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Spectral-matching-ratio modelling based on ANNs and atmospheric parameters for the electrical characterization of multi-junction concentrator PV systems

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A B S T R A C T

One of the most critical issues to evaluate the performance of multi-junction (MJ) concentrator photovoltaic (CPV) systems is related to its spectral dependence. The spectral matching ratio (SMR) index is nowadays widely used to evaluate the spectral impact on CPV systems. The limitation of the present models devoted to estimating the SMR is related to the difficulty of obtaining high-quality data of aerosols and water vapour. This paper aims to fill this gap by introducing a novel approach based on commonly available variables in atmospheric stations and/or databases. In particular, the impact of aerosols has been quantified trough the ratio DNI/GNI (i.e. direct and global normal irradiances), while the impact of water vapour has been quantified through the air temperature (T_{air}) and relative humidity (H_r). Due to the complexity for finding appropriate relationships between these variables and the SMR indexes, an artificial neural network (ANN)-based model has been used. The model shows a high quality in the evaluation of the spectral performance of MJ CPV systems through the estimation of the SMR indexes, with a correlation coefficient ranging from 0.79 to 0.98, a Root Mean Square Error ranging from 2.32% to 4.32% and a Mean Bias Error around 0%.

1. Introduction

Concentrator photovoltaics (CPV) aims to decrease the cost of solar electricity by reducing the amount of expensive semiconductor materials by mounting less expensive concentrator optics. Although there is still room for improvements, this technology has already shown promising results for cost reduction and large scale deployment at locations with high energy solar resource [1,2]. The concentrator module is the fundamental unit of CPV systems to convert the un-concentrated sunlight into electricity. Among the different elements, the solar cell is the key element to achieve the high efficiencies of this technology, i.e. > 30% at module and >40% at cell level [3,4]. Nowadays, these cells widely consist of multi-junction (MJ) chips made up of several p-n junctions interconnected in series, usually a GaInP/GaInAs/Ge structure, with the aim of maximizing the spectral absorption of the irradiance as much as possible. These cells are expensive, therefore concentrator modules also include an optical assembly usually based on a primary optical element (POE) and a secondary optical element (SOE) per solar receiver [5]. The POE is intended to concentrate the irradiance, while the SOE seeks to homogenize the concentrated sunlight over the solar cell surface and to improve the acceptance angle of the module [6]. In addition, the CPV modules usually employ a passive cooling mechanism for avoiding overheating of the solar cells based on a flat back plate or finned heat-sink due to its simplicity and reliability [7].

One of the most critical issues to evaluate the performance of CPV technology is related to its spectral dependence [8,9]. The use of MJ solar cells based on the internal series connection of several subcells with different energy gaps makes these systems much more sensitive to the incident solar spectrum than conventional single-junction PV technology [10–12]. In addition, the use of high

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concentrator optics modifies the spectral distribution of the incident sunlight and limits the systems to only convert into electricity the direct irradiance, which is much more sensitive than the global spectral irradiance [13,14]. As a consequence, MJ-based CPV systems could present annual energy losses up to 30% depending on the spectral conditions of the site considered and/or the band-gap combination of the semiconductors [15,16]. This strongly spectral dependence has proven a noteworthy impact on the levelised cost of electricity (LCOE) and could lead to failed CPV installations at unsuitable spectral locations [17]. Hence, the CPV community have devoted important efforts to evaluate and develop methods to quantify the spectral effects of CPV tailored to the special features of such technology [18].

The spectral matching ratio (SMR) is nowadays widely considered as one of the most suitable metrics for evaluating the spectral impact of MJ-based CPV [19]. Indeed, this index has recently been adopted in the final version of IEC 62670−3 [20,21]. The SMR presents a way of quantifying the relative spectral impact between two subcells in a multi-junction solar cell, with the aim to assess the input direct spectral distribution. The SMR is usually obtained by direct measurements gathered with the so-called component or isotype solar cells [22]. However, although the spectral evaluation based on isotype cells is robust and simple, this approach does not allow the spectral evaluation of CPV systems at any desired location to be conducted; it is not possible to have a sensor at any site worldwide [18]. Hence, different methods to predict the SMR from atmospheric parameters have recently been proposed [23,24]. These methods are based on analytical equations, function of the air mass, the aerosol optical depth and the precipitable water. At the same time, the limitation of these methods is related to the difficulty of obtaining high-quality data of aerosols and water vapour. The AERONET (Aerosol Robotic Network) program is a federation of ground-based sun photometer sensors established by NASA and PHOTONS which started in the early 1990s [25]. It offers unique measurements of aerosol optical depth, water vapour and other relevant atmospheric parameters at 350 remote sites. In this sense, the majority of the studies concerning the spectral evaluation of CPV systems are based on observations carried out at some of the AERONET sites [13,15,16,23,26,27].

As was mentioned, there are only two existing papers that express the SMR indexes as a function of air mass, aerosol optical depth and precipitable water [23,24]. These studies characterize the SMRs by linear combinations of the three mentioned variables and some of their interactions. In Ref. [23], the SMR of the top junction with respect to the middle junction is expressed as a linear combination of the three variables and the interaction between air mass and aerosol optical depth, while the SMR of the middle junction with respect to the bottom junction is expressed as a linear combination of aerosol optical depth and precipitable water, together with the interaction of both. In Ref. [24], a more in depth regression analysis is carried out to select the most suitable functions able to predict the SMR indexes. This way, the SMR of the top junction with respect to the middle junction is expressed as a linear combination of air mass, precipitable water and the interaction of air mass and aerosol optical depth; the SMR of the middle junction with respect to the bottom junction is expressed as a linear combination of precipitable water and two interactions of aerosol optical depth with air mass and precipitable water respectively; and, the SMR of the top junction with respect to the bottom junction is expressed in the same form as the SMR of the top junction with respect to the middle junction. These linear combinations of variables have proven to be suitable for the characterization of the SMR indexes, with root mean square errors ranging from 5.96% to 7.08% for the experimental datasets considered.

Although the models descried above allow the direct estimation of the SMR indexes at the AERONET locations, it is still not possible to approximate this metric at any desired location and to consider the effect of aerosols and water vapour. Thus, currently it is not possible to evaluate the spectral behaviour of MJ-based CPV systems at any desired location. The intention of this study is to fill this gap by introducing a novel approach. In particular, the effects of turbidity and precipitable water are approximated by using other variables easier to obtain in common atmospheric data sources, i.e. direct and global normal irradiances, air temperature and humidity. In addition, due to the complexity in finding the relationships between the input parameters and the SMRs of a MJ solar cell, an artificial neural network based model is proposed. Section 2 explains the formulation of the SMR indexes and justify the variables proposed in this study. The experimental campaign carried out for validating the model developed is described in Section 3. The discussion of the results and a comparison with two additional models, also introduced in this work, is conducted in Section 4. Finally, the main conclusions of this work are provided in Section 5.

2. Theoretical background

In this section, first, an overview of the formulation of the spectral matching ratio (SMR) indexes is provided. Second, the fundamentals behind the variables raised in this work to predict these indexes are introduced and justified.

2.1. Spectral matching ratio

The spectrally corrected direct normal irradiance, also known as effective irradiance, of each *i*-junction of a multi-junction (MJ) solar cell can be defined as [28]:

$$B_i = \frac{\int E_b(\lambda) SR_i(\lambda) d\lambda}{\int E_{b,ref}(\lambda) SR_i(\lambda) d\lambda} B_{ref} \tag{1}$$

being $E_b(\lambda)$ and $E_{b,ref}(\lambda)$, respectively, the actual and reference spectral distribution, $SR_i(\lambda)$ the spectral response of the *i*-junction and B_{ref} the reference direct irradiance. i.e. 900 W/m^2. Based on this magnitude, the SMR for the j and k junctions of a MJ solar cell can be estimated as [19]:

$$SMR_{j-junction/k-junction} = \frac{B_j}{B_k} \tag{2}$$

Bearing the above in mind, the SMR index can be understood as follows: 1) SMR = 1 represents a spectral distribution equivalent to the reference spectrum, 2) SMR < 1 represents spectral gains of the *k*-junction with respect to the *j*-junction while 3) SMR > 1 the opposite, i.e. spectral gains of the *j*-junction with respect to the *k*-junction.

Current MJ solar cells are made up of three subcells, therefore, it is necessary to define three SMRs to fully evaluate the spectral impact on CPV systems. This is usually expressed as follows [18]:

$$SMR_{top/mid} = \frac{B_{top}}{B_{mid}} \tag{3}$$

$$SMR_{mid/bot} = \frac{B_{mid}}{B_{bot}} \tag{4}$$