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Comparative assessment of the spectral impact on the energy yield of high concentrator and conventional photovoltaic technology

Eduardo F. Fernández [a,b,*], Alberto Soria-Moya [a], Florencia Almonacid [b], Jorge Aguilera [b]

[a] Centro de Estudios Avanzados en Energía y Medio Ambiente (CEAEMA), University of Jaen, Jaen, Spain
[b] Grupo IDEA, University of Jaen, Jaen, Spain

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ABSTRACT

Photovoltaic materials are spectrally selected and their electrical output is affected by the spectral distribution of the incident irradiance. The performance of high concentrator photovoltaic (HCPV) systems is more influenced by the spectral changes than conventional single-junction photovoltaic (PV) systems due to the use of multi-junction (MJ) solar cells and optical devices. Despite this, the detailed comparison of the spectral impact on the electrical output of HCPV and PV technology under the same atmospheric conditions has not been addressed yet. Because of this, this paper aims to compare the spectral impact on the energy yield of both type of devices at a monthly and annual time scale at several locations with disparate climate conditions. The spectral dependence of both technologies is quantified by using the spectral factor (SF) index in conjunction with the Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS) at five locations of the Aerosol Robotic Network (AERONET) database. The present paper shows that the current HCPV systems present annual spectral losses of around 5% with respect to PV systems at representative locations.

1. Introduction

From the outset, high concentrator photovoltaic (HCPV) technology has appeared as an alternative power source to produce more cost-effective electricity than conventional photovoltaic (PV) technology [1]. The use of optical devices to concentrate the light on high efficiency multi-junction (MJ) solar cells offers at the same time, high efficiencies and a reduction in the amount of semiconductor material [2]. The limit of the efficiency of MJ solar cells and HCPV systems is far from being reached, and an increase of 10% within the next decade is expected [3]. Taking this into account, the cumulative installed capacity of HCPV technology is tending to grow from a value of 358 MWp at the end of 2014 to more than 1 GWp in 2020 [4]. At the same time, the levelised cost of electricity (LCOE) is tending to decrease, LOCE=0.035–0.080 €/kW h in 2020, and reach lower values than conventional PV technology at locations with high annual direct normal irradiation [5]. All the above show the great potential of this technology to play an important role in the energy generation market within next decades.

On the other hand, the maturity and understanding of HCPV technology when operating in outdoors is clearly lower than conventional PV technology. Because of this, important efforts are still needed in order to achieve a better understanding, increase the investors' confidence and therefore promote the market expansion of HCPVs as a real alternative energy source to conventional PVs [6]. One of the more relevant differential issues between HCPV and PV technology is related with the influence of the spectral variations on their electrical output [7]. The use of MJ solar cells based on the internal series connection of several subcells with different energy gaps [8], and optical devices which modify the spectral distribution that strikes on the solar cells surface [9], make HCPV devices more sensitive to the incident spectral distribution.

Because of this, the scientific community has devoted great efforts to understand the impact of the input spectrum on the performance of HCPV technology under real operating conditions. The use of the SMARTS model in conjunction with AERONET data source have been used by Muller et al. [10] to evaluate the effect of air mass, aerosol optical depth and precipitable water on the performance of different HCPV modules in Golden (USA) over 9 months. Hashimoto et al. [11] studied the impact of spectral changes on the performance of different HCPV one-cell modules during a clear and a very clear day through the SMR (spectral matching ratio) index measured with a spectroradiometer. An alternative procedure based on isotype solar cells and the spectral parameter Z has been proposed by Peharz et al. [12,13] to evaluate the spectral impact on the electrical output of different HCPV modules over several months at Freiburg (Germany). A similar

* Corresponding author. Tel.: +34 9543213520.
E-mail address: fenandez@ujaen.es (E.F. Fernández).

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approach based on the SMR index registered with isotype solar cells has been also used by García-Domingo et al. [14] to evaluate the spectral impact on the electrical characteristics of various HCPV modules over the course of a year in Jaen (Spain). The contour diagram of the performance ratio of a HCPV system analysed during a year at Miyazaki (Japan), as a function of the cell temperature and spectrum, quantified with the APE (Average Photon Index) index gathered with a spectroradiometer, has been obtained by Husna et al. [15]. The studies above are focused on analysing the instantaneous impact of spectral variations on the performance of HCPV modules or systems. Other recent work addresses the spectral impact on an annual time scale since it is directly related with the annual energy yield of the systems. Victoria et al. [16] quantified the annual spectral losses on the energy yield of different HCPV modules in Madrid (Spain) by the use of the SMR index measured with isotype solar cells. Fernández et al. [17] evaluated the annual average spectral impact on the performance of several HCPV modules made up of different types of MJ solar cells and optical devices through the spectral factor (SF) index with spectra simulated with the SMARTS model and data obtained from AERONET at five locations (Solar Village (Saudi Arabia), Alta Floresta (Brazil), Frenchman Flat (USA), Granada (Spain) and Beijing (China)). The same HCPV modules and a similar approach have also been used by Soria-Moya et al. [18] to estimate the annual energy spectral losses as a function of latitude. Chan et al. [19] quantified the impact of air mass, aerosol optical depth and precipitable water on the annual energy harvested by a HCPV module at five AERONET sites (Rogers Dry Lake (USA), Tamanrasset (Algeria), Sede Boqer (Israel), Solar Village (Saudi Arabia) and Jaipur (India)) by using the Syracuse simulation model [20] and spectra generated with the SMARTS model.

At the same time, single-junction PV devices are also spectrally selected and their power and energy output is also affected by spectral variation under real operating conditions. Because of this, the spectral dependence of these devices is also continuously being analysed by the scientific community and a wide number of studies can be found in the literature. Minemoto et al. [21] analysed the impact of the spectral variations in some PV devices as a function of the APE index measured with a spectroradiometer, as well as the contour diagrams of the performance ratio of several PV devices as a function of APE and module temperature [22–25], over the course of a year at Kusatsu (Japan). The APE and SF indexes gathered with a spectroradiometer have been used by Ishii et al. [26] to evaluate the spectral impact on the performance ratio of a wide number of PV technologies during 17 months at eight selected locations in Japan (Sapporo, Nakatsugawa, Otsu, Kobe, Katsuragi, Tosu, Isahaya and Okinoerabu). A similar approach has been followed by Nofuentes et al. [27] to analyse the spectral dependencies of some commercial PV devices during a year at Jaen (Spain). The work above represent examples of studies concerning the instantaneous impact of spectral changes on the performance of PV devices. As in the case of HCPV technology, other researchers have recently conducted different studies to analyse the spectral impact on an annual or monthly time scale. Alonso-Abella et al. [28] quantified the spectral impact on the monthly and annual energy yield of a wide number of commercial PV devices by using the SEDES2 spectral model and Meteonorm software at four locations (Stuttgart (Germany), Tamanrasset (Algeria), Madrid (Spain) and Jaen (Spain)). Fernández et al. [29,30] evaluated the average annual spectral impact on the performance of various new generation solar cells by also using the SF index in conjunction with the SMARTS model at six AERONET locations (Solar Village (Saudi Arabia), Alta Floresta (Brazil), Frenchman Flat (USA), Granada (Spain), Beijing (China) and Edinburgh (Scotland)). The analysis of the effect of spectral variations on the monthly and annual energy yield of different commercial PV devices, by using the SF index and spectral measurements of around 3.5 years performed with a spectroradiometer, has been also conducted by Dirnberger et al. [31] at Freiburg (Germany).

The examples above represent relevant studies concerning the analysis of the effect of spectral variations on the performance of both technologies. These studies allow different conclusions to be reached. It seems clear that HCPV systems show a higher spectral dependence than conventional PV systems. However, it can be also concluded that the impact of the spectral variations on both technologies depends on the atmospheric characteristics of each particular site (i.e. air mass, aerosol optical depth and precipitable water). Moreover, the procedures and approaches used by the authors to analyse the spectral impact on HCPV and PV technology are different. Hence, based on the current studies, the direct comparison between the spectral impact on the electrical output of HCPV and PV technology under the same climate conditions is not possible and has not been done. At the same time, the energy harvested by photovoltaic systems is directly related with their bankability [32]. Bearing this in mind, this paper is focused on the comparative evaluation of the spectral impact on the energy yield of HCPV and PV technologies under a wide range of atmospheric conditions. In order to achieve this goal, the approach previously used by the authors in [17], where the annual average spectral impact on the performance of several HCPV systems but not on the energy yield was analysed, has been followed. So, the present study allows the analysis and comparison between the performance and potential of HCPV and PV technologies to be done in terms of the spectral behaviour.

2. Methods and materials

2.1. Spectral factor and energy yield

The power output of a HCPV or PV system is mainly determined by the incident irradiance, spectral distribution and the operating cell temperature. Hence, the maximum power (P) of a PV device can be expressed with a low margin of error as [26]:

$$P \approx \frac{P^*}{G^*} \cdot G \cdot \mathrm{TF} \cdot \mathrm{SF} \tag{1}$$

and of a HCPV device as [33]:

$$P \approx \frac{P^*}{\mathrm{DNI}^*} \cdot \mathrm{DNI} \cdot \mathrm{TF} \cdot \mathrm{SF} \tag{2}$$

where P^*, G^* and DNI* are the maximum power, global irradiance and direct normal under the standard test conditions (STC), G and DNI are the incident global and direct normal irradiance, TF is the thermal factor and SF is the spectral factor.

The TF quantifies the effect of cell temperature of the power output of a PV and HCPV device as [27,34]:

$$\mathrm{TF} = 1 + \gamma (T_c - T_c^*) \tag{3}$$

where γ is the maximum power temperature coefficient, T_c is the cell temperature and T_c^* is the cell temperature under STC.

The spectral factor quantifies the influence of the input spectrum on the power output of a single-junction PV device as [35]:

$$\mathrm{SF} = \frac{\int E_g(\lambda) SR(\lambda) d\lambda \int E_{g,ref}(\lambda) d\lambda}{\int E_{g,ref}(\lambda) SR(\lambda) d\lambda \int E_g(\lambda) d\lambda} \tag{4}$$

where λ is the wavelength, $E_g(\lambda)$ is the incident global spectral distribution, $E_{g,ref}(\lambda)$ is the reference global spectrum and SR(λ) is the spectral response of the PV device.

Following the same approach, the impact of the incident spectral distribution on the power output of a HCPV device can be