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Modeling energy flexibility of low energy buildings utilizing thermal mass

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ABSTRACT

In the future energy system a considerable increase in the penetration of renewable energy is expected, challenging the stability of the system, as both production and consumption will have fluctuating patterns. Hence, the concept of energy flexibility will be necessary in order for the consumption to match the production patterns, shifting demand from on-peak hours to off-peak hours. Buildings could act as flexibility suppliers to the energy system, through load shifting potential, provided that the large thermal mass of the building stock could be utilized for energy storage. In the present study the load shifting potential of an apartment of a low energy building in Copenhagen is assessed, utilizing the heat storage capacity of the thermal mass when the heating system is switched off for relieving the energy system. It is shown that when using a 4-hour preheating period before switching off the heating system, the thermal mass of the building releases sufficient heat to maintain the operative temperature above 20°C for 15 hours. This potential increases with longer preheating period. The thermal behaviour of the external envelope and internal walls is examined, identifying the heat losses of the external envelope and the thermal capacity of the internal walls as the main parameters that affect the load shifting potential of the apartment.

KEYWORDS

energy flexibility, load shifting, thermal mass, low energy buildings, energy simulation

INTRODUCTION

In the future energy system a considerable increase in the penetration of renewable energy is expected. The fluctuating pattern of sources like solar and wind would create peaks and deficiencies in the energy production, which would challenge the stability of the system, as both the production and the consumption side would have fluctuating patterns. This would lead to imbalances of the electricity grid requiring changes to the balancing strategies (Hermanns and Wiechmann, 2009). Initially, the focus of such strategies was on the electrical system, but recently a multi-carrier energy system is of interest, including electricity grids, gas grids and district heating and cooling. Energy storage (Beaudin et al., 2010) and Demand Side Management (DSM) (Mohsenian-Rad et al., 2010) and would have a key role facilitating the future energy system. Typical methods to achieve DSM include peak load reduction, shifting demand from on-peak hours to off-peak hours (load shifting), introduction of flexible load shape and energy consumption reduction (strategic conservation) (Müller, 2015).

The building sector appears to have great potential for load shifting, due to the large mass of the building stock, and studies have been performed so as to utilize this mass for thermal energy storage (Wolisz et al., 2013; Reynders et al., 2013; Kensby et al., 2015; Ma and Guo, 2015; Masy et al., 2015).

The purpose of the present study is to perform a building energy simulation of an apartment of a low energy building in Copenhagen and evaluate the heat load shifting potential by

utilizing the thermal mass. A scenario is examined, in which the apartment is preheated before the heat supply is cut off to avoid a peak in the operation of the system. In the next section, the scenario examined is described and the basic inputs for the model are given. Afterwards, the results from the simulated cases are presented. Eventually, the main outcomes are discussed and final conclusions are given.

METHODS

In the multi-carrier future energy system the demand patterns will have to become flexible in order to facilitate the system to integrate a large share of renewables. It has been indicated by the district heating operators that in the future it might be favourable for the district heating system to stop supplying specific districts for certain time intervals. The purpose of the simulated scenario was to identify the effect such a stop would have in an apartment. The focus was on the impact of the thermal mass on the apartment's thermal behaviour. One of the key parameters investigated was the duration of the time that the apartment would need to be preheated before such a stop, in order for the thermal comfort to be maintained. The apartment modelled for this study belongs to a multi-family house building, which was built in 2016 in Copenhagen, Denmark, and is connected to the local district heating system. The apartment was modelled in IDA Indoor Climate and Energy (ICE, version 4.7), and dynamic simulations were performed with a time resolution of 5 minutes.

The thermal behaviour of a building consists of a complicated mechanism and is affected by various parameters. This study had a focus on the thermal mass of the building, isolating it from exogenous parameters, such as the daily operation of the building, users' patterns and ambient weather conditions. Thereby, a synthetic weather file was created with stable ambient conditions. Using the Design Reference Year data for Denmark (DRY, 2013), an average day of the heating season for Denmark was estimated, having 3°C temperature, 4.7m/s wind speed and 85% relative humidity. The solar radiation was not included in the study, as solar gains could account for an amount of energy added uncontrollably into a building, which would not allow for the thermal mass to be isolated. Internal gains from occupants, equipment and lighting were not included, as they depend on occupants' behaviour and there could be a range of amplitude and patterns, which would impede the isolation of the thermal mass. Internal masses for furniture and interior constructions were not included as well.

The scenario examined was divided in three periods; the steady state conditions, the preheating period and the cool down period with heating being switched off. Initially, the model was simulated for 5 days to ensure steady state conditions inside the zone and within the walls (days #1 - #5). During the steady state period the operative temperature setpoint was set to 20°C according to EN/DS 15251 (2007), Category II, which corresponds to "normal level of expectations and should be used for new and renovated buildings". Operative temperature above 20°C was considered as minimal comfort temperature. In day #6, the operative temperature setpoint was increased to 22°C, which lasted for 4 hours, as a preheating period in order for the thermal mass to absorb heat. Then, the heating system was turned off and the apartment was left to cool down for the next days (until day #10). During the cool down process, the focus was at the first day of this cooling period, observing the thermal response of the apartment.

The simulated apartment had an area of 81 m² and 2.6 m height. The north and south walls were exposed to the ambient, while the east and west walls, as well as the floor and ceiling were attached to similarly heated spaces. The building was designed according to the Danish design regulations for 2020. Table 1 shows the properties of main components and materials.

Table 1: Properties of main components and materials

Components	Thickness [m]	U-value [W/(m ² ·K)]	Surface [m ²]	Materials
External wall	0.55	0.12	25.7	Concrete Insulation Brick
Internal wall	0.2	3.43	49.4	Concrete
Internal floor/ceiling	0.45	0.27	161.5	Wood Concrete Insulation
Windows	3 pane glazing	0.81	18.51	-
Materials	Thermal conductivity [W/(m·K)]	Specific heat [J/(kg·K)]	Density [kg/m ³]	
Concrete	1.65	1000	2200	
Insulation	0.037	750	20	
Brick	1.2	840	1600	
Wood	0.17	2000	750	

Mechanical ventilation was included in the system with constant flow of 0.5 ach, according to EN/DS 15251 (2007), using heat recovery with efficiency 0.8. Infiltration was accounted as constant flow of 0.1 ach, according to DS 418 (2011) for new buildings. Regarding the heating system, the building was connected to the district heating system and the heating emission system inside the apartment was floor heating of 16 W/m², supplied with 40°C water temperature and controlled with a proportional controller on the room operative temperature.

RESULTS

As a reference value, the time constant of the apartment was calculated as the ratio of the thermal capacity to the steady-state heat losses (Antonopoulos and Koronaki, 2000), including transmission, ventilation with heat recovery and infiltration. The thermal capacity was approximately 108 kWh/K and the heat losses 37 W/K, leading to a time constant for the apartment of 878 hours. This is a very high value compared to a typical Danish building. The limited losses were attributed, firstly, to the fact that the apartment had a relatively small façade compared to the total wall area and secondly, as previously explained, the examined apartment was built according to the 2020 regulations, so it was an airtight building with very low values of heat transfer coefficients, both for the external walls and the windows.

Dynamic simulations were performed for the scenario explained in the METHODS section. During the steady state conditions, the operative temperature was maintained at 20 °C. Subsequently, the temperature was allowed to increase until 22 °C during the 4-hours preheating period. Since the heating system of the apartment was floor heating, the system had a slow response, so the operative temperature was increased only until 20.6 °C. The operative temperature increase achieved was small, so the temperature increase of the ceiling, internal and external wall surfaces was minor, as depicted in Figure 1a. The floor surface had the highest surface temperature at all times and achieved a distinct temperature increase during the preheating period, as expected. Figure 1b depicts the surface heat fluxes for the ceiling, one of the external walls and one of the internal walls. Negative values indicate that heat was absorbed in the walls, while positive values indicate that heat was released from the walls to the room. It may be seen that the ceiling and the internal wall behaved similarly, absorbing heat during the preheating hours and emitting back to the room, shortly after the

cooling down phase began. Although the external wall absorbed heat within the preheating hours, heat was never released back in the apartment.

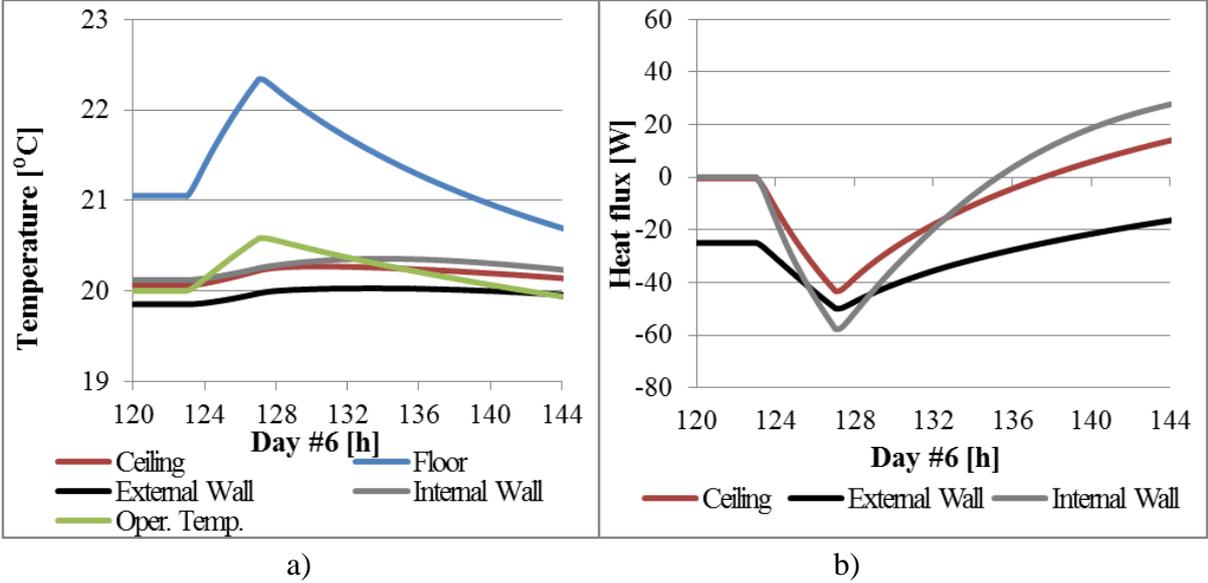


Figure 1. a) Surface temperatures during day #6 (hours counted since day #1). b) Surface heat fluxes during day #6 (hours counted since day #1).

During the steady state conditions, the heating system ran uninterrupted generating 1.15 kWh for a duration of 2h, as it is depicted in the energy balance in Figure 2a. During the first two hours of the cool down period the internal walls, including floor and ceiling, released 0.81 kWh. This accounted for 61% of the demand, namely heat losses from the windows, external walls and thermal bridges, mechanical ventilation and infiltration.

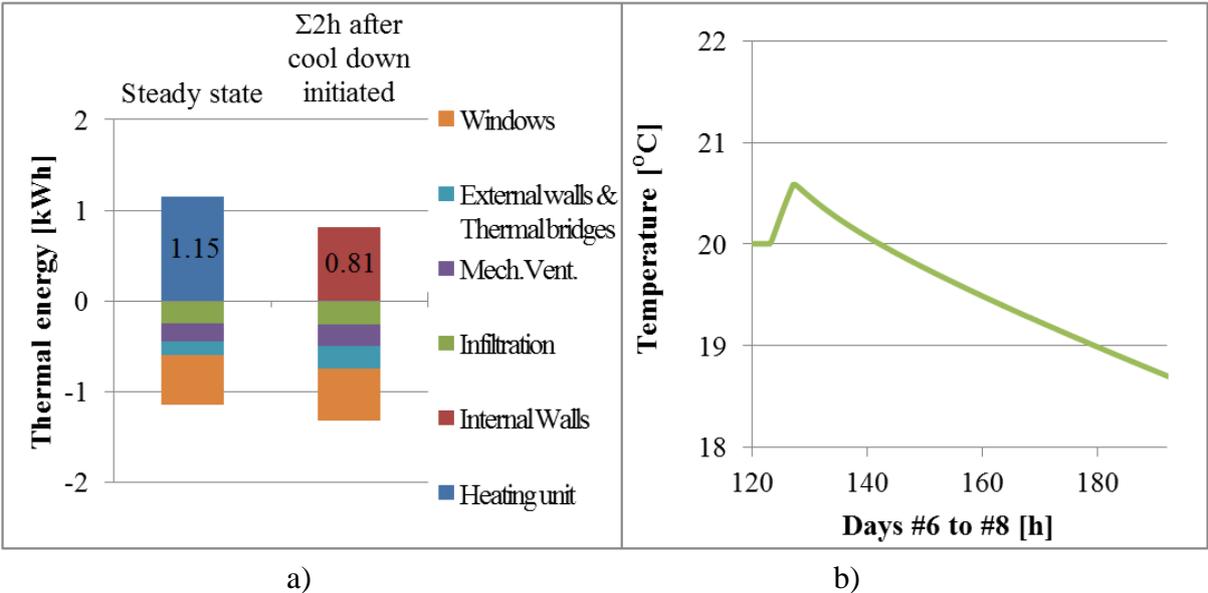


Figure 2. a) Energy balance for a duration of 2h. b) Operative temperature during days #6-#8 (hours counted since day #1).

Letting the apartment cool down for the following days, it may be observed from Figure 2b that the operative temperature still remained above 20 °C for a considerable amount of hours. In this case, with 4 hours of preheating, the operative temperature remained above 20 °C for 15 hours after the heating system stopped working, only by recovering heat from the internal walls, ceiling and floor. During these 15 hours, 7 kWh were recovered from the thermal mass of the apartment. This indicates that the heat flows released are sufficient for a load shifting to be planned.

In order to investigate the effect of the duration of preheating, simulations were performed for different preheating periods, decreasing to 2 hours and increasing to 6 hours of preheating. The results may be seen in Table 2.

Table 2. Thermal response of the apartment for different preheating periods

Basic case apartment	Preheating duration		
	2 h	4 h	6 h
Max operative temperature difference during preheating [°C]	0.3	0.6	0.8
No. of hours operative temperature above 20°C [h]	8.3	15.1	21.2
Energy recovered from thermal mass during above hours [kWh]	3.79	7.04	10.09

It can be observed from the table that the slow response of the heating system did not allow the operative temperature to increase considerably in any of the preheating periods, hence thermal comfort is almost not affected. However, one may notice the effect of the different preheating periods on the number of hours that the operative temperature can be maintained above 20°C, being approximately 8 h, 15 h and 21 h for the different preheating periods. Respectively, the thermal energy recovered during these hours varied between 3.8 kWh, 7 kWh and 10.1 kWh.

It could be observed that the heat recovered from the thermal mass came from the internal walls, including the ceiling and the floor. Thereby, the capacity of the thermal mass of the internal walls, should be considered as one of the main contributors to the load shifting potential of the apartment. On the other hand, the building envelope did not contribute to the heat recovery. Nevertheless, the external envelope is of equal importance for the load shifting potential of the apartment, since it governs the losses to the ambient. Thereby, it should be investigated in terms of total heat loss, rather than the capacity of its thermal mass. In addition, the total surface area of the external walls was rather small compared to the total surface area of the internal walls, ceiling and floor. Therefore, in order to examine the different behaviour of the internal and external walls, two scenario cases were created.

In the first case, the effect of thermal capacity of the internal walls on the load shifting potential was investigated. The material of the internal walls was changed from concrete to aerated concrete, with the following thermal properties; thermal conductivity of 0.2 W/(m·K), density of 500 kg/m³ and specific heat of 800 J/(kg·K). This apartment would have a thermal capacity of 29 kWh/K, the same heat losses as the base case apartment (37W/K), leading to a time constant of 238 hours, namely 640 hours less than the base case apartment. In the second case, the effect of the heat losses of the building envelope on the load shifting potential was investigated. The windows were replaced with windows of a U-value of 2.8 W/(m²·K) and the infiltration was increased to 0.87 ach, both typical values of Danish existing buildings.

This apartment would have a thermal capacity of 108 kWh/K, heat losses of 126 W/K, leading to a time constant of 238 hours, equal to the first case. The results are presented in Table 3.

Table 3. Thermal response of the apartment for the two scenario cases examined

	Case 1: Aerated concrete for internal walls			Case 2: Increased heat losses from building envelope		
	Preheating duration			Preheating duration		
	2 h	4 h	6 h	2 h	4 h	6 h
Max operative temp. difference during preheating [$^{\circ}\text{C}$]	1.1	1.7	2.0	0.2	0.3	0.5
No. of hours operative temp. above 20°C [h]	6.1	9.5	11.2	1.7	2.9	3.9
Energy recovered from thermal mass during above hours [kWh]	0.36	2.49	3.37	2.08	4.90	6.61

As expected, in both cases the hours that the operative temperature remained above 20°C were reduced, and so was the difference between the different preheating periods. In the first case, the temperature increase achieved during the preheating periods was considerably higher, but since the thermal capacity of the internal walls was reduced, the energy recovered from thermal mass was considerably lower, namely from 0.4 kWh to 3.4 kWh for the different preheating periods. Taking, for example, the 4 h preheating period, the internal walls managed to cover only 8% of the demand in the first 2 hours of the cool down period, compared to the 61% which was presented in the base case apartment.

In the second case, the apartment behaved similarly to the base case apartment. A very small temperature increase was observed during the preheating periods, but the high capacity of the internal walls recovered from 2.1 kWh to 6.6 kWh for the different preheating periods. This corresponds to the internal walls covering 76% of the demand in the first 2 hours of the cool down period for the 4 h preheating period scenario. However, the hours that the minimal comfort temperature was maintained were considerably reduced, due to the increased losses through the building envelope.

DISCUSSIONS

The operative temperature setpoint of 20°C used as minimal comfort temperature corresponds to a “normal level of expectations” and should be used for new buildings, according to EN/DS 15251 (Category II). However, a lower temperature of 18°C could also be used corresponding to “moderate, acceptable level of expectations”. In this case, the potential for load shifting would be considerably increased. Furthermore, the upper limit of 22°C was not reached in most cases, due to short preheating periods and slow response of the floor heating system. Different control of the floor heating system, for example supplying higher water temperatures, could achieve higher temperature increase during the preheating period. This would yield a higher amount of heat being stored and released back in the apartment, thus better load shifting potential. Even further, the upper limit could be increased if the preheating period would be during the time that occupants are not present in the apartment.

Regarding the two scenario cases, they resulted in limited load shifting potential. In the case of the decreased thermal capacity of the internal walls, the hours that the minimal comfort temperature was maintained were reduced by 37% for the preheating period of 4 hours, while in the case of the increased heat losses of the building envelope, the hours that the minimal comfort temperature was maintained were reduced by 80% for the same preheating period.

The duration of the preheating period had a considerable impact on the number of hours that the minimal comfort temperature was maintained, varying from 8h to 21h for 2h to 6h preheating period for the base case scenario. This provides different possibilities for Demand Side Management, adjusting to projections of the system's needs. The duration of the period that heating can be switched off could be used as an indicator for the flexibility performance of a building. This report has shown that it would depend strongly on the thermal mass of the apartment, but not exclusively. The degree of insulation of the building envelope is also substantive.

Finally, it should be noted that for this study, the time of the switch off of the heating was not influential, as there were no solar or internal gains, since the target was to isolate the effect of the thermal mass. Further on, more realistic cases should be studied including solar and internal gains, using different occupancy schedules and identifying the impact on load shifting potential.

CONCLUSIONS

It has been shown that for an apartment of a low energy building in Copenhagen the thermal mass can be utilized as thermal energy storage, thus facilitating heat load shifting for several hours, without the contribution from internal or solar gains. This potential increases with longer preheating periods.

Two cases were examined, first changing the thermal capacity of the internal walls and second the heat losses of the external envelope such that the static time constant became equal in both cases. It was shown that the external and internal walls, including floor and ceiling, contributed to the load shifting potential of the apartment, though in different terms. The internal walls recovered the heat that was absorbed during the preheating period, covering for a certain amount of hours part of the demand. The properties of the materials used in the internal walls defined the heat capacity of the internal walls, which governed the potential for load shifting of the apartment. On the other hand, the building envelope affected the potential for load shifting, only in terms of heat losses to the ambient. The heat that was absorbed in the external walls during the preheating period was not released in the apartment, but it was gradually lost to the ambient due to heat conduction. Thereby, in the second case, the heat losses of the external envelope governed the potential for load shifting of the apartment.

Finally, the relative size of the internal versus the external walls partly defines the impact of the two types of walls. In the present case the area of the outer walls was so small that thermal capacity of the external walls had infinitesimal impact on the load shifting potential.

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