Comparative assessment of simplified indexes for the spectral characterisation of photovoltaic systems

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ABSTRACT

The electrical output of a photovoltaic system is often related to the plane-of-array global irradiance and the cell operating temperature. However, the spectral distribution of the irradiance also influences the system electrical behaviour, through its coupling with the spectral response of the photovoltaic material employed. Many authors have evaluated the spectral performance of different types of semiconductors under real operating conditions worldwide by using different methods and spectral indexes. However, there are not comparative studies on the accuracy of these methods in the literature. In this paper, two simplified existing indexes and a novel introduced index are compared to the spectral factor method in order to assess their relative accuracy for the climate of Granada, Southern Spain, and considering the most widespread used photovoltaic materials. Results show the election of a suitable index depends on the type of material, availability of spectral response information of the material, computing capabilities and required accuracy. The maximum annual relative error with respect to the spectral factor considering every index and material is 1.77%, while the maximum monthly relative error can reach 4.22%.

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1. Introduction

It is well known that the spectrum of the incident light affects the electrical response of a photovoltaic (PV) device [1–3]. Because of this, the scientific community has agreed on a standard spectral irradiance, which is used as reference for the power rating of the PV modules under the so-called Standard Test Conditions (STC). These reference spectra were adopted based on detailed spectral models and knowledge of the extinction processes that occur in the atmosphere [4]. Fig. 1 shows the global (for terrestrial non-concentrating PV applications) and direct (for terrestrial concentrating PV applications) standard spectra as defined by the American Society for Testing and Materials (ASTM) [5]. However, the terrestrial standard spectra rarely occur in real outdoor operating conditions, where the changing atmospheric conditions modify the incident spectrum over the day and throughout different seasons of the year. Because of this, the spectral behaviour of a PV device can differ from that observed under the normalized operating conditions. This highlights the importance of the spectral

characterization of the PV materials, which has implications in the long-term energy harvesting of the PV systems [6–8].

In the last decades, many authors proposed different methods for quantifying the spectral influences on different PV materials. Several spectral indexes were defined and different measuring equipment and experimental set-ups were used for the study of the spectral behavior under particular outdoor conditions (power analysis) or under long-term studies (energy analysis). The common set-up includes the use of a spectroradiometer and a reference pyranometer. The main difficulty found was related to the need of periodic maintenance and calibration of the spectroradiometer, when dealing with long-term energy studies. Another difficulty is the need of knowing the Spectral Response (*SR*) function of the PV material, which is not often provided by the manufacturers and requires a special and expensive experimental set-up to be measured for a specific solar cell. Basically, this set-up filters a wide-spectrum light source into a discrete succession of narrow spectral bands, each of which is directed onto the test device. The measurement of the solar cell short-circuit current under the monochromatic light allows the *SR* to be obtained for a specific wavelength [9,10]. Some other alternatives have been proposed in order to avoid these difficulties. For instance, the direct

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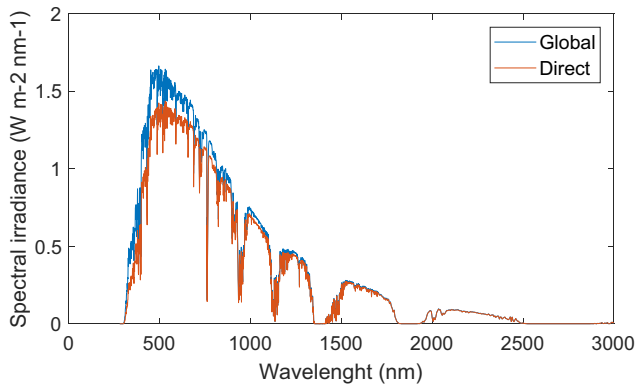**Fig. 1.** Global and direct standard spectra as defined by the American Society for Testing and Materials [5].

Fig. 2. Normalized spectral response of the five kinds of PV materials analysed in this work.

measurement of the solar cell short-circuit current can avoid the use of a spectroradiometer and the need of the *SR* function, but temperature effects, and especially angle-of-incidence effects, can disturb the measured current and create uncertainty and vagueness when quantifying spectral gains or losses with respect to the reference spectrum [11].

In this paper, an overview of fundamental concepts related to the spectral characterisation of PV devices is presented and three indexes available in the literature for the PV energetic spectral evaluation are reviewed (Weighted Average Spectral Factor, *<SF>*, Spectral Enhancement Factor, *SEF*, and, Integrated Useful Fraction Ratio, *IUF/IUF**). From this preliminary analysis, it appears clearly that a simpler index can be proposed. This new index, which has never been used in the literature, is defined and named as Spectral Average Useful Fraction (*SAUF*). Furthermore, a comparative assessment of the three simplified indexes (*SEF*, *IUF/IUF**, and *SAUF*) with respect to the *<SF>*, which is taken as reference index, under the real spectral conditions of Granada, Southern Spain, is carried out for five different PV materials (monocrystalline silicon, m-Si, polycrystalline silicon, p-Si, amorphous silicon, a-Si, cadmium telluride, CdTe, and, copper indium gallium selenide, CIGS). In this comparative study, the *<SF>* index is adopted as reference because of its proven ability to accurately quantify the spectral gains or losses when compared to the reference spectrum. The other simplified indexes present some advantages for their use that will be analysed in the subsequent sections. However, it is worth mentioning that the relative accuracy of these simplified indexes has not yet been evaluated in the literature under the same operating conditions, so the presented comparative assessment can be considered an interesting contribution to the field.

The rest of the paper is structured as follows: in Section 2, the fundamentals of the spectral characterisation of PV materials are outlined; in Section 3, the three available spectral indexes (*<SF>*, *SEF* and *IUF/IUF**) are formulated and reviewed; in Section 4, the new index (*SAUF*) is defined and justified; in Section 5, the sources of spectral data for Granada used in the study are presented; Section 6 shows and discusses the results of the comparative assessment; finally, Section 7 presents the conclusions of the work.

2. Spectral characterisation of PV materials

In order to understand the conversion of photons to electricity in a PV material, the *SR* characteristic function of the material is commonly used. The *SR* function is defined as the amperes generated by a solar cell in short-circuit per watt of incident light of a given wavelength. Fig. 2 shows typical normalized *SR* functions for some of the most widespread PV materials employed
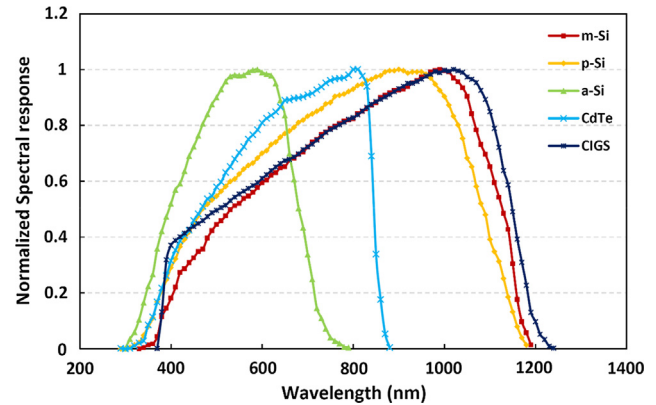
nowadays, i.e. those analysed in this study. The normalized *SR* is obtained for each material as the ratio of the *SR* function to the maximum value of the *SR* function, i.e. the normalized *SR* function reaches its maximum at unity. Normalized values are usually used to represent the *SR* because they allow an easier comparison between different PV materials. As can be seen in the figure, different PV materials have different absorption limits, i.e. photons of higher wavelength than this limit cannot be absorbed and transformed to electricity. This absorption limit is related to the material band-gap. Low band-gap semiconductors, such as m-Si, p-Si or CIGS, show a high absorption limit of around 1200 nm, and vice versa high band-gap semiconductors, such as a-Si or CdTe, show a low absorption limit of around 800–900 nm.

The electrical behavior of a given solar cell will change depending on the coupling of the material *SR* function and the incident spectral irradiance. The spectral irradiance varies with the atmospheric conditions because of scattering and absorption phenomena. This attenuation depends on the amount of substance traversed by the solar rays in their course through the atmosphere and on the optical properties of the different atmospheric constituents. Three main weather variables have been identified as determinant for characterising the spectral irradiance at a given instant: air mass (*AM*), aerosol optical depth (*AOD*) and precipitable water (*PW*) [12,13]. The *AM* parameter quantifies the increase of the amount of substance traversed by the sun rays with respect to a vertical trajectory and can be calculated form the sun's zenith angle. The presence of aerosols in the atmosphere (small particles suspended in the air either in solid or liquid state with different sizes and optical properties) causes an attenuation of the spectral irradiance, which can be represented by the *AOD* parameter. The *PW* parameter is used to account for the presence of water vapor in the atmosphere, understood as the volume of liquid water that would be obtained if all the water vapor aloft was condensed. The three parameters are variable over space and time (both daily and seasonally). The change of each one of these parameters will affect the spectral irradiance in a different form as discussed below.

First, the increase of *AM* produces a strong attenuation on the ultraviolet region of the spectrum, and therefore, a red-shift of the spectral distribution. *AM* increases when the sun rays traverse a longer trajectory through the atmosphere, i.e. at sunrise and sunset periods (daily variation), at winter seasons (seasonally variation) and in high latitudes (spatial variation). Second, the increase of *AOD* produces an appreciable attenuation on the ultraviolet–visible region of the spectrum, and therefore, a red-shift of the spectral distribution. *AOD* increases with the amount of aerosols in the atmosphere, for instance due to suspended dust, pollen