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Worldwide analysis of spectral factors for seven photovoltaic technologies

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ABSTRACT

This work presents a worldwide analysis of the PV spectral factor for seven different PV technologies including crystalline silicon and thin film modules. The annual spectral factor for the analyzed technologies is evaluated at 124 sites which cover widely the most important climatic zones. This dataset allows determining the spatial and geographical distribution of the spectral gains/losses with respect to reference conditions for the analyzed PV technologies. The spectral factors are computed from hourly global tilted spectral irradiances for a whole year using the SMARTS2 spectral solar radiation model with atmospheric inputs from the MACC reanalysis dataset. Overall, it is found that the annual spectral factor for crystalline silicon technologies is rather homogenous worldwide with maxima spectral losses and gains of ≈3% and ≈1%, respectively. The annual spectral factor for thin film devices, on the contrary, displays a latitudinal pattern with spectral losses mainly occurring in northern hemisphere locations and spectral gains occurring in tropical zones. Both spectral gains and losses may reach up to ≈10% in the case of amorphous silicon devices. The correlation analysis between average photon energy (APE) and spectral factor shows high correlation values for thin film devices. However, the data dispersion is large, which discourages the use of APE as a measure of the spectral performance of PV systems.

1. Introduction

Solar energy generation using photovoltaic (PV) technologies is continuously increasing worldwide with steep growing trends foreseen for the upcoming years (International Energy Agency, 2015). In this framework of growth, the bankability of PV technologies is getting more and more interest. The main factors influencing the energy yield of PV systems, and consequently in some bankability aspects, are the plane-of-array (POA) solar irradiance, the type of system (e.g. open rack modules on PV plants, building-integrated systems, etc.), module temperature and the solar spectrum. The efficiency of PV modules is evaluated, mainly at laboratory and manufacturing level, under the so called standard test conditions (STC), which refer to 1000 W m^{-2} of incident solar irradiance on the POA with spectral given by the global AM1.5 reference spectrum (ASTM G173(03), 2012, Gueymard et al., 2002; IEC 60904-3, 2016), for optical air mass 1.5 and module temperature of 25 °C. Normal operation of PV modules usually differs from STC, working over a wide range of temperatures, irradiance, and spectra. For this reason, alternative operating conditions and approaches have been considered for rating the performance and the annual production of PV modules in the field (ASTM E2939-13, 2013; Emery, 2003; IEC 61853-1, 2011; IEC 61853-2, 2016; Wohlgemuth, 2012). For example, in the IEC 61853 standards, the PV module output must be measured at 23 different sets of temperature and irradiance conditions, using either a solar simulator (indoor) or natural sunlight (outdoor).

Since the spectrum of the incident solar irradiance under outdoor conditions very rarely matches the assumed spectrum under STC, the efficiency values determined under STC do not account for the variations of the actual solar irradiance spectrum with respect to the AM1.5 standard spectrum. These spectrum-related mismatches are overall referred to as spectral mismatch error. PV module parameter mainly affected by a varying spectral distribution is the short-circuit current but, additionally, maximum power, fill factor and efficiency could also become altered for some technologies (as for amorphous silicon and multijunction solar cells).

Spectral errors can be analyzed by measuring the incident spectral irradiance and computing the spectral mismatch factor or spectral factor (hereinafter referred to as SF) for the PV system. There are several works and studies where local solar spectra have been measured in campaigns with field spectroradiometers for determining the spectral factor (Alonso-Abella et al., 2014;

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Eltbaakh et al., 2013; Fernández et al., 2014; Ishii et al., 2011; Minemoto et al., 2009a, 2007; Nofuentes et al., 2014; Okullo et al., 2011; Pérez-López et al., 2007; Senthilarasu et al., 2015; Sirisamphanwong and Ketjoy, 2012). However, this observational spectral information is seldom available and typically restricted to short measurement campaigns with observations frequently over the horizontal surface (eventually over the POA). An alternative methodology that can be used when local experimental spectral information is not available consists of modeling the incident spectra with a radiative transfer model. A recent study using experimental atmospheric information from 34 AERONET stations has been performed for multijunction solar cells typically used in concentrated photovoltaic (Núñez et al., 2016). Radiative transfer models are generally complex and they are normally used in the atmospheric physics community. In particular, clear-sky spectral transmittance models such as SMARTS2 (Simple Model of the Atmospheric Radiative Transfer of Sunshine) can be very appropriate and useful for being used in PV spectral studies due to: its proved accuracy as long as detailed and accurate input data is provided, much faster execution times compared to more detailed radiative transfer models, and the capability of calculate global tilted spectral irradiance (Gueymard, 2008, 2005, 2001). In fact, reference spectral distributions used by the PV community are synthetically generated by SMARTS2 model for a particular set of input parameters characterizing some typical atmospheric conditions that fits the reference standard global spectrum (IEC 60904-3, 2016). Evaluating SF only from clear-sky situations may be argued as a limitation (which actually is). However, most cloudy situations reduce drastically the PV yield which, however, peaks under clear-sky conditions. Thus, clear-sky situations become arguably more relevant than cloudy situations for the overall system's performance under actual operating conditions. In addition, for solar radiation wavelengths below ≈1 μm the relative spectral response of most PV cells is the highest while the spectral response of clouds is rather flat and thus of little spectral influence (Ruiz-Arias and Gueymard, 2015). On the contrary, the spectral extinction of solar radiation by atmospheric aerosols, which are the critical atmospheric constituent under clear-sky conditions, is monotonic throughout the entire short wave spectral range, being particularly steep below ≈1 μm over polluted areas (Ruiz-Arias and Gueymard, 2015).

The results that come from experimental campaigns are not thoroughly intercomparable because they come from different regions and time-scales but, in general, they qualitatively state the influence of varying spectral irradiance on the performance of a PV device and remark the dependence of the spectral impact on the local conditions (latitude, longitude, climate, etc.), although this assessment has not been demonstrated quantitatively (Dirnberger et al., 2015a,b). Several authors have used the APE (Average Photon Energy) index as a characteristic signature of the spectrum to investigate correlations with the spectral factor (Cornaro and Andreotti, 2012; Ishii et al., 2013; Nofuentes et al., 2014). APE is thus a meaningful index as indicator of some characteristics of the spectrum and its uniqueness was statistically studied for evaluating outdoor performance of PV modules (Minemoto et al., 2009b); however other studies question and doubt the convenience of this index for the evaluation of PV performance (Gueymard, 2009). Nevertheless, higher correlation between the spectral factor and APE has been observed by several authors for thin film devices since their narrower spectral response make them more sensitive to spectral variations (Ishii et al., 2013, 2011; Minemoto et al., 2009a, 2007; Nofuentes et al., 2014).

This work presents estimations of the spectral factor for 124 worldwide sites uniformly distributed according to the different climatic zones for several PV technologies and shows geographical distribution of the annual spectral factor for seven different PV devices. The solar spectrum at every site has been computed with SMARTS2 model at hourly basis for a whole year. The APE index has also been estimated from the computed spectra and its correlation with the spectral factors is investigated for the different PV technologies.

2. Spectral factor and average photon energy

The SF describes the relative performance of a PV module operated under the STC spectrum with respect to its performance under arbitrary incident solar irradiance. It can be used therefore as an estimation of the relative energetic gain or loss due to the actual spectral differences from the standard conditions for a particular device. The SF originates from the so-called mismatch factor MM, an important parameter used for adequate primary and secondary calibration of solar cells and for measurements of different PV devices under spectral distributions apart from the reference conditions or when adjusting solar simulator's irradiance. The SF is defined by the IEC (International Electrotechnical Commission) as (IEC 60904-7, 2008):

$$SF = \frac{\int E(\lambda)SR(\lambda)d\lambda \int E_{ref}(\lambda)d\lambda}{\int E_{ref}(\lambda)SR(\lambda)d\lambda \int E(\lambda)d\lambda} \tag{1}$$

where E_{ref} (W m^{-2} nm^{-1}) is the spectral irradiance of the standard reference spectrum, E (W m^{-2} nm^{-1}) is the actual incident spectral irradiance, and SR is the relative spectral responsivity of the PV module. Therefore, according to the definition and Eq. (1) SF values higher than 1 mean spectral gain and values lower than 1 indicate spectral loss from standard conditions. The short circuit current of a PV module is proportional to the product of the spectral irradiance and the normalized spectral responsivity of the module integrated over the wavelength range,

$$I_{sc} \propto \int E(\lambda)SR(\lambda)d\lambda \tag{2}$$

Therefore, the spectral factor in Eq. (1) may be rewritten in a simpler way as (Alonso-Abella et al., 2014; Andrews and Pearce, 2013),

$$SF = \frac{I_{sc}G^*}{I_{sc}^*G} \tag{3}$$

where G is the incident broadband irradiance and the asterisk denotes standard or reference conditions. Taking into account that $I_{sc}{}^*$ and G^* are constant in time (when devices are linear with irradiance and polarization and temperature effects are disregarded), the Eq. (2) can be easily modified to estimate the SF for a period of time which would give information on the spectral gains or losses along that period (i.e. monthly or annual basis). Thus the expression for the cumulative monthly or annual estimations for the spectral factor, SF_m and SF_a respectively, are (Alonso-Abella et al., 2014):

$$SF_{time} = \frac{G^*\sum_i I_{sc}}{I_{sc}^*\sum_i G} = \frac{G^*\sum_i \int E(\lambda)SR(\lambda)d\lambda}{I_{sc}^*\sum_i \int E(\lambda)d\lambda} \tag{4}$$

where time refers to a period of time (month or year) and i indicates all the values within the specified time period.

On the other hand, APE index is defined as the average energy per photon of the spectrum and can be estimated by,

$$APE(eV) = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda)d\lambda}{q\int_{\lambda_1}^{\lambda_2} \phi(\lambda)d\lambda} \tag{5}$$

where q is the electronic charge (1 eV), E is the spectral irradiance and ϕ the photon spectral flux density. The photon spectral flux density is defined as,