Estimation of satellite-derived regional photovoltaic power generation using a satellite-estimated solar radiation data

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Abstract
A large number of photovoltaic (PV) power systems have been adopted in Japan after a feed-in tariff was introduced in 2012. However, PV power generation data from residential rooftop and/or ground-mounted PV systems, and larger MW-size PV plants have not been measured accurately in real-time. This is because PV power monitoring instruments (e.g., smart meters) have not collected a sufficient amount of power generation data. In order to realize adequate safety control of electric power systems under high PV-penetration conditions, it is important to fully understand the temporal and spatial variations associated with PV power generation. In this study, we estimated the PV power generation for a regional area (i.e., prefecture or municipality) in terms of PV power installation capacity and satellite-estimated solar irradiance using a Japanese geostationary satellite, Himawari-8. The satellite-derived regionally integrated PV power estimations were validated with reference data provided by electric power companies. The validation results showed that these estimations were comparable to the reference data, provided by the Kyushu Electric Power Company Inc. (Kyushu) and the Tokyo Electric Power Company Inc. (TEPCO). However, the results also identified slight overestimations of PV power in the spring and summer seasons. An advantage of the proposed method is that it does not require land-based monitoring instruments, which can lead to increased operational cost savings for PV power systems. Furthermore, in consideration of future PV power penetration scenarios, it is suggested that PV power in excess of regional power demands could be generated under the same weather conditions.

Keywords
geostationary satellite, satellite-derived PV power generation
1 | INTRODUCTION

Electric power in Japan is primarily supplied by thermal power plants (LNG: 44.0%, coal: 31.6%, and oil: 7.7%). Virtually, Almost all nuclear power plants (1.1% of the total energy supply) were halted after the Fukushima nuclear power plant accident in March 2011, which was caused by the Great East Japan Earthquake and the associated Tsunami. Hydropower contributes approximately 9.6% of the electric power in Japan, and other types of renewable energy contribute approximately 4.7%.

Recently, large photovoltaic (PV) power systems become more attractive after a feed-in tariff was introduced in 2012.1 PV power generation has a large variability on both temporal and spatial scales because it is dependent upon solar irradiance, or global horizontal irradiance (GHI), which is associated with cloud and aerosol variabilities under various weather conditions.

PV power that is generated by residential and factory rooftop systems, and small-, medium-, and large-scale solar plants has not been directly measured in real time, even by the electric power companies in Japan, because PV power generation data cannot be accurately collected by its monitoring instruments (ie, smart meters). This is true even in substations and residences distributed over a regional area. This is a serious safety issue for the control of electric power grids because it is not possible to accurately measure PV power generation under different weather conditions.2 Therefore, information on regionally integrated PV power generation for a regional area in real time and/or on a quasi-real time scale has been required for distribution system operators (DSO) and transmission system operators (TSO) in power grids.

If the PV system capacity for each regional area is considered, we will be able to perform a regionally integrated estimation of the PV power generation for power grids.3,4 A new application of “Sikkari SUN” (http://ssspv.net) was developed for residential rooftop PV monitoring. This is a PV power monitoring application based on a combination of satellite-derived solar irradiance measurements with PV system installation information for each house and building.

In April 2015, the Organization for Cross-Regional Coordination of Transmission Operators in Japan (OCCTO)5 established to secure a stable electrical supply for power systems (including distributed renewable energy) within the ten electric power grid regions in Japan.

Ruf et al6 performed an experiment to quantify residential PV power generation using satellite-derived solar irradiance measurements. They validated the feed-in power of residential PV systems using smart meters (12 residential PV systems).

In Japan, high-accuracy GHI monitoring has been conducted in the operational observatory of the Japan Meteorological Agency (JMA). However, there are only a few surface GHI monitoring stations (less than 50) in Japan, and there are many more areas that contain PV power systems. In an energy management system, PV power generation for regional areas (eg, power service area, municipality-wide area) is required for the above-mentioned reasons. The satellite-based solar power estimation technology for regionally integrated electric power and municipality-wide areas would be a useful tool for optimizing several aspects of the electric power systems (eg, power transmission, power storage) with distributed PV power generation.

GHI estimation technologies using monitoring datasets obtained from geostationary satellites (Himawari, Meteosat etc.)7,8 have been improved. In our proposed method, a geostationary satellite would perform a quasi-real-time estimation of PV power generation at a uniform horizontal resolution, even for regions with no surface GHI instruments or smart meters. This would allow for increased cost savings because the amount of surface monitoring equipment would be reduced. Furthermore, a solar radiation consortium has provided a GHI estimation for Asian and Oceanian areas9 on a quasi-real-time scale. However, installed PV capacity for a municipality-wide area is critically important for accurate PV power estimation, and for the short-range and day-ahead forecasts for regional areas.10,11 PV regional estimation based on satellite-estimated GHI and PV regional capacity has not yet been conducted.

In this study, an estimation of PV power generation using satellite-estimated GHI data, while considering PV system capacity on a municipality-wide scale, is conducted in Japan for the first time. Furthermore, excessive PV power generation with high PV penetration in future scenarios is discussed.

A GHI dataset estimated from the Himawari-8 geostationary satellite, the amount of PV power installation for a regional area, and the method of PV power estimation are explained in Section 2. The results and discussion of our study are described in Section 3. Finally, summary conclusions and suggestions for future research in this field of study are briefly described in Section 4.

2 | DATA

2.1 | Satellite-estimated solar irradiance (AMATERASS) data set

The detailed specifications of the Himawari-8 satellite are summarized in the research by Bessho et al.12 Himawari-8 was launched on 7 July 201513 and has been monitoring atmospheric conditions, and its data have been compiled and archived. A satellite-estimated GHI monitoring dataset (called “AMATERASS”) has been obtained from the solar radiation consortium9 and JST/CREST TEEDDA.14 For regional PV power estimation, the AMATERASS dataset was used.
Satellite-based GHI estimation was performed at the surface on the basis of a technique that employs a radiative transfer model and a neural network. In order to estimate surface GHI, a radiative transfer model was used with satellite-observed spectral radiance data for each wavelength as an input with one-dimensional (vertical) calculation. Because a prior version of the geostationary satellite, Himawari-7, was previously used to collect this type of data, its algorithm has been improved for data obtained from Himawari-8.

In the algorithm, cloud properties (e.g., optical thickness, particle size, and cloud-top temperature) that influence the GHI are considered. Damiani et al. validated the satellite-estimated GHI data with ground-based data under clear-sky conditions and they reported a total mean bias error (MBE) within the range of 10-15 W/m².

For Japan, the horizontal grid spacing is 1 km and the satellite-estimated GHI dataset is provided every 2.5 minute. Himawari-8 covers a wide region that extends from the Asian continent to Oceania around the western Pacific Ocean. For the region excluding the Japanese region, the GHI dataset has been provided at intervals of 10 or 30 minute. This dataset is freely available for research purpose.

### 2.2 PV system installation

Information on the installed renewable energy capacity (e.g., PV power systems, wind power, and hydropower) for each prefecture and for municipality-wide scale areas is available on the METI website. Ten electric power grid regions exist in Japan, and the location of each region is presented in Figure 1.

Since April 2014, PV system installation information has been updated every month. Figure 2A,B show a time series of PV power installed capacity for all of Japan and individual prefectures from 2014 to 2017. The prefecture of Ibaraki currently has the largest number of PV systems. The installed PV power capacity for a regional area shows large variations and diversity for individual prefectures.

Figure 2C,D present maps of PV power installation for current (March 2017) and future (certified capacity by the METI) scenarios respectively. Currently, PV power installations are concentrated in the region that extends from western to central Japan. However, PV power installations will increase across all the Japanese islands in the future.

If the entire PV installation capacity certified by the METI (84.51 GW) will be installed in future, the current capacity of 37.98 GW will increase 2.2 times across all of Japan. Table 1 shows PV power installations for the ten electric power grid regions for current and future scenarios.

### 2.3 Regionally integrated electric power demand and PV power generation data

In each power grid region, the electric power companies have recently been provided with regionally integrated electric power demands and renewable energy data, including the PV power generation, which can be found on their websites. The time interval for each dataset is hourly. However, electric power companies in Japan do not collect regionally
integrated PV power generation data in real time because they cannot accurately gather it from the current monitoring systems. Regionally integrated PV power generation datasets have been estimated from surface monitoring instruments (pyranometers installed in the power service area, PV power generation measurement equipment associated with MW-size PV power plants). MW-size PV power generation data can be monitored directly by the electric power companies. Regionally integrated PV power generation data is scaled from the surface monitoring data considering the PV installed capacity in a region.

Therefore, to validate our PV power estimations using Himawari-8, the regionally integrated PV power generation data provided from the two electric power companies were used as reference data. The PV power generation reference data (called PV\textsuperscript{ref}) and the power demand data obtained from Electric Power Company Inc. (Kyushu, Japan) and Tokyo Electric Power Company Inc (Tokyo, Japan). (TEPCO) do not include the consumption of each electric power company because it is accounted for as a surplus electricity purchase.\textsuperscript{18,19}

In this study, the Kyushu and TEPCO service areas were the target regions used for validation. The population served by the Kyushu and TEPCO companies is approximately 13 million and over 30 million respectively. For the Kyushu area, large PV power systems have been installed for a moderately sized population (electric demand), whereas TEPCO covers the largest electric power demand area in Japan.

2.4 | A method of PV power estimation

To estimate the PV power generation for regional areas, it is necessary to use various elements of PV systems (eg, PV cell efficiency, PV capacity, and angle of PV modules).\textsuperscript{20} In JIS C 8907,\textsuperscript{20} it is noted that PV power generation could be estimated from several data, including the integration of the GHI, PV system capacity, power losses in the system, a temperature factor, and the GHI at the standard test condition. A simple method of PV power estimation using the GHI and temperature has been reported in previous studies\textsuperscript{3,20}, as expressed in

\[
PV_{\text{est}} = GHI \times PV_{\text{inst}} \times PCS_{\text{loss}} \times \text{System loss} \times \frac{1}{G_s} \times \text{Temp_{loss}} \tag{1}
\]

\[
\text{Temp}_{\text{loss}} = 1.0 + \frac{\alpha_{\text{max}} (T_{\text{air}} + \Delta T - 25.0)}{100} \tag{2}
\]
where PV\textsubscript{est} and PV\textsubscript{inst} are the PV power generation estimation and PV installation capacity for a regional area (electric power grid, each prefecture and each municipality) respectively. Here, power losses associated with the power conditioning system (PCS\textsubscript{loss}) and PV system (System\textsubscript{loss}) including specifications of the PV systems, module azimuth, and tilt and rated power, were set at 0.95 and 0.95, respectively, on the basis of information obtained from previous studies\textsuperscript{3,20} and parameter tuning in this study. \(G\) is the GHI at standard test conditions, which is given as 1.0 kW/m\(^2\). Temp\textsubscript{loss} is a reduction parameter associated with the PV module temperature (change in efficiency with module temperature).\textsuperscript{21,22} \(\alpha_{p}\) is the temperature dependency of PV power generation and is set at −0.485%. \(T\textsubscript{air}\) and ∆\(T\) (=20°C)\textsuperscript{20} are the atmospheric temperature and the difference in PV module temperature respectively. For the PV module temperature offset (∆\(T\)) reported in JIS C 8907,\textsuperscript{20} a temperature offset of 18.4°C for a PV array field and 21.5-25.4°C for residential rooftop PV systems is used. In this study, regional power generation was calculated by assuming a constant temperature offset because various types of PV power systems are actually installed in both study areas. In order to estimate the PV module temperature, the initial and short-range forecast temperature data (\(T\textsubscript{air,i}\)) were used for each model grid from a numerical prediction model (mesoscale model, MSM) from the JMA with a horizontal resolution of 5 km.\textsuperscript{23} Initialization temperature data and short-range forecasts up to 2 hours ahead were used from 3 hours forecast cycles in the MSM because hourly spatially uniform observation data has not been collected and was thus unavailable.

Typical elements of PV power systems are assumed in this estimation because various PV power systems are actually installed for a city area. In order to obtain a more detailed estimation of the PV power generation for a regional area, the specifications of every type of PV module used in each system would be needed, and such detailed information was not available or easily obtainable. Therefore, to calculate an estimated value for regional PV power, a satellite-estimated GHI was integrated for each of the two study areas.

Similar issues are associated with the many slant angles of PV systems on rooftops and other power plants. There is no statistical information on slant angles of PV systems in Japan. In this study, we used a flat angle (or GHI) in our estimation as the simplest method. Satellite-estimated GHI grid data closest to the location of each municipality office were used as representative points for each municipality. Therefore, the spatial variation of the GHI within each municipality was not considered in our calculations. The objective using the satellite-derived estimates of PV power generation was to develop a robust method for a particular electric power company service area without using surface monitoring data (eg, pyranometers, PV power generation information from PV plants and/or residential PV systems, and electrical flow data).

2.5 | Metrics

In order to evaluate regional satellite-derived integrated PV power generation data, three metrics were used, that is, the MBE, the mean absolute error (MAE), and the root mean square error (RMSE), expressed as follows:

\[
MBE = \frac{1}{n} \sum \epsilon \tag{3}
\]

\[
MAE = \frac{1}{n} \sum |\epsilon| \tag{4}
\]

\[
RMSE = \sqrt{\frac{\sum \epsilon^2}{n}} \tag{5}
\]

where \(\epsilon\) is the difference in PV power generation between the PV satellite estimations of power generation (PV\textsubscript{est}) and reference data (PV\textsubscript{ref}) provided by an electrical company (\(\epsilon = PV\textsubscript{est} - PV\textsubscript{ref}\)). PV\textsubscript{est} is the satellite-derived PV power generation explained in Section 2.4, and PV\textsubscript{ref} is the PV power generation reference data obtained from the electric power companies, as presented in Section 2.3.

3 | RESULTS AND DISCUSSION

3.1 | Validation of satellite-derived regionally integrated PV power generation

Kyushu and TEPCO provided their regionally integrated PV power generation data for an 18-month period after April 2016 on their website (see Section 2.3). First, the validation of our satellite-derived regional PV power generation estimates using Kyushu and TEPCO reference data was performed. For the Kyushu and TEPCO areas, 7.03 GW and 9.82 GW PV power systems have been installed as of March 2017. Furthermore, a large amount of PV power generation capacity (over 17 GW for Kyushu and over 21 GW for TEPCO) may be installed in the future (Table 1).

In order to investigate the seasonal variation in PV power estimation error, a comparison of regionally integrated PV power generation was used, as shown in Figure 3A. One-hour time interval data were used for the Kyushu-estimated reference data provided by Kyushu (PV\textsubscript{ref}) and the satellite-derived regionally integrated PV power generation (PV\textsubscript{sat}) for the Kyushu area (Figure 1). The 2016 fiscal year (April 2016 to March 2017) was used as the validation period, with each color indicating the plots for each month. The scatter plots of the 1h interval data for PV power generation, namely, the satellite-derived data and the Kyushu reference data, were found to be close to the one to one line (correlation
coefficients (R) for each month are within the range 0.97-0.98), and our satellite-derived estimates that were calculated without surface monitoring data (eg, pyranometers, PV power generation from residential PV and/or MW-size PV plants) corresponded to the Kyushu reference data collected from surface instruments.

For the larger of the two PV electric power demand areas (TEPCO) (Figure 3B), the PV system capacity is approximately 2.8 GW larger than that of Kyushu. Therefore, a larger amount of regionally integrated PV power was derived from the TEPCO area. In this larger area, our satellite-derived regionally integrated PV power generation estimates were also close to the reference data provided by TEPCO. Based on the correlation coefficients (from 0.95 to 0.97 for TEPCO), the variation between our estimates and TEPCO reference data tended to be larger than those associated with the Kyushu area.

Figure 3 also shows an overestimation of satellite-derived regionally integrated values compared with the Kyushu- and TEPCO-estimated PV power generation data for the spring and summer seasons. One reason for this is the overestimation of the GHI from Himawari-8 data under cloudy conditions. Damiani et al indicated point-by-point validation results of satellite-derived solar irradiance in 2016 based on ground observations at the Chiba station (in the TEPCO area) (Figure 2 in the paper by Damiani et al), and noted that the correlation coefficient was approximately 0.95, the MBE was approximately 20-30 W/m², and the RMSE ranged from approximately 80-100 W/m². They also suggested that this overall influence on the RMSE was associated with cloudy conditions. The solar radiation consortium will improve the treatment of aerosol distribution for satellite-estimated GHI products (personal communication with members of the solar radiation consortium³).

In order to quantitatively estimate seasonal variations in satellite-derived regionally integrated PV power generation data, several evaluation metrics (see Section 2.5) for each month of the 2016 fiscal year are shown in Table 2. Relatively smaller MBE values (89.2 MWh and 90.7 MWh), MAE values (257.5 MWh and 251.3 MWh), and RMSE values (314.7 MWh and 312.8 MWh) were found for November and December 2016. The largest errors were found in May 2016, and the MBE, MAE, and RMSE values for May 2016 were 571.0 MWh, 572.2 MWh, and 664.4 MWh respectively. The “MAX” and “MIN” values in Table 2 indicate the largest positive and negative estimation errors for each month respectively. The largest positive estimation error (1689.8 MWh) was found in March 2017 and the largest negative estimation error was found in January 2017 (−1426.7 MWh). During the late spring and early summer (from May to July 2016), a temporary decrease in MBE, MAE, RMSE, and MAX values was found in June because of the regional decrease in PV power generation, associated with the annual rainy season. The rainy season for the target area ranged from 4 June to 18 July 2016 for the northern part of Kyushu, and from 24 May to 18 July 2016 for the southern part of Kyushu.

For TEPCO (Table 3), a relatively large positive errors (809.0 MWh) and RMSE values (1028.6 MWh) compared to Kyushu were found in March 2017. In the TEPCO area, snowfalls are often caused in a winter season when a surface low pressure that located off the southern coast of the TEPCO area moves to easterly. Under a snow event, PV power do not generate because of the interception of solar irradiance by the snow cover on PV modules. The method of satellite-derived

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**FIGURE 3** Comparison of regionally integrated photovoltaic (PV) power generation with 1 h time interval data between the reference data provided by (A) Kyushu and (B) TEPCO and satellite-estimated PV power generation for each electric power area (unit: MWh) during the 2016 Japanese fiscal year (April 2016 to March 2017). Correlation coefficients for each month are shown on the right-hand side of this figure. Fitting lines for each month are indicated by color.
PV power generation in the current version can cause overestimation because of not taking account of the snow. The largest estimation errors of “MAX” and “MIN” in the 2016 fiscal year reached over 3051.6 MWh in March 2017 and −3401.0 MWh in May 2016. Generally, PV estimation errors were relatively smaller in the winter season because of the low solar irradiance.

A sensitivity analysis was performed in a case of 5% power loss. Here, we show the impact of other parameters on the estimation results (Figure 4). From the analytical results of 5% power loss, scatter plots tended to be close to the one-to-one line. In this estimation, we give a simplified parameter assumption in Equation (1). In order to improve the regionally integrated PV power generation estimates, other parameters must be considered based on the statistical information of actual PV system instruments in the future.

Normalized PV power generation data were obtained using regionally installed PV capacity (Figure 5). For Kyushu and TEPCO, 7.03 GW and 9.82 GW of PV power have been installed (Table 1), and there was a small differences in the scatter plots between Kyushu and TEPCO due to the difference in the correlation coefficients, which ranged from 0.01 to 0.02 for each month.

### 3.2 Time variations of the PV power generation

The time variation of regionally integrated PV power generation was investigated. Figure 6A shows the time series of regional PV power generation from satellite-estimated GHI data (GWh; gray circles at the 2.5 minute time intervals, “Est ALL” shown in the legend) in a clear sky case on 15 April 2016. The regular climatic conditions in April for the study area were moderate (not too hot seasons) and the electric power demand tended to be small over the course of the year. The black circles at 1 hour time intervals (“Kyuden Data” noted in the legend) indicate PV power reference data provided by Kyushu. The red stars indicate electric power

| Year | Month | MBE   | MAE   | RMSE  | MAX   | MIN   |
|------|-------|-------|-------|-------|-------|-------|
| 2016 | 4     | 536.8 | 540.6 | 635.1 | 1496.2| −82.4 |
| 2016 | 5     | 571.0 | 572.2 | 664.4 | 1416.2| −155.2|
| 2016 | 6     | 456.1 | 457.3 | 531.2 | 1198.7| −142.2|
| 2016 | 7     | 530.0 | 530.0 | 615.0 | 1375.3| 4.9   |
| 2016 | 8     | 493.7 | 499.0 | 583.6 | 1222.3| −97.7 |
| 2016 | 9     | 369.2 | 379.7 | 460.5 | 1117.2| −126.1|
| 2016 | 10    | 184.7 | 263.3 | 320.0 | 970.4 | −479.9|
| 2016 | 11    | 89.2  | 257.5 | 314.7 | 767.0 | −671.7|
| 2016 | 12    | 90.7  | 251.3 | 312.8 | 1038.2| −596.8|
| 2017 | 1     | 221.6 | 300.1 | 374.9 | 1076.6| −1426.7|
| 2017 | 2     | 270.3 | 343.8 | 430.3 | 1589.4| −398.8|
| 2017 | 3     | 491.0 | 497.1 | 604.0 | 1689.8| −144.2|

| Year | Month | MBE   | MAE   | RMSE  | MAX   | MIN   |
|------|-------|-------|-------|-------|-------|-------|
| 2016 | 4     | 508.3 | 572.8 | 717.6 | 2004.3| −911.6|
| 2016 | 5     | 598.0 | 676.5 | 831.8 | 2090.1| −3401.0|
| 2016 | 6     | 597.3 | 640.8 | 763.2 | 1894.4| −749.6|
| 2016 | 7     | 725.2 | 738.6 | 880.3 | 2076.9| −590.5|
| 2016 | 8     | 707.2 | 728.7 | 850.5 | 1988.3| −556.9|
| 2016 | 9     | 472.1 | 535.0 | 642.5 | 1500.3| −709.3|
| 2016 | 10    | 387.4 | 456.1 | 572.0 | 1505.0| −469.1|
| 2016 | 11    | 117.0 | 453.3 | 540.3 | 1238.2| −1449.2|
| 2016 | 12    | 141.3 | 471.7 | 530.3 | 2317.2| −824.0|
| 2017 | 1     | 308.4 | 462.1 | 589.0 | 1371.2| −571.6|
| 2017 | 2     | 572.2 | 641.0 | 796.7 | 1766.6| −485.7|
| 2017 | 3     | 809.0 | 853.2 | 1028.6| 3051.6| −570.0|

### TABLE 2 Estimation metrics of photovoltaic power generation for Kyushu of MBE, MAE, RMSE, MAX, and MIN (unit: MWh) during the 2016 Japanese fiscal year (from April 2016 to March 2017). “MAX” and “MIN” indicate the largest positive and negative estimation errors for each month respectively. The maximum values and the minimum values are shown with bold and italic respectively.
demand (1 hour time intervals) for the Kyushu power area and other colors indicate PV power estimations for each prefecture (see the left panel in Figure 1). Figure 6B shows the cloud map from the Himawari-8 satellite image taken at 12:00 LST (LST = UTC + 9 hour) on the same day, and the yellow square indicates the location of the Kyushu area. These data were provided by the National Institute of Information and Communications Technology (NICT) Science Cloud. The regionally integrated PV power generation data from Himawari-8 was similar to the reference PV power generation from Kyushu. Satellite-derived regionally integrated PV power generation resulted in a relative overestimation. On 15 April 2016, PV power generation occupied approximately half of the electric power generation under clear sky conditions.

METI provided the PV power installation capacity for each municipality. Using this information combined with satellite-estimated GHI data, the PV power generation for each municipality was estimated without data from surface GHI instruments. Figure 7 shows a time series of PV power generation in the Kyushu area on the same day (a clear sky condition on 15 April 2016). The top panels show the estimates for four prefectures (the northern part of Kyushu), and the bottom panels show the estimates for three prefectures (the southern part of Kyushu). Each plot is shown at 2.5 minute time intervals for each municipality. For several cities with large PV system installations, large PV power generation values were found under the same GHI clear sky conditions. In particular, Oita city (Figure 7D), Kita-kyushu city (Figure 7C), Kagoshima city (Figure 7F), Miyazaki city (Figure 7G), and Kumamoto city (Figure 7E) included PV power installations of 250, 225, 168, 167, and 147 MW respectively (the location of each prefecture is shown in Figure 1). The second-largest MW-size PV plant (approximately 82 MW, as of November 2017) in Japan, supported by the Kyocera Corporation (https://global.kyocera.com/news/2013/1101_nnms.html), is installed in Kagoshima city. This means that large MW-size PV power plants in Japan could have a strong impact on PV power generation for local and regional areas under various weather conditions (not shown). In addition, the regional characteristics of PV power generation were found on the basis of the different PV system installations in each municipality.

3.3 | Spatial variations of the PV power generation

The spatial variations (regional characteristics) in satellite-derived PV power generation were also investigated. Figure 8A shows the map of the satellite-derived data for each municipality in Kyushu early in the morning at 08:00 LST on 15 April 2016. Figure 8B shows a GHI map from Himawari-8 at the same time. On this early morning (weak GHI conditions), similar GHI values under clear-sky conditions excluding the Kagoshima prefecture (cloudy conditions were observed in the southern part of Kyushu), were observed for all of Kyushu. However, regional differences in PV power generation for each municipality were found in because of the different PV system installations, as shown in Figure 8A.

However, at 12:00 LST (Figure 8C,D), large PV power generation in both the northern and the southern parts of Kyushu was produced. In particular, many PV power generation areas were produced from several municipalities under the same clear-sky conditions (Figure 7). Based on these results, it can be concluded that regional variations in satellite-derived PV power generation were due to the different PV power system installations available in each municipality. This was particularly true under clear-sky conditions.

3.4 | Future scenarios of PV power installations

Here, we considered a future scenario involving PV power installations in the Kyushu electric power area (approximately 17 GW; Table 1). Table 4 shows a comparison of PV system installations in current (left of Table 4, as of March 2017) and future (right of Table 4) scenarios for each prefecture in the Kyushu electric power area. In future scenarios, increased PV power installations of over 9.8 GW capacity (from 3.2 GW at the current situation) will be expected to expand into the southern part of Kyushu (Kagoshima, Miyazaki, and Kumamoto).

Figure 9 shows a time series of satellite-derived PV power generation estimates for future scenarios under the same clear-sky condition observed on 15 April 2016 (Figure 6A). The PV power generation for all of Kyushu will exceed the regionally integrated electric power demand. Under the same clear-sky conditions, the PV power generation will surpass the current electric demand for Kyushu in cases of larger PV penetration. Although base-load power generation in the future is not shown in this figure, further surplus PV power generation may result.

These results suggest that countermeasures for PV power curtailment and/or the storage of PV power in batteries would be required in future scenarios. For all of Kyushu, large PV power generation could result in the future under the proposed large PV installation scenarios (Figure 10). Compared to the regional variations in PV power generation in the current situation (Figure 8C), the regional characteristics of PV power generation in the future could be complex.
Therefore, information on distributed PV power generation will be an important issue affecting the stable control of electric power systems and the capacity of transmission power lines.

4 SUMMARY

In this study, estimates of regional PV power generation for the Japanese islands were calculated using data from the Himawari-8 geostationary satellite. Satellite-derived regionally integrated PV power generation data were validated and compared to a reference dataset obtained from Kyushu and TEPCO. In this study, the installed PV power capacity on a municipality-wide scale was considered to monitor regional PV power generation in quasi-real-time. METI provided a PV power capacity penetration dataset for prefectures and municipalities. Temporal and spatial variabilities in PV power generation in cases involving a large number of PV system installations were also evaluated for future scenarios. The satellite-derived PV power generation was found to be close to that of the regionally integrated PV reference data obtained from Kyushu and TEPCO. The estimation errors included seasonal variations, such as overestimation during the spring and summer seasons. Several real-world parameters (e.g., module azimuth angle, tilt angle, PV system capacity, types of PV systems, and system efficiency) for each PV system should be considered in future studies in order to more accurately estimate PV power generation. The change in efficiency with module temperature should also be considered. However, the PV system information for each system is not sufficiently summarized because the information has not been effectively recorded or compiled. Therefore, the proposed estimation of satellite-derived PV power generation is...
equivalent to a prototype estimation. The issue of accuracy in these estimation methods will remain an important topic in future studies.

Current satellite-estimated GHI data (AMATERASS data) shows the overestimation of the GHI compared to surface observations. GHI values are calculated using algorithms that were developed in a previous study, not including actual information on aerosol optical depth (AOD). Therefore, an overestimation of PV power generation could result in cases where a thick aerosol event takes place under...
clear-sky conditions. A satellite-estimated GHI algorithm that considers AOD atmospheric distribution should lead to improved satellite-derived PV power generation.

From the analysis on regionally integrated PV power generation under future large PV-penetration scenarios, excessive PV power generation was estimated in excess of the
electric power demand for Kyushu. This suggests that the PV curtailment control for a regional area under particularly clear sky conditions, and/or the installation of large battery systems to store excessive PV power be required to stabilize electric power control.

This study is the first approach for PV power estimation that considers PV power capacity penetration for regional areas (municipality-wide and power service area areas) and uses a Japanese geostationary satellite. This fundamental method can be useful for regional PV estimation for other countries and can be applied to other satellites (eg, GOES series satellites in the USA, Meteosat series satellite in Europe).26,27

A short-range forecast of the satellite-derived regionally integrated PV power generation (up to 4 or 5 hour ahead) will be required for safe energy management of the overall electric power system, including future scenarios that involve large amounts of PV power penetration. This, too, should be the subject of future research.

Proposed estimation will be useful for power TSO and DSO (electric power companies have a role of TSO and DSO in Japan). The proposed PV power generation estimation method should be useful in the analysis of PV power generation during rapid variations of PV power generation (ie, ramp events) in order to estimate their impact on the power grid,28-30 because it provides data with a high temporal and spatial resolution.

Furthermore, the method described in this study may have higher potential for various energy management scenarios in the field of safe energy control (eg, electric power management, energy storage management, electrical transmission, and measures for PV curtailment.31-34

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NOMENCLATURE:

AOD aerosol optical depth
CREST Core Research for Evolutional Science and Technology
EMS energy management system
DSO distribution system operators
GHI global horizontal irradiance
JST Japan Science and Technology agency
Kyushu the Kyushu Electric Power Company Inc.
MAE mean absolute error
MBE mean bias error
METI Ministry of Economy, Trade and Industry
MSM Meso-Scale Model
JMA the Japan Meteorological Agency
OCCTO the Organization for Cross-regional Coordination of Transmission Operators in Japan

TABLE 4 Photovoltaic system installations of current (left) (as of March 2017) and future (right) scenarios for each prefecture in the Kyushu electric power area (unit: MW)

| Prefecture | Current (March 2017) | Future | MW |
|------------|---------------------|--------|----|
| No. 1 Fukuoka | 1756.8 | Kagoshima | 3800.6 |
| No. 2 Kagoshima | 1348.6 | Miyazaki | 3101.6 |
| No. 3 Kumamoto | 1049.2 | Kumamoto | 2939.5 |
| No. 4 Oita | 867.2 | Fukuoka | 2516.0 |
| No. 5 Miyazaki | 831.7 | Oita | 2445.0 |
| No. 6 Nagasaki | 707.5 | Nagasaki | 1600.8 |
| No. 7 Saga | 507.0 | Saga | 760.7 |

FIGURE 9 Same as Figure 6A, but for the future photovoltaic (PV) case (17 GW PV system installation in Kyushu)
Satellite–estimated PV power generation (Future)
Miniciparities B2 PV Integ (Ikou+NEW)
2016 04 15 120000

PV photovoltaic
RMSE root mean square error
TEPCO the Tokyo Electric Power Company Inc.
TSO transmission system operators

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