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# Evaluation of solar spectral irradiance distribution using an index from a limited range of the solar spectrum

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ABSTRACT

The output energy of photovoltaic (PV) modules under outdoor conditions is greatly influenced by the spectral irradiance distribution of the solar spectrum. To analyze this effect on PV modules, the spectral irradiance distribution, which is one-dimensional data, has to be represented by a zero-dimensional index. The average photon energy (APE) is an index for spectral irradiance distributions, which represents the average energy per photon in a spectrum. We have previously analyzed the uniqueness of the shape of the solar spectrum in the wavelength range of 350–1050 nm, and one corresponding value of APE showed a specific shape of spectral irradiance distribution. In this study, new indexes were calculated for a limited wavelength range of 350–750 nm and multiple bands of 450–500 nm and 800–850 nm of the solar spectrum for easy measurement and calculation. The result shows the uniqueness of new indexes to the shape of measured solar spectrum and the standard deviations were found to be quite small. This indicates that the new indexes are reasonable for representing the spectral irradiance distribution and its effect on PV performance.



## 1. Introduction

The performance of photovoltaic (PV) modules installed outdoors is greatly influenced by various ambient environmental factors such as incident irradiance, the module temperature and the spectral irradiance distribution. PV modules are rated by output power and energy conversion efficiency under the standard test condition (STC; solar irradiance: 1.0 kW/m$^2$, solar spectrum distribution: AM1.5G and module temperature: 25 °C). However, this particular environmental condition rarely occurs under actual outdoor conditions in Japan [1,2]. It would be more practical for PV modules to be evaluated by their performance under realistic outdoor conditions based on the numerous published reports on the outdoor performance of PV modules [3–9]. The solar spectral irradiance distribution is influenced by atmospheric elements such as moisture and ozone [10]. We have statistically analyzed several sets of spectral data and experimentally determined the effects of atmospheric elements, without considering the basic properties of the elements. Because the spectral irradiance distribution is one-dimensional data, to treat the data statistically, a zero-dimensional index is needed. An index of the average photon energy (APE) was proposed by Gottschalg's group of Loughborough University [11], and the relationship between APE and the performance of PV modules has been demonstrated [12–14]. We have statistical evaluated the outdoor performance of PV modules with contour maps as a function of APE and module temperature [15–18]. APE is defined as the average energy per photon in a spectrum. The value of APE is calculated by dividing the integrated irradiance by the integrated photon flux density. From this definition, each solar spectrum has a signature APE value, though the APE value does not specify the shape of the solar spectrum. We have previously statistically analyzed the uniqueness of APE calculated in the wavelength range of 350–1050 nm ($APE_{350-1050}$) for the spectral irradiance distribution in the wavelength range 350–1050 nm and determined the APE value that uniquely describes the shape of the solar spectrum at Kusatsu city, Shiga prefecture in Japan [19]. In this study, for easier measurement and evaluation of the spectral irradiance distribution, APE values were calculated from limited data of a narrower wavelength range or from multiple-bands of solar spectra with the full spectral information retrieved from a limited spectral range, thereby avoiding the high cost of installing a spectroradiometer to measure the full wavelength range of the solar spectral irradiance distribution. The experimental set up for gathering limited spectral data can be made to be relatively simple, allowing low cost measurements. For example, an APE value can be calculated from the irradiances of two

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spectral bands using two pyranometers with spectral bandpass filters instead of spectroradiometers. Pyranometers and bandpass filters are generally much cheaper than spectroradiometers. We analyze the uniqueness of the APE indexes and report on the effectiveness of these new indexes in describing the spectral irradiance distribution and evaluate the effect of their use on the performance of PV modules.

## 2. Experimental details

### 2.1. PV modules and measurement setup

Various kinds of Si-based PV modules were installed at Kusatsu city, Shiga prefecture in Japan (north latitude 34°58′, east longitude135°57′). All PV modules facing due south were tilted at 15.3°. Solar spectra in the wavelength range 350–1050 nm were recorded by a spectroradiometer (MS-700, EKO Seiki, Tokyo, Japan). The temperature of the rear of the PV modules (module temperature) and global tilted irradiance (GTI) were measured by a thermocouple and pyranometer, respectively. The measurement equipment experienced the same exposure conditions as the PV modules. The environmental data and output energy from the PV modules were measured every 1 min. The APE value was calculated by dividing the integrated irradiance by the integrated photon flux density, to give the average energy per photon [11]:

$$\mathrm{APE}_{a-b}(\mathrm{eV}) = \frac{\int_a^b E(\lambda)\mathrm{d}\lambda}{q\int_a^b \Phi(\lambda)\mathrm{d}\lambda} \quad \Phi(\lambda) = \frac{E(\lambda)}{E_{\mathrm{photon}}(\lambda)}, \tag{1}$$

where $q$ is the electronic charge, $E$ is the spectral irradiance, $\Phi$ is the spectral photon flux density and $E_{\mathrm{photon}}(\lambda)$ is the energy of a photon of wavelength $\lambda$. The values of $a$ and $b$ were changeable. First, $a$ and $b$ were set to 350 nm and 1050 nm for the maximum range of the measurement system of the spectroradiometer ($\mathrm{APE}_{350-1050}$). Next, $a$ and $b$ were set to 350 nm and 750 nm ($\mathrm{APE}_{350-750}$). In addition, a new APE was calculated from the irradiance data of two bands of 50 nm, 450–500 nm and 800–850 nm. These bands were chosen because there are useful bandpass filters for these spectral bands. The APE derived from two bands is given by

$$\mathrm{APE}_{\mathrm{band}\ a-b,c-d}(\mathrm{eV}) = \frac{\int_a^b E(\lambda)\mathrm{d}\lambda + \int_c^d E(\lambda)\mathrm{d}\lambda}{q\left(\Phi_{\mathrm{band}\ (a-b)} + \Phi_{\mathrm{band}\ (c-d)}\right)}$$
$$\Phi_{\mathrm{band}\ (a-b)} = \frac{\int_a^b E(\lambda)\mathrm{d}\lambda}{E_{\mathrm{photon}}\left(\frac{a+b}{2}\right)}, \tag{2}$$

where $E$ is the irradiance of the spectral bands, $\Phi_{\mathrm{band}}$ is the photon flux calculated by the central wavelength of each spectral band and $E_{\mathrm{photon}}(\lambda)$ is the energy of a photon of wavelength $\lambda$. $a$, $b$, $c$ and $d$ are set to 450, 500, 800 and 850, respectively ($\mathrm{APE}_{\mathrm{band}\ 450-500,\ 800-850}$). In this equation, the total number of photon with two spectral bands was calculated approximately in the denominator and total energy with two bands was obtained in the numerator. This is quite similar to the definition of APE. It was important that the uniqueness of ratio of each spectral band to total irradiance on the selection of two spectral bands. The two spectral bands of 450–500 nm and 800–850 nm were selected as short wavelength element and long wavelength element because standard deviations of ratios of these spectral bands to total irradiance were quite low [19]. In this case, the central wavelength values of each spectral band of 475 nm and 825 nm were used to calculate the photon flux of each spectral band. This is because $\mathrm{APE}_{\mathrm{band}}$ was assumed to be calculated from the measurement of the irradiance of two bands and the spectral irradiance distributions cannot be defined by two pyranometers. APEs calculated from a solar spectrum have different values. For example, $\mathrm{APE}_{350-1050}$, $\mathrm{APE}_{350-750}$ and $\mathrm{APE}_{\mathrm{band}\ 450-500,\ 800-850}$ were calculated to be 1.88, 2.22 and 2.04 eV, respectively, for the AM1.5G reference spectrum [19–21]. As an index of the outdoor performance of PV modules, the performance ratio (PR) is used. PR indicates the PV module efficiency not including the effect of the irradiance intensity, and is defined as the actual output energy divided by the nominal output energy calculated from the PV module efficiency under STC.

$$\mathrm{PR}(\%) = \frac{E_{\mathrm{load}}/P_{\mathrm{max}}}{H_{\mathrm{A}}/G_{\mathrm{S}}} \times 100, \tag{3}$$

where $E_{\mathrm{load}}$ is the output energy (kWh), $P_{\mathrm{max}}$ is the rated power (kW), $H_{\mathrm{A}}$ is the integrated tilt irradiance, known as tilt irradiation (kWh/m$^2$) and $G_{\mathrm{S}}$ is the standard irradiance of 1.0 kW/m$^2$.

### 2.2. Methodology for analyzing uniqueness of the APE

The uniqueness of each APE value was characterized by a methodology similar to that adopted by the International

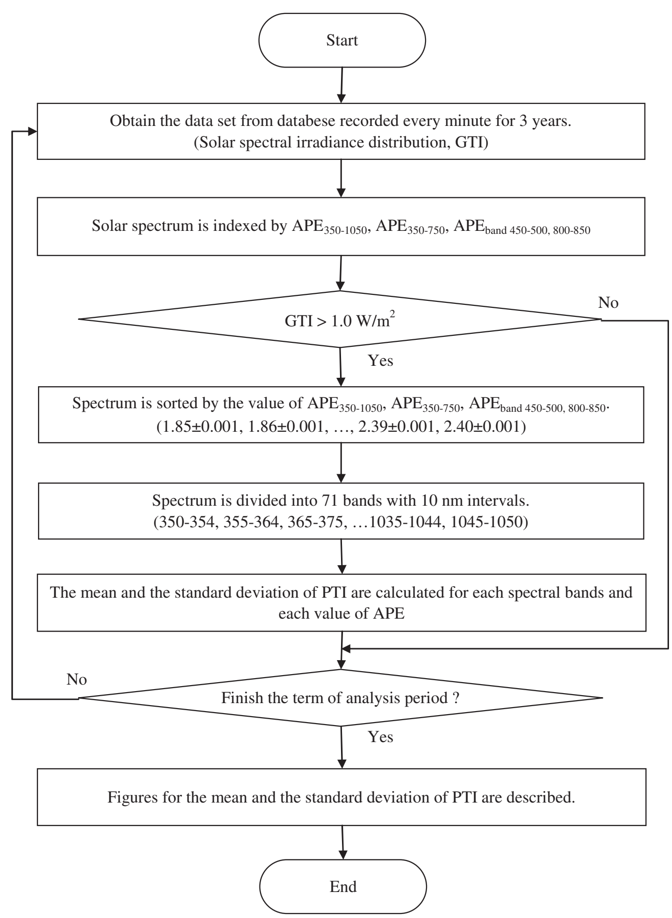


**Fig. 1.** Flowchart of demonstration of uniqueness of indexes for spectral irradiance distribution.