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Improving self-consumption of on-site PV generation through deploying flexibility in building thermal mass

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Abstract. As PV is considered prospective for decarbonizing the building sector, the self-consumption of on-site PV generation, which is susceptible to the temporal mismatch between solar radiation and energy demand, greatly affects the overall performance of improving building autonomy. As an important way to lessen the dependence of the decentralized PV energy system on the grid, internal flexibility from buildings is receiving increasing attention. This research sought to contribute to our understanding of the flexibility potential of Building Thermal Mass (BTM). In this aim, the load-shifting potential of BTM and the impacts on the self-consumption of rooftop PV generation were evaluated in a single-family residential building. To ensure a satisfying accuracy, this research proposed a novel framework that integrates multi-agent system and resistance-capacitance modelling techniques. The proposed methods represent the thermal network by means of circuit analogy and perform indoor thermal control based on stochastic occupant behaviours and appliance usage. The proposed BTM modelling framework is of great potential in flexibility estimation of BTM and could be used to assist the demand-side management.

1. Introduction

The building sector accounts for approximately one third of the total energy consumption worldwide and has been identified as an important sector to reduce carbon emission. As a continuation of the great decline of PV panel costs, the rooftop PV (RPV) becomes an attractive renewable technology for decarbonizing and improving self-autonomy of the building sector. In Germany, of the 38.2 GW and over 1.5 million PV system, about 39% is small-scale residential PV installations [1]. New groups are emerging in the traditional energy system with identities as prosumers, who are both energy users and producers.

The prosumers with RPVs usually claim energy autonomy as the on-site PV generation exceeding the building demand and rely on the external flexibilities to bridge the temporal mismatch between generation and demand [2]. Therefore, they utilize the electricity infrastructure even more than traditional power users, and may contribute more to the peak effects in the grid [3]. For the equity and security of the electricity grid, the prosumers should improve the self-consumption of RPV generation as much as possible [4].

To manage the RPV electricity feed-in to the grid requires flexibility, which is the ability to respond to the mismatch between energy supply and demand. Among the available flexibility sources within buildings, Building Thermal Mass (BTM), which is the structural thermal capacity of the building, is a cost-efficient option. A well-insulated building has large thermal capacity and a 1 K increase/decrease

of indoor temperature indicates considerable heat absorption/release of BTM. The BTM could be considered as a large pool of thermal energy storage. Compared to the common energy storage systems, i.e. batteries and hot water tank, BTM requires far less investment. Moreover, the availability of BTM is getting larger, benefiting from the promotion of building insulation endorsed by national building energy-efficiency standards in many countries.

One of the common approaches to deploy the flexibility in BTM is preheating/precooling, which is to use electricity from RPV to heat/cool the building during unoccupied periods before occupants arrive. Another is to control the set-point temperature in a reasonable range so that the excess PV generation could be turned into thermal energy and stored in BTM. In addition to the building insulation function, the approaches mainly depend on the thermal energy storage and thermal energy conservation of BTM [5].

Previous research projects investigating the flexibility in BTM have adopted various methods to conduct analyses. However, the established models are often over-detailed or over-simplified, which cannot capture the dynamics of BTM while suit the intelligent analysis for demand-side management [5]. The Resistance-Capacitance (RC) based building physic model turned out to be a suitable option for BTM modelling with a satisfying accuracy while not cause too much computation burden. RC model provides a computationally tractable way to predict the thermal states of the BTM and could be used for estimating the effects of various indoor thermal control strategies. Moreover, the deployment of building thermal mass involves private individuals with various preferences. The diversity and stochastic nature of occupant behaviours should be integrated into the BTM models.

The aim of this study is to contribute to our understanding of the flexibility of BTM. In this aim, the load-shifting potential of BTM and the impacts on the self-consumption of RPV generation were evaluated in a single-family residential building adopting preheating control strategies. In this research, an integrated BTM modelling framework was proposed, adopting Multi-Agent System (MAS) and RC modelling techniques.

The remainder of this paper is organized as follows. The Section 2 proposed the integrated BTM modelling framework and applied the framework to a case study of a single-family house to estimate the flexibility of BTM. In Section 3, the results were presented and discussed. At last, the conclusions and the implication of the future research work are presented in Section 4.

2. Methods

2.1 Multi-agent system framework.

In this research, a single-family house located in 36°N, 116°E with 2 working residents was studied. The parameters of the building envelope are in accordance with the Chinese building energy-efficiency standard *JGJ 26-2010*. The house is equipped with RPV and individual Heating System (HS). A MAS framework consisting of 8 types of agents was proposed. Figure 1 illustrates the framework topology and the information exchange. Their functions are showing below.

- Environment agent gets predicted local weather conditions, such as solar radiation, outdoor temperature and wind speed, and provides references for RPV generation and BTM thermal state calculation.
- RPV agent calculates RPV electricity output based on solar radiation and ambient temperature, using the equations presented in Section 2.2.
- Occupant agents generate occupancy profiles and decide the comfort zone of indoor thermal environment, based on which the preheating control strategy is performed. During occupation, the occupant agents generate stochastic appliance usage behaviours and send trigger instructions to corresponding appliance agents.
- Appliance agents consume electricity on the specific commands from occupant agents. The correspondence of appliance usage and occupant behaviours could be found in authors' previous work [6].
- BTM agent performs thermal state prediction for the indoor thermal control module. The calculation is based on RC model, which is introduced in Section 2.3.

- EMS agent is the centre of the flexibility deployment, responsible for integrating external and internal information from other agents and establishing preheating control instructions.
- HS agent is under the control of EMS agent. It works during the occupation to provide space heating to the house, or works during the non-occupation to thermal charge the BTM using RPV generation under preheating control instructions.
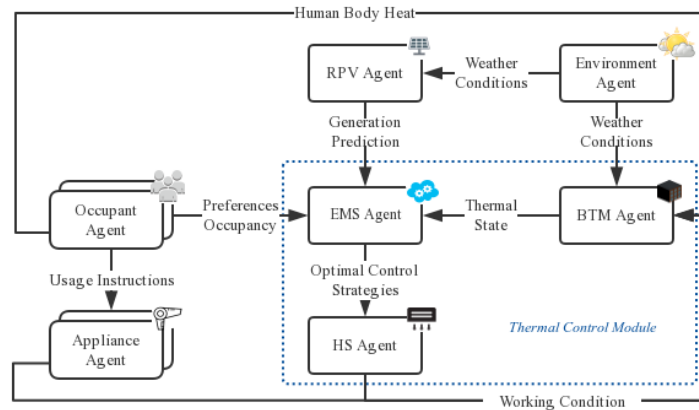
Figure 1. Illustration of the proposed MAS topology.

2.2 Electrical balance

In the studied house, the electrical balance is established in equation (1). The RPV generation could be used to supply the household energy loads. The shortage and excess of RPV electricity will be covered by the grid.

$$P_A + P_{HS} = P_{RPV} + P_G \qquad (1)$$

where P_A and P_{HS} represents the energy demand of household appliances and HS, respectively; P_{RPV} and P_G represent the power from the RPV and electricity grid, respectively. The RPV generation is calculated based on equation (2)-(6).

$$T_c = T_a + s_a(N_{ot} - 20)/0.8 \qquad (2)$$

$$I = s_a[I_{sc} + K_i(T_c - 25)] \qquad (3)$$

$$V = V_{oc} - K_v * T_c \qquad (4)$$

$$P_{PV}(s_a) = N * FF * V * I \qquad (5)$$

$$FF = \frac{V_{MPP} * I_{MPP}}{V_{oc} * I_{sc}} \qquad (6)$$

where T_c represents cell temperature and T_a represents the ambient temperature; s_a is average solar irradiance; N_{ot} is nominal cell operating temperature; I_{sc} is short circuit current; V_{oc} is open-circuit voltage; K_v and K_i represent voltage temperature coefficient and current temperature coefficient, respectively; FF is fill factor; I_{MPP} is current at maximum power point; V_{MPP} is voltage at maximum power point; P_{PV} is output power of PV module during state y.

2.3 Thermal balance

The thermal balance is established adopting RC model, as illustrated in Figure 2. The thermal charge because of the space heating is reflected to the temperature, which is analogous to voltage in electrical circuit. The calculation of the thermal states of walls and rooms is performed by the BTM agent, based on the equation (7) and (8).

$$C_{wi} \frac{dT_{wi}}{dt} = \sum_{j=0}^{N_{wi}} \frac{T_j - T_{wi}}{R_{wi,j}} + \alpha_{wi} A_{wi} q_r \qquad (7)$$

$$C_{ri}\frac{dT_{ri}}{dt} = \sum_{j=0}^{N_{ri}} \frac{T_j - T_{ri}}{R_{ri,j}} + \varepsilon_{wi}A'_{wini}q_r + \dot{m}c_{pa}(T_{i,ri} - T_{ri}) + q_i + q_{int} \quad (8)$$

where subscript *wi* and *ri* represent the corresponding wall and room, respectively; *C* is heat capacity; *T* is temperature; $R_{wi,j}$ and $R_{ri,j}$ are thermal resistance between node *wi* and *j*, and that between *ri* and *j*, respectively. The thermal resistance between nodes are calculated by equation (9)-(12). α is absorptivity coefficient; ε is transmittance coefficient; A_{wi} and A'_{wini} are the total area of wall and window, respectively; q_r is the total solar radiation reaching the surface; q_i is heat gains from infiltration and ventilation, q_{int} is the internal heat gains, calculated by equation (13).

$$R_1 = \frac{1}{h_{wi,o}A_{wi}} \quad (9)$$

$$R_2 = R_3 = \frac{L_{wi}}{2k_{wi}A_{wi}} \quad (10)$$

$$R_4 = \frac{1}{h_{wi,i}A_{wi}} \quad (11)$$

$$R_{wini} = \frac{1}{h_{wini,o}A_{wini}} + \frac{L_{wini}}{k_{wini}A_{wini}} + \frac{1}{h_{wini,i}A_{wini}} \quad (12)$$

$$q_{int} = \dot{m}c_{pa}(T_o - T_{ri}) + q_{occ} + q_{app} \quad (13)$$

where R_1 and R_4 indicate the convective thermal resistance between wall *i* and outdoor and indoor environment; R_2 and R_3 indicate the conductive thermal resistance of wall *i*; C_{oa} is the capacitance of outdoor air; T_1 and T_2 indicate the temperature of the exterior and interior surface of wall *i*; *k* is thermal conductivity, *h* is convection heat transfer coefficient; $\dot{m}$ is the air mass flow into the room for space heating; c_{pa} is the specific heat of air; T_o is the temperature of the inlet air from ducts; q_{occ} and q_{app} are the internal heat gains from occupants and appliances, respectively.
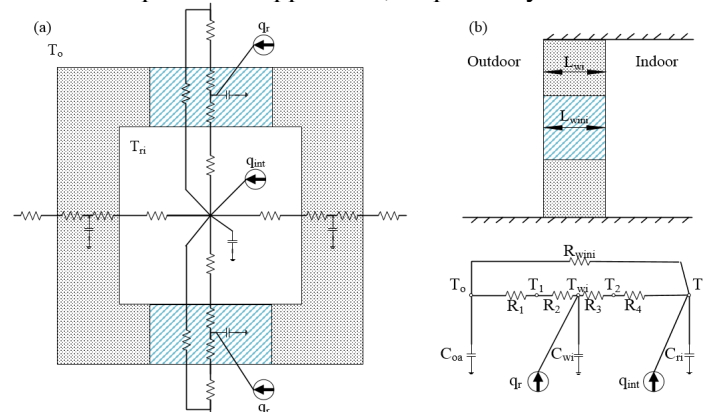
Figure 2. Illustration of the RC model of the studied building.

*2.4 Preheating control strategies*

In the studied house, the occupancy arrival was set between 5:00-6:00. The residents go out for work during the day and come back home in the evening, which means that the peak of household energy demand occurs in the inactive period of RPV. The temporal mismatch leads to a rather low self-consumption of RPV generation. In this research, a series of preheating control strategies were proposed to shift the evening heating load to the RPV active period.

- Duration: The preheating was scheduled in the mid-afternoon with a duration of 3 hours that started at 14:00 or 2 hours that started at 15:00.
- Set-point temperature: The desired indoor temperature of residential househould is typically around 18 °C. However, with certain incentives (typically economic), the endurable indoor temperature of occupants could be several degrees higher. In the research, 5 types of set-point temperature setting were adopted, from 19 °C to 23 °C.

3. Results
The MAS model was simulated for 4 days and the results from the last day was used, for the purpose of stabilizing the BTM temperature. The output power of the RPV is presented in Figure 3. In the mid-afternoon, electricity from the RPV was used for preheating.
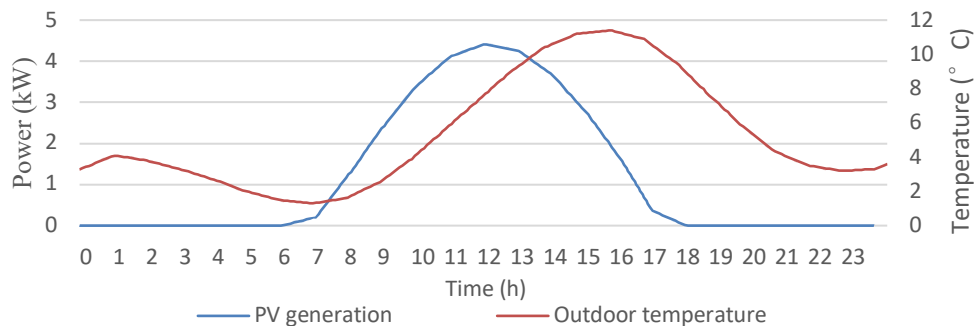
Figure 3. Output power of RPV.

The indoor temperature profiles of the 3-hour and 2-hour duration scenarios were presented in Figure 4 and Figure 5, respectively. In the selected day, the arrive time of the occupants was at 17:12, which was also the start time of HS. In the preheating scenarios, the start time of HS after arrive was delayed certain time. The delay time increased as the preheating set-point temperature increasing, as a result of increasing heat energy stored in the BTM. The load-shifting consumption of evening heating demand was presented in Figure 6, and the self-consumption of PV generation in the scenarios was presented in Figure 7.
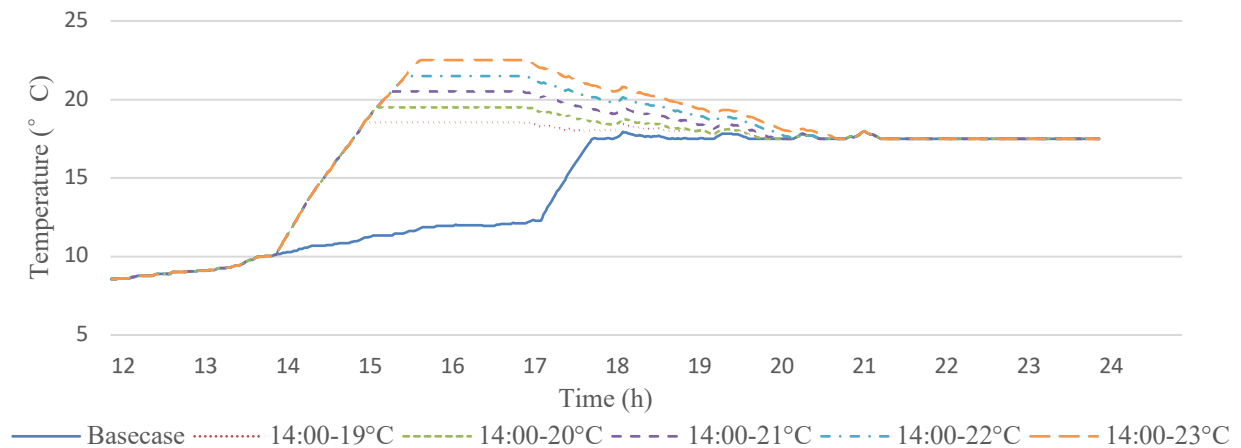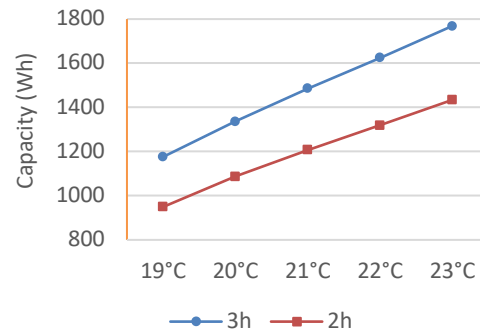
Figure 4. Indoor temperature profiles of 3-hour duration preheating scenarios.
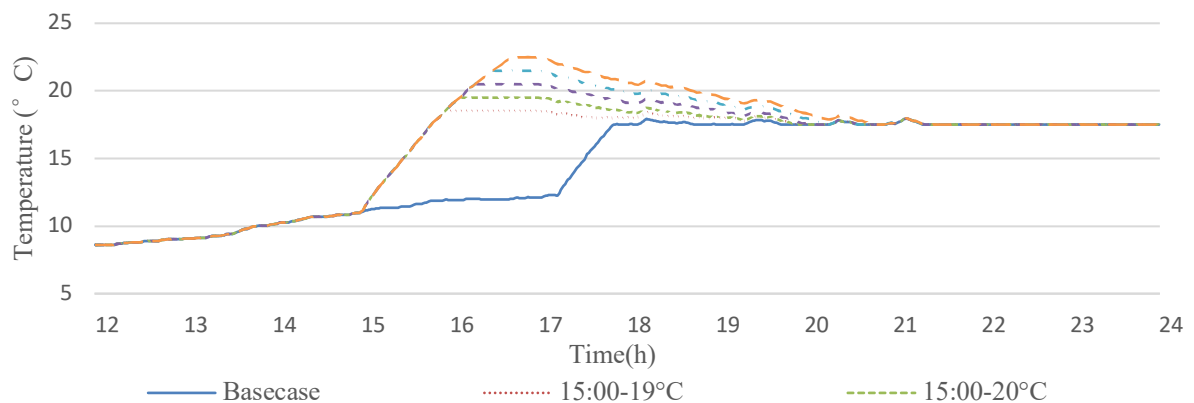
Figure 5. Indoor temperature profiles of 2-hour duration preheating scenarios.
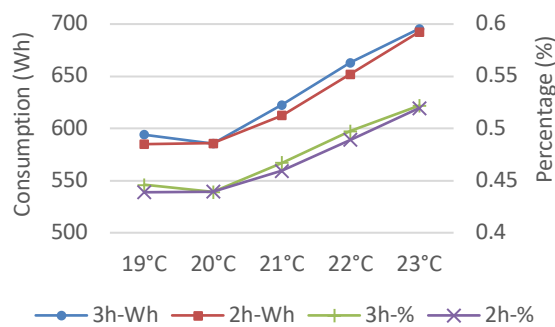
Figure 6. Load-shifting capacity and percentage of the evening heating demand.

Figure 7. Self-consumption of PV generation.

4. Conclusions

The BTM is an important supplement to the existing storage system. This research proved that the BTM of a standard-compliant building could effectively shift the evening heating demands to the afternoon, and thus could significantly improve self-consumption of the on-site PV generation. Moreover, the flexibilities in BTM could also be utilized as a cost-efficient option for consuming renewable energy from off-site plants. The choice of the suitable duration and preheating temperature could bring economical profits to the residents when considered with certain energy pricing and feed-in tariff. The proposed integrated BTM modelling framework could provide these research a computational-efficient solution with a satisfying accuracy.

References

[1] Dharshing S. Household dynamics of technology adoption: A spatial econometric analysis of residential solar photovoltaic (PV) systems in Germany. Energy Research & Social Science. 2017; 23:113-24. Doi: https://doi.org/10.1016/j.erss.2016.10.012.
[2] McKenna R. The double-edged sword of decentralized energy autonomy. Energy Policy. 2018; 113:747-50. Doi: https://doi.org/10.1016/j.enpol.2017.11.033.
[3] Wang Y, Liu L, Wennersten R, Sun Q. Peak shaving and valley filling potential of energy management system in high-rise residential building. Energy Procedia. 2019; 158:6201-7. Doi: https://doi.org/10.1016/j.egypro.2019.01.487.
[4] Gautier A, Hoet B, Jacqmin J, Van Driessche S. Self-consumption choice of residential PV owners under net-metering. Energy Policy. 2019; 128:648-53. Doi: https://doi.org/10.1016/j.enpol.2019.01.055.
[5] Le Dréau J, Heiselberg P. Energy flexibility of residential buildings using short term heat storage in the thermal mass. Energy. 2016; 111:991-1002. Doi: https://doi.org/10.1016/j.energy.2016.05.076.
[6] Wang Y, Lin H, Liu Y, Sun Q, Wennersten R. Management of household electricity consumption under price-based demand response scheme. Journal of Cleaner Production. 2018; 204:926-38. Doi: https://doi.org/10.1016/j.jclepro.2018.09.019.