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Influence of clearness index and air mass on sunlight and outdoor performance of photovoltaic modules

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ABSTRACT

Influences of clearness index (Kt) and air mass (AM) on both the sunlight and the outdoor performance of photovoltaic (PV) modules were analyzed. The Kt and AM strongly affect the intensity of solar irradiation and spectral irradiance distribution. In this study, the impacts of Kt and AM on an index for spectral irradiance distribution of average photon energy (APE) are analyzed using a contour maps and then the impacts of the environmental factors on the outdoor performance of single crystalline Si (sc-Si) and amorphous Si (a-Si) PV modules is discussed. As the result, it was found that APE increases with decreasing the Kt and AM. Furthermore, it was found that the outdoor performance of a-Si PV modules strongly depended on APE compared to sc-Si PV modules. Thus, APE can be estimated from the contour map with the Kt and AM.

1. Introduction

Outdoor performance of photovoltaic (PV) modules is influenced by ambient environmental conditions such as rain, ambient temperature and wind. To design PV modules, it is important to analyze the influences of environmental factors on the outdoor performance of PV modules. The outdoor performance of PV modules is affected by the environmental factors, such as irradiance intensity and spectral irradiance distribution, which depend on both weather and air mass (AM) that cause attenuation, scattering and absorption of sunlight. Especially, in new types of PV modules which are based on thin-film semiconductors such as amorphous Si (a-Si) and a-Si/microcrystalline Si, the performance of these PV modules are affected by the spectral irradiance distribution [1,2]. To understand the outdoor performance of new types PV modules, it is important to analyze the effects of both weather and AM on the spectral irradiance distribution. Therefore, we focused on clearness index (Kt) [3] which indicates weather conditions and AM. In this study, the effects of the AM and Kt on the spectral irradiance distribution was analyzed by contour map. Also, the reliability of the contour map was discussed statistically. Furthermore, the behavior of the outdoor performance of the single crystalline Si (sc-Si) and the a-Si PV modules were compared with the spectral irradiance distribution.

2. Experiments

The spectral changes due to the path through the atmosphere are represented by the relative optical AM. AM is defined by the equation

$$\mathrm{AM} = 1/\sin\alpha, \tag{1}$$

where α is the solar elevation angle.

Spectral variation due to the weather condition could be represented by the Kt, defined as the ratio of total irradiance measured on a horizontal plane at the Earth's surface to the total extra-terrestrial irradiance incident on a horizontal plane at the top of the atmosphere

$$\mathrm{Kt} = \frac{H}{H_0/\mathrm{AM}}, \tag{2}$$

where H is the measured horizontal irradiance, H_0 is the calculated extra-terrestrial irradiance. Kt is approximately 0.6–0.8 at fine weather.

The sc-Si and a-Si PV system with capacities of 5 and 2 kW were installed at Kusatsu city in August 1998, facing due south with a tilt angle of 15.3°. Daily average irradiation was 3.9 kWh/m^2. This is almost equivalent to daily average irradiation of Japan's main island. The system was connected to a utility grid through inverter. Direct-current output, and output voltage, were measured every 1 min. The solar spectrum with the wavelength range of 350–1050 nm were recorded every 1 min by a spectro-radiometer (MS700, EKO, Japan) installed at the same exposure condition as the PV modules. To analyze the influences of environmental factors on both the sunlight and the outdoor performance of the PV mod-

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ules, the contour maps of the spectral irradiance distribution and the outdoor performance of the PV modules as a function of AM and Kt were created.

As the index of the outdoor performance of PV modules, performance ratio (PR) is used. PR indicates PV module efficiency without the effect of the irradiance intensity, which is defined as the actual output energy divided by the nominal output energy calculated from the solar module performance under standard test condition (STC: 1 kW/m^2, AM1.5 standard solar spectrum).

In order to analyze the effect of solar spectrum, the index for the spectral irradiance distribution of average photon energy (APE) [4] was used. APE is calculated from measurements of spectral irradiance by dividing the irradiation by the integrated photon flux density, yielding the average energy per photon. The APE value for the standard solar spectrum calculated with this range is 1.88 eV [5,6].

The contour maps of APE and PR as a function of AM and Kt were created to separate the influences of the two environmental parameters. In the plots, the ranges for AM and Kt are 1–3 (0.1 step) and 0–1 (0.05 step), respectively. Instantaneous PR values measured every 1 min were collected for each environmental conditions and then the contour maps of the average APE, standard deviation (σ) and average PR value were created. Here, the data points with the PR lower than 200% were used to omit the uncertainness of the operation timing of the inverter for maximum power point tracking. Also, the data points with the APE higher than 1.85 eV and lower than 2.04 eV were used to reduce the σ. The data points of APE and the integrated irradiance decreased of 2.6% and 0.9% compared to the unlimited ones, respectively. Using the same method, the contour map of data points for APE were created to show the distribution and frequency of the environmental conditions. In this study, the data period of double years from January 2006 through December 2007 was used. The total number of data points was approximately 300,000.

3. Results and discussion

3.1. AM and Kt impact on solar spectrum

Fig. 1 shows the contour map of the average APE as a function of AM and Kt. APE decreases with increasing Kt which closely related to the amount of cloud. In other words, APE decrease with decreasing amount of cloud because the cloud consists of water vapor which absorbs long-wavelength range light with low energy. Also, APE decreases with increasing AM because more short-wavelength range light scattered with AM. Therefore, APE have a close relationship with both AM and Kt.

Fig. 2 shows the contour maps of (a) σ and (b) data points of APE as a function of AM and Kt. The weighted mean of σ by the data points was approximately 0.024 eV. The σ value in the place where most data were pointed was approximately 0.017 eV at around AM = 1.1 and Kt = 0.8. The distribution of σ was mostly similar to that of the data points. Thus the high σ values would be influenced by the small number of data points. However, the σ value was not small enough for practical use. Thus, it is necessary for analyzing APE with different amount of water vapor range to reduce the σ value.

APE have a close relationship with both AM and Kt. However, the σ value of the APE is not small enough for practical use. To reduce the σ value, it is necessary for analyzing APE with different amount of water vapor range.

3.2. AM and Kt impact on PR

Fig. 3 shows the contour maps of the average PR for (a) a-Si and (b) sc-Si PV modules as a function of AM and Kt. The comparison of

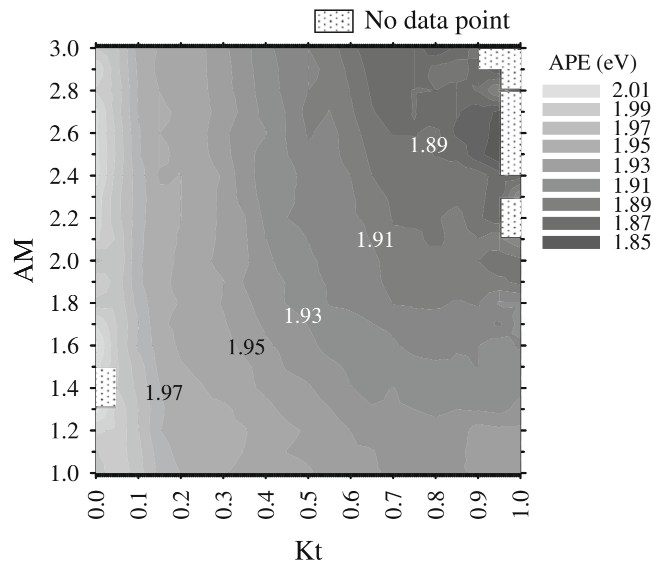

Fig. 1. Contour map of average APE as a function of AM and Kt.

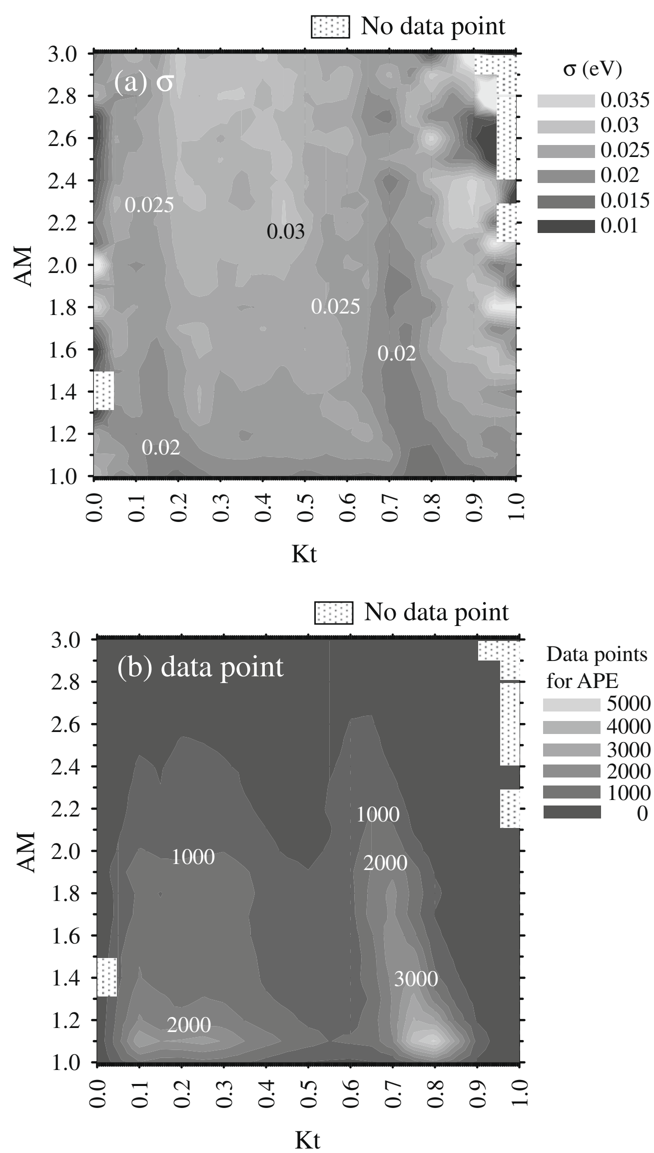

Fig. 2. Contour maps of (a) σ and (b) data points of APE as a function of AM and Kt.