Original Paper

Solar Spectrum Estimation and Impact of Input Parameters

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This paper investigated a solar spectrum estimation method based on the SMARTS2 code and the specific impact of input parameters i.e. turbidity and precipitable water vapor (PWV) on the estimation. The turbidity measured by the filter type spectroradiometer called skyradiometer was used for increasing the estimation accuracy. The results of three different estimation methods for obtaining PWV from GPS sensor, skyradiometer and conventional humidity measurement were compared. The estimated solar spectrum was verified by grating type spectroradiometer and conventional instruments. As a consequence, each parameter set was sufficient to estimate solar spectrum, especially, the parameter set consisted of the turbidity from skyradiometer and the PWV from conventional humidity measurement was the most accurate.

本論文では、放射伝達モデル SMARTS2 を利用した日射スペクトル強度の推定手法について検証した。スペクトル分布は、多接合型等の次世代太陽電池の評価に重要である。太陽電池評価に必要なスペクトル分布を決定付ける主要なパラメータは、大気混濁度と可降水量である。これらのパラメータを異なる推定手法を用いて日射スペクトル強度を推定し、その推定精度について明らかにした。大気混濁度はフィルタタイプ分光放射計の測定値を基に換算した。一方、可降水量の推定には、次の3つの手法を用いた。1) GPS センサーを利用した手法、2) フィルタタイプ分光放射計を利用した手法、3) 温度・湿度からの換算手法である。異なる手法により推定された可降水量を用いて SMARTS2 により日射スペクトル強度を推定し、グレーティングタイプの直達分光放射計の観測値と比較・検証した。温度・湿度からの換算手法による結果が観測値と最も良く一致する。本研究により、いずれの手法を用いた場合においても、太陽電池を屋外で評価するための十分な精度が得られることを確認した。

Key Words

Solar spectrum, Photovoltaic, Skyradiometer, SMARTS, Energy rating

1. Introduction

Solar spectral distribution is one of the dominant factors which influence on the performance of photovoltaic (PV) devices, especially concentrator photovoltaic (CPV) devices consisting of multi-junction solar cell^{1) ~ 6)}. For investigating the power generation performance of these devices under actual outdoor conditions, the accurate measurement of solar spectral irradiance is required. However, the measurement at preferable location or area is difficult due to the high cost of measurement. For this reason, several attempts based on simulation have been made to obtain the accurate information of solar spectral irradiance. They show that the accuracy of modeled spectra is strongly dependent on the important atmospheric

parameters at the location of interest, especially on turbidity and PWV, which are also the key factors for PV and CPV characterization^{7) ~ 9)}. Both parameters largely change in a short time and their ranges of variation depend on location and season. In general, these parameters can be retrieved from different data sets measured by various meteorological instruments on the ground or by satellites. Thus, for spectrum simulation on the basis of different observations, the use of these parameters suffer from several kinds of nonnegligible errors in spectrum estimation due to spatial or temporal interpolation in the data acquisition process. Therefore, in order to increase the accuracy of spectrum estimation by simple process, it is necessary to investigate the impact of these parameters on the accuracy of spectrum simulation.

In the previous work¹⁰⁾, we presented a method
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of solar spectrum estimation based on the atmospheric measurements on the ground. The simulation of direct normal spectral irradiance (DNSI) has been carried out by using the SMARTS2 (Simple Model for the Atmospheric Radiative Transfer of Sunshine2) code¹¹⁾ in clear sky conditions. The present method of the current study is similar to the previous report¹⁰⁾. However, an improvement has been achieved in using the values of PWV retrieved from different measurements (GPS, skyradiometer, etc.). One of the purpose of the current study is to investigate the impact of these important parameters on the accuracy of spectrum estimation by comparing the simulation errors of PWV obtained from different sources, and the other is to find simple and accurate method of solar spectrum estimation.

2. Experiment and modeling

2.1 Experiment

The SMARTS2 version 2.9.5 was used to generate DNSI. The area of this experiment is in Okayama, Japan. Fig. 1 shows the locations of the area, where the solar spectrum estimation was performed and necessary atmospheric parameters for this estimation were obtained. The base site is at a small hill called Kyoyama (34.7° N, 133.9° E, altitude 69.3 m) where our CPV experimental system has been installed, and the experiment started on Jan. 1, 2011. At this site, direct normal irradiance (DNI) is measured with an EKO MS-54 pyrhelimeter which covers the wavelength range from 200 nm to 4000 nm, and DNSI is measured by two spectroradiometers of EKO MS-710 and MS-712, which were equipped with proper collimating tubes. The collimating tubes were designed to have the same field of view (FOV 5°). Two instruments cover the wavelength

ranges from 350 nm to 900 nm and from 900 nm to 1700 nm, respectively. Moreover, ambient temperature and relative humidity measurements are continuously recorded. On the other hand, spectral radiation at multi-channel wavelengths is measured with a Prede POM-02 skyradiometer, the filter type spectroradiometer, located at Okayama University about 1 km away from the base site. Furthermore, GPS measurement at the observation points of Meteorological Research Institute (MRI) (GPS_A, GPS_B and GPS_C) is carried out simultaneously, and the values of PWV were retrieved by MRI measurements.

The MS-54 pyrhelimeter has been approved by the first class specifications of the ISO 9060 standard and the WMO Guide. It was calibrated by comparing a reference instrument of $\pm 0.5\%$ accuracy by manufacturer. The measurement uncertainty of MS-710 and MS-712 spectroradiometers is approximately $\pm 13\%$ between 350 nm and 450 nm, $\pm 5\%$ from 450 nm to 1600 nm, and $\pm 24\%$ between 1600 nm and 1700 nm, according to the manufacturer certification. The bandwidths (full width at half maximum, FWHM) of MS-710 and MS-712 spectroradiometers are less than 5 nm and 7 nm, respectively.

2.2 Solar spectrum modeling

The important parameters for spectral estimation were investigated. To begin with, the optical characteristic of aerosol was analyzed for obtaining accurate turbidity. First, spectral aerosol optical depth (AOD) was retrieved at seven wavelengths (0.34, 0.38, 0.4, 0.5, 0.675, 0.87 and 1.020 μm) from the POM-02 measurement data. The AOD at 0.5 μm was used as turbidity in this simulation. Secondly, the Angstrom wavelength exponents below 0.5 μm and above 0.5 μm were obtained separately. Thirdly, the single scattering albedo and asymmetry were set to the default values.

Then the PWV was estimated. In this experiment, the values of PWV were obtained with three methods in order to evaluate the accuracy of solar spectrum estimation. These values were retrieved from the POM-02 measurement at 0.94 μm wavelength, from GPS measurement at three observation points and from the measurement of the ambient temperature and the relative humidity at the experiment site, respectively. The value of PWV from the measurement of the ambient temperature and the relative humidity on the ground was calculated by following equation, which was derived from two works by C. Gueymard^{12)~13)} and followed to M. William method⁸⁾;

$$w = 0.1 \left(0.4976 + 1.5265 \frac{T}{273.15} \right)$$

Fig. 1 Locations of present experiment in Okayama

Fig. 2 An example of simulated direct normal spectra at various AMs

Table1 The important parameters used in Fig.2

Date	Time	AM	AOD _{0.5}	PWV(cm)
12.08.08	12:15:00	1.0	0.18	3.18
11.04.04	09:20:00	1.5	0.10	0.78
11.01.08	09:45:00	2.5	0.10	0.83
11.01.08	08:40:00	4.0	0.10	0.83
11.01.08	08:20:00	5.0	0.11	0.83

$$\begin{aligned}
 & + \exp \left[13.6897 \frac{T}{273.15} - 14.9188 \left(\frac{T}{273.15} \right)^3 \right] \\
 & \times \left(216.7 \frac{R_H}{100T} \exp \left[22.330 - 49.140 \frac{100}{T} \right. \right. \\
 & \left. \left. - 10.922 \left(\frac{100}{T} \right)^2 - 0.39015 \frac{T}{100} \right] \right)
 \end{aligned} \quad (1)$$

where w is PWV (cm), T is ambient temperature (K), and R_H is relative humidity (%).

Finally, using above described parameters and other data sets as the inputs of the SMARTS2 code, the simulation was performed in clear sky conditions during the period from Jan. 8, 2011 to Nov. 25, 2012. The DNSI in the wavelength range from 280 nm to 4000 nm, and its integration, *i.e.* the DNI, were generated. Fig. 2 shows an example of simulated direct normal spectra at various air masses (AM). The important atmospheric parameters used in this example are shown in Table 1. In this table, the AOD_{0.5} represents the AOD at 0.5 μm and the values of PWV were calculated by equation (1).

3. Result and discussion

Fig. 3 shows the direct normal spectra simulated by using different sources of PWV and direct normal spectrum measured by MS-710 and MS-712 spectroradiometers on

Fig. 3 The direct normal spectra simulated and measured on Apr. 28, 2012 at 8:50 (top), and the relative error of simulated spectrum (bottom)

Apr. 28, 2012 at 8:50, the same date and time under the value of AM close to 1.5 (top), and the relative error of simulated spectrum (bottom), *i.e.* the relative error between simulated spectrum and measured data. As shown in Fig. 3 (top), the shapes of the simulated spectra are almost similar to that of the measured spectrum. However, the spectral irradiances are slightly different from that of the measured spectrum, in particular, in the wavelength ranges from 350 nm to 450 nm and from 800 nm to 1500 nm. The differences between the simulated and measured spectral irradiance are illustrated in detail in Fig. 3 (bottom). Since the FWHM of simulated spectra (more than 0.5 nm)

is different from that of measured, the simulated spectra were smoothed to have the same FWHM as the spectroradiometers before these comparisons. It is clear from Fig. 3 (bottom) that most of the differences between the simulated and measured spectral irradiance are within the instrument uncertainty in the wavelength range from 450 nm to 1600 nm, except for several absorption bands, where some of the solar radiation is absorbed by water vapor in the atmosphere. Because turbidity causes solar radiation to attenuate slowly with wavelength variation, the parts of slow variations with wavelength, in Fig. 3 (bottom), suggest that the accuracy of the turbidity and the Angstrom wavelength exponents retrieved from the POM-02 measurement leads to the same accuracy of simulated spectrum as that of the measurement. On the other hand, there are several water vapor absorption bands in the wavelength ranges from 925 nm to 985 nm, from 1110 nm to 1170 nm and from 1330 nm to 1520 nm. The larger value of PWV causes the stronger absorption of water vapor, that results in the large attenuation of spectral irradiance at these bands, and the smaller the weaker. Thus, the values obtained from different methods in this study, larger or less than that of actual condition, lead to minus or plus relative errors greater than 20% at its absorption bands, especially, even lead to 100% at the band from 1330 nm to 1520 nm, where the spectral irradiance is close to zero. Similarly, the error below 450 nm tends to increase with wavelength decreasing, because the instrument uncertainty also has the same trend in wavelength range from 350 nm to 450 nm.

A more sensitive stability analysis was performed by comparing the simulated DNI with that of measured. Fig. 4 shows daily variation of the relative error of simulated DNI, *i.e.* the relative error between simulated DNI and measured data, at Kyoyama (top), daily variation of PWV obtained from various sources (bottom) in Okayama area on Apr. 28, 2012. These results illustrate that the values of PWV from different sources are below 2 cm on that day, but the maximum difference among these values is nearly 1 cm, and it results in the maximum difference of about 7% of the relative error of simulated DNI.

Fig. 5 shows daily variation of the relative error of simulated DNI at Kyoyama (top), daily variation of PWV obtained from various sources (bottom) in Okayama area on Aug. 8, 2012. These results illustrate that the values of PWV from different sources are below 3.5 cm on that day, but the maximum difference among these values is nearly 1.5 cm, and it results in the maximum difference of about 4% of the relative error of simulated DNI. As can be seen from Figs. 4 and 5, the larger the value of PWV, the smaller the maximum difference among these relative errors. It is

Fig. 4 Daily variation of the relative error of simulated DNI at Kyoyama site (top) and daily variation of PWV in Okayama area (bottom) on Apr. 28, 2012

inferred from this tendency that the errors of the values of PWV obtained with various methods do not vary with variation of their actual value and as a result the maximum difference among these values remains nearly constant or varies in a small range. Therefore, as the actual PWV value increases, the relative errors between the PWV values and their actual value decrease so that similarly the maximum difference among the relative errors of simulated DNI decreases.

Fig. 6 shows the daily average of the relative error of simulated DNI at Okayama site (top), and daily average of PWV obtained from various sources (bottom) in Okayama area, from Jan. 28, 2011 to Nov. 25, 2012. These results illustrate that the seasonal variations of the PWV at these sites vary from 0.2 cm to 5 cm. The relative error of the simulated DNI ranges from -4% to 8%, despite of daily and seasonal variation of the PWV. Fig. 6 also reveals that the maximum difference of the PWV from different sources is approximately from 0.5 cm to 1.5 cm, which results in about 2-7 % of the maximum relative error of simulated DNI. This fact is the main source of the relative error of the simulation.

Fig. 5 Daily variation of the relative error of simulated DNI at Kyoyama site (top) and daily variation of PWV in Okayama area (bottom) on Aug. 8, 2012

Fig. 7 shows the relative error of simulated spectrum at various AMs on Nov. 25, 2012. In this case, the values of PWV from ground measurement were used. These results illustrate that most of the differences between the simulated and measured spectral irradiance do not vary with the variation of AM and are within 10 % in the wavelength range from 450 nm to 1600 nm, except for several absorption bands of water vapor, although the differences below 450 nm and above 1600 nm vary with the variation of AM.

4. Conclusion

The DNSI has been simulated by using the SMARTS2 code, based on the important atmospheric parameters (turbidity and PWV) obtained from various measurements on the ground in clear sky conditions. The impact of these important parameters on the accuracy of spectrum estimation was investigated. The results of this study reveal that the variation from 0.5 cm to 1.5 cm of the maximum difference among PWV values from different sources leads to about 2 - 7 % of the maximum relative

Fig. 6 Daily average of the relative error of simulated DNI at Kyoyama site (top), and daily average of the precipitable water obtained from various sources (bottom) in Okayama site

Fig. 7 The relative error of simulated spectrum at various AMs on Nov. 25, 2012. Here the values of PWV from ground measurement were used for this simulation

error of simulated DNI, depending on the magnitude of their actual PWV value. The difference between simulated and measured spectra caused by turbidity error is within the instrument uncertainty in the main wavelength range.

According to the relative error of simulated DNSI and its DNI, those, simulated by using the PWV from the ambient temperature and the relative humidity, are in good agreement with the measured data, in comparison with other methods.

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