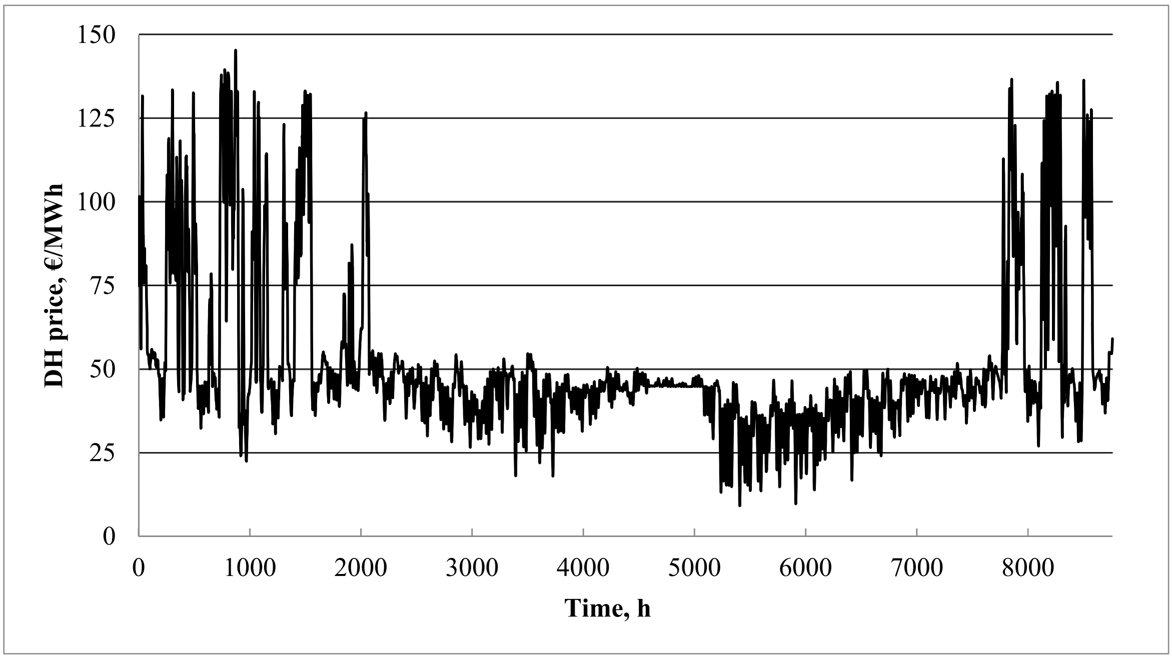

Figure 2. Hourly DH prices.

2.3. Weather Data

This study used the Finnish TRY2012 [23] for building simulations. The TRY2012 accumulated the weather monitoring results and docketing from 1980 to 2009 at the Helsinki-Vantaa airport weather station [23], which can represent the current climatic conditions per hour in southern Finland (e.g., outdoor temperatures, relative humidity, wind velocity, as well as solar radiation). Therefore, the TRY2012 exemplifies a typical weather year in Finland. Figure 3 shows the hourly relative humidity and temperature from TRY2012 [23].

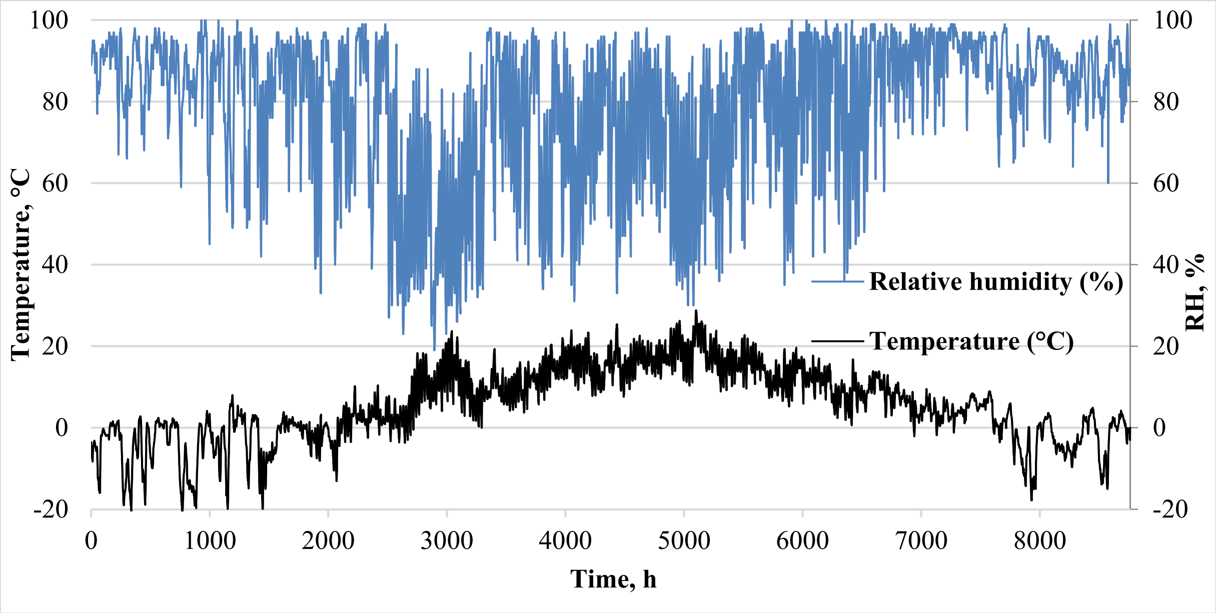

Figure 3. Temperatures and relative humidity for TRY2012 [23].

2.4. IDA ICE (Building Simulation Tool)

This paper adopted the IDA Indoor Climate and Energy (IDA ICE) building simulation tool [24], which can be used to study the multi-zone situations, the dynamic indoor air quality modelling, and the thermal comfort and energy use in buildings. Nowadays, the IDA ICE building simulation tool has been widely accepted and validated in many studies [25–29] and thus was used in this paper.

3. DR Control Simulation

3.1. Building Description

An educational office building was selected as the studied building in this paper, which is located at Aalto University campus in Espoo, Finland. The building was renovated in the early 2000s, originally built in the 1960s. There are four floors in the building, whose total heated net floor area is 8616 m^2, while the fourth floor was chosen as the modelled and studied floor, which has a heated net floor area of 586 m^2. Figure 4 shows the target floor layout in this paper.

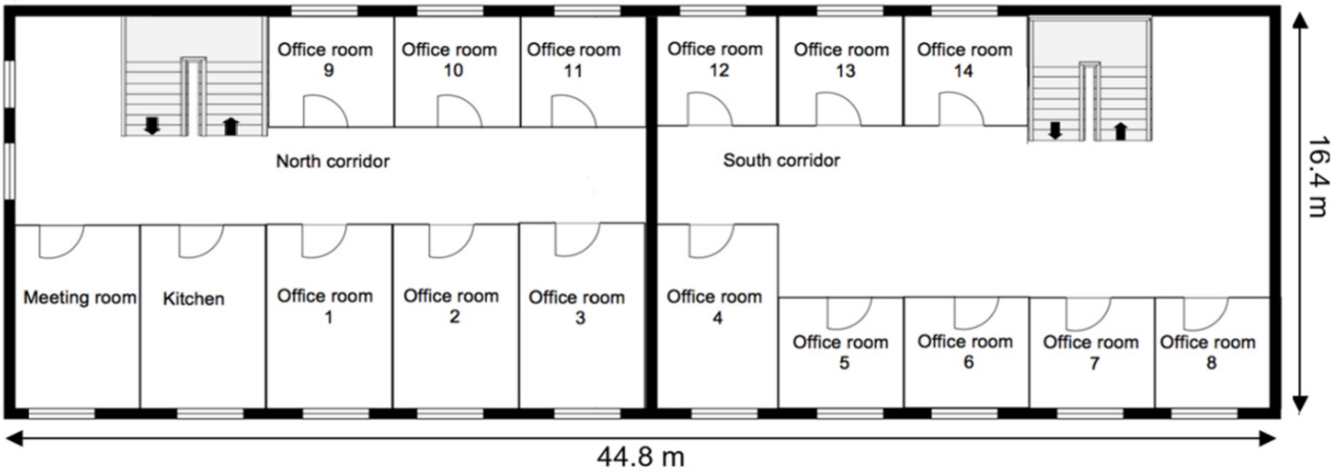

Figure 4. The layout of the modelled and studied floor**.**

3.1.1. Building Structure

All the structures (e.g., external and internal walls) of the studied building are massive concrete. Thus, the building has very high thermal mass with considerable energy flexibility [30,31], which is suitable for applying heating control approaches. Table 1 shows the building envelope information, while Table 2 shows the conductance of the thermal bridges in the studied building.

Table 1. Building envelope information of the studied building.

Building Envelope	Area (m^2)	U-Value [W/(m^2 K)]	Conduction (W/K)
Roof	586	0.30	176
Walls	252	0.38	97
Windows	109	1.10	120
Thermal bridges	-	-	17
Total	943	0.43	410

Table 2. Conductance of thermal bridges in the studied building.

Conductance of Thermal Bridges	Value (W/m,K)
External wall/External wall	0.06
External window perimeter	0.04
Roof/External wall	0.08

The conductance of thermal bridges was arranged according to Finnish building code D5 [32], while the simulations adopted the building air leakage rate (1.6 ACH) at a pressure difference of 50 Pa, which was adopted according to Vinha et al. [33]. The argon-filled low-E glass elements were used to replace the inner windowpane for renovation of the original two-pane windows, and the new windows with these new elements were equipped with solar protection in the south or west directions. The g-value (namely, solar heat transmittance) of the windows with solar protection was 0.38, while for the rest of the windows, it was 0.59.

3.1.2. Technical Systems

The buildings are connected to the DH networks for space heating supplies and ventilation, which also adopted a water radiator heating system as the heat distribution system. In addition, under the circumstance that the design outdoor temperature is −26 °C without solar and internal heat gains, the dimensioning heating power is set as 40 kW for both space heating and ventilation in the target floor. The dimensioning temperatures of the heat distribution system are 70/40 °C concerning the design outdoor temperature.

In this study, the inlet water temperature for the heating system is adjusted by the control curve, defined with the outdoor temperature. The presented control curve was used for the three heating control approaches. However, additional modifications on inlet water temperature were implemented only in the centralized DR cases detailed and described in Section 3.2.3.

In addition, the target building adopted the ventilation system combining the mechanical supply and heat recovery-based exhaust ventilation. Constant air volume (CAV) ventilation is used in the office rooms and corridors, while variable air volume (VAV) ventilation is used in the meeting rooms and lecture halls.

3.1.3. Internal Heat Gains

This study used the 40% occupancy rate based on studies [34–37]. The workstation amount in the rooms corresponds to a maximum occupant number of four. They are assumed to occupy rooms between 8:00–16:00 during the workdays. The occupant heat gain is determined as 1.2 MET and a clothing of 0.75 ± 0.25 clo, which represents the heat load of 126 W/occupant [38]. The installed lighting has the specific heat load of 7.5 W/m^2 on average in the rooms. The heat load of the equipment is set by calculating a laptop and a screen in use (altogether 50 W/occupant).

3.2. Heating Control Approaches

This study conducted three different approaches to reduce the heating cost. To achieve this aim, two DR controls, including decentralized and centralized ones, and peak demand limiting in which no DR control was involved were studied based on decreasing the contract power of the DH connection.

The decentralized and centralized DR approaches reduced the heating energy cost. To apply these within the DH of buildings, the price trend classification was used. To figure out the trend of the DH price, it is assumed that the 24-hours-ahead DH prices are available each moment. The used method to determine the price trend was presented by Alimohammadisagvand et al. [39] and applied for this study, as well. However, the peak demand limiting approach saved the contract power fee of the DH connection and heating energy cost.

3.2.1. Acceptable Indoor Air Temperatures

The acceptable room air temperatures were designated based on the latest indoor environment classification from the Finnish Society of Indoor Air Quality [40], which ranged from 20.0 °C to 24.5 °C. In addition, the acceptable room air temperatures followed the office building design recommendations for operative temperature and met class II (20–26 °C) on the indoor environmental standard SFS-EN 16798-1 [41].

3.2.2. Decentralized DR Control

The set points of indoor temperature are determined based on the trend of the DH energy price as follows:

- When there is an increasing price trend and a low-level outdoor temperature (limiting outdoor temperature of 0 °C), the building is heated up under the maximum set point of indoor air temperature (24.5 °C);
- When there is a decreasing price trend, the stored heat energy in the building structures is used through decreasing the set point of indoor air temperature to the minimum (20.0 °C);
- When there is a flat price trend, the normal set point of indoor air temperature of (21.0 °C) is adopted for heating up the building.

Figure 5 presents how the decentralized DR controls the set point of indoor temperature, where $T_{SH,set}$ represents the set point of indoor air temperature, $T_{SH,min}$ is the minimum set point of indoor air temperature, $T_{SH,norm}$ is the normal set point of indoor air temperature, and $T_{SH,max}$ is the maximum set point of indoor air temperature. In addition, $T_{avr,24}$ represents the mean outdoor temperature during the previous 24 h, and $T_{lim,out}$ represents the limiting outdoor temperature, namely, the maximum outdoor temperature.

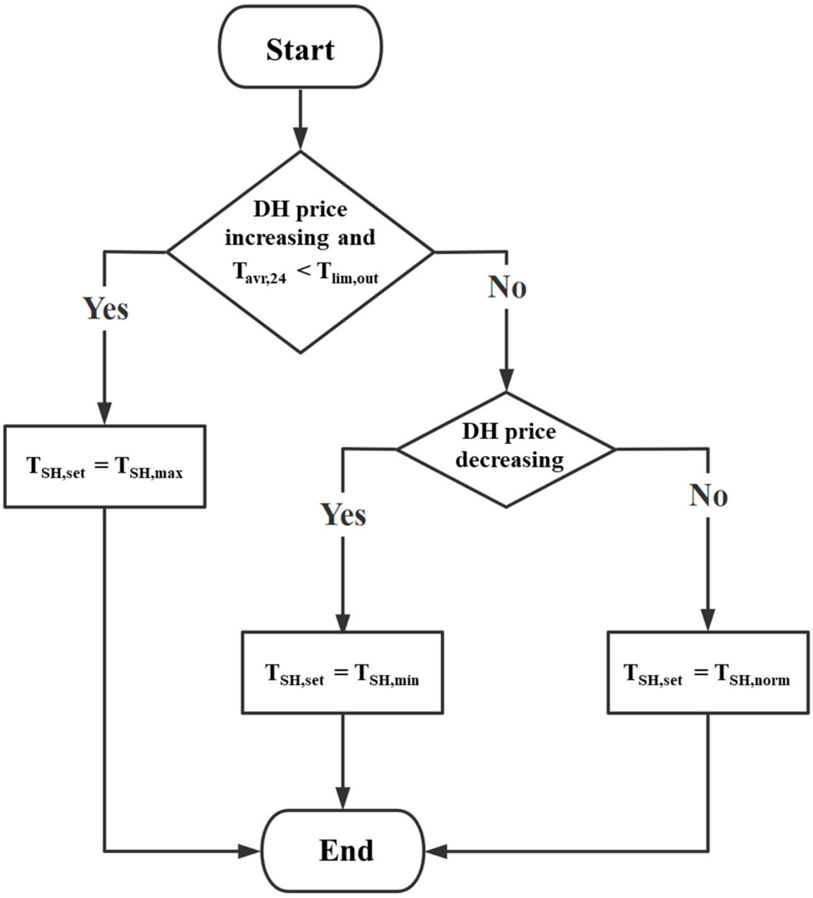

Figure 5. Decentralized DR control of space heating.

3.2.3. Centralized DR Control

Centralized DR control was studied by adjusting the inlet water temperature of the radiator circuit according to the trend of DH energy price and outdoor temperature. The effect of modified inlet water temperatures on the relative heating power of the radiator circuit was studied by Martin [42] using the method presented by Stephan [43]. Figure 6 shows inlet water temperature control curves in the reference case and in the cases with the relative heating power change of −80 to +20% compared to the reference case.

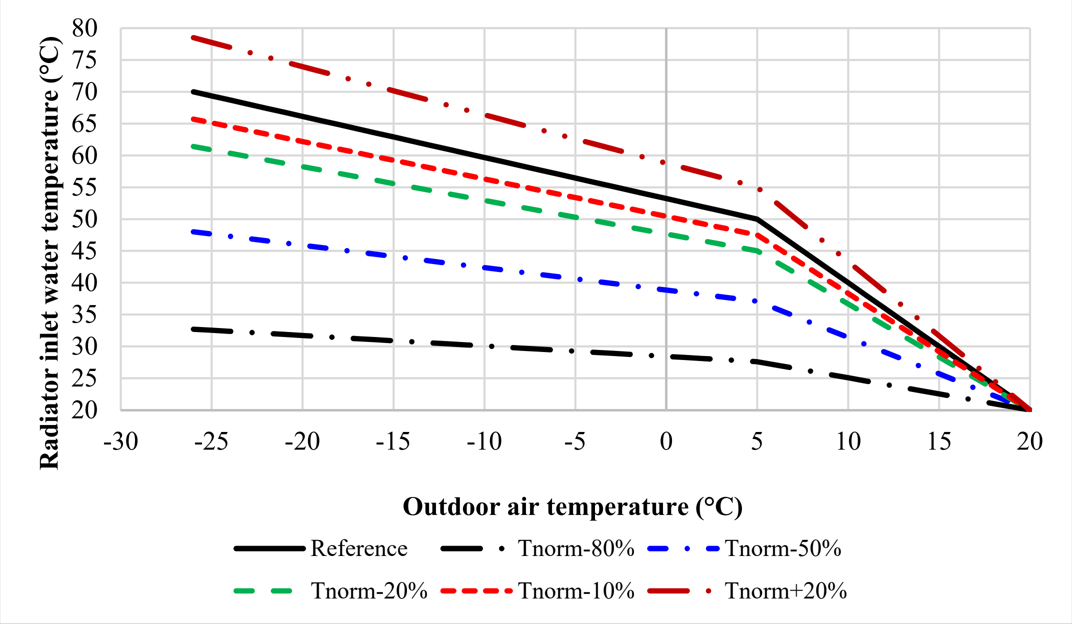

Figure 6. Radiator inlet water temperature control curves in the reference case and in the cases with relative heating power decreases.

Then, the inlet water temperature modifications were executed by DR control. The set point indoor air temperature is 21 °C, and the radiator inlet water temperature is regulated by the centralized DR control as follows:

- Once the trend of DH price is increasing and the outdoor temperature is low (the outdoor temperature is lower than the 24 h moving average outdoor temperature, which is namely $T_{out} < T_{avr,24}$), the indoor air temperature should also be checked to adjust the inlet water temperature. If $T_{air} > T_{SH,max}$, the indoor air temperature is beyond the maximum acceptable value, so the inlet water temperature is not changed and it is kept at the normal level; otherwise higher inlet water temperature is used corresponding to 20% relative heating power increase.
- When there is a decreasing trend of DH price and the indoor air temperature is not too low ($T_{air} > T_{SH,min}$), the lower inlet water temperature is used corresponding to a relative heating power decrease of either 10, 20, 50, or 80%, depending on the case. Otherwise, once the indoor air temperature is dropping too much ($T_{air} < T_{SH,min}$), the inlet water temperature is kept at the normal level.
- Finally, as soon as the trend is flat, then the inlet water temperature is at the normal level.

Moreover, Figure 7 shows how the centralized DR control was implemented. When there is an allowable trend of indoor temperature increase, T_{air} is the indoor air temperature of each room in the studied building, T_{in} is the inlet water temperature of radiators, T_{norm} is the normal inlet water temperature based on the reference radiator inlet temperature curve at a certain outdoor temperature, and $T_{norm\text{-}n\%}$ means that the inlet water temperature is based on the control curve of n% relative heating power change.

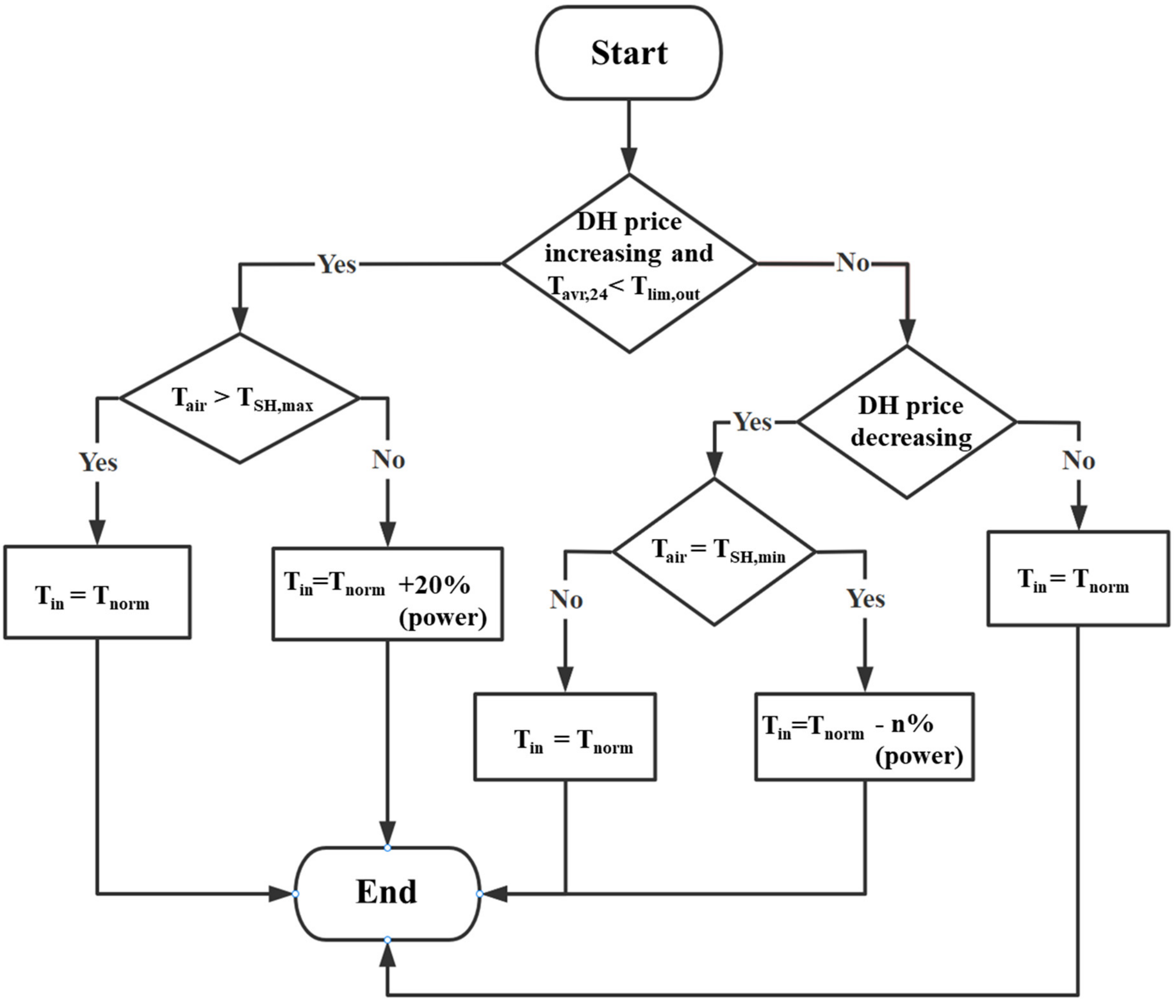

Figure 7. The centralized DR control of space heating.

3.2.4. Peak Demand Limiting

The contract power of DH is determined by the power demand under the circumstance of the dimensioning outdoor temperature without considering the solar and internal heat gains. These cold outdoor temperature conditions (design outdoor temperature is −26 °C in southern Finland) occur quite rarely, and the heat gains (e.g., lighting, equipment, occupants, and solar) also decrease the building heating power demand, which indicates the potential of the contract power to decrease for economic benefit. The cost-saving potentials of contract power decrease and their effect on indoor temperatures were studied. This heating control approach uses different maximum DH water mass flows through the substation. Compared with the nominal flow of the reference case, the reduction mass flows are 35%, 43%, and 50%, respectively. It can be noted that this approach does not use a DR control for the DH cost savings. Moreover, the space heating temperature set point is fixed at 21 °C and the reference control curve of inlet water temperature shown in Figure 6 was used.

The total DH power demand of space heating and ventilation in the whole studied building is 528 kW at dimensioning conditions requiring a mass flow rate of 1.8 kg/s. The building cost-saving potential in power charge based on peak demand limiting was analyzed for cities in southern Finland, Helsinki, and Espoo using the prices of two different DH providers, A and B. The stable heat package provided by DH provider A, which provides a constant relative power charge according to the nominal power, was used for the Espoo region, and the DH provider B, which provides a power charge according to the building nominal mass flow rate, was used for the Helsinki region, and both were considered.

4. Results and Discussions

The simulation results of the three above-mentioned optimization approaches are presented in this chapter. The building models have been validated by Vand et al. [35], as the building models are the same in this article as in Vand et al. [35]. In the DR control approaches (decentralized and centralized ones), only the heating energy cost was analyzed since these approaches do not affect the power fee of the DH connection. However, in the peak demand limiting approach, both the heating energy cost and power fee should be analyzed in the results, as they are all affected by the peak demand limiting approach.

4.1. Breakdown of Energy Consumption

Table 3 presents the breakdown of the delivered DH and electricity in the reference case without DR control and peak demand limiting. The set point of indoor air temperature in the educational office building is constantly set to 21 °C during the heating season.

Table 3. Energy consumption for the reference case.

DH (kWh/m^2,a)			**DH (kWh/m^2,a)**				
Space heating	AHU heating	Total DH	Electric cooling	Equipment	HVAC auxiliary	Lighting	Total electricity
69.4	59.2	128.6	1.0	3.8	38.7	13.9	57.4

Notations: DH = district heating, AHU = air handling unit, HVAC = heating ventilation and air-conditioning.

The total consumptions of DH and electricity in the building are 128.6 and 57.4 kWh/m^2,a, respectively. The building DH energy consumption is 69.1% of the total delivered energy use, of which the space heating part requires 54% of DH energy consumption.

4.2. Decentralized DR Control

Table 4 shows the annual energy consumptions and costs for the reference case, the minimum temperature set point case, and the decentralized DR case, and the reference case and minimum temperature set point case have fixed set points of indoor air temperature during the heating season.

Table 4. DH consumption and cost per year by using the decentralized DR control.

Case Study	**Indoor Air Temperature Set Point Range (°C)**	**Total DH Consumption**		**DH Energy Cost**	
		kWh/m^2,a	**%**	**€/m^2,a**	**%**
Reference	21.0	128.6	0.0	8.20	0.0
Minimum temperature set point	20.0	121.3	−5.7	7.79	−5.0
Decentralized	20.0–24.5	125.3	−2.7	7.77	−5.2

Notations: DH = district heating.

The maximum cost saving occurred while the decentralized DR control was applied, compared with the reference case whose set point of indoor air temperature is 21 °C. However, the difference between the minimum temperature set point (20 °C) case and the decentralized DR case is insignificant concerning the cost savings.

The decentralized DR control approach can save the DH energy cost up to 5.2% compared to the reference case, meaning around EUR 3700 annually for the whole building. By using the minimum set point of indoor temperature in the studied building, the DH energy cost drops by up to 5.0% and returns around EUR 3530 annually for the whole building. This shows that the decentralized DR control is slightly beneficial compared with the minimum temperature set point case (20 °C); however, the DR case consumes 3% more DH annually. Because the cost saving directly connects to less energy usage in this building type, the decentralized DR control charges the building more often by the minimum temperature set point (20 °C) than charges it by the maximum set point (24.5 °C). For the same reason, the heating energy saving of the case with the minimum temperature set point is higher.

Figure 8 presents the duration curve of indoor air temperatures in the coldest room and the acceptable indoor air temperatures during the occupied hours (2835 h). For the 20 °C temperature set point case, the indoor air temperature is lower than the reference case (21 °C temperature set point) over 80% of the occupied hours (2268 h), and almost 3% of the occupied hours (85 h) are below the minimum acceptable indoor air temperature. Furthermore, for the decentralized DR case, the room air temperature is below the minimum set point of indoor air temperature for almost 3% of the occupied hours (85 h). For almost 40% of the occupied hours (1134 h), the room air temperature of the decentralized DR control case is lower than the reference case (21 °C temperature set point), and for almost 30% of the occupied hours (850 h), it is vice versa. The decentralized DR control approach maintains the room air temperature between the minimum and maximum acceptable indoor air temperature set points for 97% of the occupied hours (2750 h), while there are also hours in which the room air temperature is lower than 20 °C, accounting for the remaining 3% of the occupied hours (approximately 85 h).

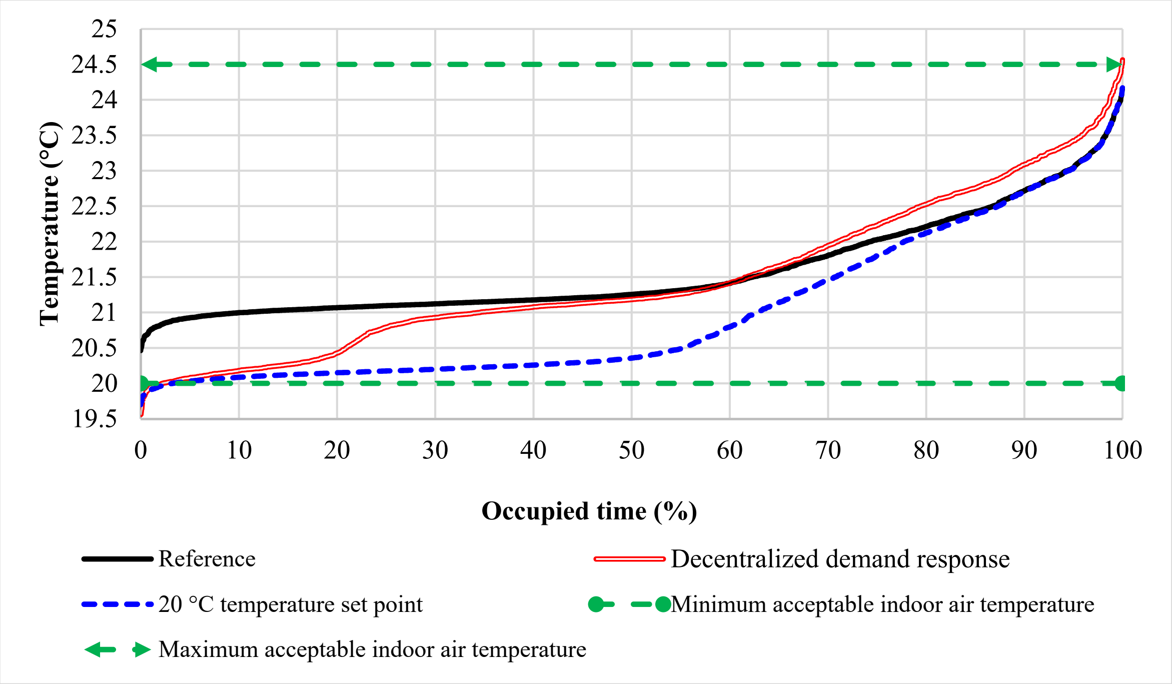

Figure 8. Indoor air temperatures in the coldest room (namely, office room 8 in Figure 4) within the occupied hours (2835 h) with and without DR control.

4.3. Centralized DR Control

The centralized DR control of space heating is conducted by decreasing/increasing the radiator inlet water temperature. Table 5 presents the results of different cases, including the reference, minimum temperature set point, and centralized DR control cases.

Table 5. DH consumption and cost per year by using the centralized DR control.

Case Study	Indoor Air Temperature Set Point Range (°C)	Total DH Consumption		DH Energy Cost	
		kWh/m^2,a	%	€/m^2,a	%
Reference	21.0	128.6	0.0	8.20	0.0
Minimum temperature set point	20.0	121.3	−5.7	7.79	−5.0
$T_{norm-10\%}$	21.0	128.3	−0.2	8.18	−0.2
$T_{norm-20\%}$	21.0	128.1	−0.4	8.17	−0.4
$T_{norm-50\%}$	21.0	127.4	−0.9	8.13	−0.9
$T_{norm-80\%}$	21.0	126.7	−1.5	8.08	−1.5

Notations: DH = district heating.

All the centralized DR cases can only achieve limited heat energy cost savings. The highest cost saving is around 1.5% for the case that uses the maximum inlet water temperature reduction ($T_{norm\ -80\%}$), and this returns around EUR 1030 for the whole building. This takes, however, a significant reduction of inlet water temperature (see Figure 6) to achieve the small cost saving (EUR 0.12/m^2,a). A comparison between the centralized DR control approach and the minimum temperature set point case shows that this DR control approach is not cost-effective. This is because the radiator thermostat valves in the reference case have large deviations from the nominal flows. Thus, accompanying the inlet water temperature decrease in the centralized DR cases, the mass flow through the radiator is simply increased by the thermostat for the compensation of reduced inlet water temperature. It is realized that the heating energy cost saving is higher once the decentralized DR control is used compared with the centralized DR control. Figure 9 shows the duration curve of the mass flow rate through the radiator in the coldest room for the studied centralized DR cases.

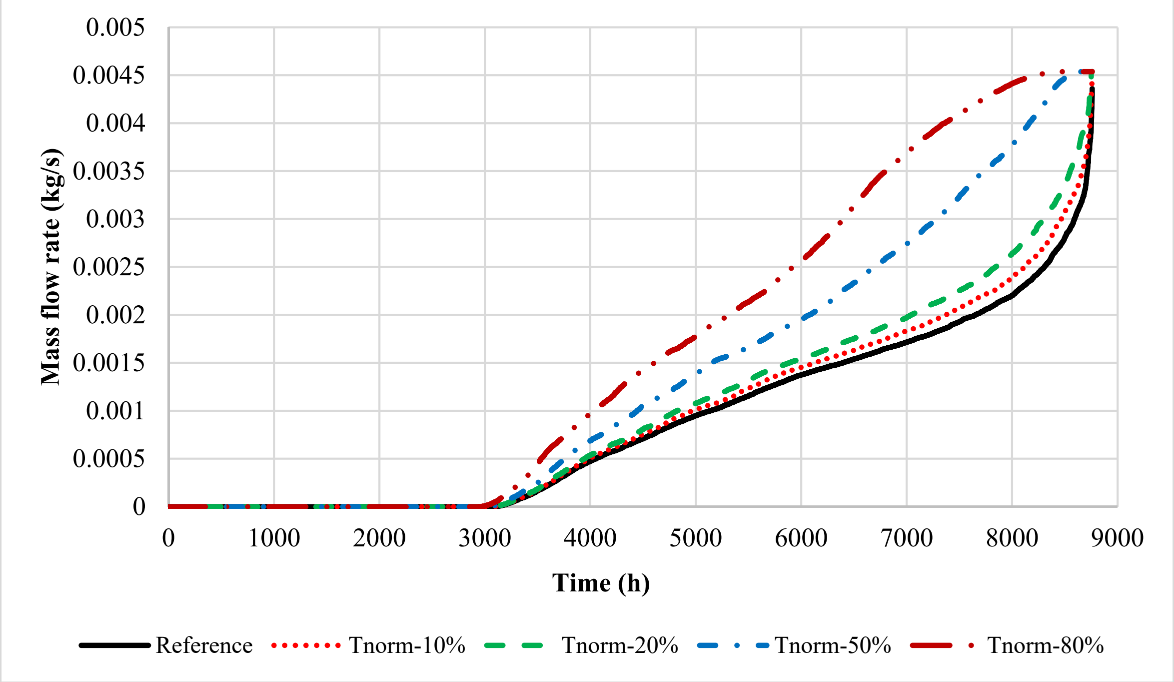

Figure 9. Duration curves of simulated radiator mass flow rate during the year with and without the centralized DR.

Figure 10 presents the indoor air temperature duration curves for the centralized DR control cases through the occupied hours. This figure shows the centralized DR control's influence on the indoor air temperature compared with the reference case. The indoor air temperature drops from 21 to 20 °C for the reference, $T_{norm\text{-}10\%}$, $T_{norm\text{-}20\%}$, $T_{norm\text{-}50\%}$, and $T_{norm\text{-}80\%}$ cases, for around 8% (227 h), 9% (255 h), 10% (283 h), 27% (765 h), 35% (992 h), and 62% (1 758 h) of the occupied hours. The greater the adjustment range of the inlet water temperature curve, the greater the drop in the indoor air temperature. However, compared with the reference case, the indoor air temperature is still not significantly lower. It may be concluded that the centralized DR approach has no significant influence on the thermal comfort nor the energy cost savings. These indoor air temperatures influenced by the centralized DR control are well-maintained at the acceptable level (20.0–24.5 °C) and only for the $T_{norm\text{-}80\%}$ case, the indoor air temperature drops below 20 °C for a few hours (85 h), which only accounts for 3% of the occupied time.

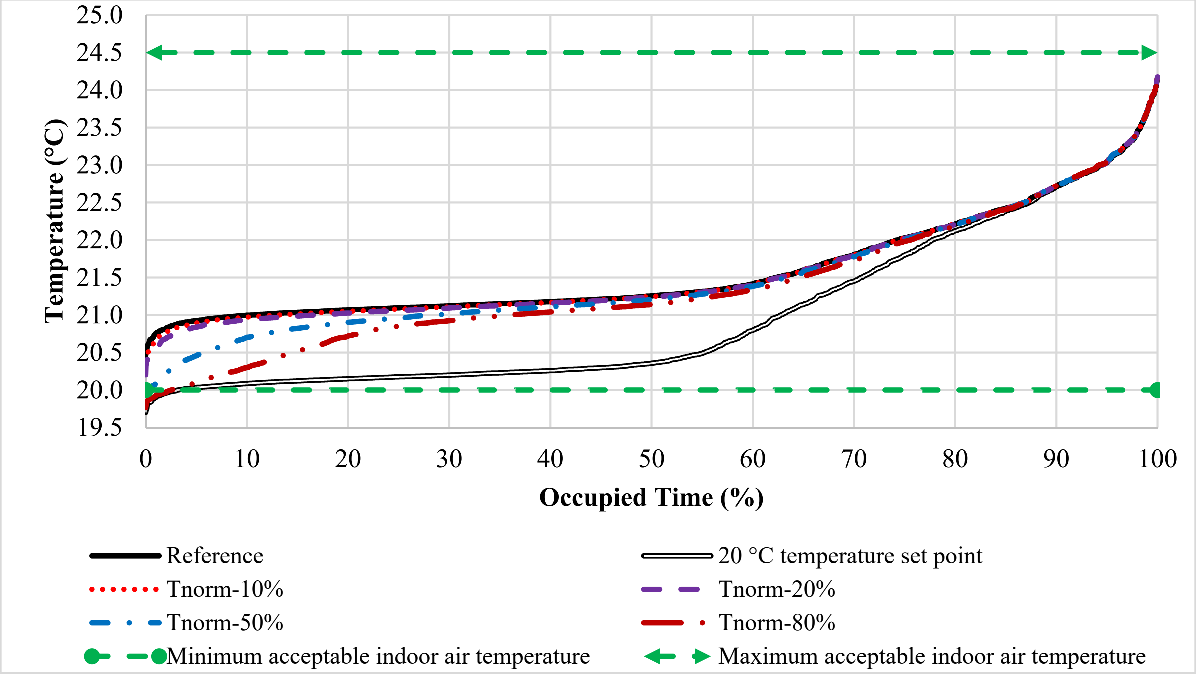

Figure 10. Indoor air temperatures of the coldest room (namely, office room 8) during the occupied hours (2835 h) with and without DR control.

4.4. Peak Demand Limiting

The dimensioning heating power is set as 40 kW for both space heating and ventilation on the studied floor, which is the reference case for the peak demand limiting cases. Table 6 shows the studied three peak demand limiting cases of DH power.

Table 6. Peak demand limiting cases.

Case	Dimensioning Power (kW)	Peak Demand Limiting	Available Power (kW)
Reference	40	-	40
Pnom-35%		−35%	26
Pnom-43%		−43%	23
Pnom-50%		−50%	20

The power demand limiting considered both the space heating and reheating of supply air in the AHU. Figure 11 shows the DH power duration curves of the space heating and ventilation during the heating season.

This simulation analysis did not survey outdoor temperatures colder than −20°C, as the Finnish TRY2012 weather data were used, which have been shown to describe the current climatic conditions of southern Finland [23]. A normal usage of the building was assumed while the dimensioning power of 40 kW was calculated without solar and internal heat gains. Therefore, under these conditions, the referenced maximum power demand of DH is 28.4 kW. The nominal power (P_{nom}) was diminished by 35% ($P_{nom-35\%}$) and only 0.5% of the annual heating hours were influenced. The case involving a 43% peak power cut ($P_{nom-43\%}$) influenced the annual heating hours of 3.4%. Finally, the 50% peak power limiting case ($P_{nom-50\%}$) affected the annual heating hours by up to 10.4%.

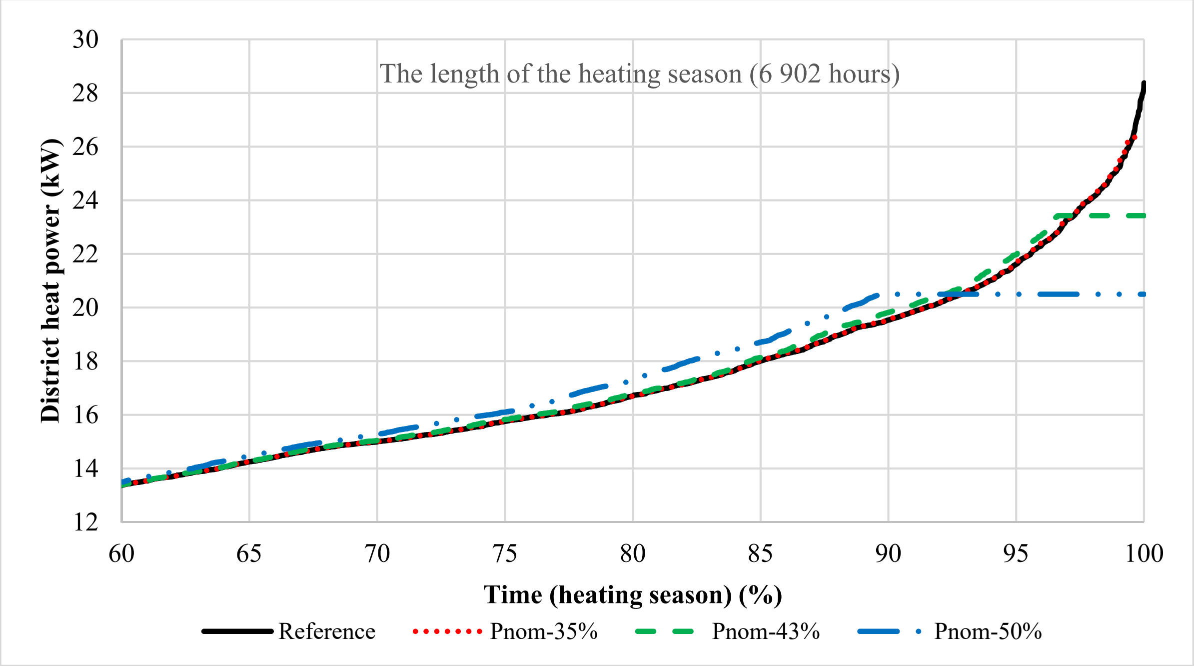

Figure 11. The duration of DH power demand of space heating and ventilation in the reference and peak demand limiting cases.

Restricting the DH power decreases the indoor air temperatures and requires, compared with the reference case, more heat power to achieve the indoor air temperature back to the set point. This fact occurs, for instance, in the Pnom-50% case where the influenced hours are approximately 20% of the annual heating hours. This example, presented in Figure 12, shows influenced power usage and the indoor air temperature of the coldest office room.

Figure 13 shows the power-limiting effect on the indoor air temperature of the coldest room in the simulated fourth floor concerning the temperature duration curves during the occupied hours.

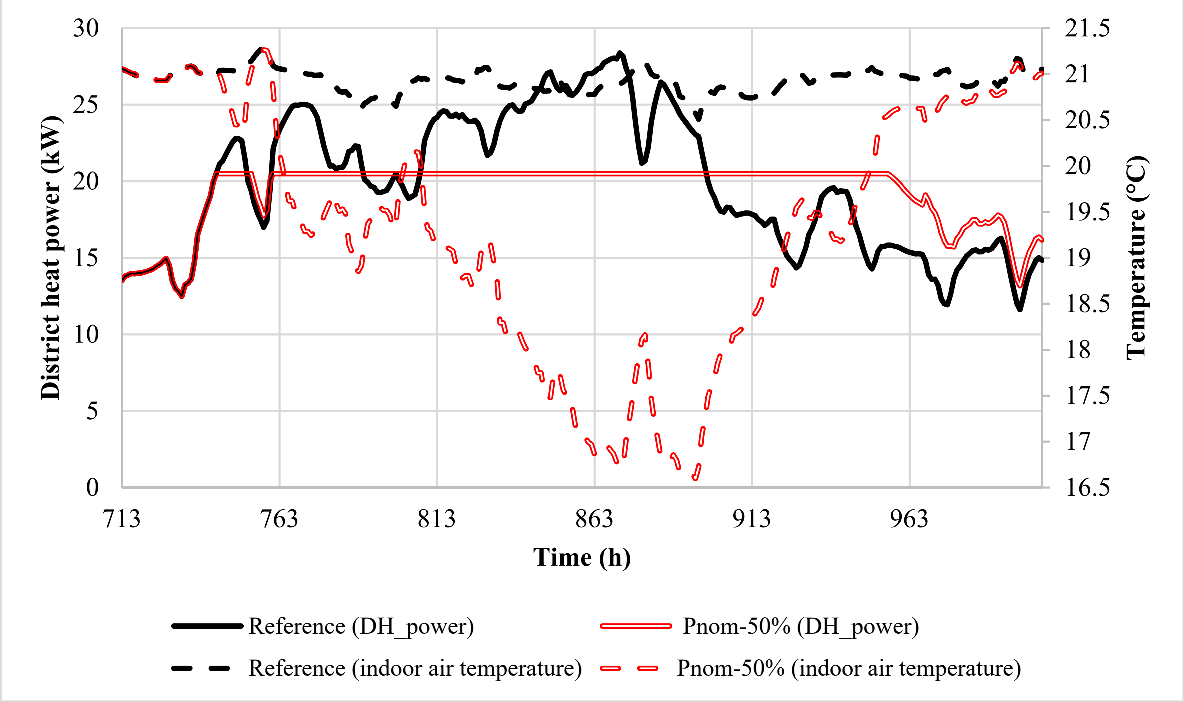

Figure 12. Peak power demand-limiting effect on indoor temperature of the coldest room (namely, office room 8) and power usage for the Pnom-50% case compared with the reference case.

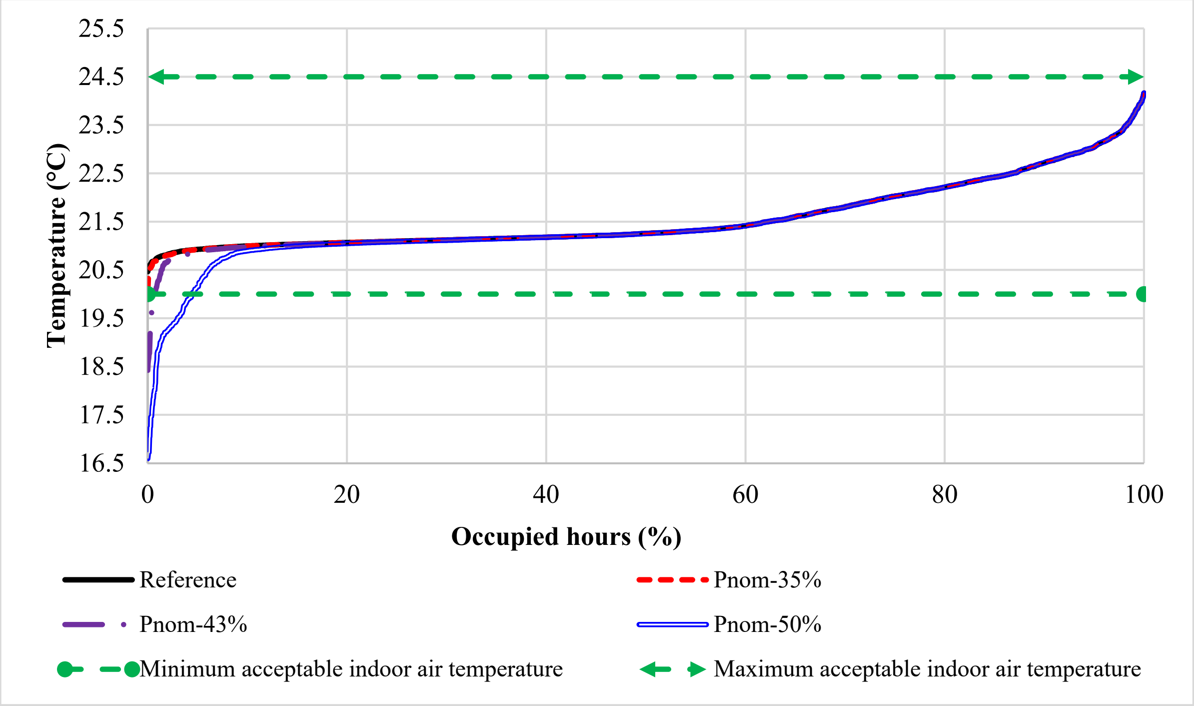

Figure 13. Temperature duration curves of the coldest room (namely, office room 8) for cases with different peak demand limiting during occupied hours.

There is no influence on the room air temperature under the circumstance of 35% peak demand limiting. Thus, the DH contract power can be decreased by 35% in the studied building, and the indoor temperature can be maintained at the acceptable range. However, the contract power could be decreased more, depending on how much a customer is willing to compromise on thermal conditions. A peak demand limiting of 43% affected the minimum room air temperature (18.4 °C), and there were 17 h (0.6% of the occupied hours) that the temperature was lower than 20 °C. Limiting power by 50% caused a minimum temperature of up to 16.6 °C, and around 124 h (4.4% of the occupied time) were lower than 20.0 °C.

Table 7 presents annual DH energy costs and power fees of two DH providers, while the prices shown in Table 7 are for the simulated floor as well as the whole building. The energy costs were calculated using the same hourly DH price defined in Section 2.2, but the power fees are based on the pricing of the energy providers A and B.

Table 7. DH energy and power demand and costs for reference and peak demand limiting cases.

Case	Total DH Energy Consumption (kWh/m^2,a)	Max. Hourly DH Power Demand (kW/m^2)	DH Power Fee (Provider A)	DH Power Fee (Provider B)	DH Energy Costs	Total DH Cost (Provider A)	Total DH Cost (Provider B)
			(€/m^2,a)				
Reference	128.6	28.37	5.23	1.53	8.20	13.43	9.73
Pnom-35%	128.6	26.35	3.40	1.11	8.20	11.60	9.31
Pnom-43%	128.6	23.42	2.98	1.02	8.18	11.16	9.20
Pnom-50%	128.5	20.49	2.62	0.93	8.09	10.71	9.02

Notation: DH = District heating; Max. = Maximum.

According to the simulation results in Table 7, the total DH consumptions per m^2 keep almost the same in the cases with or without the peak demand limiting, but the maximum hourly DH load in one year decreased to varying degrees in different peak demand limiting cases, which means the peak demand is indeed somewhat balanced. Even in the case with 35% peak demand limiting, the maximum hourly DH load can be decreased by 7.1% (2.0 kW/m^2), while that with 50% peak demand limiting can achieve a decrease of 27.8% (7.9 kW/m^2).

Both the DH power fee and the DH energy cost should be considered, as they could be affected by the peak demand limiting. The annual power charge differs significantly between the DH providers A and B, while DH provider A's charges are 280–340% more expensive than those of the provider B in the simulation cases. Owing to the fixed power charge of DH provider A, the annual cost per area (m^2) can be saved by up to 35%, 43%, or 50% depending on the cases with corresponding peak demand limiting, respectively. For DH provider B, the cost-saving range per m^2 is from 27.1–39.2% depending on each peak demand limiting case. As the power charge structures differ from different DH providers, the results show that under the circumstance that the building is connected to the DH provider B, it is possible to achieve a maximum annual cost saving of EUR 5194 (EUR 0.60 /m^2,a) for the whole building with 50% peak demand limiting. Meanwhile, if the building is connected to DH provider A, even the smallest peak demand limiting of 35% can cut the power charge up to EUR 15,782 (EUR 1.83/m^2,a) for the whole building, which is significantly higher than the peak demand limiting with DH provider B (e.g., three times more than a 50% peak demand limited by the DH provider B).

Apart from the DH power fees, peak demand limiting also slightly affects the total DH energy consumptions based on Table 7. Peak demand limiting of 35 and 43% has very little impact on the DH energy costs, but that of 50% will cause 1.3% DH energy cost savings, which could annually be EUR 948 for the whole building. The total DH cost savings (including the energy cost and DH power fee) with different peak demand limiting (35, 43, and 50%) range from 13.6 to 20.3% concerning the DH provider A distributor, while ranging from 4.3 to 7.3% concerning the DH provider B distributor.

Based on the thermal comfort and energy cost, the 43% peak demand limiting case can be executed in the building with the acceptable indoor air temperatures (only sacrificing a small amount of thermal comfort) and absolute annual cost savings of EUR 4 383 and EUR 19,389 (EUR 0.51 and EUR 2.25/m^2,a) for the whole building if the building is connected to the DH provider B or DH provider A distributor, respectively.

In addition, a peak demand limit of 35% has no impact on the room air temperatures, which are always beyond 20 °C. Under this circumstance, thermal comfort is not sacrificed and it can achieve an annual cost savings of EUR 3571 and EUR 15,782 (EUR 0.42 and EUR 1.83/m^2,a) concerning the DH providers B or A, respectively, for the whole building.

5. Conclusions

This paper examined the influence of the decentralized and centralized DR and peak demand limiting approaches on the heating energy cost and thermal comfort for an educational building with a DH system. This study used the IDA ICE building simulation tool to find out the influence of these approaches to reduce the heating cost while maintaining the acceptable thermal comfort. The DR controls are based on the hourly DH energy prices to save heating energy costs. The principle of peak demand limiting is to cut heating costs by reducing the DH power fee, and it is not considered in the DR control approach.

The decentralized DR approach was able to reduce the heating energy cost by up to 5.2% by controlling space heating. Regarding the centralized DR control, the total heating energy cost-saving potential was negligible and only 1.5% cost saving was achieved. By using the peak demand limiting of 35%, the heating cost saving was up to 35% depending on the DH provider without any impact on the thermal comfort.

According to the presented results, the occupant's thermal comfort is well-maintained once the decentralized and centralized DR are applied. The DH contract power can be decreased by 35% in the studied example building at normal operating conditions while maintaining the occupants' thermal comfort at the acceptable level. However, the contract power could be decreased more, depending on how much a customer is willing to compromise on thermal conditions.

While the thermal comfort is maintained for the occupied hours, the maximum monetary savings for the whole building based on the annual heating energy cost and power charge are 6.27, 1.81 and EUR 26.93/m^2 for the decentralized and centralized DR control approaches and peak demand limiting of 35%, respectively. These outcomes show that the peak demand limiting performance is significantly beneficial. Although there is a considerable difference between the decentralized and centralized energy systems, their DR control visions are accomplished beneficially, respectively.

The results and conclusions of this study depend mainly on dynamic energy pricing, the way in which a DH producer sets power charges, and climatic conditions. The results and conclusions could be generalized in cases where the above-mentioned factors are similar to this study.

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