The inherent thermal storage capacity of buildings – potential for load shifting with electricity powered heating systems

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1. Abstract

The ever-increasing installation of renewable electricity generation with volatile feed-in comes hand in hand with the challenge of matching generation and demand at all times, and induces the need for energy storage and more flexible demand. Thereby, the large and predictable thermal demand of the building stock could contribute flexibility if electricity powered heating systems are used. This simulation based analysis indicates great potential for load shifting by the activation of structural thermal building mass with electric heating systems. Depending on the utilized system, load shifting of few hours and up to many days is feasible, with just limited impact upon user comfort. Further, storage efficiencies in range of 88 % to 96 % are detected.

Keywords: load shifting, electric heating systems, thermal mass, demand side management

2. Introduction

With ever-increasing installations of renewable electricity generation with volatile feed-in, the management of the electricity generation and distribution becomes increasingly challenging. In order to balance electricity generation and demand in the power grid, the integration of flexible electricity consumers and energy storages is required. About 18 % of the German final energy consumption is accounted to space heating in residential buildings [1]. Therefore, it is interesting to analyse whether such a large energy demand can be managed to contribute demand flexibility to the power grid. Since the observed demand concerns thermal energy, the potential for flexible consumption can be only leveraged through the application of electric heating systems. Thereby, active usage of the inherent inertia and storage capacity of the building’s structural mass can increase the flexibility. Such Demand Side Management (DSM) approach is even more attractive in face of a constantly decreasing primary energy factor for electricity.

3. Approach and Modelling

In this simulation based study, the potential for load shifting by the activation of the inherent thermal building mass with electricity based heating systems is analysed. The analysis is based on the observation of a single room within a one family house. It is examined how much thermal energy can be stored by charging the thermal mass of the room using different electric heating systems. All simulations are implemented with the modelling language Modelica in the simulation environment Dymola using a complex physical building model [2]. The observed 18 m² room comprises a window area of 2.3 m² on the west oriented façade and is located at the first floor’s south-western corner of the building. Exterior walls are modelled according to the German EnEV 2009 insulation standard and are considered to consist of massive bricks, mineral wool insulation, lime plaster on the outside and gypsum plaster on the inside. The floor is made of concrete with a screed layer above and mineral wool underneath; the roof is mainly made of wood and mineral wool. The modelled windows have an U-value of 1.3 W/(m²·K). For accurate representation of the thermal mass, all physical components are modelled individually and each material is discretized into few millimeter thick layers. It is assumed that all inner walls are adiabatic to their adjacent rooms. In table 1, the properties of the main materials are given.
The set-point of the operative indoor temperature is 21 °C during the day-time (7 a.m. to 11 p.m.) and 18 °C at night. In the analysed scenario, an exemplary phase of abundant renewable generation is assumed from 11 a.m. till 2 p.m. and the thermal activation of the building is performed by increasing the set-temperature during this time. As a result, the heating power output of the analysed supply systems is increased until the chosen comfort-limit temperature of 23 °C is reached. After the activation phase, the temperature set-point is reduced back to 21 °C and the simulation is continued for several days to investigate the impact of load shifting upon the future heat demand. As the thermal boundary condition a typical week in January was chosen from the German test reference year for the region of North Rhine-Westphalia [3]. Internal thermal loads (occupancy, equipment and lighting) are considered according to the Swiss standard (SIA 2024) [4]. Furthermore, the room model is equipped with a ventilation system with heat recovery (efficiency: 70 %, air exchange rate: 0.5 per hour).

For this analysis different hydraulic (H) and direct electric (DE) heating systems are examined. The major advantage of hydraulic heating systems is the high efficiency when supplied by a heat pump, however direct electric heating systems are distinctly simpler and cheaper. Furthermore, heating systems emitting heat through convection and radiation (such as radiators, H; air heating, DE; electric surface heating, DE) are distinguished from building structure integrated heating systems (such as radiant floor heating, H; concrete core activation (CCA), H or DE). In case of the floor heating (H), the pipes are embedded in the floor’s screed layer. For the CCA system (H or DE), the heat is injected within the concrete layer beneath the screed layer, which increases the thermal activation potential while reducing the capability for rapid room temperature adjustments. For the radiant floor heating and the hydraulic CCA a star-type RC-network based on Koschenz [5] is used.

4. Results

In the following section, the simulation results of the building activation are presented exemplarily for the radiator and the CCA system. In figure 1, the effect of load shifting on the room temperature and the required heating power is shown for the radiator system.

![Figure 1. Resulting room temperatures and required heating power for the radiator system](image-url)
It can be seen, that the increased room temperature set-point leads directly to an increased heat output of the radiator, resulting in a sudden increase of the room temperature. Within the whole activation phase an additional amount of 1.6 kWh heat is transferred to the room and the operative temperature rises up to 22.9 °C. When the temperature set-point is reduced back to 21 °C, the room cools down quickly, however, due to the heat stored in the thermal mass of the building and the supply system, heating operation can be interrupted completely for almost 3 hours. Even afterwards, when the heat flow from the thermal mass is not sufficient to uphold the required room temperature anymore, the stored thermal energy enables a significant reduction of heat demand till the end of the day and a slight reduction on the following day. However, the increased room temperature during activation results in additional heat losses through ventilation and transmission. Overall 1.45 kWh out of the stored 1.6 kWh are recovered for heating purposes, thus 9% of the shifted energy is lost yielding a storage efficiency of 91%.

In figure 2, the effect of load shifting on the room temperature and the regular heating power is shown for two different scenarios of CCA operation. In this analysis, CCA is used only as a “storage heater” during the activation phase (CCA power is out of scale in figure 2). The regular heating demand (given in figure 2 on the right) is covered by a flexible electric surface heating.

![Figure 2: Resulting room temperatures and heating power of the electric surfaces for two scenarios of the CCA](image)

In the first case (red dotted line), the equivalent of the daily heat demand (4 kWh) is stored in the floors thermal mass within the activation phase (75 W/m²; 1350 W for 3 h). Due to the high thermal inertia and capacity of the floor, its surface temperature rises up just slightly and the stored heat is released slowly to the room over a period of several days. In this case, the daytime room temperature is not influenced at all and regular heating operation cannot be interrupted completely at any time. Nevertheless, the building’s heating demand is reduced for several days after activation and the temperatures during night set-back increase slightly. Due to the very small impact upon the room temperature, there is only very little additional heat loss. Thus, 3.85 kWh are recovered out of the stored 4 kWh, yielding a storage efficiency of 96%.

The second case (green dashed line) represents an extreme scenario in which the CCA uses the activation phase to store as much energy as possible without violating the comfort limit of 23 °C (350 W/m² / 6200 W for 3 h). In this case, the thermal mass of the floor is charged with 18.6 kWh during the overheating phase. Because of the time-delayed heat release from the activated floor, room temperature rises slowly and reaches 23 °C nine hours after the activation phase. Thereby, floor temperature rises to a maximum of 25.6 °C. The increased room temperature persists for the next 89 hours, eliminating any heating demand for nearly four days. Due to the mostly radiative heat transfer of the CCA, the resulting heat losses through transmission and ventilation are moderate even in this scenario. Overall 16.6 kWh out of the stored 18.6 kWh are recovered, indicating 11% losses and yielding a storage efficiency of 89%.

In table 2, the main simulation results for all investigated heating systems are summarized. Furthermore, the impact of the thermal insulation standard on the load shifting potential is illustrated by using the example of CCA. Therefore, the results of load shifting for a higher (passive house) and a lower (EnEV 2002) insulation standard are also given in table 2.
It can be seen, that with an increasing insulation standard, heating operation can be interrupted for a longer period after activation. However, due to the lower heat demand in general, smaller amounts of energy can be stored in the building, lowering the potential to provide flexibility.

Table 2. Comparison of the results for load shifting with different heating systems

<table>
<thead>
<tr>
<th>Heating system</th>
<th>Stored energy in kWh</th>
<th>Interruption time in h</th>
<th>Heat losses in kWh (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator</td>
<td>1.6</td>
<td>2.8</td>
<td>0.15 (9 %)</td>
</tr>
<tr>
<td>air heating</td>
<td>1.7</td>
<td>0.65</td>
<td>0.2 (12 %)</td>
</tr>
<tr>
<td>elec. surface heating</td>
<td>1.9</td>
<td>5.0</td>
<td>0.16 (8 %)</td>
</tr>
<tr>
<td>radiant floor heating</td>
<td>2.4</td>
<td>13.8</td>
<td>0.21 (9 %)</td>
</tr>
<tr>
<td>CCA (EnEV 2009)</td>
<td>4 / 18.6</td>
<td>0 / 89</td>
<td>0.15 (4 %) / 2 (11 %)</td>
</tr>
<tr>
<td>CCA (EnEV 2002)</td>
<td>22.3</td>
<td>64</td>
<td>2.2 (10 %)</td>
</tr>
<tr>
<td>CCA (passive house)</td>
<td>13.3</td>
<td>182</td>
<td>1.6 (12 %)</td>
</tr>
</tbody>
</table>

5. Discussion and Conclusions

It is shown that the activation of structural building mass through electric heating systems results in distinct load shifting potential and can be used as a source of flexibility for the future power grid. However, the detected potential strongly depends on the supply system used for load shifting. Heating systems that emit heat by convection and radiation are in general only suited for short-term load shifting. Among these, purely convective heating systems are characterized by the lowest potential since they depend on the room air as the heat transfer medium. These systems only allow for interruption of heating operation in the range of an hour and the long term activation impact is very limited. In contrast, mainly radiative heating systems can directly activate the building’s thermal mass, allowing for heating interruptions of few hours and a reduced heating demand afterwards. For all these heating systems, thermal activation results in a higher room temperature for a short period of time, and that might interfere with the residents’ comfort if the activation is performed while the building is occupied.

Heating systems, integrated directly in the building’s thermal mass allow load shifting for several days. Even without distinct changes in indoor temperatures the heat demand can be reduced for many days. If a moderate long term increase of indoor temperature is permitted, total heating operation can even be shifted for several days. Thus, a large amount of heating power can be shifted to a very short time period allowing to accommodate short-term renewable production peaks and resulting in a high DSM potential. Nevertheless, discharge of the stored energy cannot be controlled once the activation was performed. This emphasizes the importance of predictive control strategies for a smart building control. Furthermore, the implementation of such DSM requires dynamic electricity prices for end-consumers to encourage utilizing the found demand flexibility and compensate the risk of comfort reductions. Future research will focus on the development of predictive control algorithms for thermal mass activation, considering predictions of renewable energy production, heat demand and occupancy.

6. References