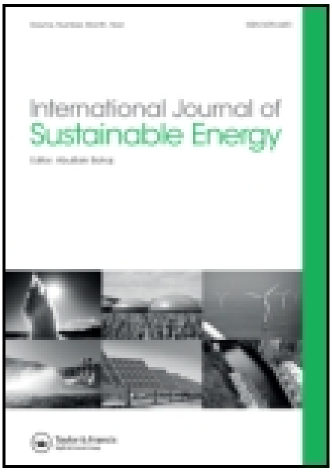

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Changes in heat load profile of typical Danish multi-storey buildings when energy-renovated and supplied with low-temperature district heating

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Denmark has a long-term objective of being free of fossil fuels by 2050, with the energy supply mix for buildings being fossil-free by 2035. Energy consumption for existing buildings needs to be decreased concurrent with the conversion from fossil-fuel supply to renewable-energy (RE) supply. When end-use savings are implemented in buildings concurrent with the application of low-temperature district heating (LTDH), the heat profiles of the buildings will change. Reducing peak loads is important, since this is the dimensioning foundation for future district heating systems. To avoid oversized RE-based capacity, a long-term perspective needs to be taken. Applying LTDH in existing buildings without changing the heating system implies reduced radiator performance, so it is of great importance that acceptable comfort temperatures can still be provided. The results indicate that it is possible to apply LTDH most of the year without compromising on thermal comfort if energy renovation is also implemented.

Keywords: energy renovation; end-use savings; space-heating demand; peak load; heat load profile; low-temperature district heating

1. Introduction

Europe has a vision of reducing energy consumption significantly. In Denmark, the government has a long-term objective of being completely independent of fossil fuels by the year 2050, with the energy supply mix for buildings already being free of fossil fuels by 2035 (Danish Minister of Climate 2011; Danish Energy Agency 2010). Urgent action is, therefore, needed to meet the requirements for the future energy system. The solution is to combine energy savings and renewable-energy (RE) supply in an optimal way. The building stock accounts for about 40% of overall energy use in Europe (Lechtenböhmer and Schüring 2011). This energy consumption needs to be reduced by carrying out energy renovations and increasing energy efficiency, and the present heat supply needs to be converted into RE sources.

The design of new low-energy buildings has been in focus in recent years and much research has been carried out to design buildings optimised from an energy perspective (Abel 1994; Chwieduk 2001; Karlsson and Moshfegh 2007; Thyholt and Hestnes 2008; Zhu et al. 2009). However, on average less than 1% of the building stock is replaced per year with new low-energy buildings in Europe (Hartless 2003), which underlines the importance of looking at the existing building

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stock, which will be around for many years. The potential for energy savings is large (Kragh 2010; Kragh and Wittchen 2010; Weiss, Dunkelberg, and Vogelpohl 2012) and several studies (Kragh 2010; Kragh and Wittchen 2010; Lund et al. 2010; Rasmussen 2010; Tommerup 2010) show that reductions on the scale of approximately 50–75% can be achieved.

One common way of providing space heating (SH) and domestic hot water (DHW) to buildings in densely populated areas is by using district heating (DH) (Reidhav and Werner 2008). In Denmark, about 60% of the total heat demand today is provided by DH (Grontmij 2013), and according to Dyrelund et al. (2010) that share will need to be increased to 70% by 2035. DH systems can be designed on the basis of the heat supply from RE sources, so DH is a very important technology for realising the strategy of heating all buildings without using fossil fuels.

Future DH systems using RE need to be planned on the basis of a long-term strategy to avoid oversized heating plants (Harrestrup and Svendsen 2012; Plan 2013). Reducing the heating demand of existing buildings before investing in changes in supply can save half the initial capital investment, which indicates the importance of carrying out energy savings now (Harrestrup and Svendsen 2012; Plan 2013). The marginal cost of saving one unit of energy by carrying out a renovation is about 45 €/MWh (Plan 2013), while the cost of supplying one unit of energy from DH in 2013 is 60 €/MWh (without taxes) and 93 €/MWh (with taxes) (Hofor 2013). According to Plan (2013), the cost of supplying one unit of energy based on geothermal heat could be around 69 €/MWh (without taxes) if accelerated energy renovations are carried out from today. This emphasises the importance of carrying out energy savings in buildings now and designing the district heat production based on a long-term perspective.

Traditional DH systems operate with a supply temperature of approximately 70°C and a return temperature of 40°C. Applying low-temperature DH, with a supply temperature of 55°C and a return temperature of 25°C, will give us an opportunity to exploit the low-temperature RE heat sources, i.e. geothermal heat, solar heat, etc. With lower operational temperatures in the DH net, the heat losses from the distribution pipes will decrease. These changes will increase the efficiency of DH systems. The study made by Dalla Rosa and Christensen (2011) explains the design concept of low-temperature district heating (LTDH). Theoretical investigations on low-temperature operation have been carried out in EFP (2007) and Olsen et al. (2008), and applied in Brand, Dalla Rosa, and Svendsen (2010) and EUDP (2008).

Low-temperature DH operates with a temperature of 55°C, which means that the legionella problems that can occur in DHW systems need to be considered. According to the German Standard (DVGW 1993) and research done in Germany (Rühling and Rothmann 2013), the risk of legionella growth is small as long as the water volume is less than 3 l and the temperatures are above 50°C or below 20–25°C. If each home uses a local substation that contains small amounts of water and is able to boost the water temperature this problem will be avoided. Moreover, recent research in Sweden has shown good results using UV-disinfection (Efsen 2012; Teknikmarknad 2011).

When end-use savings are implemented in buildings connected to a DH system, the heat demand profiles for the individual buildings will change, which will affect the heat profile for the entire DH system. Researchers in Sweden looked into how the end-use heat savings in buildings will affect DH production, including costs and primary energy savings (Gustavsson et al. 2011). They found that a significant amount of the primary energy savings was in the peak load units. In their study, the peak loads were supplied by light fuel oil boilers, but in the future, such peak loads will have to be covered by RE systems, which will be expensive. Therefore, after implementing energy-saving measures, the heat load duration profiles for the buildings are important, since they are the dimensioning foundation for the future DH systems. To avoid oversized RE-based capacity, a long-term perspective needs to be taken.

Studies (Tol and Svendsen 2012a, 2012b) have investigated low-temperature DH for buildings with existing radiators, focusing on the relationship between supply temperature, mass flow rate and the dimensioning of the pipe distribution system based on future and current situations. One study (Brand et al. 2012) focused on finding the best heating system solution, while achieving good thermal indoor comfort, for new low-energy single-family houses based on LTDH. However, we found no research on LTDH for existing multi-storey buildings using the existing radiator system, which focuses on achieving good indoor thermal comfort as well as implementing end-use savings.

This study describes a method for supplying LTDH to existing multi-storey buildings, focusing on the implementation of various levels of energy renovation and achieving good thermal indoor comfort. Furthermore, it describes a dynamic dimensioning method for the future DH capacity based on the RE supply. The study investigates to what extent it is possible to reduce the peak loads when supplying low-temperature DH, without compromising on the indoor thermal comfort of the renovated building. We examined the relationship between the reduction in annual heat savings and changes in heat load profiles.

Two building blocks from the early 1900s located in typical urban areas in Denmark were investigated, and end-use savings were carried out concurrently with conversion to low-temperature DH supply.

2. Methods

Two building blocks, one in Aarhus and the other in Copenhagen, were used as case studies for this investigation. They are both located in typical urban areas and are from 1910 and 1906, respectively. Both of them are typical for a large share of the existing buildings in urban areas, which have large energy-saving potential. The existing state of the buildings was analysed, after which energy-saving measures were implemented to decrease energy consumption. Three levels of energy renovation were investigated (Table 1).

Three different energy renovation strategies were investigated, since it might be too optimistic a goal to carry out *extensive* energy renovations on all buildings within a short period. So it was important to investigate various levels of renovation in order to find out whether low-temperature DH can provide acceptable comfort temperatures with a small degree of energy-saving renovation. It might also be too expensive to carry out *extensive* energy renovation on all buildings now. It might be more reasonable to build new, instead of carrying out relatively expensive renovation measures. Simply replacing windows is a relatively cheap and easy way of obtaining some savings now. Furthermore, a number of buildings are protected, so the external façade must be preserved. The Internal façade insulation needs to be applied, which is costly and takes up the inside space, and can lead to problems with moisture and fungi (BYG-ERFA 2013; Morelli et al. 2012).

The building energy simulation software IDA-ICE 4 (EQUA 2013) was used for numerical simulations to determine the energy consumption before and after the implementation of energy-saving measures. The DRY weather file for Denmark was used for the simulations. According to the Köppen–Geiger Climate Classification, Denmark is indexed as belonging to the category Cfb (C: warm temperature, f: fully humid, b: warm summer) (Kottek et al. 2006), and according to the heating degree day (HDD) method, Denmark has an index of 3479 HDD (European Commission 2008).

Table 1. Energy renovation levels.

	New windows (with solar shading)	Mechanical ventilation (heat recovery = 85%, minimum air change 0.5 h^{-1})	Basement insulation	Roof insulation	Façade insulation
Extensive renovation	X	X	X	X	X
Intermediate renovation	X	X	X	X	
Window renovation	X	X			

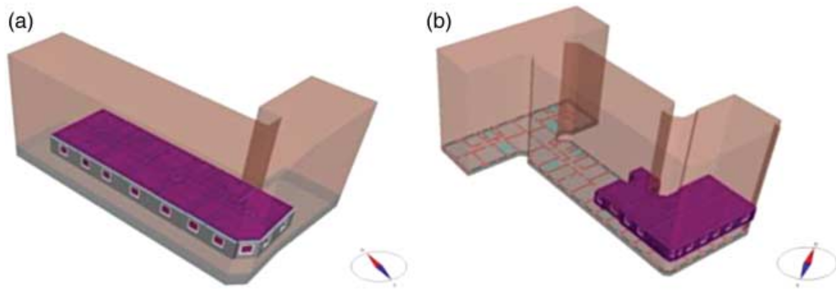

Figure 1. (a) 3D-models of the buildings in Aarhus and (b) 3D-models of the buildings in Copenhagen.

2.1. *Description of the buildings*

2.1.1. *The building in Aarhus*

The building consists of five floors for residential living plus an unheated attic and basement. The overall heated area is 850 m^2. The load-bearing construction is made of wooden beams and brick walls. There is no façade insulation, but the building went through a renovation in 1989 upgrading some parts of the building envelope, so the roof is insulated with 200 mm stone wool. However, the horizontal division between the ground floor and the basement has no insulation. The windows were replaced with double-glazing. The ventilation is natural, coming from opening windows and leaks. Only *extensive* and *intermediate* renovation was carried out, because the windows had already been changed in 1989 and the energy-saving potential in simply replacing the windows would be rather small compared with a building that has not yet been renovated. Only one floor was modelled in IDA-ICE as representative for the entire building (Figure 1).

2.1.2. *The building in Copenhagen*

The building in Copenhagen also consists of five floors for residential living, plus an unheated attic and basement. The overall heated area is 3409 m^2, spread out over 43 apartments. The bearing construction is made of wooden beams and brick walls. There is no insulation in the façade, roof or the horizontal division between the ground floor and the basement. The windows are old one-layer inefficient windows. Fresh air is provided by natural ventilation from opening windows and leaks. All three levels of energy renovation were carried out – the *extensive*, *intermediate* and *window* renovation. Three apartments were modelled in IDA-ICE as representative for the entire building (Figure 1).

The U-values and infiltration for both buildings before and after the various renovation measures are presented in Table 2. To include the heat loss from the roof and to the basement, the extra heat losses from here have been included in the models as a weighted average in the U-value for the façade. The thickness of the façade varies, with smallest thicknesses at the top and under the windows, so the façade U-value was based on a weighted average, representing the entire building façade. The radiators were dimensioned based on the heat losses from the zones in the existing building using an annual simulation with IDA-ICE. The radiators were dimensioned based on a supply temperature of 70°C and a return temperature of 40°C (Korado 2013).

2.2. *Annual heat demand and heat load profile*

The savings in annual heat demand were studied and compared with the savings at peak load. Since peak load production is very costly, it is desirable to reduce the peak load as much as possible. So

Table 2. *U*-values for the buildings before and after renovation.

U-values and infiltration	Copenhagen Existing	Copenhagen Renovated	Aarhus Existing	Aarhus Renovated
Façade (W/m^2 K)	1.34	0.16	1.34	0.16
Windows (W/m^2 K)	4.50	0.97	2.90	1.28
Roof (W/m^2 K)	1.20	0.11	0.20	0.13
Horizontal division between ground floor and basement (W/m^2 K)	1.20	0.16	1.50	0.30
Infiltration (h^{-1})	0.5	0.05	0.5	0.05

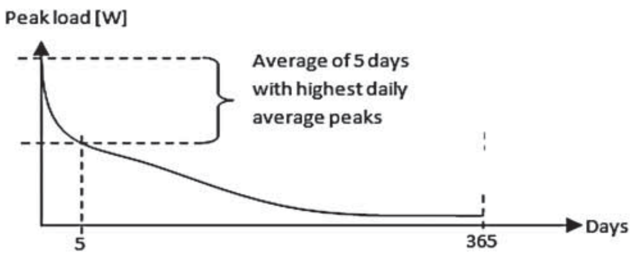

Figure 2. Sketch of duration curve for SH – daily average.

we investigated the lower limit to which it is possible to dimension peak load production and still provide an acceptable indoor thermal comfort when the building has been renovated. The savings and indoor comfort were studied for dimensioning peak load production based on daily average values. Furthermore, we investigated whether it is possible to go one step further and dimension peak load production based on an average of the five days with the highest daily average values without compromising on indoor thermal comfort (Figure 2).

2.3. *Return temperature from building to DH network with low-temperature DH*

With low-temperature DH, it is crucial to have the same cooling of the DH water in the system. Traditional DH systems have a $\Delta T = 30$ K (70–40°C), so the return temperature should be 25°C if the supply is 55°C. If ΔT is decreased, the mass flow rate needs to be increased to achieve the same power output. If the existing distribution pipes in the DH network are to be used, the mass flow rate cannot be increased, which implies that ΔT in the system needs to stay at 30 K. The return water from the building to the DH network was logged and analysed.

3. Results

3.1. *Annual energy consumption*

3.1.1. *The building in Aarhus*

As a result of the energy-saving measures, the total energy consumption decreased as shown in Table 3. If the building undergoes an *extensive* renovation, it is possible to achieve an annual heat reduction of about 70–80% and a total energy reduction of about 60–70%, which is in accordance with the findings in Kragh (2010), Kragh and Wittchen (2010), Lund et al. (2010), Rasmussen (2010) and Tommerup (2010). The differences in the reduction in annual energy and annual SH are due to the extra energy used for mechanical ventilation. A consumption of 4–5 kWh/m^2

Table 3. Annual energy demand and reduction compared with existing building.

	Existing	Extensive renovation[a]				Intermediate renovation[a]			
	SH set point = 20°C	SH set point = 20°C		SH set point = 22°C		SH set point = 20°C		SH set point = 22°C	
		CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
SH (kWh/m^2)	133	38	29	55	43	106	95	136	124
DHW (kWh/m^2)	13	13	13	13	13	13	13	13	13
Mechanical ventilation (kWh/m^2)	–	5	5	5	4	5	4	5	4
Total (kWh/m^2)	146	56	47	72	61	124	112	154	141
SH reduction[b] (%)	–	71	78	59	68	20	28	−3	6
Total energy reduction[b] (%)	–	62	68	51	58	15	23	−5	3

[a]Supply temperature: 55°C year round.
[b]Compared with existing building.

for mechanical ventilation is in accordance with the findings and suggestions in Tommerup and Svendsen (2006). When a building undergoes a renovation, it is often observed that the occupants discover an increased comfort level and, therefore, increase the room temperature from 20°C to 22°C. The increase of 2°C results in an increased SH demand of about 30%, which indicates the importance of user behaviour for the energy savings achieved. If an *intermediate* renovation is carried out, it is possible to achieve a reduction in SH demand of 20–30% if the set point for the room is kept at 20°C. If this is increased to 22°C, the energy savings are negligible, so in this case, user behaviour is crucial for achieving savings. Low-temperature DH with a supply temperature of 55°C was applied in both renovation levels, and it was possible to reach a minimum comfort temperature of 20°C in both cases without having to increase the supply temperature in cold periods.

Furthermore, Table 3 shows that the use of variable air volume (VAV) ventilation provides lower total energy consumption than constant air volume (CAV) ventilation. This is due to extra heat losses in cold periods with CAV. The Danish Building Regulations 2010 (Danish Energy Agency 2013) set a maximum energy consumption for residential buildings at $(52.5 + 1650/A)\,kWh/m^2 = 62\,kWh/m^2$ including SH, DHW and energy for ventilation, with A being the heated area. An *extensive* renovation makes it possible to obtain an energy level in accordance with these requirements.

3.1.2. *The building in Copenhagen*

For the building in Copenhagen, Table 4 shows that an annual heat reduction of about 70–80% and a total energy reduction of about 60–70% can be achieved if the building undergoes an *extensive*

Table 4. Annual energy demand and reduction compared with existing building.

	Existing	Extensive renovation		Intermediate renovation		Window renovation	
	20°C	20°C	22°C	20°C	22°C	20°C	22°C
SH (kWh/m^2)	128	22	34	66	86	80	103
DHW (kWh/m^2)	13	13	13	13	13	13	13
Mechanical ventilation (kWh/m^2)	–	8	8	8	8	8	8
Total	141	43	55	87	107	101	124
SH reduction[a] (%)	–	82	73	48	33	38	20
Total energy reduction[a] (%)	–	69	61	38	24	29	12

[a]Compared to the existing building.

renovation. This is similar to the building in Aarhus. The mechanical ventilation system in this building is based on CAV and the consumption is slightly higher than the building in Aarhus at 8 kWh/m^2, but still in accordance with Tommerup and Svendsen (2006). If an *intermediate* renovation is carried out, it is possible to reach a reduction in SH demand of 30–50%, depending on the set-point temperature for the rooms. Occupant behaviour has proportionately greater influence on the SH savings when fewer energy-saving measures are implemented. *Window* renovation on its own provides approximately 10% less than the *intermediate* renovation. The old windows were very inefficient, so a lot of the saved energy is due to the replacement of windows (20–40%).

Low-temperature DH is implemented with a building supply temperature of 55°C. It was possible to reach a minimum comfort temperature of 20°C for all three renovation levels without having to increase the supply temperature in cold periods.

As for the building in Aarhus, it is possible to obtain an energy level that complies with the requirements for new buildings in the Danish Building Regulations 2010 (Danish Energy Agency 2013) if an *extensive* renovation is carried out.

3.2. *Changes in heat load profile*

3.2.1. *The building in Aarhus*

When energy-saving measures are implemented, the heat load profile for the individual building changes. Figure 3 shows the duration curve for daily average SH loads, with the heat demand becoming more constant over the year as a result of the energy savings. The more energy-saving measures are implemented, the lower the duration curve becomes (less loads) and more constant the heat demand is. This means that the DH plant will not have to invest in so much renewable supply capacity because the peak loads are lower. Furthermore, the demand will be more constant, which will also result in lower costs for the DH plants.

Table 5 shows the reduction in the peak load based on the hour with the highest load. As shown, the reduction is about 40–50% for the *extensive* renovation and between 15% and 20% for the *intermediate* renovation.

We also investigated whether it is possible to dimension the DH capacity for the renovated building, based on an average of the five days with the highest daily average heat loads, without compromising on indoor thermal comfort. For this investigation, one scenario for each renovation level was chosen. For the *extensive* renovation, the investigation was based on a scenario with VAV and a set-point temperature of 22°C while, for the *intermediate* renovation, we chose a scenario with VAV and a set point of 20°C. Table 6 shows the peak loads and the peak load reductions compared with the existing building, based on the different dimensioning scenarios for the *extensive* and *intermediate* renovations, respectively. Table 7 shows the thermal indoor comfort

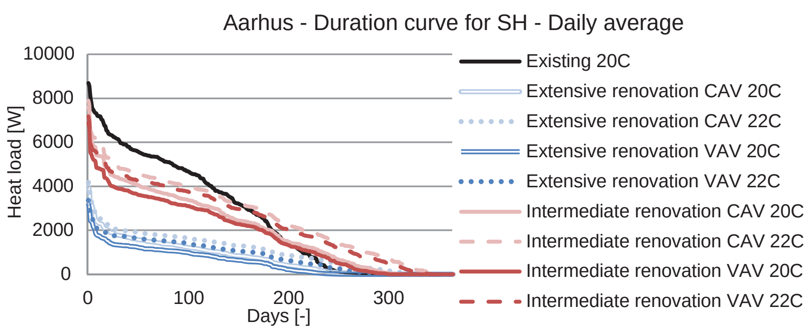

Figure 3. Duration curve for SH – daily average.

Table 5. Reduction in peak load compared with the existing building based on hourly values.

	Extensive renovation				Intermediate renovation			
	SH set point = 20°C		SH set point = 22°C		SH set point = 20°C		SH set point = 22°C	
Percentage	CAV	VAV	CAV	VAV	CAV	VAV	CAV	VAV
Reduction in peak load (hourly values)	43	52	42	52	14	20	15	21

Table 6. Reduction in peak load compared with the existing building.

	Extensive renovation		Intermediate renovation	
	Peak load (VAV–SH set point = 22°C) (W)	Reduction (%)	Peak load (VAV–SH set point = 20°C) (W)	Reduction (%)
Hour with the highest load	4918	52[a]	8127	20[a]
Day with the highest average load	3361	61[b]	6884	21[b]
Average of five days with the highest daily average load	2853	67[b]	5958	31[b]

[a]Reduction compared with the existing building with the highest hourly load.
[b]Reduction compared with the existing building with the highest daily average load.

Table 7. Temperatures in the living zones and hours outside comfort limits.

Average of five days with the highest daily average load	Living room 1	Living room 2	Living room 3	Living room 4	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4
Extensive renovation-SH $T_{set\ point} = 22°C$								
Ti_max (°C)	26.4	26.4	26.3	26.7	26.0	25.7	26.3	26.0
Ti_min (°C)	20.7	20.8	20.2	20.2	20.2	20.1	20.3	20.0
Ti < 20°C	0	0	0	0	0	0	0	0
Intermediate renovation-SH $T_{set\ point} = 20°C$								
Ti_max (°C)	26.3	26.3	26.2	26.6	25.9	25.5	26.2	25.9
Ti_min (°C)	18.1	18.2	17.0	17.9	17.3	17.3	17.2	17.3
Ti < 20°C	101	90	208	97	144	170	145	168
Ti < 19°C	15	14	59	15	42	46	47	39
Ti < 18°C	0	0	18	2	12	13	15	13
% Hours below 20°C	1.2	1.0	2,4	1.1	1.6	1.9	1.7	1.9
% Hours below 19°C	0.2	0.2	0.7	0.2	0.5	0.5	0.5	0.4
% Hours below 18°C	0	0	0.2	0	0.1	0.1	0.2	0.1
Ti < 20°C with SH set point = 22°C	14	13	54	14	32	36	44	33
Ti < 20°C with increased supply temperature to 70°C in cold periods	13	10	44	13	23	26	34	25

in terms of hours outside the desired temperature range. As shown, it is possible to reach the same reduction in the peak loads as for the annual SH reduction (Table 3) when the dimensioning of the DH capacity is based on the average of the five days with the highest daily average loads. With the *extensive* renovation, there are no hours below 20°C. With the *intermediate* renovation, a significant proportion of hours are below the limits with the lowest temperature being 17.4°C, which is not acceptable. If the set point for the room is raised to 22°C during cold periods, however, it is possible to avoid hours below 20°C for most of the year. This will increase the annual energy consumption, but the effect will be small, 2.4% over the year at the most. If the supply temperature is increased to 70°C in cold periods, the number of hours below 20°C slightly decreases, but it is not possible to completely avoid hours below 20°C. However, the number of hours below 20°C varies between 10 and 44, which is less than two days.

3.2.2. *The building in Copenhagen*

The same tendency of a reduction of the peak loads and a change in the duration curve is seen with the building in Copenhagen. Figure 4 shows the duration curve for SH based on the daily average; the heat demand becomes more constant over the year as a result of the energy savings. The more energy-saving measures implemented, the lower the duration curve becomes (less loads). This is beneficial for the DH companies in terms of initial capital investment costs and the degree of utilisation of the plants.

Table 8 shows the reduction in the peak load based on the different dimensioning scenarios. As shown, the reduction for the *extensive* renovation is about 60% for the hour with the highest load, 65% for the day with the highest average load and 70% for an average of the five days with the highest daily average loads. For the *intermediate* renovation, the reduction is about 30–35% for the hour and day with the highest load, and about 40% for the average of five days. The *window* renovation results in reductions of about 20–25% for the hour and day with the highest load, and about 30% for the average of five days.

Table 9 shows the hours outside the thermal indoor comfort range for the *extensive, intermediate* and *window* renovations. The set point is 20°C and it was not possible to keep a minimum temperature of 20°C all year round. If the set-point room temperature is increased to 22°C in very cold periods, it is possible to avoid any hours below 20°C for all renovation levels. Furthermore,

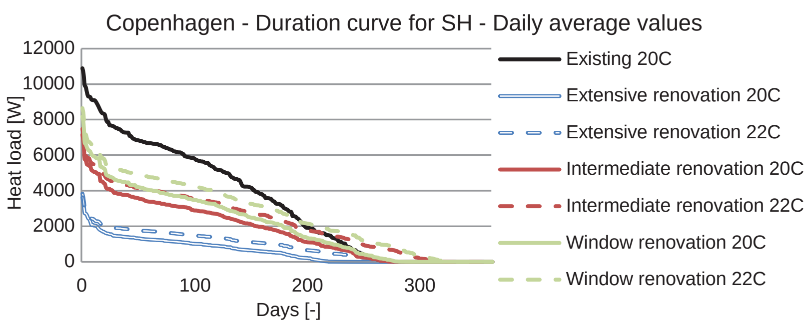

Figure 4. Copenhagen: duration curve for SH – daily average values.

Table 8. Reduction in peak load compared with the existing building.

Reduction compared with existing building (supply = 55°C all year)	Extensive renovation		Intermediate renovation		Window renovation	
	20°C	22°C	20°C	22°C	20°C	22°C
Hour with the highest load[a] (%)	58	57	31	30	23	21
Day with the highest average load[b] (%)	67	65	34	31	25	21
Average of five days with the highest daily average load[b] (%)	72	70	43	40	34	30

[a]Reduction compared with the existing building with the highest hourly load.
[b]Reduction compared with the existing building with the highest daily average load.

Table 9. Temperatures in the living zones and hours outside comfort limits.

Average of five days with the highest daily average load	Living room 1	Living room 2	Living room 3	Bedroom 1a	Bedroom 2a	Bedroom 2b	Bedroom 3a	Bedroom 3b
Extensive renovation 20°C								
Ti_max (°C)	27.0	27.2	26.5	27.0	27.0	26.9	26.5	26.5
Ti_min (°C)	18.8	19.3	18.8	18.9	19.4	19.2	18.7	18.2
Ti < 20°C	35	16	35	28	13	27	41	35
Ti < 19°C	5	0	4	4	0	0	6	4
% Hours below 20°C	0.4	0.2	0.4	0.3	0.2	0.3	0.5	0.4
% Hours below 19°C	0.1	0	0.1	0.1	0	0	0.1	0.1
Ti < 20°C with SH set point increased to 22°C	0	0	0	0	0	0	0	0
Intermediate renovation 20°C								
Ti_max (°C)	26.7	27.2	26.8	26.8	26.9	26.8	26.8	26.7
Ti_min (°C)	18.3	18.6	18.3	19.0	19.2	18.8	18.3	18.6
Ti < 20°C	56	38	55	17	23	40	55	44
Ti < 19°C	14	9	12	1	0	5	4	8
% Hours below 20°C	0.6	0.4	0.6	0.2	0.3	0.5	0.6	0.5
% Hours below 19°C	0.2	0.1	0.1	0	0	0.1	0.1	0.1
Ti < 20°C with SH $T_{\text{set point}}$ increased to 22°C	0	0	0	0	0	0	0	0
Window renovation 20°C								
Ti_max (°C)	26.9	27.4	27.2	26.9	27.2	27.1	27.1	27.0
Ti_min (°C)	18.2	18.3	18.1	19.0	19.1	18.8	18.1	18.5
Ti < 20°C	64	42	62	16	29	42	61	47
Ti < 19°C	16	13	15	0	0	5	15	10
% Hours below 20°C	0.7	0.5	0.7	0.2	0.3	0.5	0.7	0.5
% Hours below 19°C	0.2	0.2	0.2	0	0	0.1	0.2	0.1
Ti < 20°C with SH $T_{\text{set point}}$ increased to 22°C	0	0	0	0	0	0	0	0

if the occupant wants to have an indoor room temperature of 22°C, the supply temperature from the DH plant can be increased from 55°C to 70°C in cold periods.

3.3. *Return temperature from building to DH net*

When low-temperature DH is applied with an unchanged flow rate, the performance of the radiators decreases by a factor of 2.5. If the flow is increased, the performance will increase as well, but to

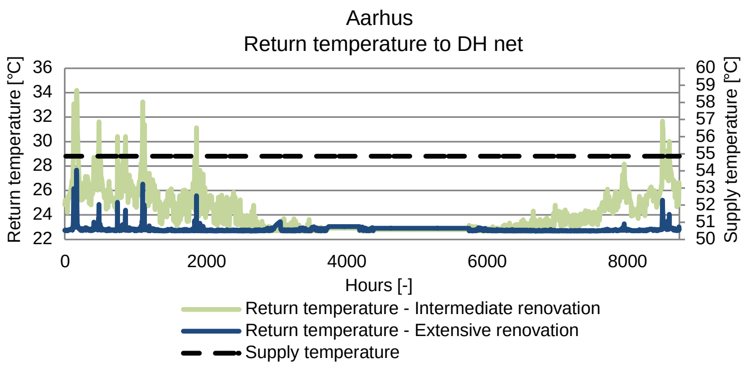

Figure 5. Return temperature to DH network for building in Aarhus.

obtain an acceptable cooling of the DH water in the radiator (30 K), the flow cannot be increased (see Section 2.3), so the supply temperature may need to be increased in cold periods.

The return temperatures from the buildings to the DH network are presented in Figures 5 and 6 based on a supply temperature of 55°C all through the year. The figures are based on a set-point temperature for the room of 22°C. The return temperature will be higher for a set-point temperature of 22°C than for a set-point temperature of 20°C, and thus represents the worst-case scenario. In general, the lower the level of energy renovation implemented, the higher the return temperature is. $\Delta T = 30\,\mathrm{K}$ can only be achieved in the case of *extensive* renovation, whereas with *intermediate* and *window* renovation, it cannot be achieved the entire year. The solution is to increase the supply temperature when $\Delta T = 30\,\mathrm{K}$ is not achieved.

Figure 7 shows the return temperature and the ΔT for the building in Aarhus with *intermediate* renovation when the supply temperature is increased to 60°C in cold periods. The weather-compensated curve related to the supply temperature is shown in Figure 8.

Figures 9 and 11 show the return temperature and the ΔT for the building in Copenhagen for the *intermediate* and *window* renovations, respectively, when the supply temperature is increased to 60°C or 70°C in cold periods. The weather-compensated curves related to the supply temperature are shown in Figures 10 and 12.

4. Discussion and conclusions

Energy renovations were carried out on two typical Danish building blocks from the early 1900s in urban areas. It was found that the end-use energy consumption for both buildings can be reduced to the level the Building Regulations 2010 (BR10) require for new buildings – approximately 50–60 kWh/m^2 – when extensive energy renovation is implemented. This implies a combined solution where the façade, the roof and the basement are insulated, the windows are replaced with new energy-efficient windows with solar shading and mechanical ventilation with heat recovery installed. This is in agreement with what has been found in other studies (Kragh 2010; Kragh and Wittchen 2010; Lund et al. 2010; Rasmussen 2010; Tommerup 2010).

It was found that, if the expensive façade insulation is excluded, it is still possible to obtain end-use energy savings of 30–50% depending on whether the set-point temperature for the rooms is 20°C or 22°C. User behaviour has a significant impact on the energy savings achieved, and this impact is proportionately greater when fewer refurbishment measures are implemented.

Moreover, we found that the heat load profiles over the year generally decrease and become more constant as a result of the energy renovation, which is of great benefit to heating companies, since it provides a better utilisation of the heating capacity and, therefore, reduces the costs.

The dimensioning peak load was found to be reduced by the same percentage as the reduction in the annual SH, if the dimensioning is based on an average of the five days with the highest daily average loads. Furthermore, we found that it was possible to achieve an acceptable indoor thermal comfort with a minimum temperature of 20°C for the building in Copenhagen. For the building in Aarhus, a few hours corresponding to a total less than two days, were below 20°C with an *intermediate* renovation. This is generally not acceptable, and suggests that dimensioning criteria based on an average of five days with the highest daily average load might be too much for new DH capacity if an *intermediate* renovation is carried out. However, there were no problems for the building in Copenhagen or for the *extensive* renovation case in Aarhus. The conclusion we draw from this is that it depends on the savings achieved in the specific building and on the design of its existing heating systems. An average of five days with the highest daily average loads might be slightly too high in some cases, but acceptable in other cases.

The reduction in peak load leads to lower costs for investment in new RE supply capacity, which is beneficial to DH companies. Figure 13 shows our findings for possible reductions in the annual demands and in the peak loads.

The investigation indicated that it is possible to supply buildings with LTDH for most hours of the year without compromising on indoor thermal comfort. In cold periods, it might be necessary to increase the supply temperature to either 60°C or 70°C because, with LTDH, the performance

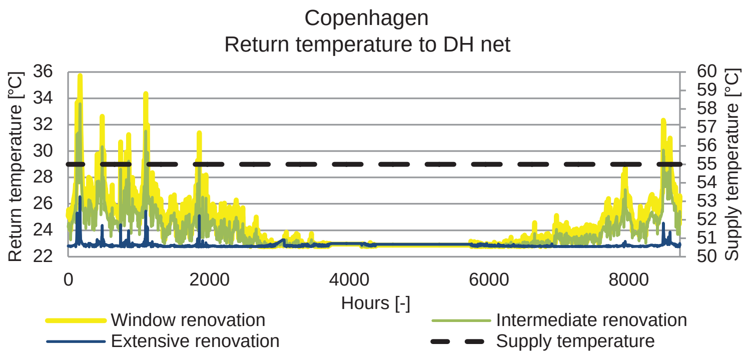

Figure 6. Return temperature to DH network for building in Copenhagen.

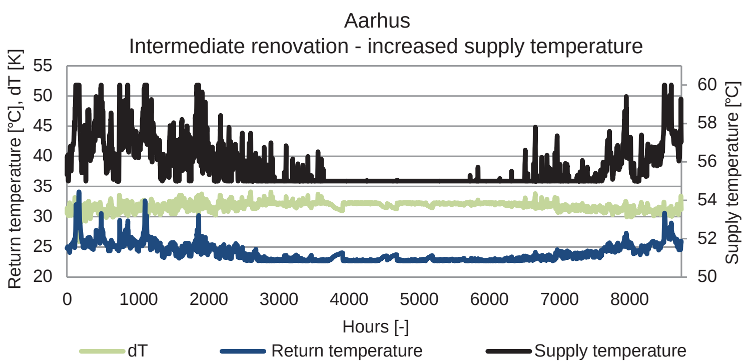

Figure 7. Increased supply temperature, return temperature and ΔT for the building in Aarhus – intermediate renovation.

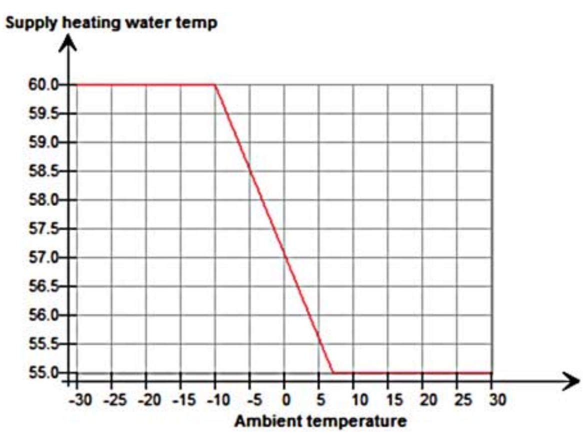

Figure 8. Aarhus: intermediate renovation. Supply temperature as a function of the outdoor temperature.

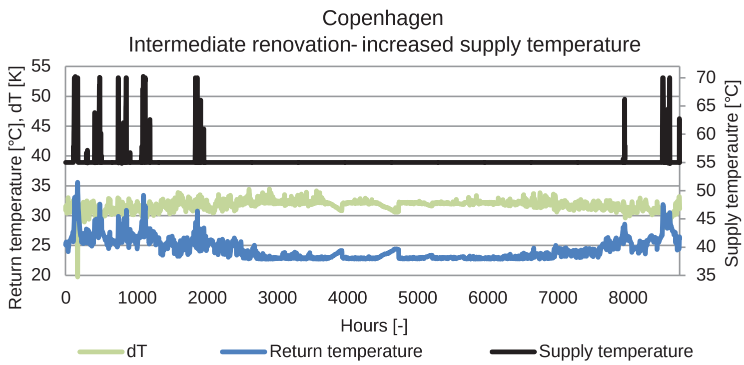

Figure 9. Increased supply temperature, return temperature and ΔT for the building in Copenhagen – intermediate.

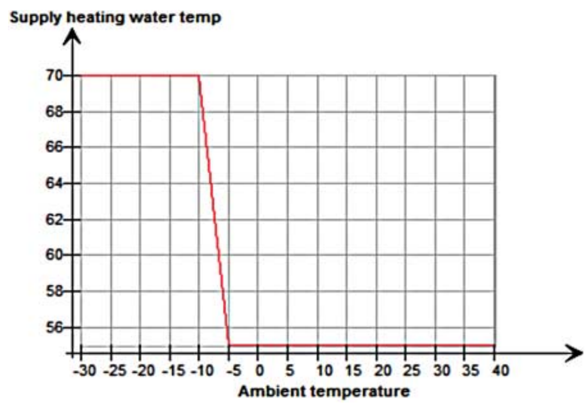

Figure 10. Copenhagen: intermediate renovation. Supply temperature as a function of the outdoor temperature.

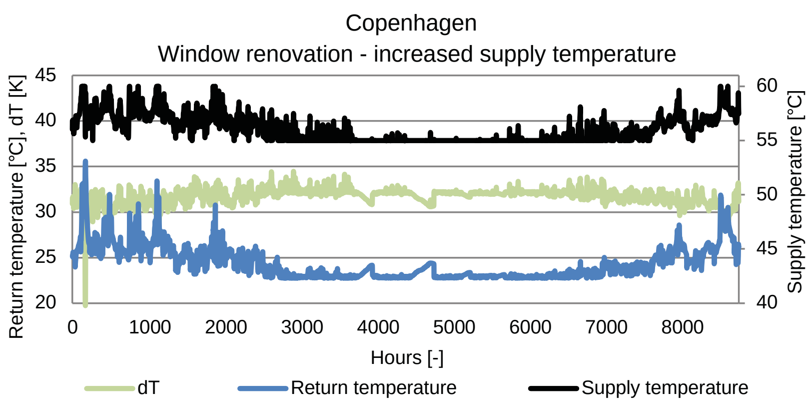

Figure 11. Increased supply temperature, return temperature and ΔT for the building in Copenhagen – window renovation.

of the radiators decreases by a factor of 2.5 with an unchanged flow rate. If the flow is increased, the performance will increase, but to obtain an acceptable cooling of DH water in the radiator (30 K), the flow cannot be increased. If we are to keep the existing DH distribution net, it is crucial that the cooling of the DH water for LTDH application corresponds to a traditional system (30 K), so the return temperature is of great importance. We found that it is possible to obtain a

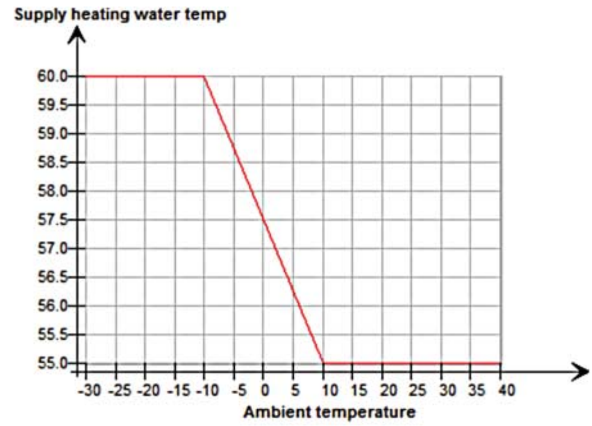

Figure 12. Copenhagen: window renovation. Supply temperature as a function of the outdoor temperature.

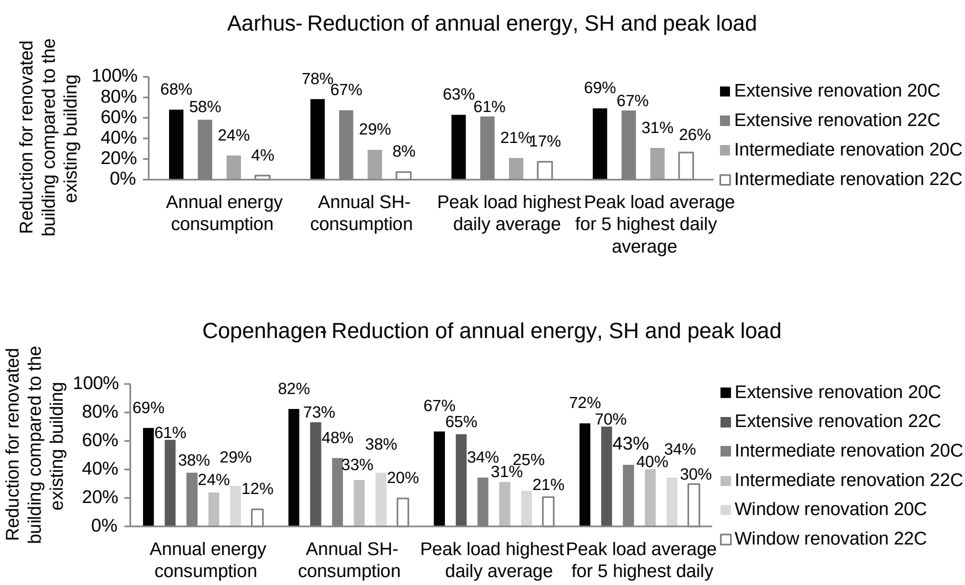

Figure 13. (a) Reduced energy consumption and peak loads in Aarhus and (b) reduced energy consumption and peak loads in Copenhagen.

return temperature of 25°C in the case of *extensive* renovation, but that for the *intermediate* and *window* renovations the supply temperature needs to be increased slightly. If the increase is to 60°C, the period required will be longer than if the increase is to 70°C. However, increasing the supply temperature to 60°C can still be considered relatively low-temperature operation, and the supply temperature will reach a 60°C operation only when the outdoor temperature is lower than −10°C. Increasing the supply temperature to 70°C will be needed for a shorter period. In this case, the supply temperature starts increasing when the outdoor temperature is below −5°C and will increase proportionally until the outdoor temperature is −10°C. The period when the outdoor temperature is lower than −5°C is less than 5% of the year. This indicates that LTDH operation for existing buildings that undergo renovation is possible most hours of the year.

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