Activation of the building thermal mass to store PV surplus energy

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Abstract
Since 2018, a terraced house complex with shared energy system is monitored and evaluated regarding PV self-consumption and efficiency (Figure 3). Beside heat pumps and photovoltaics (PV), different kind of storage units are integrated and used to store PV surplus. Thermal storage units for heating and domestic hot water as well as an electrical storage are integrated into the higher-level control system and are charged selectively. However, since the capacity limits have been reached, additional storage options are interesting. The thermal mass of the building offers additional potential to store PV surplus energy. This paper evaluates the operation of thermal mass activation for the terraced house complex in order to increase the PV self-consumption and decrease the grid consumption.

The simulation study of thermal mass activation is realized in TRNSYS. Increasing the room set point temperature of 20 °C by 2 K during PV production, aims to a reduction of the grid consumption by 47 % and an increase of PV self-sufficiency from 23 % up to 64 %. At the same time, the mean deviation of the room set temperature increased from 1.7 K to 2.0 K. The results are compared to real measured data from the terraced house.

Key Innovations
- Activation of the building mass to store PV surplus
- Integration of the operation strategy into a real building control system
- Evaluation of the simulated results with measured data

Practical Implications
An efficient option to store PV surplus is to activate the building mass. For implementation, the room temperature setpoints must be set automatically by a central control system. The precondition is that access to the base station of the floor heating is possible. In this case, the setpoints are varied by modifying an XML file. An increase of the set point by 2 K is sufficient. This increases the actual room temperature by 1.5 K. An operating cost saving of 7.2 % can be achieved

Introduction
In the recent years, the interest for heat pump (HP) and for renewable technologies has grown in the field of single-household buildings. Heat pumps, thermal storages and photovoltaic-systems can contribute to the energy transformation of our society. They are able to adapt their consumption to the production of electricity. The components are labelled with “smart grid ready” (BWP 2013). But there is a lack of suitable and simple operation strategies. Higher control systems or Building Energy Management Systems (BEMS) are rarely used in single household buildings. Interaction of generators and floor heating systems is often not present.

In Germany there are about 40 GW installed PV power. Due to governmental policy the feed in rate decrease rapidly and approx. 8 Ct/kWh for new installations are refunded. There again the consumer rate for electricity today is about 30 Ct/kWh.

On the other hand, a decrease in investment cost could still encourage individuals to buy PV panels. Moreover, as explained later in this paper, PV panels coupled with specific heating system may lead to benefits, not only from the revenues coming from the sale of electricity, but also from the reduction of electricity consumption during peak loads by storing the surplus energy produced by these panels.

Since 2012 Fisch has published several results optimizing the efficiency of heat pump and PV system with different storages (Fisch et al., 2016). This work is mostly inspired by the work of G. Hausladen. He investigated the load management potential considering the heat storage into the building structure. He assessed the influence of several factors such as the type, the mass and the insulation of the building and the heating system (Hausladen, et al., 2016). The load management potential of buildings are further evaluated by Auer (Auer, et.al. 2017).

Many projects and papers already addressed an optimal load management for buildings in order to increase the PV self-consumption. The following activities can be mentioned by way of example

E. Georges et al. assessed the implementation of a method for an optimal load management (Georges et al., 2017). They analysed the load matching potential (between consumer electricity consumption and local electricity production) and the influence of retail and buy-back tariff by aiming to minimize the electricity cost for the end-user. They obtained significant improvement regarding the load matching and the cost saving.
Vanhoudt et al. searched on peak-shaving by the mean of self-consumption (Vanhoudt et al., 2013). They implemented a market based multi-agent control system where every device is represented by an agent which consumes or produces electricity and all these needs are organized according their priority. They managed to increase the self-consumption.

Operating strategies are evaluated in the projects SOL2Heat (2017) and PV KWK (2016) and Seiffert reports on the evaluating of thermal comfort in buildings with sophisticated operation strategies (Seiffert et al. 2016).

In this work, a control strategy is investigated in simulation and real operation, which activates the thermal building mass by increasing the setpoint in the entire building. Figure 1 shows the process of the control strategy, which depends on the available PV power. As soon as a PV power of 1 kW is exceeded, the setpoint is increased by 1 K to 6 K, depending on the variant. If the PV power is less than 1 kW, the default setpoint, e.g. 20°C, is set. In real operation the interface between control strategy and building energy management system is realized by a SQL Server Database, which also serves as monitoring database.

Heating is provided by a floor heating with a pipe outside diameter of 16 mm and a pipe spacing of 10 cm. The pipes are enclosed in 6 cm screed. Mechanical ventilation is implemented with decentralised ventilation units with a heat recovery of 60%. The heat recovery of 60% includes additional heat losses through infiltration and window airing. To avoid overheating in the transition period and summer, the ventilation is operated without heat recovery if the respective room temperature exceeds 24.5 °C and 25.5 °C in the bathrooms. In addition, the outdoor temperature must be at least 2 K below the room temperature. The window shading depends on the solar radiation of the respective orientation. Internal loads due to persons are represented by a presence profile with 60 W per person. The profile is assigned to the living room and three bedrooms depending on the time of day. Internal loads due to household electricity are represented by an electrical profile and only occur in the living room. Both profiles represent one day and are repeated daily.

**Simulation**

To evaluate the thermal building mass and its influence on thermal comfort, energy consumption and distribution as well as operating costs, a thermal-energy building simulation is carried out in the software TRNSYS (2017). The two buildings under consideration are part of a row house complex that shares a common energy generation and use. The terraced houses, built in 2017 to nearly passive house standards, have been monitored for energy efficiency since April 2018 and are permanently occupied. The corner house (HC) and the middle house (HM) next to it are modelled room by room and each comprise 16 zones, 11 of which are heated via floor heating (see Figure 2). The zones have individual room control for temperature and ventilation. The buildings are characterised by a high construction with u-values of 0.13 W/m²K.

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Figure 1: Flow chart of control strategy for activating the thermal building mass

Figure 2: View isometric southwest. TRNSYS3D.

Figure 3: East view of the terraced house complex

In the control strategy, the activation of the thermal building mass was implemented by increasing the setpoint from a PV power surplus of 1 kW. The PV surplus is defined by the generated PV power of the entire row house complex minus the total household electricity. Since only two houses are considered in the simulation, the PV power surplus is divided by 4, which is shared by houses C and M.

In the basic variant, each heated zone has a setpoint of 20 °C and 24 °C in bathrooms. The thermal building mass is activated by increasing the setpoint temperature from 1 K to 6 K. As soon as the setpoint is increased by more than 3 K, the setpoint for avoid overheating also increases by 1 K each time. In bathrooms, the setpoint for avoid overheating increases according to the setpoint increase.

Figure 1: Flow chart of control strategy for activating the thermal building mass

Physical energy and building system

Amount of PV power

PV power < 1 kW

PV power > 1 kW

Monitoring data

Lower setpoint dT0

Upper setpoint dT1...6

SQL Server (Data exchange)
The adjustment prevents a conflict between activating the building mass, which should allow the room temperature to increase, and preventing overheating, which should force the room temperature to decrease. With the basic variant, a total of 7 variants are created. Boundary and starting conditions of the simulation are taken from the measurement data and from the German Weather Service from the year 2019. The simulation time is one year at 0.25 time step.

Results and Measurements
The results of the simulation are presented below. First, the potential of the thermal building mass is investigated and then an annual simulation of the 7 variants is evaluated. In addition, the activation of the thermal building mass was implemented in the control of the terraced house complex in November 2020. The results of measurement are shown.

Simulation
To determine the available potential of the thermal building mass, the switch-on and switch-off duration as well as the switch-on and switch-off power are first determined. The switch-on/off power is considered to be the thermal heating power of the house. Constant boundary environmental conditions are assumed. The outdoor temperature is constant at 0 °C and there is no solar radiation. The flow temperature of the floor heating is constant at 30 °C. Ventilation and internal loads are as described above. The switch-on duration and power are determined with a setpoint increase from 20 °C to 22 °C, the switch-off duration and power from 22 °C to 20 °C. Figure 4 shows the mean house temperature and heating power, but without bathrooms, as these do not contribute to the activation of the thermal building mass at 24 °C. When considering the possible switch-on duration, it becomes apparent that approx. 16-17 hours are required to heat the rooms up to the upper limit value of 22 °C for both houses.

The switch-on power is initially 8 kW, but is still between 8 kW and 6 kW over a period of 6 hours. As the mean house temperature and total power are shown, it becomes apparent that individual rooms reach the setpoint sooner or later. A complete switch-off does not take place after the setpoint is reached. On the other hand, the switch-off duration is significantly higher.

20 °C again. In house C (see Figure 5, top), the heating of individual rooms takes place significantly earlier and more frequently than in house M (see Figure 5, bottom). The switch-off power is about 4 kW.

Figure 5: Switch-off duration and power for house C (top) and house M (bottom)
In a next step, the 7 variants are simulated in TRNSYS (2017). The results of the simulation for the year 2019 are evaluated in terms of thermal comfort, energy consumption and operating costs. To evaluate thermal comfort, the mean absolute temperature deviation from setpoint 20 °C as well as the overheating hours are evaluated. Values greater than 26 °C are defined as overheating. Furthermore, the energy distribution of grid and PV power is assessed. Figure 6 shows the overheating hours and the grid consumption of the 7 variants (dT0 to dT6) for the corner house and the middle house. There is a minimal increase in the overheating hours. Only in variant dT6 there is a clear increase. The grid consumption decreases visibly up to variant dT2 and then flattens out. The course of the mean temperature deviation also increases slightly, as can be seen in Figure 7. The course of the PV self-sufficiency also shows a clear increase up to variant dT2, after which the curve flattens out.

Figure 6: Overheating hours and grid consumption for house C (top) and house M (bottom)
Figure 7: Mean temperature deviation and PV self-sufficiency for house C (top) and house M (bottom)
The small increase in overheating hours and mean temperature deviation becomes clear when the temperature curve of a winter week is considered. Figure 8 shows the setpoint and room temperature as well as the heating power of the living room in house C for one week in February 2019 from the simulation for variant dT0 and dT6. Despite the maximum setpoint of dT6, the room temperature is increased by a maximum of 3 K (see Figure 5, bottom).

Since the heating energy increases when the setpoint temperature is increased, the rise in heating energy consumption and the resulting energy costs are to be examined below, taking into account the PV direct consumption. To determine the energy costs, the electricity costs for the grid are assumed to be 0.34 €/kWh. The PV direct costs are assumed to be 0.0243 €/kWh for insurance and administration for the 1st case and 0.0883 €/kWh with additional EEG levy\(^1\) for the 2nd case. The feed-in tariff is 0.11 €/kWh. Figure 9 shows the annual heating energy and operating cost savings with and without the EEG levy. As well, the curve flattens out at about dT2. When considering the 2nd case with EEG levy, the operating costs even rise again.

Figure 10 shows the measurement results for the period of one week in November/December 2020 with short activation periods. The supply temperature of the floor heating was between 30 °C and 31 °C. The setpoint and the room temperature are mean values of the whole house, which is also a middle house. The setpoint without PV power is 20 °C except for three rooms with 18 °C. With PV power, the setpoint is 22 °C in all rooms. The setpoint increase took place on three days for about 2 hours each. The mean room temperature was increased by 0.2 K to 0.3 K. A maximum mean room temperature of 20.5 °C was reached. The switch-on power is approx. 8 kW and agrees with the potential analysis. After the setpoint increase, the power is less than 1 kW. On days without setpoint increase, the power fluctuates between 0 kW and 3.3 kW. For comparison, Figure 11 shows a week in February 2021 with frequent and longer-lasting setpoint increases. There is a higher temperature increase, which results from the long-lasting setpoint increase on the one hand and from a higher supply temperature of the floor heating on the other. The flow temperature was increased in this heating phase for comfort reasons that are not related to the activation of the building mass. In this week of February 2021 the supply temperature was 33 °C. Due to the higher outdoor temperature and solar radiation, a stronger temperature increase is also possible. The mean room temperature rises over the week and reaches about 21.5 °C. A maximum drop of 0.5 K occurs overnight. This means that the room temperature remains permanently elevated. The maximum heating power during PV heating is approx. 10 kW due to the higher supply temperature. There is hardly any grid heating at night.

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\(^1\) Tax to finance the expansion of renewable energies
The daily heating energy is shown in Figure 12. One day is summarised from 9 a.m. to 8:45 a.m. of the following day to analyse the effects of PV heating. Compared to the days close in time, the daily heating energy consumption is significantly higher, especially during PV heating. During grid heating, however, the heating energy consumption is significantly reduced. PV heating describes the heating energy that was expended during the setpoint increase. Grid heating is the heating energy outside the setpoint increase. Figure 13 shows the course of the mean room temperature and setpoints as well as the outdoor temperature and solar radiation. The solar radiation was only recorded from 23 November 2020.

Figure 11: Measured course of mean set and room temperature and heating power (top) in a house M as well as solar radiation and ambient temperature (bottom) for one week in February 2021

During grid heating, however, the heating energy consumption is significantly reduced. PV heating describes the heating energy that was expended during the setpoint increase. Grid heating is the heating energy outside the setpoint increase. Figure 13 shows the course of the mean room temperature and setpoints as well as the outdoor temperature and solar radiation. The solar radiation was only recorded from 23 November 2020.

Figure 12: Measured daily heating power in a house M

Figure 13: Measured course of mean set and room temperature and heating power (top) in a house M as well as solar radiation and ambient temperature (bottom) from 11.11.2020 until 31.03.2021

To compare the heating energy and operating costs, two terraced houses that were operated without a setpoint increase are evaluated. Reference house A has a slightly higher mean room temperature over the period, while reference house B has a mean room temperature that is about 1 K lower. The rate of PV self-sufficiency of the reference houses are similar. The thermal activated house M achieves a significantly higher rate of PV self-sufficiency. The comparison is shown in Table 1.

Table 1: Comparison of House M with two reference houses.

<table>
<thead>
<tr>
<th>House</th>
<th>Mean room temperature</th>
<th>PV self-sufficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>House M</td>
<td>20.59 °C</td>
<td>46.6 %</td>
</tr>
<tr>
<td>House A</td>
<td>20.95 °C</td>
<td>20.1 %</td>
</tr>
<tr>
<td>House B</td>
<td>19.61 °C</td>
<td>24.9 %</td>
</tr>
</tbody>
</table>

Figure 14 shows the heating energy consumption and calculated operating costs for the period of the setpoint increase from 11.11.2020 until 31.03.2021. The electricity prices are the same as in the simulation study. The calculation of the electrical energy from the thermal energy measurement is based on an average coefficient of performance of the heat pumps of 5. Although the mean room temperature of house M and house A is very similar, house A has an 18.5 % lower heating energy consumption. When considering the operating costs with a distinction between PV and grid heating, as well as the profit from the feed-in tariff, it becomes apparent that house M has only slightly higher operating costs despite its higher heating energy consumption. Without taking the EEG levy into account, the operating costs are even reduced by 20.7 % compared to house A. A comparison with house B shows that the significantly lower heating energy consumption of 39.5 % less (due to very low heating setpoint temperature) cannot be compensated financially by the operation of the setpoint increase. The operating costs of house B without EEG levy are reduced by 60.7 % compared to house M.

Figure 14: Measured daily heating power in a house M

Discussion

The simulation results show that the activation of the thermal building mass with PV power offers good potential for reducing grid consumption while maintaining thermal comfort. Likewise, the operating costs can be reduced both with and without the EEG levy but with the EEG levy, the cost savings drop again after 3 K. A setpoint increase of 2 K provides the best result. The energy and financial results do not improve thereafter. The thermal comfort only deteriorates strongly with very high setpoint increases of 6 K.

The assessment of the storage potential shows that a room temperature increase from 20 C to 22 °C leads to a thermal power of 6 kW to 8 kW over a period of 6 hours. After approx. 6 hours, the thermal power is reduced because some rooms have already reached their setpoint.
the room-by-room building model, there is no complete switching off of the thermal power, as some rooms are already heated again depending on their temperature. The setpoint of 22 °C is reached in 16-17 hours. When switching off from 22 °C to 20 °C, it takes 34 hours or more than 48 hours until the setpoint is reached. A thermal output of 4 kW can be switched off. As well, some rooms have already fallen below their setpoint and heating starts 20 hours respectively 40 hours after switch-off. Comparing the results to other research activities (Hausladen et al., 2016), similar results could be achieved. The results from the potential analysis could be implemented and validated in this field test.

The control strategy was implemented in the terraced house complex. The temperature curve as well as the switch-on power are very similar to the results from the potential analysis. When looking at the daily thermal energy balance, especially during the PV heating, it becomes apparent that the energy consumption is higher on days when the building mass is activated. Compared to the days close in time, the heating energy consumption is significantly higher. During grid heating, however, the heating energy consumption is significantly reduced.

In comparison to two houses of the terraced house complex without setpoint increase with mean room temperatures of 0.39 K more (house A) and 0.98 K less (house B), a significantly higher rate of PV self-sufficiency of 46.6 % compared to 20-25 % is shown. Due to the higher rate of PV self-sufficiency, the higher heating energy consumption can be compensated financially, but not if the heating energy consumption is greatly reduced (- 40 %) due to lower room temperatures in house B. Especially without taking the EEG levy into account, positive effects on the operating costs can be seen and show a reduction of 20.7 % compared to the house A.

Since only 3 houses participated in the test operation, of which only one house used the control permanently, the influence on the performance of the shared energy system cannot be determined.

**Conclusion**

This paper has shown the potential of thermal building mass. In a simulation study, the available potential of the thermal building mass was analysed. As well, in an annual simulation, the setpoint increase is evaluated in terms of thermal comfort, energy consumption and operating costs. In addition, the activation of the thermal building mass was implemented in the control of the terraced house complex in November 2020.

The assessment of the storage potential at constant conditions shows that a room temperature increase from 20 °C to 22 °C leads to a thermal power of 6 kW to 8 kW over a period of 6 hours. The setpoint of 22 °C is reached in 16-17 hours. When switching off from 22 °C to 20 °C, it takes 34 hours or more than 48 hours until the setpoint is reached. A thermal output of 4 kW can be switched off.

The annual simulation results show that the activation of the thermal building mass under consideration of PV power offers good potential for reducing grid consumption while maintaining thermal comfort. A setpoint increase of 2 K provides the best result. In this case, the degree of PV self-sufficiency increases from 21 %/ 25 % to 62 %/ 66 %, the grid consumption decreases by 46 %/ 49 % and the cost saving is 7.2 %/ 6.0 % for a corner house/ middle house. The energy and financial results do not improve thereafter. For both houses, increasing the room set point temperature of 20 °C by 2 K during PV production, aims to a reduction of the grid consumption by 47 % and an increase of PV self-sufficiency from 23 % up to 64 %. At the same time, the mean deviation of the room set temperature increased from about 1.7 K to about 2.0 K.

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In summary, it could be shown that the activation of the thermal building mass offers a very good storage potential that can be easily tapped. The control strategy is simple and easy to implement. In real test operation, there is a positive influence on the rate of PV self-sufficiency and operating costs when additional taxes for PV consumption are removed. But the thermal energy balance shows that the energy consumption is significantly higher.

**Acknowledgement**

Will be added after review.

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