A simplified methodology for estimating solar spectral influence on photovoltaic energy yield using average photon energy

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Abstract
Nowadays, investors, customers, and even suppliers focus on the bankability of photovoltaic (PV) technologies. However, few studies have investigated the annual net effect of solar spectrum. In this study, we estimate the net effect of the solar spectrum on the annual energy yield of c-Si and a-Si modules by two parameters. One parameter is a direct calculation from spectral factor (SF). The other parameter uses average photon energy (APE) and a regression line or curve. The estimations by the two parameters are quite consistent, whereas there is 1.2% difference between the estimations at most. Therefore, APE would be a useful index to quantify the effect of the solar spectrum.

Introduction
The installation of photovoltaic (PV) power generation systems has shown high growth rates in recent years. The European Photovoltaic Industry Association (EPIA) [1] has reported that global Solar PV installations reached 29.7 GW in 2011. The rapid growth of the PV markets results in a decrease in the cost of solar electricity. Nowadays, investors, customers, and even suppliers focus on the bankability of PV technologies. In order to determine the bankability of solar PV projects, it is required to estimate the annual energy yield with accuracy and precision. The dominant factors, which influence the energy yield of PV modules, are solar irradiation, module temperature, and solar spectrum. However, few studies have investigated the net effect of solar spectrum on the annual energy yield of PV modules, because there would be few data sets of solar spectrum that cover a whole year.

The effect of solar spectrum is in particular sensitive to solar cells with narrow spectral response ranges, such as hydrogenated amorphous silicon (a-Si) solar cells, organic solar cells (OSC), and dye-sensitized solar cells (DSSC). The shapes of spectral responses are slightly different among the same kind of solar cells, because of differences in film thickness, amount of impurity or dopant, encapsulation, manufacturing process, etc. Furthermore, the shape of the spectral response of a given technology may be influenced by temperature, irradiance intensity, and voltage [2–4]. However, restrained variations in the spectral response (particularly if related to a scaling factor) should result in little change in the spectral factor (SF) or
mismatch factor (MMF), because not the absolute but the relative spectral response is used to calculate these parameters. These parameters are defined in the following section according to IEC 60904-7 and IEC 61853-3 [5, 6]. Eventually, if the conversion efficiency of a solar cell were enhanced to the upper limit, the shape of the spectral response would be likely to converge on the ideal shape. Recently, seasonal performance variations due to the impact of solar spectrum have been actively investigated in European countries [7–11].

In this study, we use the spectral responses of a c-Si and a-Si single-junction device and assume them to be representative for these two technologies. The relative spectral responses of a crystalline silicon (c-Si) module and an a-Si module are used in this study. The purpose of this study is to investigate the impact of the solar spectrum on the annual energy yield of these technologies by using two parameters. One parameter uses SF or MMF, which is an index indicating the ratio of available solar irradiance between an actual solar spectrum and the standard AM1.5G spectrum [11–21]. The other parameter uses average photon energy (APE). APE is the average energy of the photons included in a solar spectrum, indicating that the solar spectrum is “blue-rich” or “red-rich” [22–30]. Theoretically, APE would not be a unique characteristic of solar spectrum, because the shape of the solar spectrum could be complexly changed by solar altitude and atmospheric conditions such as air mass (AM), aerosol optical depth (AOD), and the amount of precipitable water (PW) [31, 32]. Therefore, we investigate the relationship between these two parameters (SF, APE) for the above mentioned technologies. The regression line or curve of SF on APE is calculated by the least-squares method. If there is a general relationship between these two parameters, the influence of the solar spectrum on the energy yield of the above mentioned technologies can be evaluated using only APE simply and easily.

**Experimental Methods**

The solar spectrum at the optimum tilt angle for south-facing solar panels has been measured by Japan Weather Association (JWA) since 2008 at four locations in Japan: ST01 (Sapporo), ST02 (Tosu), ST04 (Gifu), and ST05 (Okinoerabu), as shown in Figure 1. The optimum tilt angles are 36°, 26°, 32°, and 22°, respectively. In addition, other meteorological parameters have been monitored in parallel, including both in-plane and horizontal global solar irradiance and solar spectrum, direct solar irradiance, ambient temperature, humidity, wind direction, and velocity. The measurement and data collection systems were compiled by CLIMATEC Inc., Japan. The measurement system at the Tsukuba Center of National Institute of Advanced Industrial Science and Technology (AIST) shown in Figure 2 has been installed in year 2011 only. We investigate the solar spectra measured at the optimum tilt angle at four stations except ST03 (TKB) for 3 years from 2008 to 2010.

Solar spectra have been measured using a spectroradiometer with two measuring heads of MS-710 and MS-712 (EKO Instruments Co. Ltd., Japan), which cover the wavelength ranges from 350 to 900 nm and from 900 to 1700 nm, respectively. The measurement interval is one minute. In order to classify the solar spectra by irradiance

![Figure 1. Five locations where the various meteorological parameters have been measured by Japan Weather Association (JWA).](image-url1)

![Figure 2. Meteorological measurement station (ST03) at Advanced Industrial Science and Technology (AIST) Tsukuba Center.](image-url2)
intensity, we introduce integrated spectral irradiance (ISI) $W/m^2$, which is given by,

$$ISI = \int E(\lambda) d\lambda,$$

where $E$ is the spectral irradiance and $\lambda$ is the wavelength. The solar spectra were classified by ISI into four categories indicated in the legends of Figure 3. APE is given as follows:

$$APE = \frac{\int E(\lambda) d\lambda}{q_e \int \Phi(\lambda) d\lambda},$$

where $q_e$ is the electronic charge and $\Phi$ is the photon flux density. It should be noted that APE is different from the integrated wavelength range. The APE of the standard AM1.5G spectrum in the range between 350 and 1700 nm is approximately 1.59 eV. APE expressed in the unit of electronvolt can be also expressed as effective wavelength ($\lambda_{eff}$) in the unit of wavelength [28, 31]. SF or MMF is given by the following:

$$SF = \frac{\int SR(\lambda) E_{\text{AM1.5G}}(\lambda) d\lambda}{\int E_{\text{AM1.5G}}(\lambda) d\lambda} \frac{\int E(\lambda) d\lambda}{\int SR(\lambda) E(\lambda) d\lambda};$$

where $SR$ is the relative spectral response and $E_{\text{AM1.5G}}$ is the standard AM1.5G spectrum [33]. The number of the analyzed solar spectra is more than 700 thousand in each location.

In order to estimate the effect of the solar spectrum on the energy yield of the PV modules, we introduce effective solar irradiance ($G_{eff}$), which is solar irradiance corrected by the effect of the solar spectrum. $G_{eff}$ is given by the following:

$$G_{eff} = \frac{G}{SF},$$

where $G$ is the solar irradiance measured by a pyranometer (EKO/MS-802) at each site. $G_{eff}$ indicates $G$ corrected by the ratio of available energy in the measured solar spectrum to available energy in the AM1.5G spectrum for a technology. The calculation is conducted for the data.

Figure 3. Relationship between average photon energy (APE) and spectral factor (SF) of the c-Si photovoltaic (PV) module at each site. The solid lines indicate the regression lines calculated by the least-squares method.
The regression lines suggest that the performance of c-Si modules is only little influenced by the effect of the solar spectrum. This can be explained by the "offset effect" [21]. The range of the spectral response of c-Si modules is approximately between 350 and 1200 nm. The increase or decrease in spectral irradiance due to Rayleigh scattering at shorter wavelengths below 700 nm is considered offset by the decrease or increase in spectral irradiance due to absorption by water vapor at wavelengths around 730, 820, 930, and 1150 nm.

Figure 4 shows the relationship between APE and SF of the a-Si module at each site. As in the case of the relationship of the c-Si module, the dispersion of the SF of the a-Si module increases with decreasing ISI. The SF of the a-Si module clearly decreases with increasing APE, although the SF of the c-Si module seems to be constant for APE. The branches, which are shown by the SF of the c-Si module at APE higher than 1.8 eV, are not shown by the SF of the a-Si module. The range of the spectral response of a-Si modules is approximately between 350 and 800 nm. Because of the narrow spectral response biased toward shorter wavelength, it is well known that the performance of a-Si modules is significantly influenced by the effect of solar spectrum. The SF indicates that the performance of the a-Si module varies by about ±20% only by the effect of the solar spectrum, even at ISI higher than 400 W/m² around the latitude of Japan. Although the relationship of the c-Si module seems to be linear, the relationship of the a-Si module is not linear clearly. Consequently, we calculate the regression curves (cubic approximation) by the least-squares method.

The regression lines in Figure 3 are quite similar to each other. The regression curves in Figure 4 are also similar each other. If there is a general relationship between APE and SF of solar cells, we can determine a unique regression line or curve for a kind of solar cell. Figure 5 shows the relationship between the APE and SF of the c-Si module for all solar spectra shown in Figure 3. The regression line is given by the following:

\[
SF_{c-Si} = -0.12306APE + 1.19371
\]

Figure 6 shows the relationship between the APE and SF of the c-Si module for all solar spectra shown in Figure 4. The regression curve is given as follows:

\[
SF_{c-Si} = -11.605APE^2 + 59.894APE^2 - 103.617APE + 60.970
\]

In order to verify the above equations, we calculate the effective solar irradiation for the c-Si and a-Si modules at each site in 2008 by the direct parameter using equation (3) and by the approximate parameter using equations (5) or (6).
Figure 4. Relationship between average photon energy (APE) and spectral factor (SF) of the a-Si photovoltaic (PV) module at each site. The solid lines indicate the regression curves calculated by the least-squares method.

Figure 5. Regression line (black color) of the spectral factor (SF) of the c-Si module calculated from all data. The gray lines indicate the regression lines at each site shown in Fig. 3.

Figure 6. Regression curve (black color) of the spectral factor (SF) of the a-Si module calculated from all data. The gray curves indicate the regression lines at each site shown in Fig. 4.
Figure 7 shows the monthly solar irradiation and effective solar irradiation at the optimum tilt angle, which is estimated by the direct and approximate parameters. The approximate estimation is in good agreement with the direct estimation. The effective solar irradiation for the c-Si module is almost equal to the solar irradiation all the year around. However, the effective solar irradiation for the a-Si module is higher and lower than the solar irradiance at Sapporo (Fig. 7A), Tosu (Fig. 7B), and Gifu (Fig. 7C) in summer and winter, respectively. Exceptionally, the effective solar irradiation for the a-Si module is always higher than the solar irradiance at Okinoerabu (Fig. 7D), which is located in the south of Japan.

Finally, we estimate the annual effective solar irradiation. Figure 8 shows the annual average ambient temperature versus the annual solar irradiation or effective solar irradiation at the optimum tilt angle in 2008. The annual effective solar irradiation for the a-Si module at Okinoerabu is larger than that at Gifu, although the solar irradiation at Okinoerabu is smaller than that at Gifu. Table 1 shows the net effect of the solar spectrum on the annual energy yield of the c-Si and a-Si modules at each site. The results indicate that solar spectrum has little influence on the annual energy yield of the c-Si module. On the other hand, the spectral influence on the annual energy yield of the a-Si module increases with decreasing latitude. The effect of the solar spectrum would enhance the annual energy yield of a-Si modules by about 8% at Okinoerabu. The approximate estimation is in very good agreement with the direct estimation, whereas there is 1.2% difference between the estimations at most. As such, APE would be a useful index to quantify the effect of solar spectrum on the energy yield of PV systems simply and easily.

Conclusions
In this study, we estimated the net effect of solar spectrum on the annual energy yield of PV modules by two
parameters. The investigated data set of solar spectrum had been measured by JWA at four stations (Sapporo, Tosu, Gifu, and Okinoerabu) from 2008 to 2010. One parameter used the SF or MMF, which was directly calculated according to the definition in IEC 61853-3. We used APE for the other parameter. The relationship between APE and SF of c-Si and a-Si modules was investigated as the regression lines or curves by the least-squares method at each station. The results suggest that both regression lines and curves were almost similar among all stations. Consequently, we calculated the common regression line or curve for all stations from all solar spectra. The SF of the c-Si and a-Si modules was simply estimated as a function of APE using the common regression line or curve in the other parameter.

The effective solar irradiance of the c-Si and a-Si modules was calculated for the data set in 2008, in order to confirm the difference between the estimations by these parameters. The monthly effective solar irradiation estimated by the approximate parameter is in good agreement with that estimated by the direct parameter. Furthermore, the annual effective solar irradiation estimated by the approximate parameter is in very good agreement with that estimated by the direct parameter. As such, APE would be a useful index to estimate the effect of solar spectrum on the energy yield of PV modules simply and easily. As future work, it would be important to confirm whether the approximate parameter can be applicable to different climate regions, such as tropical or desert climate.

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Conflict of Interest

None declared.

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