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# Uniqueness verification of solar spectrum obtained from three sites in Japan based on similar index of average photon energy

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ABSTRACT

The output energy yield from the photovoltaic (PV) module is influenced mainly by the spectral irradiance under outdoor conditions. To evaluate the effects upon PV modules, a quantitative index is essential for appropriate statistical analysis, because spectral irradiance distribution is a function of wavelength. Average photon energy (APE) is an index which represents a quantitative value of spectral irradiance distribution, and an APE value calculated from 350 to 1050 nm wavelength ($APE_{350\text{-}1050}$) uniquely describes the shape of the solar spectrum at Kusatsu-city. Meanwhile, our previous study showed that APE has effects on PV performance, especially on short circuit current ($I_{SC}$) of PV modules. Therefore, APE is a useful index of evaluation of PV performance under actual outdoor conditions. In Japan, the uniqueness of APE have been demonstrated at Ritsumeikan University in Kusatsu-city, Shiga prefecture as an index of spectral irradiance distribution and its effect on PV performance. However, the spectral characteristics in other regions of Japan with respect to Ritsumeikan University in Kusatsu-city are not yet clearly understood. This study aims to describe and discuss the uniqueness of solar spectrum obtained from three sites: Ritsumeikan University in Kusatsu-city, National Institute of Advanced Industrial Science and Technology in Tsukuba-city, and the University of Miyazaki in Miyazaki-city, Japan based on similar APE for standardization with respect to Kusatsu-city. In regard to this view, the coefficient of determination, denoted $R^2$, was used to quantify the degree of coincidence for the shape of the solar spectrum. The results obtained from the $R^2$ method were compared for evaluating consistency among three sites on the basis of Ritsumeikan University. It was found that the high $R^2$ values of 0.988–0.998 correspond to small APE errors of 0.006–0.028 eV. These errors are raised from the different sites due to the slight variations in the shapes of the solar spectrum. For further evaluation of the influence of $I_{SC}$ of different PV modules, spectral mismatch correction factor (MM) based on the irradiance obtained from a pyranometer as a function of APE is examined and compared with three sites using similar APE. Results showed that the MM of the PV modules which have spectral sensitivities in the long wavelength band is approximately 1 regardless of the APE, except for cadmium telluride (CdTe) PV module. We thus conclude that the $I_{SC}$ of different PV modules except the CdTe PV module have uniqueness, if the irradiance and $APE_{350\text{-}1050}$ measured from all three sites are similar.

## 1. Introduction

The performance of photovoltaic (PV) module under actual outdoor conditions is influenced greatly by the solar irradiance, module temperature ($T_{mod}$), and spectral irradiance distribution. The energy output is the most important parameter to determine the feasibility of using a PV module. For determining total energy output, the performance of PV modules is rated based on standard test conditions (STC: solar irradiance: 1.0 kW/m$^2$, solar spectrum distribution: AM1.5G and $T_{mod}$: 25 °C) (IEC 60891 Ed.2, 2009; JIS C 8914, 1998; IEC 61853-1 Ed.1, 2011). However, STC rarely occurs in the actual outdoor conditions in Japan. Furthermore, the spectral irradiance distribution changes over time under outdoor conditions because of the aerosol and moisture contents of the atmosphere, and therefore, it is rare to fit the standard solar spectrum AM1.5G defined in the standard IEC 60904-3 (IEC 60904-3, 2016). It is therefore very doubtful whether the performance

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of PV module estimated by the power rating method under STC is similar to the actual performance in outdoor conditions (Tsutsui and Kurokawa, 2008; Virtuani et al., 2011; Pierro et al., 2014). Nevertheless, the rating of PV module under actual outdoor conditions is needed due to the practical consideration in the process of operation (Ichida et al., 2009; Ikisawa et al., 1998; Carr and Pryor, 2004; Gottschalg et al., 2005; Malik et al., 2003; Nakada et al., 2010).

For precise rating, the effects of atmospheric elements experienced by the PV modules under actual outdoor conditions need to be considered. This is because these atmospheric elements, especially aerosol optical depths, distribution of ozone and the amount of precipitable water vapor influence the spectral irradiance distribution due to the scattering and absorption, and consequently the performance of PV modules is influenced (Faine et al., 1991). Therefore, a detailed analysis of spectral irradiance distribution is indispensable. For analysis of spectral irradiance statistically, a quantitative index is necessary because spectral irradiance distribution is a function of wavelength. Average photon energy (APE) is an index defined as the integrated irradiance divided by the integrated photon flux density that yields an average energy per photon in a spectrum (Williams et al., 2003), which represents a quantitative value of spectral irradiance distribution. Meanwhile, our previous studies have shown statistically the uniqueness of APE calculated from a single spectral band range of 350–1050 nm wavelength ($APE_{350\text{-}1050}$) as well as multiple wavelength bands with narrow ranges of 400–600 nm and 750–1050 nm at intervals of 50 and 100 nm in both cases, by analyzing several sets of spectral data obtained from the Kusatsu-city, Shiga prefecture in Japan (Minemoto et al., 2009; Kataoka et al., 2014), and its impact on PV performance especially, on the short circuit current ($I_{SC}$) of PV modules (Horio et al., 2017; Mano et al., 2017). However, the spectral characteristics with respect to APE and its effect on PV performance in other regions of Japan based in the Kusatsu-city are not yet clearly understood. Thus, understanding the uniqueness of the shape of the solar spectrum of different sites in Japan based on Kusatsu-city using similar APE for standardization are necessary to precise rating the outdoor performance of PV modules. It should be noted that although this study was conducted primarily in the particular locations within Japan based on the availability of data, this method can be used to verify the uniqueness of the solar spectrum of other global sites for standardization.

In this study, the spectral irradiance obtained from three sites: Ritsumeikan University in Kusatsu-city, National Institute of Advanced Industrial Science and Technology (AIST) in Tsukuba-city, and the University of Miyazaki in Miyazaki-city, Japan are analyzed based on similar APE in order to gain a better understanding of the significance of uniqueness of the shape of the solar spectrum, and compared among sites on the basis of Ritsumeikan University in Kusatsu-city. All three study areas are geographically distant from each other. The distance between Ritsumeikan University and AIST is approximately 400 km, the distance between Ritsumeikan University and the University of Miyazaki is around 550 km, and the distance between AIST and the University of Miyazaki is approximately 930 km. Also, their environmental conditions like average yearly temperature, rainfall, humidity and total irradiance are different, and thus these parameters influence the performance of PV modules. This crucial information is directly relevant for accurate performance rating of PV modules (Gottschalg et al., 2002). In regard to this view, the degree of coincidence for the shape of the solar spectrum is quantified using coefficient of determination denoted by $R^2$. The results obtained by the $R^2$ method were analyzed to verify the uniqueness of solar spectrum obtained from different sites. It was found that the high $R^2$ values correspond to small APE errors may result from variations in the solar spectrum. In addition, spectral mismatch correction factor (MM) based on irradiance obtained by using a pyranometer ($MM_{pyranometer}$) as a function of APE are examined, and compared among sites for further evaluation of the influence of $I_{SC}$ of different PV modules: single-crystalline silicon (sc-Si), multi-crystalline silicon (mc-Si), heterojunction with intrinsic thin layer (HIT), single-crystalline silicon back contact (BC), cadmium telluride (CdTe), and copper indium di-selenide (CIS) PV module for the first time to the best of our knowledge. Results showed that the MM of the PV modules which have spectral sensitivities in the long wavelength band is approximately 1 regardless of the APE, except for CdTe PV module. Thus, we conclude that the $I_{SC}$ of different PV modules except the CdTe measured from three sites have uniqueness, if the irradiance and $APE_{350\text{-}1050}$ calculated from all three sites are similar. A more detailed discussion will be provided in the following sections.

## 2. Experimental details

### 2.1. Measurement setup and PV module

Solar spectrum over the wavelength range of 350–1050 nm is measured by a spectroradiometer (MS-700, EKO Seiki, Tokyo, Japan). This instrument is facing due south with a tilt angle of 15.3° in a location at Ritsumeikan University, Kusatsu-city, Shiga prefecture in Japan (north latitude 34°58′, and east longitude 135°57′). It is suitable for continuous outdoor exposure, and capable of measuring spectral irradiance in all conditions. Two years of data set consist of approximately 45,320 data points recorded from January 2015 through December 2016 are used for analysis. In the case of AIST in Tsukuba-city, two types of spectroradiometer (MS-700 and MS-712, EKO Seiki, Tokyo, Japan) are used to measure the solar spectrum. A combination of solar spectrum over the wavelength range of 350–1700 nm is recorded. Both instruments are facing due south with a tilt angle of 20.0° in a location at AIST, Tsukuba-city, Ibaraki prefecture in Japan (north latitude 36°04′, and east longitude 140°08′). The data set consists of approximately 45,456 data points recorded by a similar period as the Kusatsu-city. For the University of Miyazaki in Miyazaki-city, two types of spectroradiometer (MS-711 and MS-712, EKO Seiki, Tokyo, Japan) are also used to measure the solar spectrum. Similarly, a combination of solar spectrum over the wavelength range of 300–1700 nm is recorded. Both instruments are facing due south with a tilt angle of 35.0° in a location at the University of Miyazaki, Miyazaki-city, Miyazaki prefecture in Japan (north latitude 31°49′, and east longitude 131°24′). The most recent year of data consists of approximately 27,869 data points recorded from June 2016 through May 2017 are used for calculation and analysis. For calculation of APE, the solar spectrum in the range of 350–1050 nm is considered because of the maximum capacity of the measurement system of the spectroradiometer (MS-700). The data obtained from spectrometers are recorded every 1 min interval from 4 a.m. to 8p.m.

For precise evaluating consistency of $I_{SC}$, six different types of PV modules: sc-Si PV module (SHARP NT-84L5H), mc-Si PV module (Kyocera KC32T-02), HIT PV module (Panasonic N244a), BC PV module (SunPower E20/327), CdTe PV module (First Solar FS-4100), and CIS PV module (Solar Frontier SF-160S) are investigated under indoor conditions. The spectral responses (SR) of these PV modules are measured precisely in the wavelength range of 300–1300 nm at AIST, Japan. As shown in Fig. 1, there are large differences in the sensitivity of different PV materials to spectral variation. This could be due to variation in the band gap of the materials and the device structure. The measured *SRs* of the PV modules are used for calculating irradiance-based MM as a function of APE, which will be discussed in detail in the following section.

### 2.2. Methodology for calculating APE

The APE value was calculated as the integrated irradiance divided by the integrated photon flux density, yielding the average energy per photon (eV) can be formulated as follows (1):