Definition of a Simple Index for the Spectral Characterization 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 behavior, through its coupling with the spectral response of the photovoltaic material employed. Since early in the 1990s, many authors have evaluated the spectral performance of different types of semiconductors under real operating conditions worldwide. For this purpose, different methods and indexes have been proposed. In this paper, the fundamentals of the spectral characterization of the photovoltaic materials are introduced and 3 available spectral indexes are reviewed. The analysis of the advantages and disadvantages of these indexes leads to the definition of a simple index, which has never been used in the literature. This index, named as Spectral Average Useful Fraction, could be suitable for a quick spectral evaluation of a photovoltaic system with the only requirement of knowing the average incident spectrum of the site and the absorption limit of the photovoltaic material. An extensive comparison with the 3 available indexes should be carried out in order to assess the usefulness of the proposed index. This will be the object of future works.**

***Index Terms*—Photovoltaic materials, outdoor performance, spectral characterization, spectral index.**

I. Introduction

It is well known that the spectrum of the incident light affects the electrical response of a photovoltaic (PV) device. Because of this, the scientific community has agreed 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 [1]. Figure 1 shows the extraterrestrial (for space PV applications), 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). However, the terrestrial standard spectra rarely happen in real outdoor operating conditions, where the changing atmospheric conditions modify the incident spectrum over the day and season of the year. Because of this, the spectral behavior 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 [2, 3, 4].

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. Some other alternatives have been proposed in order to avoid these difficulties. For instance, the direct 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 [5].

In this paper, an overview of fundamental concepts related to the spectral characterization of PV devices is presented in section II. Section III reviews three spectral indexes existing in

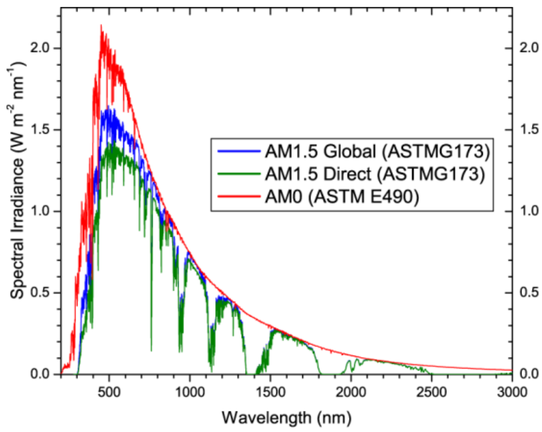

Fig. 1. Standard spectra (AM0 extraterrestrial, AM1.5 global and AM1.5 direct) as defined by the American Society for Testing and Materials (ASTM). Source: [16]

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the literature and analyzes the characteristics of each one, together with the advantages and disadvantages for their use. From this analysis, it appears clearly that a simpler index can be proposed. This new index, which has never been used in the literature, is defined in section IV. Section V details the conclusions of the work. This study can be considered as a first step in the development of a new method for the spectral characterization of PV devices and gives the key concepts for the future experimental validation of the proposed method.

II. Spectral Characterization 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. Figure 2 shows typical normalized *SR* functions for some of the most widespread PV materials employed nowadays. 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 with the material band-gap. Low band-gap semiconductors, such as mono-crystalline silicon, poly-crystalline silicon or copper indium gallium selenide, show a high absorption limit of around 1200 nm, and vice versa high band-gap semiconductors, such as amorphous silicon or cadmium telluride, 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 characterizing the spectral irradiance at a given instant: air mass (*AM*), aerosol

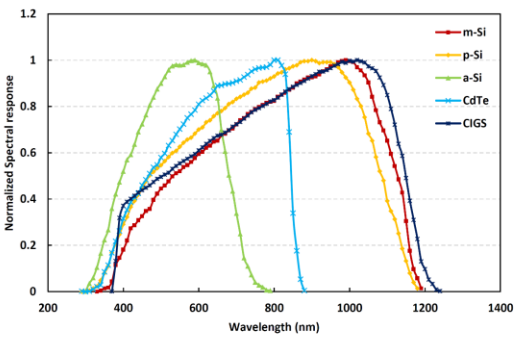

Fig. 2. Typical normalized Spectral Response of 5 types of PV materials. m-Si: mono-crystalline silicon; p-Si: poly-crystalline silicon; a-Si: amorphous silicon; CdTe: cadmium telluride; CIGS: copper indium gallium selenide.

optical depth (*AOD*) and precipitable water (*PW*) [6, 7]. 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 is 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 or pollution. Third, the increase of *PW* produces a significant attenuation on the near-infrared region of the spectrum, and therefore, a blue-shift of the spectral distribution. *PW* increases with the amount of water vapor in the atmosphere, for instance in maritime climates.

The change in these weather variables, and the corresponding change in the spectral irradiance, affects the electrical behavior of the PV devices, but this influence is not the same for every PV material. Here is when the characteristic *SR* function of the material plays its role. Basically, the coupling between the *SR* and the spectrum can be described as a function of the material band-gap. The following conclusions can be extracted [5]:

- The materials with low energy-gap are quite stable with respect to changes in *AM* and *AOD*. In contrast, the materials with high energy-gap show a worse spectral behavior as *AM* or *AOD* increases.
- The materials with low energy-gap are also quite stable with respect to changes in *PW*. In contrast, the materials with high energy-gap show a better spectral behavior as *PW* increases.

Therefore, the spectral influences are much more important in materials with high energy-gap, such as amorphous silicon or cadmium telluride. Because of this, the research on spectral characterization has mainly focused in these materials. Common crystalline silicon devices have shown, in contrast, much lower concerns with respect to their spectral behavior.

III. Review of Spectral Indexes

Many indexes have been proposed in the scientific literature for the spectral characterization of PV materials [5].

Among them, in this section, we focus on three important indexes, which will allow a new index to be defined. These three indexes are: the weighted average spectral factor (<*SF*>), the spectral enhancement factor (*SEF*) and the integrated useful fraction ratio (*IUF/IUF**). All of these indexes can be classified in the category of energetic spectral indexes for flat-plate PV devices. The "energetic" term alludes that the indexes try to quantify energy spectral gains or losses over a period of time, i.e. energy gains or losses with respect to an ideal situation in which the reference spectrum was verified at any instant. Index values greater than unity mean the PV device showed energy spectral gains with respect to the reference spectrum over the period of analysis, while values lower than unity mean the PV device showed energy spectral losses.

A. Weighted Average Spectral Factor

The instantaneous index named as Spectral Factor (SF) can be defined as [8, 9, 10, 11]:

$$SF = \frac{\int E(\lambda)SR(\lambda)d\lambda}{\int E^*(\lambda)SR(\lambda)d\lambda} \cdot \frac{G^*}{G} \quad (1)$$

Where $SR(\lambda)$ is the Spectral Response of the PV device, $E(\lambda)$ is the actual incident spectrum, G is the broadband global irradiance, $E^*(\lambda)$ is the reference spectrum and G^* is the reference global irradiance. From this index, the energetic index named as Weighted Average Spectral Factor (<*SF*>) is obtained by weighting the instantaneous SF_i values with the broadband irradiance G_i over a period of time:

$$\langle SF \rangle = \frac{\sum_i G_i SF_i}{\sum_i G_i} \quad (2)$$

The <*SF*> index has the advantage that, if properly measured, it provides a very accurate quantification of the energy spectral gains or losses with respect to the reference spectrum. However, it has two important drawbacks: first, the $SR(\lambda)$ must be known for the PV device, but this information is not often provided by the manufacturers and requires a complex experimental set-up to be measured; second, the index requires extensive computation in order to solve the convolution integral $\int E(\lambda)SR(\lambda)d\lambda$ at each time step.

B. Spectral Enhancement Factor

The Spectral Enhancement Factor (*SEF*) index is an energetic index that tries to avoid the difficult calculation of the mentioned convolution integral over time. It is defined as [12, 13]:

$$SEF = \frac{\int \langle E(\lambda) \rangle SR(\lambda)d\lambda}{\int E^*(\lambda)SR(\lambda)d\lambda} \cdot \frac{G^*}{G_{av}} \quad (3)$$

Where $\langle E(\lambda) \rangle$ is average incident spectrum (obtained by weighting the instantaneous $E_i(\lambda)$ values with the broadband irradiance G_i over the period of analysis), and G_{av} is the average irradiance over the period of analysis. As can be seen, with this index, the convolution integral is solved only once, instead of solving it at each time step. This makes easier the calculation. However, the $SR(\lambda)$ of the material must be known. Also, the relative accuracy of this index with respect to the <*SF*> has not yet been evaluated in the literature.

C. Integrated Useful Fraction Ratio

The instantaneous index named as Useful Fraction (*UF*) is defined as [14, 15]:

$$UF = \frac{\int_{\lambda<\lambda_o} E(\lambda)d\lambda}{G} \quad (4)$$

Where λ_o is the limit wavelength at which the absorption takes place in the PV material, i.e. the absorption limit. Figure 3 shows typical absorption limits of some PV materials and how they match the reference spectrum. The ratio of this index to the same index evaluated at the reference spectrum can be named as Useful Fraction Ratio (*UF/UF**):

$$UF/UF^* = \frac{\int_{\lambda<\lambda_o} E(\lambda)d\lambda}{\int_{\lambda<\lambda_o} E^*(\lambda)d\lambda} \cdot \frac{G^*}{G} \quad (5)$$

As can be seen, the *UF/UF** index is equivalent to the *SF* index by assuming flat Spectral Response for $\lambda<\lambda_o$ and zero Spectral Response for $\lambda \geq \lambda_o$. Thus, it is an approach that avoids the need of knowing the Spectral Response Function of the PV material. From this index, the energetic index named as Integrated Useful Fraction Ratio (*IUF/IUF**) can be obtained by weighting the instantaneous $(UF/UF^*)_i$ values with the broadband irradiance G_i over a period of time:

$$IUF/IUF^* = \frac{\sum_i G_i (UF/UF^*)_i}{\sum_i G_i} \quad (6)$$

The main advantage of this index is that it avoids the need of knowing the *SR* function. However, extensive computation is required to solve the integral $\int_{\lambda<\lambda_o} E(\lambda)d\lambda$ at each time step.

IV. Definition of the New Index

Table I summarizes the characteristics of the reviewed spectral indexes together with the desired characteristics of the

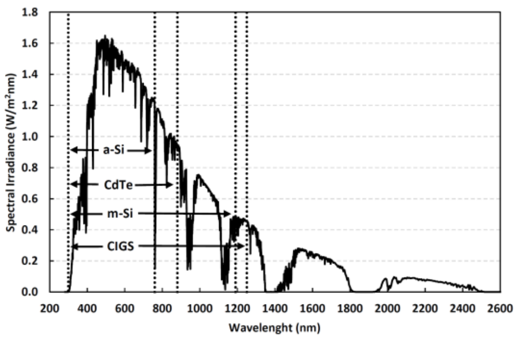

Fig. 3. Spectral absorption band of 4 types of PV materials. m-Si: mono-crystalline silicon; a-Si: amorphous silicon; CdTe: cadmium telluride; CIGS: copper indium gallium selenide.

new index that is going to be defined. As can be seen, the most accurate index is the *<SF>*, but it is also the most complex to be obtained. *SEF* and *IUF/IUF** are simplifications that avoid the extensive calculation in the first case, and the need of the *SR* function in the second case. However, the desired characteristics for the new index are both easiness of calculation and no need of the *SR* function of the material.

TABLE I. CHARACTERISTICS OF THE REVIEWED INDEXES AND OF THE NEW INDEX

Characteristic	**<SF>**	**SEF**	**IUF/IUF***	**New index**
Requires the SR function	Yes	Yes	No	No
Requires extensive computation	Yes	No	Yes	No

In order to obtain the desired characteristics, a new index can be defined, which will be named as Spectral Average Useful Fraction (SAUF), as:

$$SAUF = \frac{\int_{\lambda<\lambda_o} \langle E(\lambda)\rangle d\lambda}{\int_{\lambda<\lambda_o} E^*(\lambda) d\lambda} \cdot \frac{G^*}{G_{av}} \qquad (7)$$

With this index, the easiness of calculation is achieved as the integral must be solved only once, and the need of the *SR* function is avoided by replacing it by the absorption limit of the PV material. So, this is a very simple index that was not used in the previous literature and could be very helpful for a quick spectral characterization of different PV materials under different climatic conditions worldwide. The only requirements of the index are knowledge of the average incident spectrum for the site and of the material absorption limit.

V. CONCLUSIONS

Although many authors have proposed indexes and methods for the spectral characterization of PV systems, there is not a universal index that offers all the advantages in every specific context. The choice of a suitable index depends on different factors, such as the availability of data regarding the analyzed PV material, the availability of sources of climatic data or the available experimental set-up. Thus, it is good to have as many alternatives as possible for the analysis in order to choose the most appropriate in each case. The new index proposed in this paper has the advantage of simplicity, only requiring knowledge of the absorption limit of the analyzed PV material and of the average incident spectrum for the site. It could be used for extensive spectral analysis around the world due to its easiness of calculation. However, prior to this, the relative accuracy of the index should be experimentally validated. The comparison of different indexes under the same experimental conditions opens an interesting research line, and will be the object of future works.

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