EVALUATION OF THE EFFECT OF BATTERIES IN DISTRICT LEVEL SMART GRID

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ABSTRACT
Installation of batteries is an effective measure for absorbing surplus electricity under a large-scale diffusion of photovoltaic generation (PV). In this study, the electricity load curve of a district is calculated with estimation of electricity consumption and electricity generated by PV at the district level by a bottom-up simulation model of residential and commercial sectors. In addition, the following two battery implementation strategies are compared: 1) installation and operation of separate batteries at individual houses and 2) installation and operation of a battery in a local energy management system that accommodates surplus electricity and capacity of batteries installed in the district.

INTRODUCTION
In Japan, PV generation has been promoted as a means to reduce greenhouse gas (GHG) emissions, especially in residential areas. While the generation capacity was only 1.4 GW in 2005, the national target for PV diffusion is 28 GW by 2020 and 53 GW by 2030. However, increase in the installed capacity leads to reverse power flow, which causes several complications in the distribution system such as an increase in voltage at the demand side of distribution line and a disturbance in power flow frequency. To cope with these problems, storage batteries in the appropriate grid position are expected to be a solution. To evaluate battery effectiveness, first of all, it is important to calculate the time, location and amount of surplus electricity generated at the demand side with a detailed building simulation model.

In this study, a bottom-up model is employed to estimate power consumption by residential and commercial buildings in a district. The difference between power consumption and the electricity generated by PV is the load of and reverse flow to the distribution system. The most important feature of the residential model is that occupant behaviour is stochastically simulated using the result of a Time Use survey to accurately describe the electricity load curve in the district. Power consumption of home appliances and during operation of facilities such as air-conditioning, water heating and cooking are simulated depending on occupant behaviour. The power consumption is determined by summing up all the power consumed in a house within 5-min time intervals. For commercial buildings, power consumption is estimated in a bottom-up manner similar to that used in the residential model, although the operation of power-consuming appliances and building facilities are given by a daily schedule. Electricity load curve results are produced by applying these models to residential and commercial districts with different characteristics, and the differences in electricity load curves between weekdays and holidays under sunny and cloudy conditions are discussed.

In the last section of this paper, the capacity of storage batteries required to prevent reverse power flow outside the district is estimated. The following two battery implementation strategies are compared: 1) installation and operation of separate batteries at individual houses and 2) installation and operation of a battery in a local energy management system that accommodates surplus electricity and capacity of batteries installed in the district.

SIMULATION MODEL
Model of residential building (Shimoda Y., 2007)
In the residential building model, all households in the object district were classified into the following categories: 19 categories of households; 12 categories of building types, including 6 floor-area categories for detached houses and 6 for apartment houses; and 4 categories of building insulation levels that included no insulation, insulation meeting the 1980 standard, insulation meeting the 1992 standard and insulation meeting the 1999 standard. For each category, power consumption of a household was calculated bottom-up, beginning with the power usage of each appliance in consecutive 5-min intervals. The power usage of appliances was determined on the basis of occupant behaviour, which was based on the time allocation of living activities surveyed by the Broadcasting Culture Research Institute. For example, the lighting and heating or cooling of rooms depended on the occupancy status, and the use of other appliances depended on the activity of the occupants. However, not considering the ratio of long vacation periods in this survey, the authors estimated that half of all household occupants vacate from 7:00 a.m. 31 December through 10:00 p.m. 2 January; 7:00 a.m. 3
May through 10:00 p.m. 5 May; and 7:00 a.m. 16 August through 10:00 p.m. 18 August.

In the calculation of energy usage for heating and cooling, dynamic thermal load calculations and energy simulations were iterated for the four levels of thermal insulation. Energy consumption during heating and cooling was calculated by the weighted average of these results using the percentage of each insulation level in the object region. In this case, a detailed room air conditioner performance model that considered the dependency on outdoor air temperature and partial load was used in addition to a stochastic model of the heating and cooling operation.

Electricity generated by PV was calculated by equation (1), and PV temperature was defined by equation (2). (Yukawa M., 1996)

\[
E_p = \frac{P_{AS} \cdot H_A \cdot K \cdot (1 + \alpha (T_C - 25))}{G_s} \quad (1)
\]

\[
T_C = T_A + \left[ \frac{\Delta}{B \log (a+1)} + 2 \right] \times H_A - 2 \quad (2)
\]

\( E_p \) [kW] is electricity generated by PV, \( P_{AS} \) [kW] is capacity of PV, \( H_A [kW/m^2] \) is the amount of slope solar radiation, \( K [-] \) is performance ratio (= 0.78), \( \alpha [-] \) is PV temperature correction factor (= –0.005), \( T_C [°C] \) is PV temperature and \( G_s [kW/m^2] \) is solar radiation intensity at standard test cell condition (= 1 kW/m²). \( T_A [°C] \) is outdoor air temperature, \( A = 50, B = 0.38 \) and \( V [m/s] \) is wind velocity. PV systems were installed only for detached houses. Table 1 shows the capacity of PV installed on rooftops for 6 categories of detached houses in 4 directions. The power consumption and the electricity generated by PV of each household was multiplied by the number of households in each category, and products were summed. The total power consumption in the object region was then estimated. The overall flowchart of the model is shown in Figure 1. The weather data used in the residential model is the data of meteorological observation on the ground of 2005 for Osaka.

<table>
<thead>
<tr>
<th>Total floor area[m²]</th>
<th>North [kW]</th>
<th>West [kW]</th>
<th>East [kW]</th>
<th>South [kW]</th>
<th>Total [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>50</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
<td>0.3</td>
<td>1.4</td>
<td>2.3</td>
<td>4.0</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>0</td>
<td>1.2</td>
<td>2.8</td>
<td>4.0</td>
</tr>
<tr>
<td>113</td>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>146</td>
<td>0</td>
<td>0</td>
<td>0.4</td>
<td>3.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

![Table 1 Capacity of PV in four directions](image)

**Figure 1** Overall flowchart of residential building.
Model of commercial building (Yamaguchi Y., 2010)

In the commercial building model, all buildings in the object district were classified into 5 categories of usage including office, shop, restaurant, hotel and hospital; 9 categories of floor area; 8 categories of heat-source system and 5 categories of energy-conservation measures. Figure 2 illustrates the overall flowchart of the simulation model. This model consists of two sub-models, the energy demand model and the energy source system model, and six databases: occupant behaviour and operation; building property; climate condition, which was the same data as that used in the residential model; energy efficiency; heat-source system and energy-conservation measure. The occupant behaviour and operation database contains information on heat gain from occupants and the operation schedule for lighting, air-conditioning and other appliances such as office equipment for each space usage. The building property database contains the form of the building, total floor area, floor area of each floor, number of storeys, zoning of floor plan, window-to-wall ratio, distance to and height of buildings located opposite walls, principal usage and usage of all floors.

The minimum unit of the simulation model was the building floors. To estimate heating and cooling demands of floors, thermodynamic simulation and HVAC system simulation were performed on an hourly basis while taking into account the size, form, usage of the floor, other properties which determine internal heat gain and operation conditions of HVAC systems, and the adopted energy-conservation measures and system configuration of HVAC systems. This information was provided from the building property database. In addition, a number of common conditions were used for the other parameters in place of actual conditions in individual buildings because it was impossible to gather complete data. For the simulation of electricity, a common electricity demand profile for lighting and other equipment was assigned for each floor usage. For hot water demand and energy use in the kitchen, a common demand profile was assigned for each person using the floor.

In the energy demand model, energy demand profile for heating, cooling, electricity, hot water and cooking was quantified for building floors. The space heat load was dynamically calculated using the weighting factor method (ASHRAE 2001) developed for the HASP/ACLD (Matsuo 1985a) which is the computer program by Japanese researchers during the 1970s and 1980s (Matsuo 1985b). The demand of all floors was aggregated to be used as input information of the energy source system model.

In the energy source system model, a part-load characteristic was assumed for each component to determine electricity consumption for heating and cooling. For refrigerators and heat pumps, in addition to the part-load characteristic, the coefficient of performance (COP) was modelled from its rated COP and its regression with chilled water temperature and cooling water temperature for water-cooled refrigerators or outside air temperature and wet-bulb temperature for air-cooled heat pumps and condensing units.

The model’s structure was designed such that the simulation result considered the influence of climate conditions, the distribution of building properties and the efficiency of appliances and equipment in addition to configuration and operation of HVAC systems. This feature was obtained by integrating the floor-level simulation of the energy demand with the bottom-up structure using a number of databases to aggregate the energy consumption at the district level.

Figure 2 Overall flowchart of commercial building.
To estimate the energy consumption of the object district consisting of a variety of commercial buildings, the buildings were categorised into one of the previously mentioned building categories. The energy consumption per floor area was then calculated while assuming data for the representative buildings and applied to the total floor area of the target building. Finally, the total energy consumption of the district was determined by aggregating the total energy consumption of all the buildings.

Integration of residential and commercial sectors
To calculate the electricity load curve of the district, load curves simulated by the residential and commercial building models were summed. For the input data of residential model, the number of each category of household in each district in Toyonaka City, Osaka, was estimated from the 2005 population census and the ratio of each residential building insulation level was estimated from information quoted in the fixed asset tax rolls for the in which year the building was constructed. In the commercial building model, the properties of the commercial buildings—principal usage and usage of all floors, total floor area, floor area of each floor and number of storeys—in each district was used as input data. The total electricity load curve of the commercial sector was simulated in 1-h intervals and linearly interpolated in 5-min time-steps.

ELECTRICITY LOAD CURVE OF DISTRICT

Differences in district types
In this study, the electricity load curve of 4 district types was predicted. Table 2 shows profiles of each district (area); Figure 3 shows images of each district and Figure 4 shows the ratio of detached houses, apartment houses and commercial buildings. Area 1 is mainly composed of detached houses; Area 2 apartment houses and Area 3 commercial buildings. Area 4 is a district with mixed residential and commercial sectors.

<table>
<thead>
<tr>
<th>Table 2 Profile of each area.</th>
</tr>
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<tbody>
<tr>
<td><strong>District area (m²)</strong></td>
</tr>
<tr>
<td>Total floor area (m²)</td>
</tr>
<tr>
<td>Number of households</td>
</tr>
<tr>
<td>Number of commercial buildings</td>
</tr>
</tbody>
</table>

Figures 5–8 show the monthly average electricity load curves, which were obtained by subtracting the electricity generated by PV from the electricity consumption in each district. Each type of district was revealed to differ marginally in monthly average load curve with surplus electricity generation in Area 1 exclusively. However, 5-min time-step simulation showed that surplus electricity was also generated in Area 4 in spring and autumn. The year-round surplus electricity in Area 1 was 114 MWh; that is, about 5% of the electricity generated by PV. In Area 3, the total was 3 MWh, about 0.1% of the electricity generated by PV. It was determined by these results that problems caused by reverse power flow would be serious only at the district containing a large share of detached houses.
Seasonal differences

Figures 9–11 show differences among typical weekday load curves of summer, spring/autumn and winter in Area 1. The electricity consumption of residential and commercial sectors are represented by dotted lines; the electricity generated by PV is represented by broken lines expressed by negative load curves and total electricity load curves are represented by solid lines.

The surplus electricity is largest in spring/autumn because electricity consumption is less than that in summer or winter. The amount of surplus electricity of a day is 227 kWh in summer (Figure 9), 1253 kWh in spring/autumn (Figure 10) and 667 kWh in winter (Figure 11).

Difference between weekday and holiday

Figures 12 and 13 show typical load curves of weekdays and holidays in Area 3. The holiday electricity consumption of the commercial sector is approximately half of that of the weekday; thus, surplus electricity is generated during holidays in Area 3.
Influence of weather
The weather affects the electricity generated by PV and the electricity consumption of air conditioners because of its impact on heat load in houses and buildings. Figure 14 shows a typical load curve during a cloudy day in summer in Area 1. Compared with the typical curve of a sunny day (Fig. 9), this curve is flatter because a smaller amount of electricity was generated and consumed by cooling in lower temperature conditions.

Influence of ratio of PV installation
Figure 15 shows the monthly surplus electricity generated in Area 1 with different ratios of PV installation in detached houses. Thus far, all evaluations were estimated on the condition that all detached houses had installed PV. However, according to Figure 15, the ratio of PV installation has a large influence on the amount of surplus electricity generated. No surplus electricity was detected on the condition of 20% installation. 0.2 MWh/year surplus electricity was generated with 40% installation, 12 MWh/year with 60%, 50 MWh/year with 80% and 114 MWh/year with 100%.

ESTIMATION OF BATTERY CAPACITY
In this section, the capacity of storage batteries required to prevent reverse power flow is estimated, determined by a storage battery model with input data of electricity load curve calculated by residential and commercial building models. In addition, the following two battery implementation strategies are compared: 1) installation and operation of separate batteries at individual houses and 2) installation and operation of a battery in a local energy management system that accommodates surplus electricity and capacity of batteries installed in the area.

Model of storage battery
Table 3 shows single storage battery specifications in the simulation model. Overall flowchart of the battery is shown in Figure 16. This model initially distinguishes charge and discharge. If the amount of electricity generated by PV is greater than the electricity consumption, the storage battery is charged by the surplus electricity; if the electricity load is larger than the discharging threshold, the storage battery is discharged. The discharging threshold depends on the state of charge (SOC); that is, the proportion of the amount of charged electricity against battery capacity (Figure 17).

The terminal voltage of the storage battery was calculated by the charging or discharging of electricity, battery temperature and SOC. Figure 18 illustrates the estimation result of terminal voltage for a single storage battery with 70 Ah capacity at 25°C. In this figure, CA is the proportion of the charging/discharging current against the capacity of the single storage battery. +0.1CA indicates 7A discharge current; −0.1CA indicates 7A charge current. (Shimada T., 2005)

Table 3 Single storage battery specification.

<table>
<thead>
<tr>
<th>Nominal voltage</th>
<th>2 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity of single storage battery</td>
<td>70 Ah</td>
</tr>
<tr>
<td>Efficiency of inverter</td>
<td>90%</td>
</tr>
<tr>
<td>Self-discharge rate</td>
<td>0.1%/day</td>
</tr>
</tbody>
</table>

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Figure 13 Electricity load curve of holidays.

Influence of weather

Figure 14 Electricity load curve of cloudy day.

Figure 15 Influence of PV installation ratio.

Figure 16 Model of single battery.

Figure 17 State of charge (SOC) of single battery.
The capacity of storage batteries required to prevent reverse power flow was calculated by equation (3). (Kurokawa K., Wakamatsu K., 1994)

\[ C = \frac{E_{\text{max}}}{(DOD \cdot \text{eff} \cdot V_N)} \]  

(3)

\( C \) [kAh] is capacity of storage battery, \( E_{\text{max}} \) [kWh] is the maximum amount of surplus electricity of a day year-round, \( DOD [-] \) is depth of discharge (= 0.7), \( \text{eff} [-] \) is efficiency of inverter (= 0.98) and \( V_N [V] \) is nominal voltage (= 2.0).

Estimation result of storage battery capacity

The following two battery implementation strategies were compared: 1) calculating storage battery capacity with the electricity load curve of each household as input data, multiplying the result by the number of households in each category and summing the products (Case 1) and 2) calculating storage battery capacity with the electricity load curve of the area as input data. (Case 2 includes only residential sectors; Case 3 includes residential and commercial sectors.) While the required performance of batteries might be different between 2 strategies, the installed batteries have the same performance and DOD (depth of discharge) is 0.7 in all cases in this estimation.

Figures 19 and 20 show the capacities of batteries and the amounts of charge/discharge year-round in Areas 1 and 3 in each case. In Area 1, Cases 2 and 3 can reduce the capacity of storage batteries by 45% and 54%, respectively, and the amount of charge/discharge by 61% and 74%, respectively, compared with Case 1. In Area 3, Cases 2 and 3 can reduce the capacity of storage batteries by 25% and 82%, respectively, and the amount of charge/discharge by 29% and 98%, respectively, compared with Case 1.

These results show a huge potential of reduction in capacity of storage batteries with the local energy management system, which depends heavily on the ratio of residential and commercial buildings in the object district. However, we must consider that we cannot solve the problem of voltage increase at the distribution line inside the district in Cases 2 and 3, while we can solve it in Case 1.

CONCLUSION

In this study, the electricity load curve of districts was simulated by a bottom-up model of residential and commercial sectors, and the effects of storage battery installation at each district was evaluated.

The residential building model considered differences in households, building types, floor areas.
and building insulation levels. The commercial building model considered usage, floor areas, heat-source systems and energy-conservation measures. The electricity consumption of residential and commercial sectors was calculated by these models with stochastic occupant behaviour and weather data.

The electricity consumption was simulated for four types of districts: Area 1, a large share of which was composed of detached houses; Area 2, which was composed of apartment houses; Area 3, which was composed of commercial buildings; and Area 4, which was a mix of residential and commercial sectors. Differences in electricity load curves in each district were discussed. Surplus electricity was generated throughout the year in Area 1. Even the same district, the electricity load curve depended on seasons, weekdays, holidays and weather. It was determined that the greatest amount of surplus electricity was generated in April and May when electricity consumption was lower and PV generation was large. When the ratio of PV installation changed, there was no surplus electricity at the condition of 20% installation. 0.2 MWh/year surplus electricity was generated with 40% installation, 12 MWh/year with 60% installation, 50 MWh/year with 80% installation and 114 MWh/year with 100% installation.

In the last section of this paper, the capacity of storage batteries required to prevent reverse power flow outside the district was estimated. Results indicate that there is a huge potential of reduction in capacity of storage batteries with local energy management systems, and this effect heavily depends on the ratio of residential and commercial buildings in the object district.

The challenge that is going to have to be addressed in the near future is to study which scale is appropriate to install storage batteries while considering the voltage increase at the demand side of distribution line. Furthermore, we would like to make a proposal on the evaluation index of the electricity load curve with more detail setting about the performance of storage batteries.

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REFERENCES


