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Difference in the outdoor performance of bulk and thin-film silicon-based photovoltaic modules

Takashi Minemoto *, Shunichi Fukushige, Hideyuki Takakura

College of Science and Engineering, Ritsumeikan University1-1-1 Nojihigashi, Kusatsu, Shiga 525-8577, Japan

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ABSTRACT

Differences in the outdoor performances of bulk (multi- and single-crystalline Si) and thin-film (amorphous Si(a-Si), a-Si/micro-crystalline Si and a-Si/a-SiGe/a-SiGe) photovoltaic (PV) modules are analyzed. The influence of module temperature and solar spectrum distribution on the PV output is clarified. The PV outputs almost only depend on module temperature in bulk-type Si PV modules while that depend both module temperature and spectrum distribution in thin-film ones. Also, the PV outputs of the bulk-type Si PV modules at most frequent condition at outdoor are lower than that at the standard test condition; in contrast, it was the other way round for thin-film ones.

1. Introduction

Currently, photovoltaic (PV) modules are rated by power rating given by energy conversion efficiency under the standard test condition (STC), i.e., incident solar irradiance: 1 kW/m^2; solar spectrum distribution: AM1.5G; module temperature: 25 °C; and the total area of PV modules. The condition to measure the PV performance is important because environmental conditions greatly influence the output energy of PV modules. However, actual outdoor conditions vary from hour to hour. Considering that electricity consumer and suppliers buy and sell in units of energy, PV modules should be rated by energy rating given by an actual electrical energy generated by PV modules. However, energy rating is more complicated than power rating because energy rating needs actual operation data for PV modules and environmental data where the PV modules are installed. The understanding of the relationship between the outdoor performance of PV modules and environmental factors is important to develop energy rating. In this study, the output behaviors of bulk-type (single-crystalline Si (sc-Si) and multi-crystalline Si (mc-Si)) and thin-film-type (amorphous Si (a-Si), a-Si/micro-crystalline Si (μc-Si) tandem and a-Si/a-SiGe/a-SiGe three-stack) PV modules were characterized. We report on the influence of environmental factors, especially solar spectrum distribution and module temperature, on the outdoor performance of PV modules. Also, the outdoor environment where the PV modules are installed is presented to show the disparity between STC and outdoor conditions.

2. Experimental

The sc-Si, mc-Si, a-Si, a-Si/μc-Si and a-Si/a-SiGe/a-SiGe PV modules with capacities of 5, 5, 2, 1 and 1 kW, respectively, facing due south with a tilt angle of 15.3° are installed at Kusatsu city, Shiga prefecture in Japan (latitude 34°58′ north, longitude 135°57′ east). Solar spectra of the wavelength range of 350–1050 nm are recorded by a spectro-radiometer (MS700, EKO) that experiences the same exposure conditions as the PV modules. To analyze the effects of module temperature and spectrum on PV modules, contour graphs for performance ratio (PR) of PV modules as a function of average photon energy (APE) and module temperature (T_{mod}) were made. PR indicates PV module efficiency without the effect of irradiance intensity, which is defined as the actual output energy divided by the nominal output energy calculated from the PV module performance under STC. APE is an index that indicates a spectral irradiance distribution and is defined as the integrated irradiance divided by the integrated photon flux density, yielding the average energy per photon [1]:

$$\mathrm{APE} = \frac{\int_a^b E(\lambda)\,\mathrm{d}\lambda}{\int_a^b \Phi(\lambda)\,\mathrm{d}\lambda} \qquad (1)$$

where q is the electronic charge, E the spectral irradiance and Φ the spectral photon flux density. Because of the limitations of our measurement system, a and b are set to 350 and

* Corresponding author. Tel./fax: +81 77 561 3065.
E-mail address: minemoto@se.ritsumei.ac.jp (T. Minemoto).

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1050 nm, respectively. The APE value for the standard solar spectrum [2,3] calculated with a 350–1050 nm wavelength range is 1.88 eV.

To create the contour graphs, field test data measured every 1 min from May 1, 2004 through April 30, 2007 (3 years) were used. The total data point is greater than 80,000. The methodology is as follows:

(1) The data of T_{mod}, incident irradiance for 1 m^2, output energy of the module, which has a nominal output power of 1 kW, and the spectral irradiance distribution at the analysis period are prepared. Two-dimensional arrays for irradiance and for output energy are prepared. The arrays for the output energy and the irradiance have APE (1.85–2.05 eV, 0.01 eV step) and T_{mod} (0–100 °C, 5 °C step) for column and row, respectively.
(2) The following steps are repeated for the data measured every 1 min for analysis period, i.e., 3 years. Here, the data with irradiances higher than 0.40 kW/m^2 were used and the lower performance of modules at low irradiance were omitted.
   (a) APE of the spectrum is determined by the spectrum distribution.
   (b) The columns of both output energy and irradiance arrays for the spectrum are indexed by APE.
   (c) The rows of both output energy and irradiance arrays for the spectrum are indexed by T_{mod}. Then, the elements of the arrays for the spectrum are determined.
   (d) The output energy of the module and the irradiance of the spectrum are added to the elements of each array.
(3) PR for each element is determined as the output energy divided by the irradiance at the corresponding element.

3. Results and discussion

3.1. Outdoor condition

Fig. 1 shows (a) APE histogram of integrated irradiance and (b) contour graph of integrated irradiance as a function of APE and T_{mod} for sc-Si PV modules. Fig. 1(a) shows that a 92.6% of total incident solar irradiance has an APE of higher than 1.88 eV, indicating that the solar spectrum in Kusatsu city were significantly blue-rich compared to the standard spectrum of APE = 1.88 eV. The APE with the highest irradiance was 1.93 ± 0.005 eV, which is 0.05 eV higher than that of the standard spectrum. Fig. 1(b) shows that the most frequent condition (MFC) at outdoor was T_{mod} = 50 ± 2.5 °C and APE = 1.93 ± 0.005 eV for the sc-Si PV modules. The condition is significantly different from STC. The irradiance agreed with APE and T_{mod} of STC was only 0.872% (less than 1%) of the total irradiance, indicating that the outdoor conditions rarely meet STC. In contrast, the irradiance with APE and T_{mod} of MFC was 3.13%. Even at MFC, the fraction to total irradiance is approximately 3% so that standard outdoor condition, which represents outdoor condition at this site, should include a broad range of conditions. These results support the importance of energy rating and a necessity of a new standard test condition for outdoor power rating.

3.2. Influence of environmental factors on the PV modules

Fig. 2 shows the contour graphs of the PR for (a) sc-Si, (b) mc-Si, (c) a-Si, (d) a-Si/μc-Si and (e) a-Si/a-SiGe/a-SiGe PV modules as a function of APE and T_{mod}. In the figure, the conditions corresponding to STC, i.e., 25 °C and 1.88 eV, and MFC are indicated with circle and star symbols, respectively. As clearly

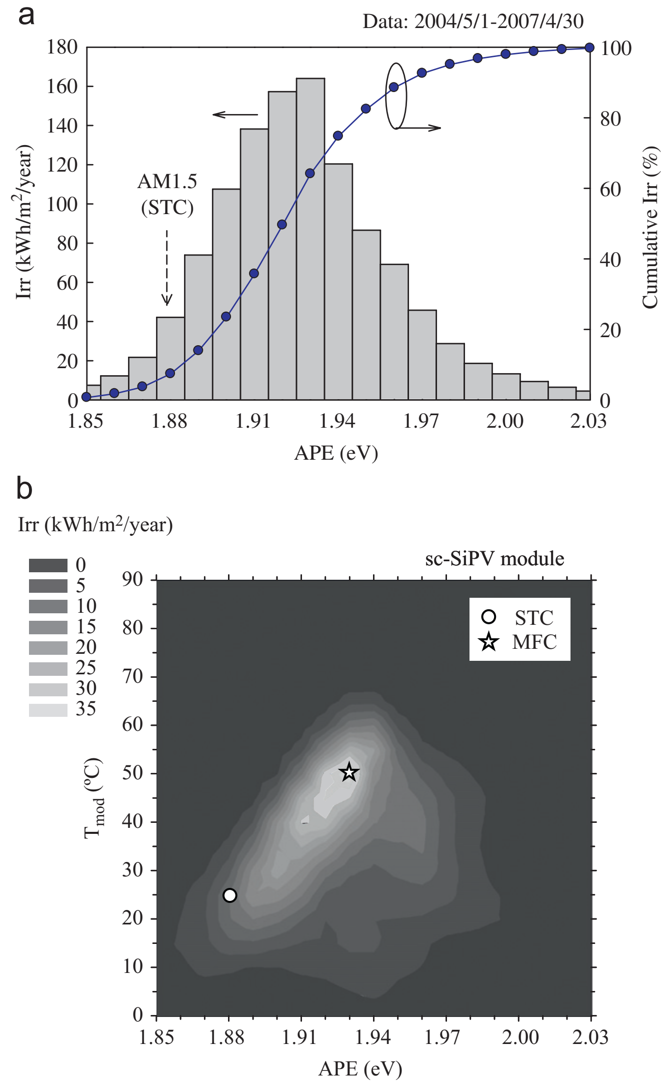

Fig. 1. (a) APE histogram of integrated irradiance (Irr) and (b) contour graph of Irr as a function of APE and T_{mod} for the sc-Si PV module for 3 years (May 2004–April 2007). In the figure, the conditions corresponding to STC (25 °C and 1.88 eV) and MFC (50 °C and 1.93 eV) are indicated with circle and star symbols, respectively.

understood from the comparison between Fig. 2(a) and (b), the contour graphs for the bulk Si PV modules, i.e., sc-Si and mc-Si PV modules, are very similar. In the sc-Si and mc-Si PV modules, the PR decreases with increasing T_{mod}, which can be seen by scanning the graph in the vertical direction (at fixed APE), while the PR does not change with the APE variations, which can be seen by scanning the graph in the horizontal direction (at fixed T_{mod}). In contrast, among the thin-film Si PV modules, the PR of the a-Si and a-Si/μc-Si PV modules depend on both T_{mod} and APE. The behavior of PR is similar in both PV modules; the PR is high at $T_{mod} > 30$ °C and APE > 1.92 eV. On the other hand, the PR of the a-Si/a-SiGe/a-SiGe PV module slightly depends on APE but not on T_{mod}.

Table 1 shows the comparison of the PR under the outdoor conditions corresponding to STC and MFC for each PV module. The PRs for bulk Si, i.e., sc-Si and mc-Si, PV modules at MFC are approximately 9% lower than that at STC; in contrast, the PRs for a-Si and a-Si/μc-Si PV modules at MFC are approximately 8% and 5% higher than that at STC, respectively. Only the a-Si/a-SiGe/a-SiGe PV module shows the almost same PR at STC and MFC (ΔPR < 1%). The result indicates that if the PV modules are