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Renovation strategies of typical Danish single-family house for optimization of energy efficiency and flexibility

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Abstract. Buildings will play a significant role in providing a safe and efficient operation of the future energy system. The aim of this work is to investigate how typical cost-effective renovation packages contribute to energy consumption reduction as well as influence the energy flexibility in a Danish single-family from 1970s, and if simple rule-based controller can contribute in peak shaving strategy. By choosing the different renovation packages, the space heating demand can decrease between 34 - 64% and the flexibility time can increase between 200 – 500%. Depending on the cut-off period, the simple RBC of turning off the heating power can further reduce the heating consumption and contribute in reducing the morning load peak with small compromise on the thermal comfort level.

1. Introduction

If we want to avoid the worst effects of climate change, there has to be a revolution in the way we generate and consume energy. Unprecedented reductions in carbon emissions are now necessary. To achieve these savings, the ability to be flexible in the way energy is used will be just as important as implementing energy efficiency and generating energy from renewable sources. As buildings and the building sector combined account for 36% of the final energy consumption and nearly 40% of CO_2 emissions worldwide [1], they will play a significant role in providing a safe and efficient operation of the future energy system. They have the potential to offer significant energy savings by application of different energy efficiency measures as well as flexibility services by intelligent control of their thermal and electric energy loads.

The heating need still represents 25% of the final energy consumption in Denmark despite the tightening of the building regulation, and in 64% of Danish households the heat demand is satisfied by district heating [2]. However, limited attention has been given to how the modulation of heat demand in buildings can enhance the operation of thermal grids that struggle with delivering the hot water to their customers during the morning peaks [3].

The renovation initiatives are focused on minimizing the overall energy consumption of the buildings and not on improving the control of heat demand in order to enhance performance of the local energy infrastructure. Yet, studies have proven that by utilizing the structural thermal mass, buildings can modulate their heat demand and thus deliver flexibility to the local energy infrastructure [4–7]. Therefore, the aim of this work is to investigate how typical cost-effective renovation packages contribute to energy consumption reduction as well as influence the energy flexibility, and if simple rule-based controller (RBC) can contribute in reducing consumption peaks, especially the morning peak, which is the critical period in the daily load of the district heating network (DH).

The structure of the paper is organized as follows. Section 2 presents the case study and the renovation packages, and Section 3 describes the control strategies and the driving factors behind their design. Section 4 identifies the limitations and the used analysed performance indicators. Section 5 outlines the analysis and results of the simulation studies, and section 6 closes with main conclusions.

2. Case study

2.1 Building

A single-family house has been investigated, as this building topology represents 60% of the heated area of residential buildings in Denmark [8]. The building corresponds to a typical house built in the 1970s made of bricks and characterized by relatively poor thermal performance (yearly energy demand of 192.3 kWh/m^2), thus being first priority on renovation roadmaps. The house has two types of emitters: underfloor heating in bathroom and toilet and radiators in other rooms. For the floor plan, dimensions and construction, details are available figure 1, table 1 and [9,10].

The building has been modelled with 9 different thermal zones, and the metrological ambient boundary conditions correspond to the weather conditions in Copenhagen for 2015.

Figure 1. Simulated single-family house from the 1970s [9]

Table 1. Building characteristics before and after renovation.

		Existing		Renovated	
Construction element	Area (m^2)	U-value (W/m^{2}K)	Thickness (m)	U-value (W/m^{2}K)	Thickness (m)
Externa wall	88	0.42	0.29	0.16[a]	0.33
				0.16[b]	0.45
				0.16[c]	0.42
Externa wall - light	4	1.7	0.17	0.38	0.15
Roof	128	1.8	0.28	0.12	0.43
Ground floor	19	0.44	0.15	0.10	0.17
Crawl floor	103	0.38	0.35	0.10	0.70
Windows/Doors	30	2.8	-	1.2	-
Air tightness		0.32 l/s per m^2		0.24 l/s per m^2	
People load	4 persons (100 W per person) Variations weekends/weekdays (nobody from 8am to 4pm)				

[a] new insulation and light finish

[b] new insulation on existing wall and light finish

[c] new insulation and new brick finish

2.2 Renovation Packages

The impact of renovation strategy on the energy efficiency and flexibility has been evaluated on two levels, i.e. a single component and renovation package (more than one component). In total, nine building components and five renovation packages were investigated. The renovation packages were developed to represent different cost-effective renovation scenarios, starting from a minor renovation including only roof and crawl floor, and finishing with major renovation involving exchange/improvements of all building envelope elements. The analysed renovation packages were developed under an EU H2020 project and described in [10] and are as follows:

- P1: renovation of 54 % of building envelope including the roof and the crawl floor
- P2: renovation of 75 % of building envelope including all constructions from Table 1 except the windows and ground floor; new insulation and light finish on the external wall
- P3: renovation of 80 % of building envelope including all constructions from Table 1 except the ground floor; new insulation on existing wall
- P4: renovation of 100 % of building envelope; new insulation on existing wall and light finish
- P5 renovation of 100 % of building; new insulation and new brick finish on the external wall

The cost efficiencies are calculated as kWh of saved energy divided by year and m^2 of the heated floor area of the building. The calculation accounts for the lifetime expectancy of each technology. However, the methodology does not yet account any incentives for the customers to reduce their peak load.

3. Scenarios of modulation

The objective of this study is to evaluate the flexibility potential and energy savings of typical renovation packages (renovation of minimum 2 building elements) applied to a single-family house from the 1970s. Two types of simple RBC are tested during the heating season (Nov 1 – April 30) and they are designed to reduce the morning peak in the district heating network and with the assumption that the house is occupied by people who work during standard office hours. Therefore, the house is empty between 8:00 a.m. and 4:00 p.m., and the operative temperature can be decreased. The two modulations are as follows:

- Cut-off – the heating power is turned off at 7:00 a.m. until a) 2:00 p.m. (7h); b) 3:00 p.m. (8h) and c) 4:00 p.m. (9h). During this period, the building is in free floating mode, and there is no lower limit for the operative temperature.
- Pre-heating before cut-off – the set-point temperature is increased by 2K for either a period of 1h or 2h before the heating power is turned off at 7:00 a.m. for the same duration as in the cut-off modulation: 7h, 8h or 9h. In total, six scenarios are analysed.

In order to have a reference, a first simulation is performed for the building before renovation with a constant heating set-point of 22ºC, which corresponds to a neutral thermal sensation [11]. The analysis was conducted using Energy+ and the building model was built in DesignBuilder.

4. Performance evaluation and limitations

For the examined scenarios, the following parameters were evaluated:

- the total energy used for space heating for the whole heating season,
- the energy saved for space heating (energy efficiency improvements),
- the autonomy time for five critical days during the heating season (in this study autonomy time is defined as time during the cut-off of heating power when the operative temperature drops from 22ºC to 20ºC) and

- the number of occupied hours outside category II thermal comfort band (for winter season 20.0 ºC – 25.0 ºC). This number should not exceed 5% of the total occupied hours, i.e. 216h for six months of the heating period [12].

Due to the size limitations, the paper presents the results for the renovation packages and the cut-off strategy for renovation package P5. The results of single component renovation and pre-heat before cut-off modulation strategy are described in [13].

5. Results

This study investigated the impact of different renovation scenarios of a typical Danish single-family house from the 1970s on energy efficiency and flexibility. Five renovation packages were analysed, each representing different renovation interventions. As shown in table 2, by applying different renovation scenarios the heating consumption is reduced by 34.2 - 64% and the autonomy time can be increased from less than 15 minutes up to 2 hours. Even a simple intervention, such as renovation of the roof and crawl floor (54% of building envelope), results in saving one-third of the energy use and almost doubling the autonomy time. Although, both the P4 and P5 include a full renovation of the building envelope, there is a small difference in energy efficiency and time constant. It is a consequence of P4 and P5 having almost the same effective thermal inertia (1.8 KJ/m^{2}K and 1.6 KJ/m^{2}K, respectively), but P4 has a higher building thermal resistance than P5 (4.0 m^{2}K/W and 3.4 m^{2}K/W respectively), which has a bigger impact on the energy efficiency and the autonomy time.

Table 2. Renovation packages performance

Renovation package	Heat consumption (kWh/m^2)	Energy efficiency improvement (%)	Autonomy time (min)
Before renovation	192.8	-	13.6 - 26.1
P1	126.9	34.2	23.0 – 41.0
P2	92.9	51.8	44.4 – 79.2
P3	71.9	62.7	69.2 – 111.7
P4	69.5	64.0	71.5 – 126.0
P5	70.8	63.3	70.7 – 115.0

The application of the cut-off control strategy has further decreased the heating consumption for the 7h and 8h cut-off period, 68.0 kWh/m^2 and 68.5 kWh/m^2. In case of the 9h cut-off period, the energy boost needed just after 16:00 to bring the operative temperature back to the set-point of 22°C, resulted in higher heating consumption of 71.6 kWh/m^2, see figure 2.

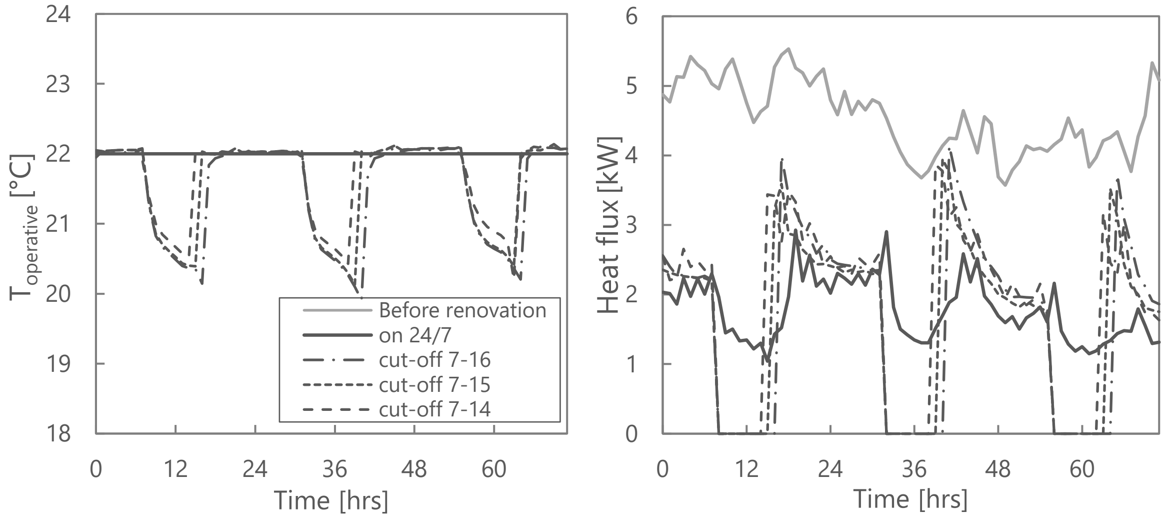

Figure 2. Change of temperature (on the left) and heating flux (on the right) for renovation package 5 with cut-off for 8h, 7h and 6h (November 4-6)

As seen in figure 2, for all scenarios the highest heating use occurred just after the end of cut-off period, i.e. 15:00, 16:00 and 17:00. The new peaks occurred at hours close to the afternoon peak that is around 6:00 p.m., which is also a critical time for the district heating system. The occurrence of new peak loads was a result that was anticipated. However, firstly the afternoon peak in the DH system is of smaller magnitude than the morning one, and secondly it can be solved at the aggregation level by differentiating the activation single sent to the customers. With regards to the building heating systems, the peaks were within the installed capacity.

According to table 3, the thermal comfort was slightly compromised for the cut-off period of 8h and 9h, 5.3 % and 7.6 % respectively. However, the minimum operative temperature was not lower than 17 ºC, and it occurred during the period when the building was expected to be unoccupied.

Table 3. Thermal comfort for P5 and cut-off control strategy

Control strategy	Number of hours < 20ºC	$T_{operative,min}$ (ºC)
Cut-off 7:00-14:00	143	18.3
Cut-off 7:00-15:00	231	18.0
Cut-off 7:00-16:00	333	17.6

6. Conclusions

The objective of this study was to firstly investigate how typical cost-effective renovation packages contribute to the improvement of energy efficiency and energy flexibility, and secondly if a simple rule-based controller can contribute in reduction of the morning peak in the district heating network. The case study was a typical single-family house from the 1970s and five renovation packages were analysed.

By choosing the different renovation packages, the space heating demand can decrease between 34 - 64% and the flexibility time can increase between 200 – 500%. The building envelope thermal resistance has a great importance for both energy efficiency and flexibility, since it conserves the heat indoors.

Depending on the cut-off period, the simple RBC of turning off the heating power can further reduce the heating consumption and contribute in reducing the morning load peak with small compromise on the thermal comfort level. However, special attention should be given to the period of afternoon activation of the heating system (end of the cut-off period) in order not to create the new peaks close to the already known afternoon peak.

Finally, future work will focus on integrating the potential cost incentives arriving from peak load reductions in the calculations of cost-optimal renovation packages.

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