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Impact of average photon-energy coefficient of solar spectrum on the short circuit current of photovoltaic modules

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A B S T R A C T

The output energy of photovoltaic (PV) modules is influenced by the spectral irradiance distribution of the solar spectrum under outdoor conditions. To rate the precise output energy of PV modules, the correction of short circuit current (I_{SC}) based on actual environmental conditions is needed, because I_{SC} significantly depends on the shape of the spectral irradiance distribution. The average photon energy (APE) is a zero-dimensional index for spectral irradiance distribution, and APE value uniquely describes the shape of a solar spectrum. Thus, APE has an impact on I_{SC} of PV modules. In this contribution, the relationship between APE coefficient and I_{SC} of the multi-crystalline silicon, single-crystalline silicon, heterojunction intrinsic thin-layer, back contact, copper indium selenide and cadmium telluride PV modules has explored. It is revealed that APE value changes the I_{SC} of PV modules which appeared to have immense possibilities of I_{SC} correction using APE coefficient. This new approach can be very effective for precise rating the output energy of PV modules under actual outdoor conditions.

1. Introduction

Installations of PV modules are growing rapidly and thus, more precise rating the output energy of PV modules under actual outdoor conditions is of high interest to researchers and manufacturers. For rating the performance of PV modules, the manufacturers typically use standard test conditions (STC) which involves only one module temperature of 25 °C, one solar irradiance of 1.0 K W/m^2, and one solar spectrum distribution (AM [air mass] 1.5G [global]) [1–3]. However, this condition of environment similar to STC occurs only very rarely in practice or would ever happen in the actual outdoors [4], especially in Kusatsu City, Japan where the study has been carried out. Also, these conditions in the environment do not hold stable. Although information regarding STC is useful for rating the performance of PV modules under indoor, it does not represent what is typically experienced under outdoor operation. Actual energy production of outdoor installed PV modules is a result of a range of operating temperatures, solar irradiances, and solar spectra. Any variation of these environmental conditions affects the performance of PV modules, and thus the output energy of PV modules measured under outdoor is typically different from the estimated energy measured under STC [5–8]. For that reason, more precise rating of the performance of PV module under realistic outdoor conditions is necessary that will be based on previously published reports on the outdoor performance of PV modules [9–14].

For highly accurate rating the output energy of PV module, the environmental factors should be measured precisely, and simultaneously the output energy should be corrected to the STC by considering environmental factors. Many atmospheric elements, particularly moisture content and ozone influence the spectral irradiance distribution, which directly limits the performance of PV modules at outdoor [15–17]. Previously, our group statistically analyzed several sets of spectral data to determine the effect of atmospheric elements using a zero-dimensional index of spectral irradiance distribution denoted by average photon energy (APE), which was calculated by dividing the integrated irradiance with the integrated photon flux density, yielding the average energy per photon [18–20]. Note that APE as the index was proposed by

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Gottschalg's group of Loughborough University calculated from the spectral irradiance distribution [21], and the effects of spectral irradiance distribution on the performance of PV modules under actual operating conditions have been demonstrated by several other research groups as well [22–25]. From the above discussion, it can be concluded that there is a strong relation between the performance of PV modules and APE. Previously, our group has shown the uniqueness of APE calculated using a single spectral band range of 350–1050 nm ($APE_{350-1050}$), and determined that the APE value uniquely describes the shape of the solar spectrum at Kusatsu city, Shiga prefecture in Japan [19]. This indicates that the APE is reasonable and useful environmental parameter for representing the spectral irradiance distribution and its effect on PV performance. For performance measurement, I_{SC} is regarded as one of the most important parameters of PV modules, I_{SC} will thus be influenced by the spectral irradiance distribution of solar spectrum considering the relationship between spectral irradiance distribution and APE index mentioned above. On the other hand, the open circuit voltage is also another important performance-indicator of PV module, but it does not depend on the spectral irradiance distribution, and thus I_{SC} has been considered eligible for analysis. Hence, the correction of I_{SC} in the context of actual environmental conditions is indispensable due to precise rating the output energy of PV modules. As far as we know the correction of I_{SC} has been performed using solar irradiance, module temperature and solar spectrum in order to evaluate the outdoor performance of PV modules, however, spectral irradiance distribution was not considered for I_{SC} correction. In the case of similar-level solar irradiance, the shape of solar spectrum may vary, as shown in Fig. 1. This indicates that the I_{SC} could be changed in some cases, even though the solar irradiance does not change. Therefore, the spectral irradiance distribution is an important factor for I_{SC} correction because the value of I_{SC} depends on the shape of the spectral irradiance distribution which can be represented by the APE index.

In this study, we report the possibility of I_{SC} correction using APE coefficient for precise rating the output energy of PV modules under actual outdoor conditions for the first time. The coefficient of APE is defined as the slope of I_{SC} divided by the I_{SC} at APE 1.88 eV (APE coefficient = slope of I_{SC}/I_{SC} at APE 1.88 eV). The slope of I_{SC} is normalized due to different values of APE and I_{SC} obtained from different PV modules. The APE index was calculated using a single spectral band range of 350–1050 nm from the spectral irradiance data. Subsequently, we calculated the I_{SC} by multiplying the solar spectrum with the spectral response of different PV modules such as multi-crystalline silicon (mc-Si), single-crystalline silicon (sc-Si), heterojunction intrinsic thin layer (HIT), back contact (BC), copper indium di-selenide (CIS) and cadmium telluride (CdTe). The spectral response of such PV modules has been measured precisely at the National Institute of Advanced Industrial Science and Technology (AIST), Japan. The impact of APE on I_{SC} of different PV modules was investigated. The result revealed that APE value changes the I_{SC} of PV modules, which indicates the possibilities of I_{SC} correction using APE coefficient. This new approach was intended to address the precise rating of output energy for different types of PV modules in actual outdoor conditions.

2. Experimental details

2.1. Measurement setup

Different types of PV modules, such as mc-Si, sc-Si, HIT, BC, CIS and CdTe with a capacity of 33.2, 87.7, 244, 323, 162 and 97.8 W, respectively, were installed at Kusatsu city, Shiga prefecture in Japan (north latitude 34°58′, east longitude 135°57′). All PV modules were mounted on the roof facing south, and were tilted at 15.3°. The environmental data, particularly, solar spectral irradiance over the wavelength range of 350–1050 nm and global tilted irradiance (GTI) were recorded by a Spectroradiometer (MS-700, EKO Seiki, Tokyo, Japan) and a Pyranometer (MS-402, EKO Seiki, Tokyo, Japan), respectively. The solar spectral irradiance in the range 350–1050 nm was considered because of the maximum capacity of the measurement system of the Spectroradiometer. The solar spectral irradiance and GTI data were recorded every 1 min interval from 4 a.m. to 8 p.m., and the output energy delivered from the respective PV modules was measured simultaneously. The exposure conditions experienced by the measurement equipment and PV modules are apparently similar. Furthermore, spectral response in the range 300–1300 nm of such PV modules was measured precisely at AIST, Japan, as shown in Fig. 2. The shaded areas in the figure indicate the spectral regions which were not considered for analysis because of lack of spectral irradiance data for these regions. Thus, a range of 350–1050 nm wavelength was used in order to match with the spectrum data measured by MS-700.

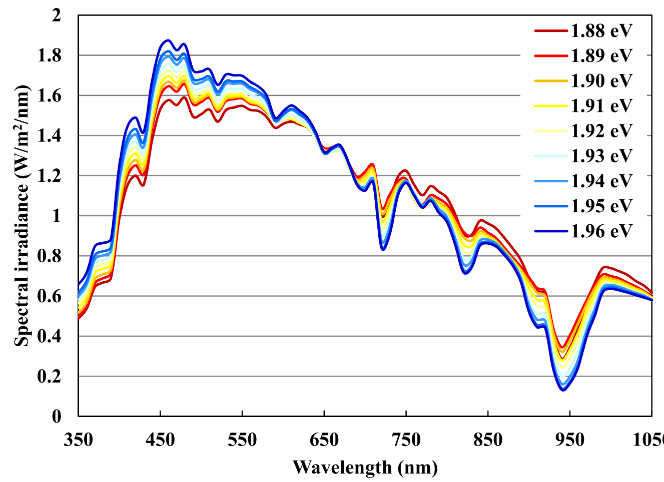

Fig. 1. Solar spectral irradiance at different APE recorded in the 5-year period from January 1, 2010 through December 31, 2014.

2.2. Methodology for calculation

The APE value of the solar spectrum was calculated as the

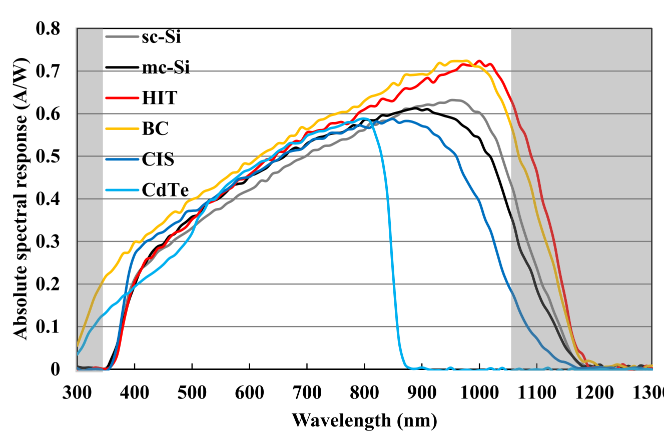

Fig. 2. Spectral responses of different PV modules were measured precisely at AIST, Japan. The shaded areas indicate the spectral regions which were not considered for analysis because of lack of spectral irradiance data for these regions.