SIMPLIFIED ANALYSIS OF THE RELATIONSHIPS BETWEEN THE PRICES AND OPTIMAL CAPACITIES OF PV SYSTEMS AND BATTERIES

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Abstract

To realize the transition towards a higher proportion of renewable energy, it is critical to understand how optimal capacities of facilities are determined depending on their costs. Using a simple electricity system model consisting of demand, photovoltaic (PV) power generation, and battery storage, this study investigated the relationships between the following three factors: (1) the prices of PV systems and batteries, (2) the share of PV-generated electricity in the total electricity demand, and (3) the cost of PV-generated electricity based on the optimal installed capacities of PV systems and batteries. The study was conducted using openly available data on Japanese power systems, including for real demands and PV power generation. This paper presents the results in terms of maps.

1 Introduction

The increasing proliferation of variable renewable energy sources (VRE), such as photovoltaic (PV) or wind power generation, is leading to a situation in which their outputs frequently exceed demands. In such situations, the additional capacities of VREs lead to just generation of larger surplus electricity and not reduce the net demand; in other words, it shows the diminishing effect of the residual electricity demand reduction. For this reason, energy storage facilities such as batteries are necessary to achieve a higher proportion of renewable energy. It is important to explore cost-effective optimal solutions concerning the amount of introduced PV and the usage of batteries (i.e. optimal sizing). Several studies have been conducted to address this issue1), 2) using bottom-up energy systems models. However, few studies have explored the relationships between assumptions and optimal solutions in energy system modeling, owing to the difficulties involved. The key question to overcome these difficulties is that of how to build a simple model of an electricity system.

In this context, Aratame's approach is interesting3). He investigated PV electricity costs and required battery systems to enable 100% renewable electricity, using a simplified model representing the essential aspects of variable renewable energy. In the study, he first calculated the PV capacity equal to the total annual demand and total annual power generation. Second, he calculated the minimum amount of battery required to offset the remaining demand and surplus power. Third, he evaluated the cost of electricity for such a system. However, he only considered the single case, although the wider possibility exists of considering the combination of the amounts of PV and battery availability.

The present study aims to analyze the relationships between the following three factors: (1) the prices of PV systems and batteries, (2) the share of PV-generated electricity in the total electricity demand, and (3) the cost of PV-generated electricity based on the optimal installed capacities of PV systems and batteries. This study follows Aratame's approach, using a simple electricity system model consisting of demand, PV power generation, and battery storage. The employed methods and data are explained in Sections 2 and 3, respectively. Results based on a single dataset and other datasets are presented in Section 4. Finally, Section 5 discusses the results.

2 Methods

This study considers a simple electricity model, consisting of demand, PV power generation, and battery storage. This simplification enables an optimal charging and discharging schedule to be obtained using a simple algorithm, and without optimization methods such as linear programming.

In this algorithm, given an hourly demand D_t, PV power generation P_t, time period t, and PV capacity x_{pv}, the residual demand r_t is calculated. Let the positive and negative components of r_t be r_t^+ (net residual demand) and r_t^- (surplus generation), respectively. Then,

$$r_t = D_t - x_{pv}P_t \tag{1}$$

The share of PV-generated electricity in the total electricity demand y is derived as follows, where c_i represents the additional demand reduction owing the electricity discharged from the battery, which is charged by surplus generation r_t^- and then discharged to net residual demand r_t^+ (for more details about the calculation procedure for c_i, see Appendix). r_t^+ and c_i are functions of the PV capacity x_{pv} and battery capacity x_{bt}. Thus, y can be represented as a function of x_{pv} and x_{bt}:

$$y(x_{pv}, x_{bt}) = 1 - \frac{\sum_t r_t^+ - \sum_i c_i}{\sum_t D_t} \quad (2)$$

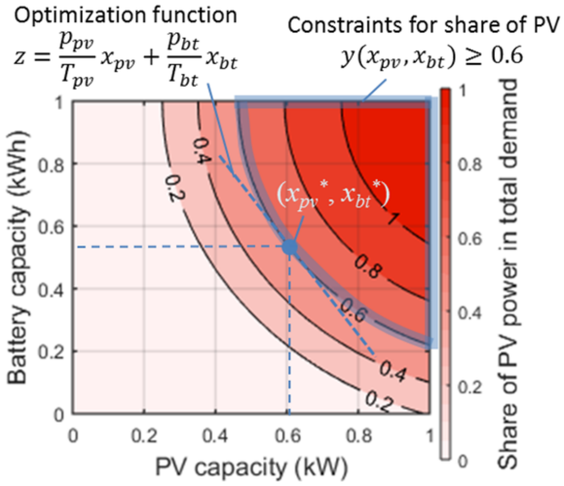

Figure 1 Schematic diagram illustrating the optimization of the PV system and battery capacity based on a map representing the relationships between x_{pv}, x_{bt}, and y.

On calculating y by substituting in many different values of x_{pv} and x_{bt}, a map is obtained, as shown in Figure 1. Using this map, the feasible regions of x_{pv} and x_{bt} that satisfy a given y can be obtained. Combining the information regarding the feasible regions with the cost-optimization function consisting of the prices of PV systems and batteries, p_{pv} and p_{bt}, the optimal capacities of the PV systems and batteries, x_{pv}^* and x_{bt}^*, respectively, are determined as the points at which the slopes of the respective tangent lines are equal to the slopes of the respective optimization functions (i.e., the ratio of p_{pv} to p_{bt}; see Figure 1). As a result, the optimal capacities of PV systems and batteries can be represented as functions of the prices of PV systems and batteries:

$$(x_{pv}^*, x_{bt}^*) = f(p_{pv}, p_{bt}) \quad (3)$$

Further, the cost of electricity from PV systems C_{RE} is calculated for a given value of the share of PV-generated electricity y_0, with assumed lifetimes of PV systems and batteries T_{pv} and T_{bt}, respectively. For simplicity, a discount rate is not considered. However, assumptions on the lifetimes can incorporate the effect of discounting. In this study, T_{pv} and T_{bt} are set to be 20 and 10 years, respectively.

$$C_{RE}(p_{pv}, P_{bt}, T_{pv}, T_{bt}) = \frac{1}{y_0 \sum_t D_t}\left(\frac{p_{pv}x^*_{pv}}{T_{pv}} + \frac{p_{bt}x^*_{bt}}{T_{bt}}\right) \tag{4}$$

3 Data

A dataset of hourly demand and hourly PV power generation for 10 utility companies (Hokkaido, Tohoku, Tokyo, Chubu, Hokuriku, Kansai, Chugoku, Shikoku, Kyusyu, and Okinawa; see Figure 2) in Japan for the fiscal years (FYs) 2016 and 2017 (from April 1st to March 31st) was employed for the model in this study4).

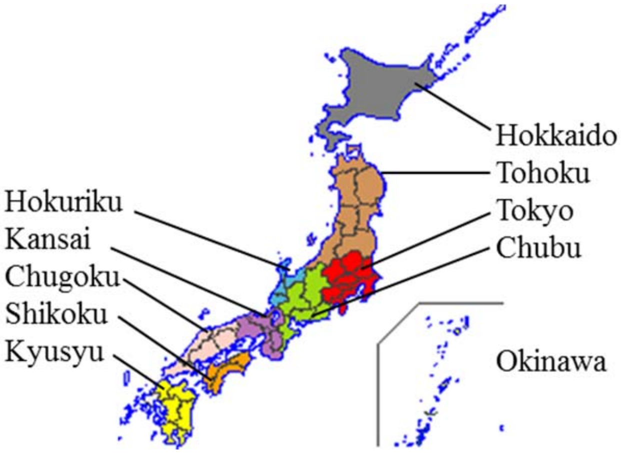

Figure 2 Covering areas of the 10 utility companies in Japan
(the original map data was obtained from Wikipedia with the permission of GNU Free Documentation License5)).

The data were normalized by setting the maximum demand and PV generation to 1 kW. Figures 3 and 4 present overviews of the datasets in terms of the hourly-base annual demands (24 hours × 365 days) in different styles. Similarly, overviews of the annual PV power generation are presented in Figures 5 and 6.

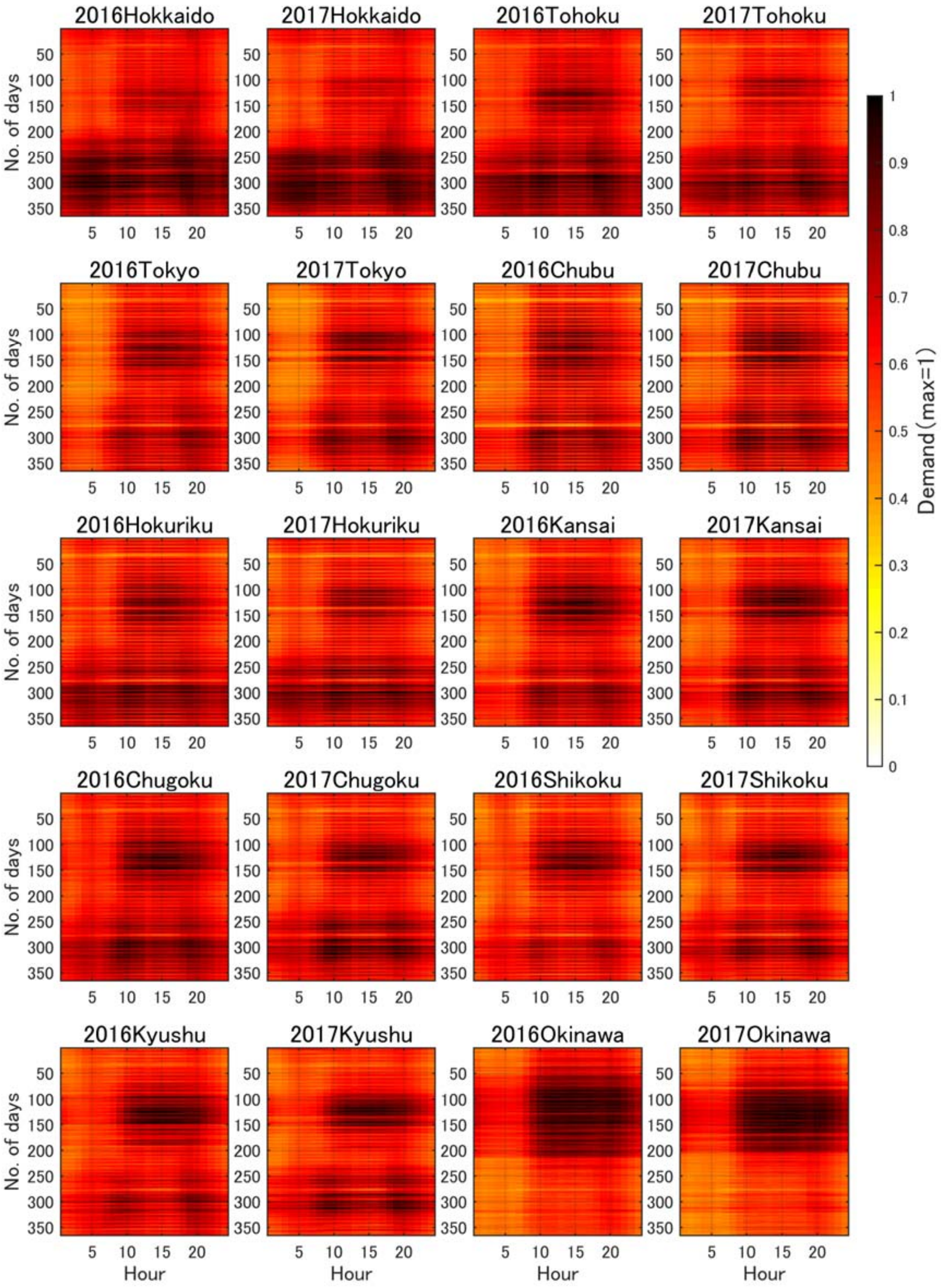

Figure 3 Overview of hourly demands of 10 utility companies for FYs 2016 and 2017 using heat-map style.

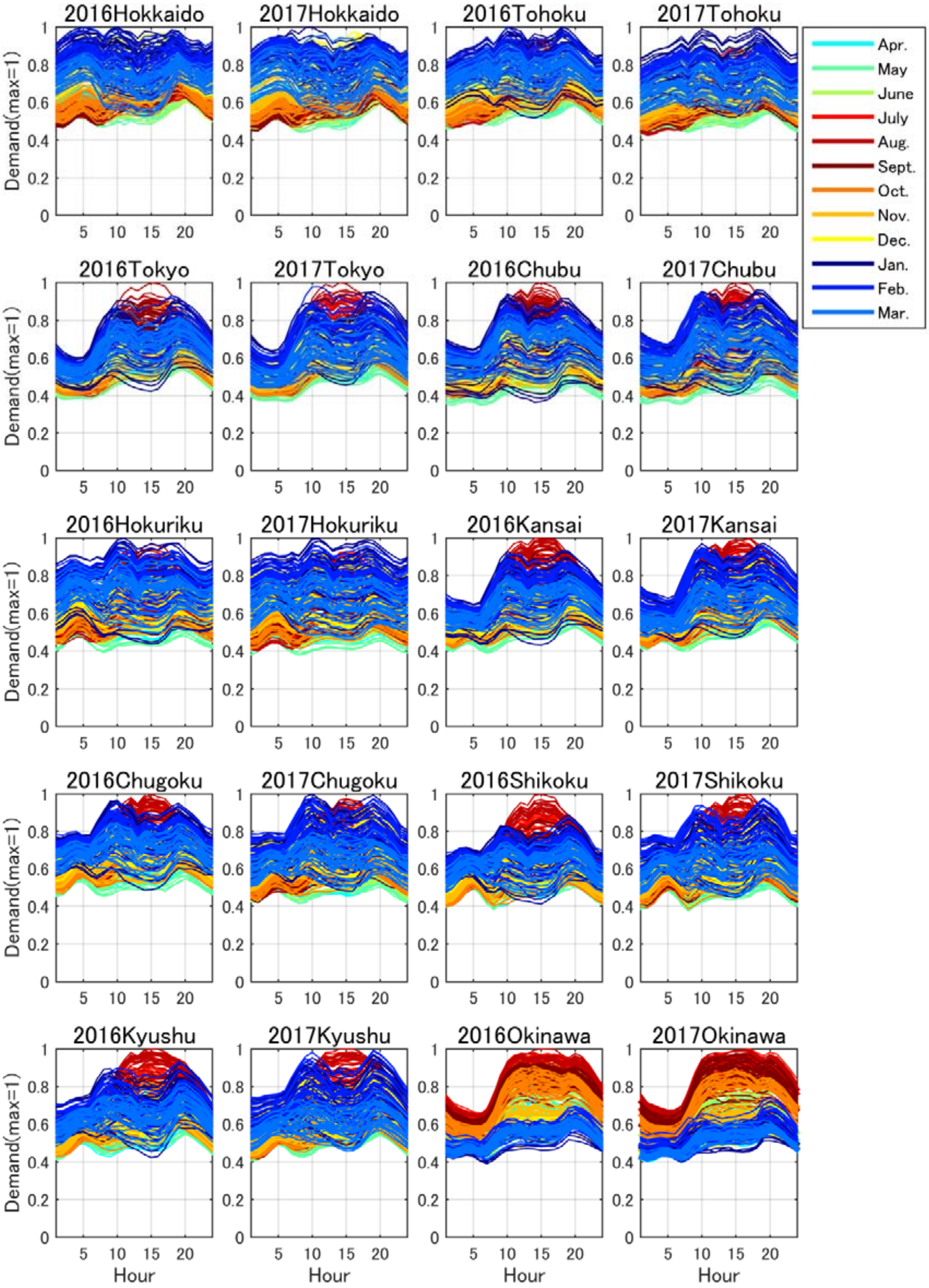

Figure 4 Overview of hourly demands of 10 utility companies for FYs 2016 and 2017 using line charts.

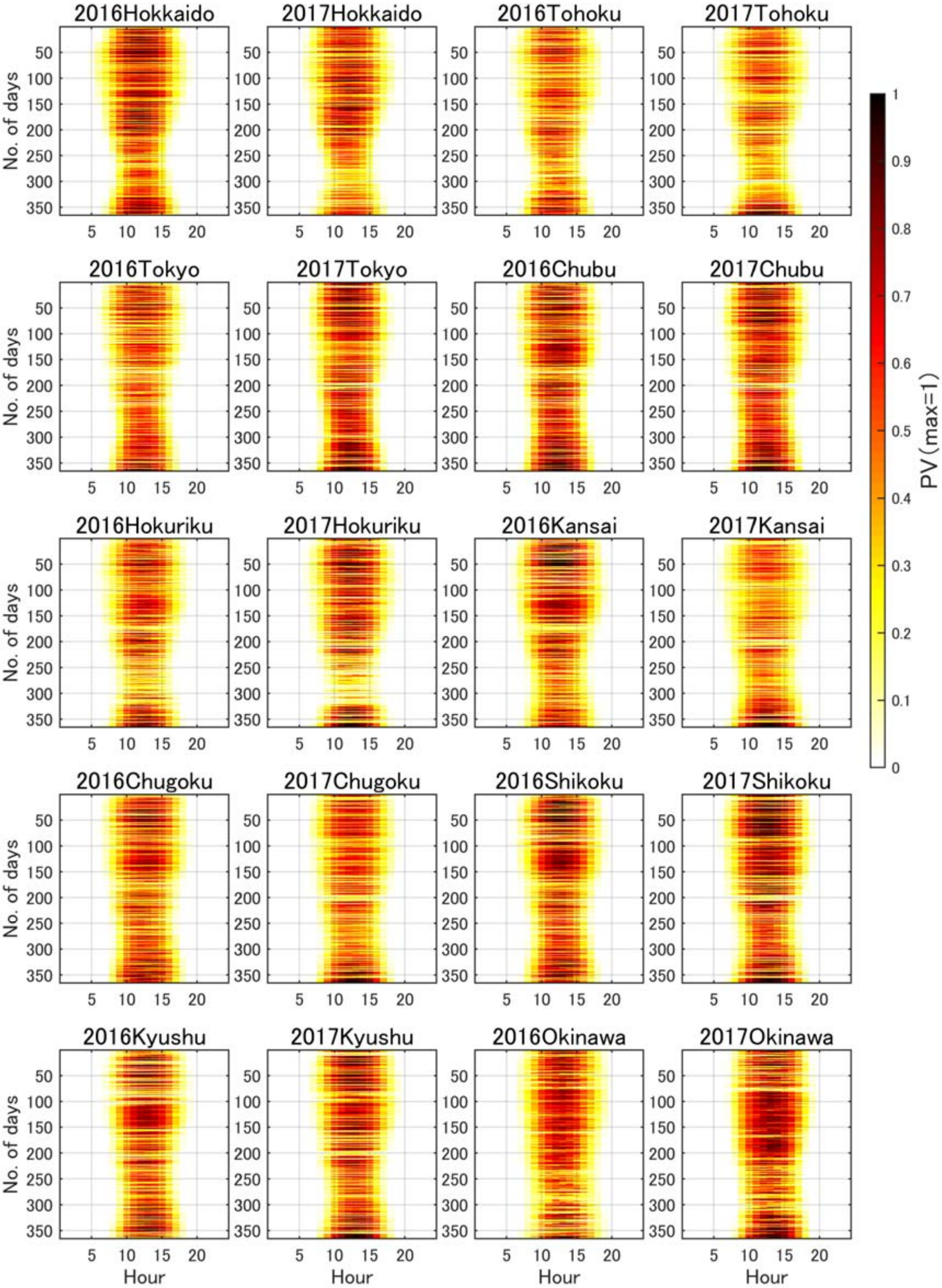

Figure 5 Overviews of hourly PV power generation of 10 utility companies for FYs 2016 and 2017 using a heat-map style.

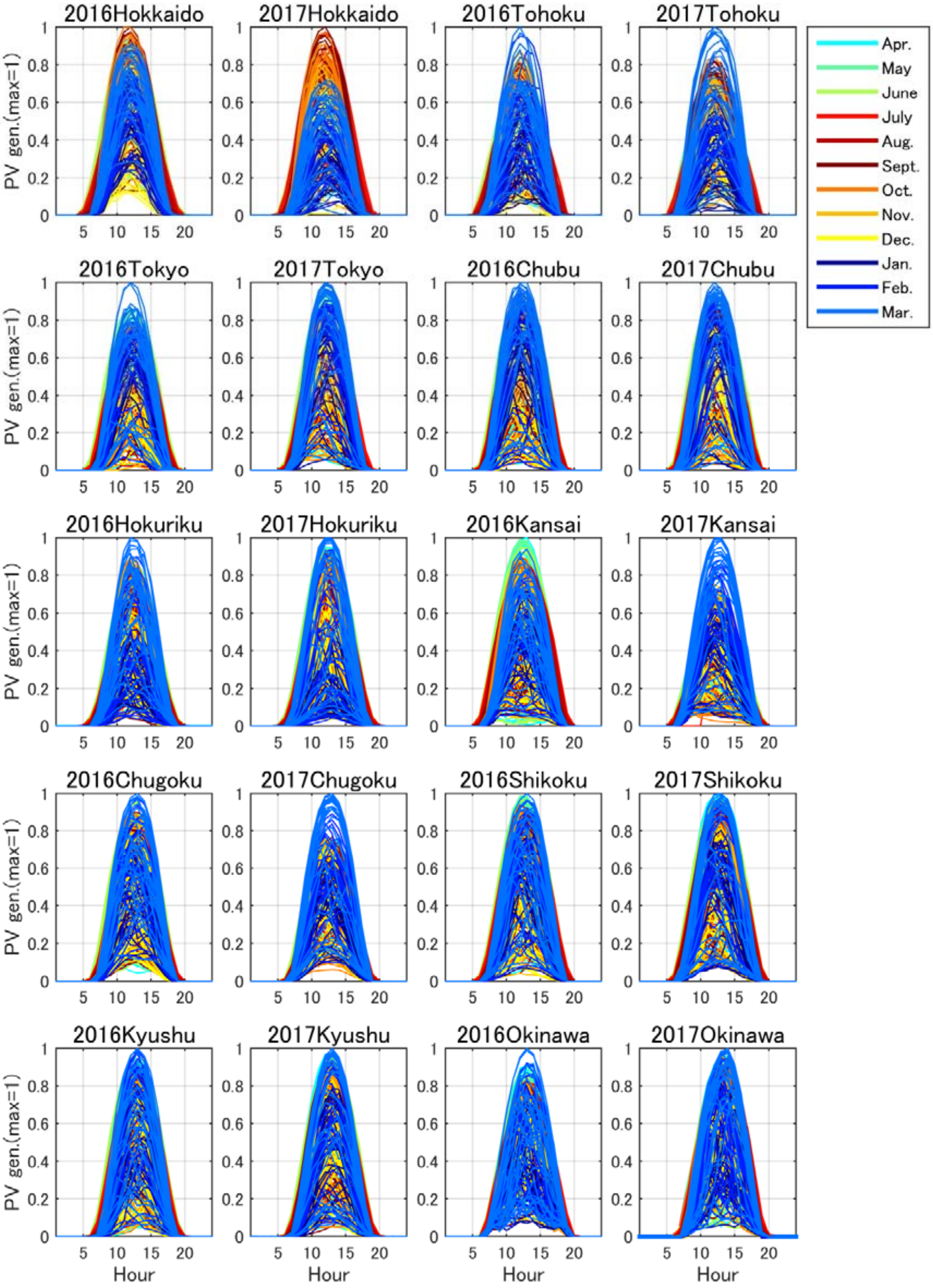

Figure 6 Overview of hourly PV power generation of 10 utility companies for FYs 2016 and 2017 using line charts.

4 Results

4.1 Contour diagrams for a single dataset

Using the single dataset for the Tokyo Electric Power Company in 2016, the results are described as follows.

Figure 7 presents a map representing the relationships between the PV capacity, battery capacity, and share of PV power in the total demand. In cases with smaller PV capacities (less than 1 kW), the contour lines are almost parallel to the y-axis. This is because the surplus generation is almost zero, and the battery does not contribute to reducing the net residual demand when the PV capacity is decreased. Greater PV and battery capacities lead to increases in the share of PV power, although increasing only one or the other of these results in a gradual decrease in PV power.

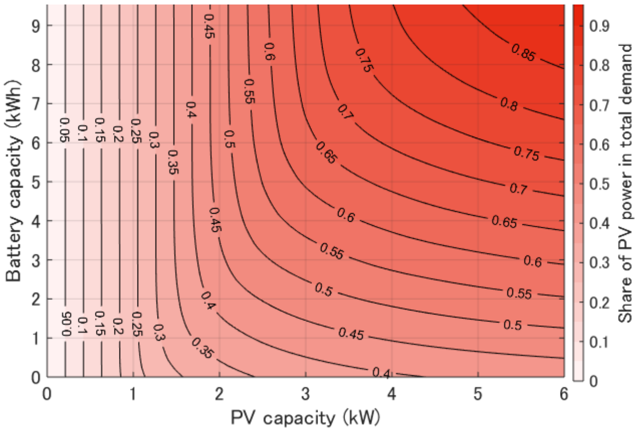

Figure 7 Map representing the relationships between PV capacity, battery capacity, and share of PV power in the total demand.

Figure 8 presents a map representing the relationships between the PV capacity, battery capacity, and PV utilization rate. In addition, Figure 9 presents a map representing the relationships between the PV capacity, battery capacity, and annual charge/discharge cycle of the battery. The annual charge/discharge cycle of the battery is calculated through the following equation:

$$s = \frac{\sum_i c_i}{x_{bt}} \tag{5}$$

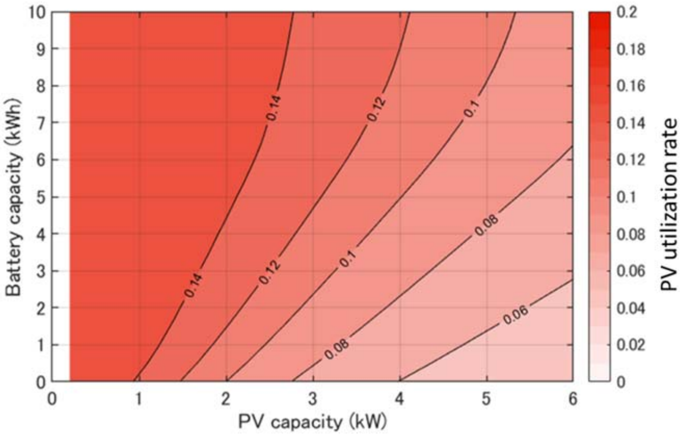

Figure 8 Map representing the relationships between the PV capacity, battery capacity, and PV utilization rate.

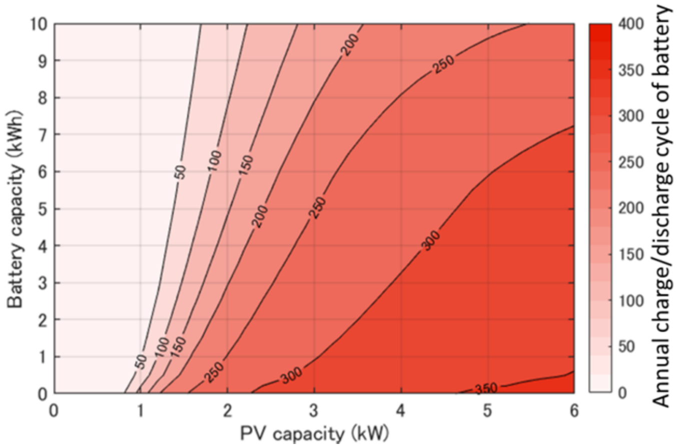

Figure 9 Map representing the relationships between the PV capacity, battery capacity, and annual charge/discharge cycle of battery.

Figure 10 presents maps representing the relationships between the PV price, battery price, share of PV power, and cost of renewable electricity, calculated based on the optimal PV and battery capacities from the above map. A larger share of PV power leads to a higher cost of renewable electricity under the same conditions for the prices of PV systems and batteries.

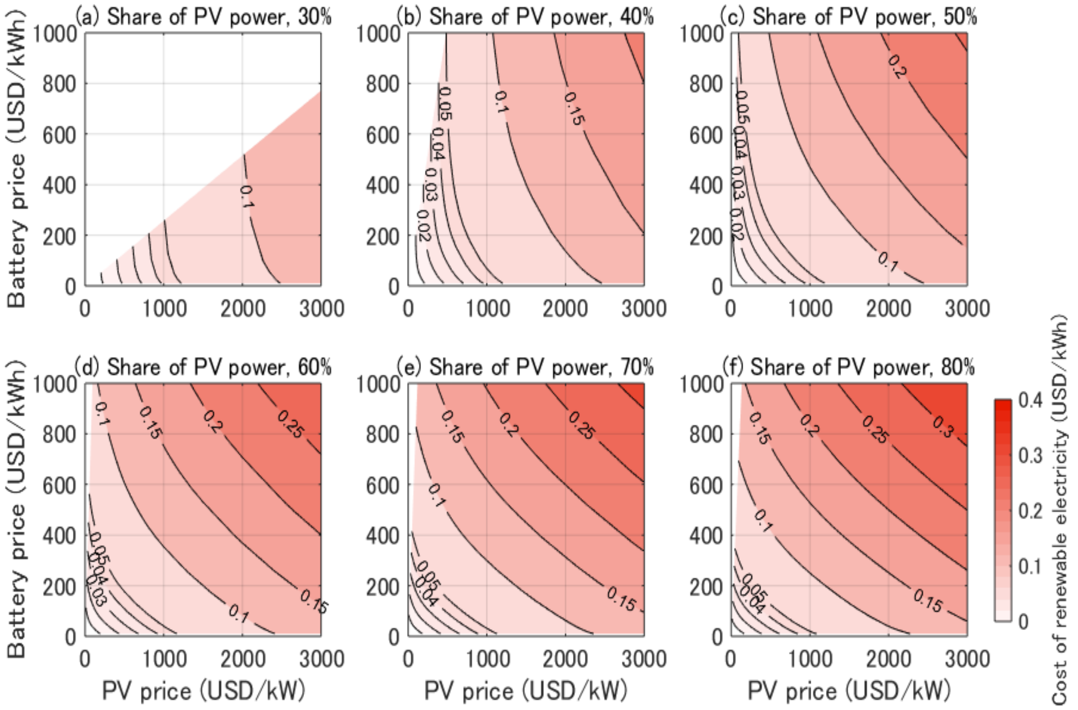

Figure 10 Maps representing the relationships between the PV price, battery price, and cost of renewable electricity with different shares of PV power.

4.2 Variety in the cost of renewable electricity with different datasets

Using 20 datasets, the relationships between the PV price, battery price, and cost of renewable electricity are obtained. To further understand the various results, nine combinations of PV and battery price (PV price: 500, 1000, 2000 USD/kW; battery price: 200, 400, 1000 USD/kWh) are selected and depicted in Figure 11.

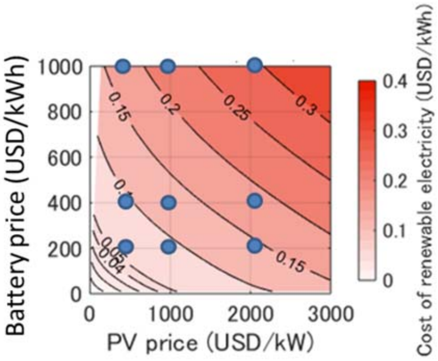

Figure 11 Maps showing combinations of PV and battery price
(the ●represent the combinations of PV and battery price selected).

The results are illustrated in Figure 12. The cost of renewable electricity for different datasets varies under conditions with the same PV price, battery price, and share of PV power generation. The range of variety increases with a higher PV or battery price, or a higher share of PV power generation. The difference between the maximum and minimum is approximately 10 cent/kWh for a PV price of 2000 USD/kW and battery price 1000 USD/kWh.

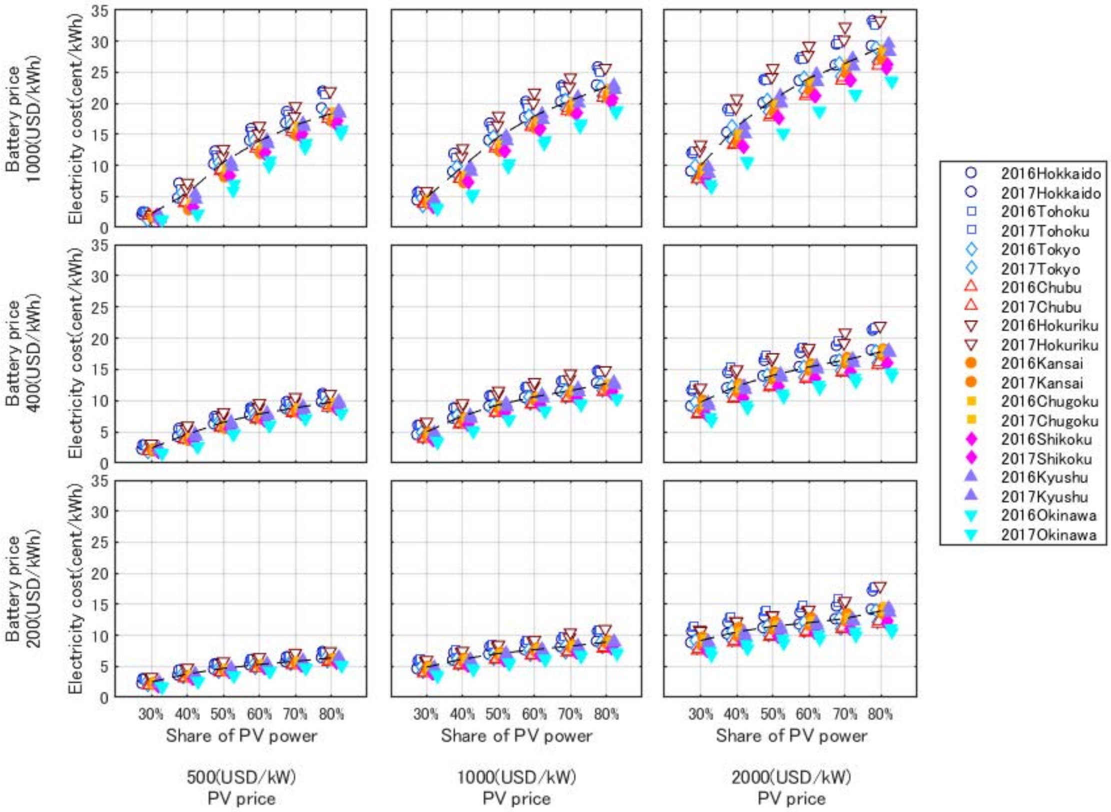

Figure 12 Maps representing the relationships between the PV price, battery price, and cost of renewable electricity with different shares of PV power (dotted lines represent the results based on the Tokyo 2016 data).

5 Discussion

This study developed a framework for analyzing the relationships between the prices and optimal installed capacities of PV systems and batteries. Renewable electricity costs were also determined for given shares of

PV power. The obtained maps could be beneficial for evaluating the effects of technological development (e.g., price decreases of PV systems or batteries) on the total costs of electricity.

The methodology presented here provides cost targets for PV and battery technologies to achieve certain costs and shares of renewable electricity.

This methodology has some limitations concerning the accuracy of output values, owing to its simplified approach, with the battery efficiency taken to be 1, no constraints on the charge/discharge rate, no consideration of a discount rate, and so on. However, these simplifications are easy to amend, depending on the required level of accuracy.

The simplicity of the methodology has some benefits. It can be applied to wide variety of systems, such as households, buildings, regions, and countries if the profiles of demand and PV power generation can be obtained. Further, any time resolution is possible. These features mean that this methodology can be useful for making the exploration space narrower when conducting a global sensitivity analysis of an original model.

The maps are entirely based on the input data (i.e., demand D_t and PV power generation P_t). This study also evaluated how the results varied with variations in the input data (i.e., the demand and PV power generation profiles). These results are similar with those of Pfenninger6). This suggests that the profiles of demand and PV power generation determine the battery size required to achieve a certain level of renewable energy utilization. Investigating this mechanism will be a future challenge.

Acknowledgement

The author would like to thank the members of the energy systems design program in Toyota Central R&D labs, for their useful comments and suggestions.

References

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2) Luthander, P, et al.; Photovoltaic self-consumption in buildings: A review, Applied Energy, 142, 2015, pp. 80–94.

3) Aratame, K; Stable supplying costs of photovoltaic and wind generation electricity, IEEJ Transactions on Power and Energy, 138 (6), 2017, pp. 451–459 (in Japanese).

4) OCCTO; https://www.occto.or.jp/keitoujouhou/ (accessed on October 1, 2018)

5) Area map for the electric companies in Japan; https://ja.wikipedia.org/wiki/%E3%83%95%E3%82%A1%E3%82%A4%E3%83%AB:%E9%9B%BB%E5%8A%9B%E4%BC%9A%E7%A4%BE%E4%BA%8B%E6%A5%AD%E5%9C%B0%E5%9F%9F%E5%9B%B3.png (accessed on March 25, 2019, with the permission of the GNU Free Documentation License)

6) Pfenninger, S; Dealing with multiple decades of hourly wind and PV time series in energy models: A comparison of methods to reduce time resolution and the planning implications of inter-annual variability, Applied Energy, 197, 2017, pp. 1–13.

Appendix

The calculation procedure for c_i is as follows.

First, let us consider the consecutive periods wherein $r_t < 0$ and the following consecutive periods wherein $r_t > 0$. This pair of consecutive periods is indexed by i (henceforth referred to as a *term*)[1].

i. The total surplus generation u_i is calculated as follows:

$$u_i = \sum_{t=t_s^-}^{t_e^-} |r_t^-| \tag{6}$$

where t_s^- and t_e^- are the times at the start and end of the period of the i-th term where $r_t < 0$, respectively.

ii. Let s_{i-1} be the amount of electricity in the battery at the end of i-th term. The amount of electricity which is charged into the battery is determined depending on the following conditions:

If $x_{bt} - s_{i-1} \leq u_i$,

then the battery is charged fully, i.e., $(s_i \leftarrow x_{bt})$, and the remainder $(u_i - x_{bt} + s_{i-1})$ is not utilized,

Else, if $(x_{bt} - s_{i-1} > u_i)$,

then all the total surplus generation is charged in the battery i.e.,$(s_i \leftarrow u_i + s_{i-1})$.

iii. The total net residual demand v_i is calculated as follows:

$$v_i = \sum_{t=t_s^+}^{t_e^+} r_t^+ \tag{7}$$

where t_s^+ and t_e^+ are the time at the start and end of the period of the i-th term where $r_t > 0$, respectively.

iv. The amount of electricity which is discharged from the battery to reduce the net residual demand is determined depending on the following conditions:

If $v_i \leq s_i$,

then the additional demand reduction equals the total net residual demand, i.e., $(c_i \leftarrow v_i)$, and the amount of electricity in the battery is updated, i.e., $(s_i \leftarrow s_i - v_i)$,

Else, if $(v_i > s_i)$,

then all the electricity in the battery is discharged, i.e., $(c_i \leftarrow s_i)$, and the amount of electricity in the battery is updated, i.e., $(s_i \leftarrow 0)$.

v. Move to the next term, i.e., $(i \leftarrow i + 1)$ and go back to the step i. while $t \leq 8760$.

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[1] Numerical example: if $r_t = [-2, -5, -6, 3, 4, 2, 8, -1, \dots]$ then $r_t^+ = [0, 0, 0, 3, 4, 2, 8, 0, \dots]$ and $r_t^- = [-2, -5, -6, 0, 0, 0, 0, -1, \dots]$. The periods $t = 1{\sim}3$ and $4{\sim}8$ correspond to the term $i = 1$. Therefore $u_1 = 2 + 5 + 6 = 13$ and $v_1 = 3 + 4 + 2 + 8 = 17$.