Analysis of the spectral variations on the performance of high concentrator photovoltaic modules operating under different real climate conditions

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Abstract: Multi-junction (MJ) solar cells show an important dependence on the incident spectrum due to the internal series connection of several cells with different band gap energies. The influence of spectral variations on the performance of HCPV modules or systems is different from in MJ solar cells since they use optical devices to concentrate the light on the solar cell surface. The spectral distribution of irradiance is affected by atmospheric parameters and changes during the course of day, month or year. Because of this, several authors have done different studies to analyse and quantify the spectral effects on the performance of HCPV modules. However, there are still important issues that have not been addressed. In this paper, a deep analysis of the spectral effects on the performance of different HCPV modules with different multi-junction solar cells and Fresnel lenses on an annual time scale and their study and comparison at locations with different climate conditions is conducted. In order to address this issue, ground-based climatologies at the locations studied, spectra simulations with the SMARTS model and the spectral factor of a HCPV module have been used. Results show that the annual spectral losses vary from 6% to 51% depending on the climate conditions of the location and the HCPV module.

Keywords: high concentrator photovoltaic, spectral effects, climate conditions.

1. Introduction

Photovoltaic devices are influenced by the spectral distribution of the incident solar irradiance. But, due to the internal series connection of several cells with different band gap energies, multi-junction (MJ) solar cells show a significantly greater spectral dependence than single-junction solar cells [1, 2].

The spectral distribution of solar irradiance is determined by multiple time-varying atmospheric factors, and several methods have been proposed to quantify the influence of the spectral variations of solar irradiance on the performance of MJ solar cells under real operating conditions [1, 3, 4, 5, 6].

Nowadays, high concentrator photovoltaic (HCPV) modules and systems are largely based on the use of MJ solar cells [7]. HCPV modules use optical devices, usually Fresnel lenses, to concentrate the light on the solar cell surface and may use secondary optical elements such as homogenizers [8]. The assembly of optical devices alters the spectral distribution of the solar irradiance that strikes the solar cell surface. Hence, the influence of incoming spectral variations on the performance of HCPV modules is inherently different to that in MJ solar cells [9].

Recently, the influence of spectral variations in the incident solar irradiance on the performance of HCPV modules has been evaluated by different authors. The spectral effects on various

HCPV mono-modules and systems during a clear and a very clear day has been studied by [9] in Okayama (Japan) from measurements gathered with a spectro-radiometer. However, as is pointed out in [10], the use of spectro-radiometers is complex and presents multiple disadvantages for long-term analyses. As a consequence, an alternative method based on isotype cells has been proposed by [10]. Isotype cells register the solar irradiance spectral variations and quantify their effects on the electrical parameters of the HCPV modules. This approach has also been used in [11] to gauge the annual spectral losses of different HCPV systems in Madrid (Spain). However, although the methods based on isotype cells are robust and simple, they are difficult to apply in remote sites for long-term studies. The use of ground-based long-term observations of atmospheric properties in conjunction with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS [12, 13, 14]) poses an alternative modeling approach for long-term studies. It allows evaluating the spectral effects at different locations if the atmospheric parameters are available. This approach has been used to study the influence of air mass, aerosol optical depth and precipitable water on the performance of different HCPV modules in Golden (USA) over 9 months [15] and in a HCPV module in Toyohashi (Japan) over a year [16].

Nonetheless, a deeper analysis of the influence of the time-varying solar irradiance spectrum on the performance of HCPV modules at locations with disparate climate conditions is required. This is crucial to leverage our understanding of the annual performance of HCPV modules under real operating conditions [17]. To address this issue, the effects of solar irradiance spectral variations on the annual performance of different HCPV modules at five locations with different climate conditions have been analysed based on high-quality ground-based climatologies at the sites studied and spectra simulations with the SMARTS model. A detailed analysis of the influence of air mass, aerosol optical depth and atmospheric water vapour content is presented.

2. Method and materials

2.1 The spectral factor of a HCPV module

The spectral factor of a single-junction PV device can be defined as [18, 19, 20, 17]:

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

where $E(\lambda)$ is the incident spectrum on the PV device, $E_{ref}(\lambda)$ is the reference spectrum and $SR(\lambda)$ is the spectral response of the PV device. The spectral factor quantifies the differential performance of a PV device between the incident and reference spectra: an SF higher than 1 represents a better performance (spectral gains) and an SF lower than 1 (spectral losses) indicates a worse performance.

The spectral factor as defined in Eq. (1) is not valid for HCPV modules since the combined use of MJ solar cells and optical devices modifies the incident spectral distribution [9, 21, 22]. Therefore, the spectral factor needs to be reformulated for use in HCPV modules.

The short-circuit current density of each junction of a MJ solar cell can be expressed as:

$$J_{sc,i} = \int E_b(\lambda)\eta(\lambda)\, SR_i(\lambda)d\lambda \qquad (2)$$

where the index *i* represents the junction considered, $E_b(\lambda)$ is the spectral distribution of direct normal irradiance (E_b) or direct normal spectrum (HCPV modules react only to direct normal irradiance due to the use of lenses), and $\eta(\lambda)$ is the optical efficiency of the HCPV module.

As junctions of a MJ solar cell are interconnected in series, the short-circuit current density of the whole device is given by [23]:

$$J_{sc} = \min(J_{sc,i}) \tag{3}$$

From equations (1), (2) and (3), the spectral factor of a HCPV module should be rewritten as:

$$SF = \frac{\min\left(\int E_b(\lambda)\eta(\lambda)SR_i(\lambda)d\lambda\right)\int E_{b,ref}(\lambda)d\lambda}{\min\left(\int E_{b,ref}(\lambda)\eta(\lambda)SR_i(\lambda)d\lambda\right)\int E_b(\lambda)d\lambda} \tag{4}$$

where $E_{b,ref}(\lambda)$ is the reference spectrum AM1.5d ASTM G-173-03 at which MJ solar cells and HCPV modules are rated [24].

Finally, the spectral effects on the performance of a HCPV module with respect to the reference conditions are computed as:

$$\Delta SF(\%) = \left(SF\left(E_b(\lambda)\right) - SF\left(E_{b,ref}(\lambda)\right)\right)100 = \left(SF\left(E_b(\lambda)\right) - 1\right)100 \tag{5}$$

where ΔSF is defined as the relative spectral factor. This equation estimates the performance of a HCPV module as a function of the mismatch among the short-circuit current densities relative to the value under the reference spectrum of the different junctions of the respective MJ solar cell. This approach has already been used by different authors and is considered as a good tool to quantify the spectral impacts on the energy output of HCPV devices [4, 5, 6, 25, 26].

2.2. HCPV modules under study

Four different HCPV module prototypes have been considered for this study. Two modules are equipped with latticed-matched (LM) monolithic triple-junction solar cells with an area of 0.763 cm^2 and the other two are equipped with metamorphic (MM) monolithic triple-junction solar cells with an area of 0.765 cm^2. Fig.1 (bottom) shows the External Quantum Efficiency (EQE) of the cells at 298 K, which are formed by the following materials and band gap energies:

- LM cell: top: GaInP (1.88 eV), middle: GaInAs (1.41 eV), bottom cell: Ge (0.67 eV)
- MM cell: GaInP (1.82 eV), middle: GaInAs (1.33 eV), bottom cell: Ge (0.67 eV)

The four modules are made up of 20 MJ solar cells with a bypass diode per cell and use passive cooling to reduce the cell temperature. One of the modules equipped with LM/MM monolithic triple-junction solar cells uses Fresnel lenses based on poly(methylmethacrylate) (PMMA) material and the other uses Fresnel lenses based on silicon on glass (SOG) material as primary optics to concentrate the light. No secondary optical elements (SOE) have been considered. Both Fresnel lenses have an area of 23 x 23 cm^2, so the modules have a geometric concentration of around 700. Fig.1(right) shows the spectral transmittance of the two Fresnel lenses at 293 K and table 1 shows the average transmittance of the four modules in the response region of each junction of the cells. As can be seen, the modules that use SOG lenses have a higher transmittance on the response regions of the top and bottom junctions while it is similar in the response region of the middle junction.

3. Individual impact of atmospheric parameters

In order to achieve a better understanding of the influence of the spectral variations of the incident solar irradiance on the performance of HCPV modules, it is appropriate to perform an individualized analysis for each of the atmospheric parameters. The atmospheric parameters with the highest influence on the performance of HCPV modules are, in order of importance: air mass, aerosol optical depth, and precipitable water [1, 16].

Optical mass is a measure of the length and amount of substance traversed by the solar rays in their course through the atmosphere. It has a differentiated spectral impact on the incoming solar irradiance at the earth surface. When the substance is dry air molecules, optical mass is known as optical air mass. Usually, it is given as the ratio with respect to the optical air mass in the zenith direction. In such a case, it is known as relative optical air mass, whose minimum value is always 1. For further references, see [27]. In this study, we used the relative optical air mass, and we will refer to it hereinafter as simply air mass or AM. For dry air molecules, air mass approximately reduces to a purely geometrical parameter that gives account of the solar position.

Aerosols are small particles suspended in the air with diameters in the range from a few nm to tenths of microns. Aerosol optical depth, hereinafter noted as AOD, is the physical magnitude to account for the amount of radiation attenuated by aerosol particles. The bigger the AOD the more radiation is attenuated. Its value changes with solar irradiance wavelength meaning that attenuation by aerosols depends on wavelength. This dependency is often represented with the Ångström law: $\tau = \beta\lambda^{-\alpha}$, where λ is the wavelength in microns, β is the AOD at λ=1 µm, and α is the so-called Ångström exponent [28]. The latter represents the spectral incidence of aerosols in the solar flux: small values of α are typical of big particles, such as desert dust, and produce flat spectral responses. Large values of α are typical of small particles such as those found in polluted areas. In such conditions, the extinction at large solar wavelengths gets smaller and the spectrum becomes redder. Further information can be consulted in [29]. Although the Ångström law represents the spectral dependence of AOD in terms of β, it can be re-formulated as $\tau = \tau_{0.55}(\lambda/0.55)^{-\alpha}$, so that, the spectral dependence is now described in terms of the AOD at 0.55 µm ($\tau_{0.55}$) for the wavelength λ given in µm. The reference value at 0.55 µm is appropriate because it is a common observed value in different aerosol data bases, including ground-based and remotely-sensed data sources.

The water vapour content of a cloudless atmosphere also matters in the whole atmospheric spectral response. Water vapour content can be summarized in several ways, one of them being the precipitable water amount (w). It is the total amount of water vapour in the zenith direction, between the surface and the top of the atmosphere. Its units are mass per unit of area. However, precipitable water is often described as the thickness of the liquid water that would be formed if all the vapour in the zenith direction were condensed at the surface of a unit area. See [27] for further information.

To analyse the individual influence of each atmospheric parameter, several spectra have been generated with the SMARTS radiative transfer model by varying one of the parameters while keeping the rest fixed at the reference values defined by the standard AM1.5d ASTM G-173-03(air mass = 1.5, aerosol optical depth at 500 nm = 0.084, aerosol model = rural, precipitable water = 1.42 cm) [5, 6, 16, 15]. The spectral effects on the performance of HCPV modules have been computed following the procedure described in Section 2.1.

3.1. Spectral influence of air mass

Fig.2 (left) shows ten simulated solar irradiance spectra from AM = 1 to AM =10. Although increasing AM values yield increasing attenuation of solar irradiance for the entire short-wave spectrum, the relative attenuation is larger in the spectral region of the top junction. Fig.2 (right) shows ΔSF for the studied HCPV modules as a function of AM. The modules have similar behaviour, with absolute maxima at different AM values between 1 and 2. This maximum represents the operating point at which the top and middle junctions generate the same current in each module. Around this point, the performance of the HCPV modules decreases due to the limiting current by one of the junctions. On the left side the current is limited by the middle junction while on the right side the current is limited by the top junction. Like the absolute maximum, the air mass influence when the top junction is limiting the current is different in the four modules. The rationale behind is the fact that the transmittance of the SOG Fresnel lens is higher than the transmittance of the PMMA Fresnel lens in the spectral region of the top junction and also because the more narrow band gap of this junction in the MM cell than in the LM cell. Hence, the spectral losses due to AM when the current is limited by the top junction are lower for the HCPV module based on SOG Fresnel lenses and MM cells.

3.2. Spectral influence of aerosol optical depth at 0.55 µm

Fig.3 (left) shows seven simulated solar irradiance spectra between $\tau_{0.55} = 0$ and $\tau_{0.55} = 1$. As in the previous case, the increase of $\tau_{0.55}$ reduces the incoming solar irradiance at all wavelengths, but removes more energy from the blue region, which is the spectral region where the top junction responds. Aerosol optical depth shows a significantly greater extinction than AM on the spectral region where the middle junction responds. Fig.3 (right) shows the ΔSF values against $\tau_{0.55}$ for the HCPV modules considered in this study. As for the AM case, the modules have similar behaviour. There is an absolute maximum at $\tau_{0.55}$ values between 0.08 and 0.18 which are reasonable typical values for rural aerosols. Again, the maximum represents the operating point at which the top and middle junctions generate the same current. Around it, the performance of the HCPV modules decreases due to the limiting current by one of the junctions. On the left side the current is limited by the middle junction while on the right side the current is limited by the top junction. Note again that, as in the previous case, the point at which the relative spectral factor is maximum and the decay of the relative spectral factor when the top junction is limiting the current is different in both modules. This is due to the fact that the transmittance of the SOG Fresnel lens is higher than the transmittance of the PMMA Fresnel lens in the spectral region of the top junction and also because the more narrow band gap of this junction in the MM cell than in the LM cell. Because of this, the spectral losses due to $\tau_{0.55}$ when the current is limited by the top junction are lower for the HCPV module based on SOG Fresnel lenses and MM cells.

3.3. Spectral influence of Ångström exponent

Since aerosol particles have a large range of sizes, the aerosol spectral responsivity on the incident solar flux is highly variable and dependent on the size distribution of the particular aerosol arrangement. The Ångström exponent is a lumped parameter to describe this spectral responsivity. Fig.4 (left) shows five simulated solar irradiance spectra with α values between 0.5 and 2.5. Overall, the spectral effect is small but, as α increases the solar irradiance at wavelengths greater than 0.55 increases For smaller wavelengths, solar irradiance decreases. In terms of the MJ cells, the effect of an increasing Ångström exponent is to increase the incident irradiance on the middle and bottom junctions whereas the irradiance stays about the same on the top junction. Fig.4 (right) shows the ΔSF values for the HCPV modules against α. Unlike for AM and $\tau_{0.55}$, now the behaviour of the modules is distinct. The relative spectral factor of the module based on LM solar cells and PMMA Fresnel lenses reaches an absolute maximum at α about 1.5, where the top and middle junctions generate the same current. The middle junction limits the current for smaller values of α and the top junction limits the opposite. On the contrary, the performance of the other modules always increases linearly within the range from α =0.5 up to α =2.5 because the top junction never limits the current due to the higher transmittance of the SOG Fresnel lens in the spectral region of the top junction and/or because the more narrow band gap of this junction in the MM cell.

3.3. Spectral influence of precipitable water

Fig.5 (left) shows six simulated solar irradiance spectra with *w* values between 0.5 and 5. As can be seen, an increase of *w* decreases the amount of solar irradiance received in the near-infra-red spectral region, where the bottom junction responds. The irradiance in the spectral region of the middle junction also decreases although to a lesser extent. Fig. 5(right) shows the ΔSF against *w* for the HCPV modules considered in this study. The behaviour of the modules based on LM and MM solar cells is different. The modules based on LM solar cells have similar behaviour. Their performance increases with an increase of *w*. This can be explained considering that although an increase of *w* produces a decrease of the current throughout the bottom junction, it never limits the current because of its narrow band gap. At the same time, the top junction current stays roughly constant and the current through the middle junction decreases slightly. Therefore, the current throughout the whole HCPV module is kept approximately constant for any value, resulting in an overall increase of the performance in the two modules. The modules based on MM solar cells have similar behaviour. Their performance increases with an increase of *w* until a value around 1.2 and decreases slightly for higher values. The different behaviour found between modules based on MM solar cells and LM solar cells can be explained due to the more narrow band gap of the middle junction on the MM solar cells. So, an increase of *w* produces a decrease of the current throughout the middle junction. Therefore, the current throughout the whole HCPV modules decreases, resulting in an overall decrease of the performance in the two modules. The small difference found between the four modules for values below 1.2 (modules based on MM solar cells) and 1.5 (modules based on LM solar cells) is due to the fact that in this region the top junction is limiting the current, so that the modules based on SOG Fresnel lenses has a better performance because of its higher transmittance on the spectral region of the top junction.

From the analyses conducted in this section, it can be concluded that AM has the largest impact on the performance of HCPV modules. It may give rise to spectral losses of around 50%. The second parameter by order of influence on the performance of a HCPV module is $\tau_{0.55}$. It may give rise to spectral losses of about 35%. In third place, *w* may explain spectral losses of up to around 2% (module based on MM solar cells and PMMA Fresnel lenses) and 4% (module based on LM solar cells and SOG Fresnel lenses) and spectral gains about 2% for modules based on LM solar cells. The influence of Ångström exponent is small, with relative spectral factors within ±2%.

4. Analysis of the spectral effects under different climate conditions

In this section, the expected annual influence of the spectral solar radiation variations at five different locations on the performance of the HCPV modules is evaluated. First, the main climate conditions at the selected locations and the procedure to compute the annual spectral factor are described. Then, the analysis results are presented and discussed.

4.1. Sites studied

The following five sites were chosen from the Aerosol Robotic Network (AERONET, [30]): Solar Village in Saudi Arabia (N 24º54’25’’, E 46º23’49’’), Alta Floresta in Brazil (S 09º52’15’’, W 56º06’14’’), Frenchman Flat in USA (N 36º48’’32’’, W 115º56’06’’), Granada in Spain (N 37º09’50’’, W 03º36’18’’) and Beijing in China (N 39º58’37’’, E 116º22’51’’). The five sites represent different climate conditions over different continents. Long-term monthly average values of AOD at 0.55 µm, Ångström exponent obtained from AOD observations between 0.44 and 0.87 µm, and precipitable water were gathered from the AERONET data set. AM was calculated as:

$$AM = \frac{1}{\cos\theta + 0.45665\,\theta^{0.07}(96.4836-\theta)^{-1.697}} \tag{6}$$

where θ is the Sun’s zenith angle [31].

Figure 6 shows the annual average values of AM during sunshine hours, $\tau_{0.55}$, α and *w* at the five sites studied. Solar Village is a desert location with low-to-medium annual average values of AM, high $\tau_{0.55}$ values, small α values and medium *w* values. Alta Floresta is a tropical location characterized by low annual average values of AM, high values of $\tau_{0.55}$ and medium α values, with a marked seasonal signal due to biomass burning, and the typical high values of *w* at any tropical site. Frenchman Flat is a desert location with medium annual average values of AM, characterized by very low values of $\tau_{0.55}$, and medium values of α and *w*. Granada is a non-industrialized medium-size city in southern Spain with medium annual average values of AM. Although it may be affected occasionally by Saharian dust intrusion events, Granada presents medium annual average values of $\tau_{0.55}$, α and *w*. Beijing site is a highly-polluted urban location with annual average medium values of AM, extremely high values of $\tau_{0.55}$, and medium α and *w* values.

4.2. Computation of the annual spectral factor

First, the value of AM was computed every minute during daylight times for a whole year at each site. From these values, the particular frequency distribution of AM (P(AM)) at each site was obtained. Then, the solar irradiance spectrum was computed for 200 AM values evenly distributed between 1 and 38 (a solar zenith angle about 90º) using SMARTS and the yearly average values of the atmospheric parameters retrieved from AERONET at each site. The spectral factor SF(AM) was then computed for the 200 solar irradiance spectra at each site using Eq. (4) for the HCPV modules studied here. Finally, the annual spectral factor was obtained as:

$$SF_{annual} = \frac{\int P(AM)SF(AM)dAM}{\int P(AM)dAM} \tag{7}$$

It represents the annual impact of the spectral variations of the incoming solar irradiance on the performance of each HCPV module at a specific location. From the annual spectral factor, the annual relative spectral factor is calculated using Eq. (5). It is important to note that the annual relative spectral factor estimated is based on the EQE of the MJ solar cells and transmittance of the lenses at the given temperatures shown in figure 1. This assumption may affect the results since under real operation conditions the temperature of the cells and lenses is going to be different. This is beyond the scope of this paper but should be studied in future work to better understand and quantify the spectral losses of a HCPV module under real operating conditions.

4.3. Results

Figure 7 shows the annual spectral impact at the five sites studied for the HCPV modules considered in this study. For all the sites, the modules present losses with respect to the reference spectrum. The site with the lowest losses is Alta Floresta, with annual spectral losses ranging from 7% to 9%. Alta Floresta has the lowest annual average AM value. Very similar results are found at Frenchman Flat, with losses ranging from 6% to 11%. At this location, although the annual average AM value is larger, $\tau_{0.55}$ is very small. The results at Granada and Solar Village are very similar to each other, with losses ranging from 10% to 15%. At Solar Village, the annual average AM value is smaller, but $\tau_{0.55}$ is larger. At Beijing, the exceptionally high $\tau_{0.55}$ values produce annual spectral losses ranging from 48% to 51% in the HCPV modules. Overall, the module based on MM solar cells and SOG Fresnel lenses has the lowest spectral losses at all the locations considered here. The reason is that the losses on the performance of the HCPV modules are mainly caused by the limitation of the current of the top junction and taking into account the more narrow band gap of the top junction of the MM solar cell and the higher transmittance of the SOG Fresnel lens in the spectral region of this junction. The module based on LM solar cells and PMMA Fresnel lenses has highest losses while the other two modules show a similar behaviour at all the locations considered here.

AM has proven the highest impact on the performance of a HCPV module. Because of this, it is the one parameter used by many authors to account for the spectral influence of the incident solar irradiance on the electrical output of a HCPV module or system [32, 33, 34, 35, 36, 37, 38, 39]. Therefore, we have conducted the next validating experiment to evaluate the appropriateness of this approach. Figure 8 shows the difference between the annual spectral impact taking into account the variations of AM, $\tau_{0.55}$, α and *w* (Fig. 7) and the annual spectral impact taking into account only the variations of AM (ΔSF_{AM}) at the five sites studied for the HCPV modules considered in this study. As is shown, Frenchman Flat is the place with the lowest annual differences with values ranging from 0.5% to 0.7% due to the low annual average $\tau_{0.55}$ value which means that the annual losses are mainly given by AM. Low annual differences are also found in Alta Floresta and Granada with values ranging from 3% to 4%. Both places show a larger annual average $\tau_{0.55}$ value than Frenchman Flat. This also explains the reason of the annual differences found in Solar Village with values ranging from 8% to 9%. Extreme annual differences are found in Beijing with values ranging from 39% to 41% because of the high annual average $\tau_{0.55}$ value which means that the annual losses are mainly given by $\tau_{0.55}$. From this analysis it can be concluded that AM it is a good tool to quantify the spectral impacts on the performance of a HCPV module in places with low $\tau_{0.55}$ values. However, places with high values of $\tau_{0.55}$ should include an additional correction to take into account the spectral influence of this atmospheric parameter in order to accurately quantify the influence of the incident spectrum on the performance of a HCPV module.

5. Conclusions and future work

An analysis of the annual influence of the spectral variations on the performance of four HCPV modules under real and different climate conditions has been conducted. In particular the locations chosen are: Solar Village, Alta Floresta, Frenchman Flat, Granada and Beijing. Also, an analysis of the individual impact of the atmospheric parameters with the highest influence on the performance of a HCPV module has been carried out in order to better understand the influence of the spectral effects under real operating conditions.

From the analysis of the individual impact of the atmospheric parameters it can be concluded that the parameters with the largest influence on the performance of a HCPV module are AM and $\tau_{0.55}$ respectively, while α and *w* have a small influence. This means that the spectral behaviour of a HCPV module under real operating conditions can be explained with an acceptable margin of error taking into account only the influence of AM and $\tau_{0.55}$.

From the analysis of the annual effects of the spectral variations on the performance of the HCPV modules considered, it can be concluded that Alta Floresta is the place with the lowest annual spectral losses (7% - 9%) due to the low annual average value of AM and Beijing is the place with the highest annual spectral losses (48% - 51%) due to the extreme annual average value of $\tau_{0.55}$. Also, a spectral correction based only on AM to quantify the influence of the incident spectrum on the electrical output of a HCPV module or system is only valid for locations with low values of $\tau_{0.55}$. This means that locations with high values of $\tau_{0.55}$ should include an additional correction to take into account the spectral influence of this atmospheric parameter. Finally, it is important to note that the module based on MM solar cells and SOG Fresnel lenses has the lowest spectral losses at all the locations here considered due to the more narrow band gap of the top junction of the MM solar cell and the higher transmittance of the SOG Fresnel lens in the spectral region of the this junction.

It is important to note that this study is based on the EQE of the MJ solar cells and transmittance of the lenses at the given temperatures shown in figure 1. However, under real operation conditions the temperature of the cells and lenses is going to be different because will be affected by the changes of direct normal irradiance, air temperature and wind speed [40, 41]. Also, other effects such as the possible influence of secondary optical elements and the possible effects of the non-uniform illumination on the solar cell surface produced by the chromatic aberration of the lenses have not been taken into account [42]. Despite the fact that these approximations have been discussed by different authors and are widely considered as a good approach to quantify the spectral influence and the electrical output of a HCPV device [4, 5] [9, 10] [15, 16] [25, 26] [34] [36, 37] [41] [43, 44], authors plan to include them in future works.

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Figure caption

Figure 1. External Quantum Efficiency of the lattice-matched (bottom left) and the metamorphic (bottom right) multi-junction solar cells at 298 K. Top: Transmittance of the Fresnel lenses (PMMA and SOG) at 293 K.

Figure 2. Effect of air mass on the spectral irradiance (left) and on the HCPV modules performance (right). The other parameters are kept constant at the reference values defined by the AM1.5d ASTM G-173-03 reference spectrum.

Figure 3. Effect of aerosol optical depth on the spectral irradiance (left) and on HCPV modules performance (right). The other parameters are kept constant at the reference values defined by the AM1.5d ASTM G-173-03 reference spectrum.

Figure 4. Effect of the Ångström exponent on the spectral irradiance (left) and on HCPV modules performance (right). The rest of parameters are kept constant at the reference values defined by the AM1.5d ASTM G-173-03 reference spectrum.

Figure 5. Effect of precipitable water on the spectral irradiance (left) and on HCPV modules performance (right). The other parameters are kept constant at the reference values defined by the AM1.5d ASTM G-173-03 reference spectrum.

Figure 6. Annually-averaged values of air mass (top-left), aerosol optical depth at 550 nm (top-right), Ångström exponent (bottom-left) and precipitable water (bottom-right) at the five sites studied considered.

Figure 7. Annual impact of the spectral variations on the performance of the HCPV modules under study at the five sites studied.

Figure 8. Annual difference between the spectral impact taking into account the variations of AM, $\tau_{0.55}$, α and *w* and the spectral impact taking into account only the variations of AM (The rest of parameters are kept constant at the reference values defined by the AM1.5d ASTM G-173-03 reference spectrum) at the five sites studied for the HCPV modules considered in this study.