Tuning The Current Ratio Of A CPV System To Maximize The Energy Harvesting In A Particular Location

M.Victoria[1], S. Askins, R. Nuñez, C. Domínguez, R. Herrero, I. Antón, G. Sala
and J. M. Ruíz

Abstract: A method based on experimental data is proposed to optimize the energy harvesting of a silicone-on-glass Fresnel-lens based CPV system. It takes into account the spectral variations along the year in a particular location as well as the thermal and spectral sensitivities of the optics and solar cell. In addition, different alternatives to tune the top/middle subcells current ratio in a CPV module are analyzed and their capacity to maximize the annually produced energy is quantified.

Keywords: solar concentrators, multijunction solar cells, DNI, spectrum

INTRODUCTION

The final objective of concentrating photovoltaic (CPV) systems is to contribute to the energy transition by generating a solar-based, cost-competitive energy. Their main advantage is the efficiency values reached by them: up to 43.5% [1] for the triple junction (3J) solar cells that are used in these systems and up to 33.9% at the module level [2] which are the highest among the different photovoltaic technologies.

The conversion efficiency of a CPV module is reported at reference conditions, for example at concentrator standard test conditions (CSTC) which implies an irradiance level of 1000W/m^2 under the reference spectrum AM1.5D G173-03, and at a cell temperature of 25ºC [3]. However, CPV systems are sensitive to atmospheric variations that may decrease their conversion efficiency mainly due to two reasons. In first place, variations in the spectral distribution of the irradiance along the year may limit the current photogenerated by one of the subcells in the stack and consequently the performance of the 3J solar cell. In second place, the ambient temperature influences the behavior not only of the solar cell but also on the concentrating optics. In particular silicon-on-glass (SoG) Fresnel lenses have been reported to be highly sensitive to temperature [4-7].

Regarding the first issue, several authors have tackled the problem of analyzing the effect of spectral variations on the energy annually produced by multijunction solar cells [8-16]. Some of them have proposed to use a certain spectrum, different from AM1.5D, or they have determined the optimum combination of subcell bandgaps that maximizes the energy harvesting. The articles cited above neglect the effect of the optics on the spectral distribution of the light reaching the solar cell, most of them assume a cell temperature higher that 25ºC, and they use modeled spectra, some of them based on SMARTS [13-16], to generate different spectra along the year that are used as inputs for their modeling. Other authors are focused on predicting the power output and energy generation of a certain CPV system and, in order to do that, they model the influence of the spectral variations on the solar cell together with the optics [17,18]. In particular, the references by Hornung [19] and Steiner [20] analyze systems comprising SoG Fresnel lenses and their temperature sensitivity by using finite element modeling and ray-tracing to predict the optics behavior.

In the present work, a model based on a fully experimental approach to determine both, the spectral and temperature variation in a location and the thermal and spectral sensitivities of a CPV module, is used to determine the annual energy losses due to variations on the atmospheric conditions. Additionally, the model is used to determine the desirable current ratio between the subcells top and middle in a module that will maximize the annual energy harvesting. Finally, different alternatives are presented to tune the current ratio of a CPV system based on modifications to the optics, that is, changes that do not include changes in the subcells bandgaps or in the thickness of the top subcell [9,21].

Throughout this article, a figure of merit is used for describing the spectrum: the Spectral Matching Ratio (SMR) [22], which is defined as the ratio between the top and middle subcell photogenerated currents under the spectrum reaching the entrance of the CPV system, divided by that ratio under the reference spectrum, that is

$$SMR = \frac{I^{E}_{L,top} / I^{E}_{L,mid}}{I^{AM1.5D}_{L,top} / I^{AM1.5D}_{L,mid}} \qquad (1)$$

where I^{E}_{L} represents the photocurrent of a subcell (top or middle) when illuminated with a particular spectral irradiance distribution E reaching the module. $I^{AM1.5D}_{L}$ stands for the photoresponse of a subcell under the reference spectrum. SMR is an indicator of how blue-shifted (SMR>1) or red-shifted (SMR<1) the light is with respect to the reference spectrum AM1.5D.

SOG FRESNEL LENS SENSITIVIY TO TEMPERATURE

Currently, several CPV systems commercially available comprise a SoG Fresnel lens. These lenses have been reported to be very sensitive to temperature mainly due to two reasons; the variation of the refractive index with temperature and the deformation on the lens facets caused by the difference in the coefficient of thermal expansion (CTE) between the glass and the silicone that compose the lens.

As a preliminary analysis of the thermal and spectral combined sensitivity of the optics let's assume a SoG Fresnel lens-based module whose efficiency peaks for a certain ambient temperature and spectral distribution (i.e. the reference spectrum where SMR=1). If SMR increases, that is, the incident spectrum shifts to blue, the current photogenerated by the middle subcell decreases lowering the system efficiency (fig.1). If the ambient temperature decreases, the refractive index of the silicone increases, the lens becomes more converging, and the amount of red light over the 3J solar cell increases [4-7]. It would be desirable that those two phenomena would happen simultaneously so some kind of compensation would take place leading to an increase of the module tolerance. Unfortunately, as fig. 2 shows, the atmosphere works exactly the other way round: blue-shifted spectra are found in summer when higher temperatures take place and vice versa. Changes on the silicone refractive index are, in practice, equivalent to variation on the system focal distance. A detailed experimental analysis of the effects of these variations combined with different spectral distribution can be found in reference [23] where the short-circuit current and the fill factor were reported to be the most sensitive parameters.

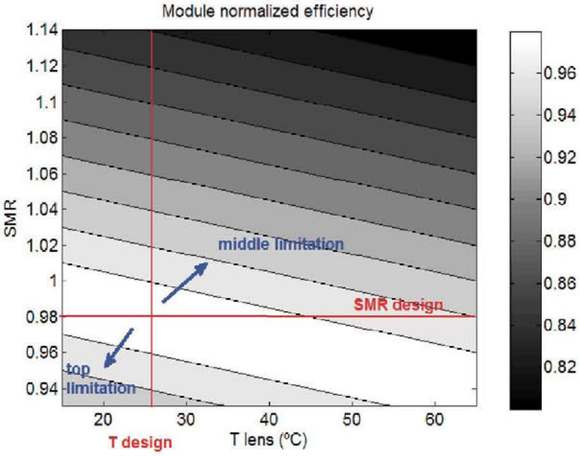

FIGURE 1. Scheme of a SoG Fresnel-lens based CPV module as a function of the lens temperature and spectral distribution of the incident light quantified by the spectral matching ratio (SMR).

EXPERIMENTAL MODEL TO CALCULATE ANNUAL ENERGY LOSSES

A model based on experimental data has been developed to estimate the annual losses experienced by a CPV module due to atmospheric variations in a particular location. The first input necessary for the calculation is the distribution of irradiance as a function of ambient temperature *T*, and spectral content (described by the parameter SMR). For illustration purposes we use the irradiance distribution in Madrid $B_{Madrid}(T,SMR)$. The second input is the thermal and spectral sensitivities of the conversion efficiency of a particular CPV module $\eta(T,SMR)$. Both inputs are experimentally measured as detailed below. As an output the model calculates the annual energy losses *AEL,* of a particular CPV system

$$AEL = 1 - \frac{\sum B_{Madrid}(T,SMR)\eta(T,SMR)}{\sum B_{Madrid}(T,SMR)} \qquad (2)$$

Temperature And Spectral Distribution Of Irradiance In Madrid

Figure 2 shows the Direct Normal Irradiance (DNI) measured along a year in Madrid as a function of the ambient temperature and spectral content. The plot represents data measured every hour between May 2011 and May 2012. DNI was measured using a Kipp & Zonen CH1-NIP pyrheliometer. The short-circuit currents of a top and middle "isotypes" were continuously measured using the Tri-band Spectro-heliometer IC-3J25 described in [24] and the SMR for every hourly irradiance measurement was determined. As predicted, blue-shifted spectra are coincident with higher ambient temperature (summer months) while red-shifted spectra are coincident with lower ambient temperature (winter months). The highest accumulated DNI in Madrid is found for SMR=1.11 and 27ºC.

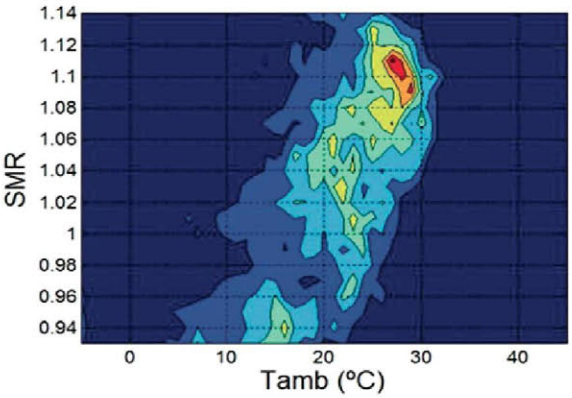

FIGURE 2. Accumulated DNI measured in Madrid along a year (May 2011 – May 2012) as a function of the ambient temperature and the spectral content quantified by the SMR and measured using a Tri-band Spectro-heliometer IC-3J25.

Efficiency Of A CPV Module As A Function Of Lens Temperature And Incident Spectrum

The thermal and spectral sensitivities of two different CPV systems were experimentally determined indoors by using the Helios 3190 solar simulator [25] together with a thermal chamber that allows the accurate control of the Fresnel lens temperature (Fig. 4 and 5). A more detailed description of those measurements can be found in [26]. As the solar simulator uses a flash lamp to illuminate the module, different spectra are obtained during the flash decay. Top and middle "isotypes" are also used to determine the SMR of the irradiance at the optics entrance for every measurement. The so called low-tolerance system comprises a SoG Fresnel lens and a bare solar cell being the geometrical concentration 476X. The so called high-tolerance system maintains the same Fresnel lens and concentration but it includes a secondary optical element (SOE).

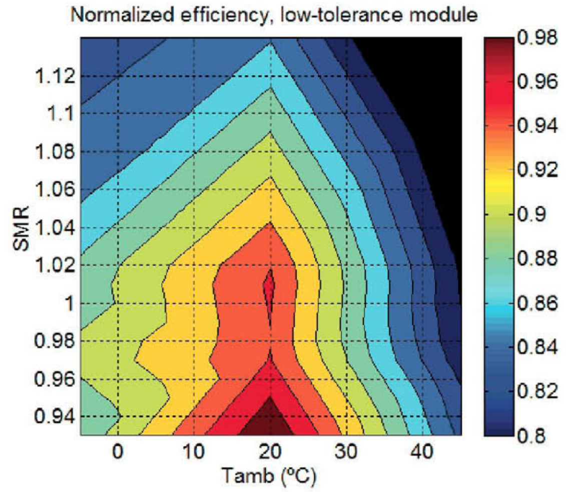

FIGURE 3. Normalized module efficiency measured indoors for the low-tolerance system as a function of the ambient temperature and the DNI spectral content.

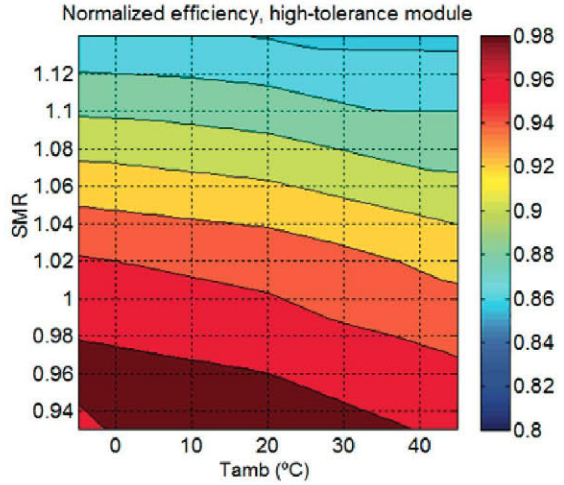

FIGURE 4. Normalized module efficiency measured indoors for the high-tolerance system as a function of the ambient temperature and the DNI spectral content.

For the low-tolerance system, AEL are estimated to be 17.8% compared with a system where efficiency is constant independently of ambient temperature and incident SMR. The main reason for such high losses is the fact that system efficiency peaks at SMR=0.94 but the majority of the irradiance reaching the module in Madrid takes place with a spectral distribution where SMR is close to 1.11. This difference, together with the high thermal sensitivity of the system, translates into significant losses.

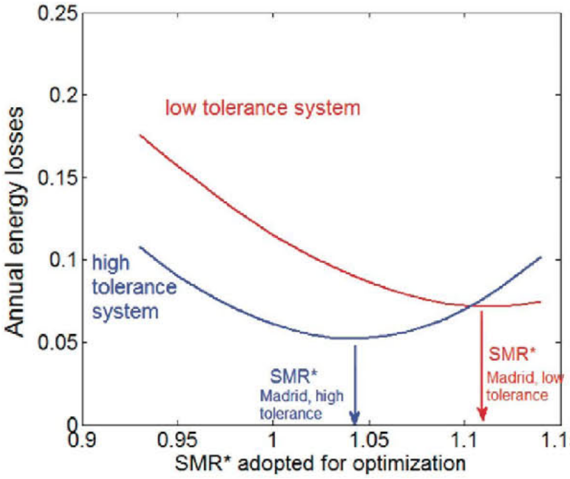

FIGURE 5. Annual energy losses strongly depend on the spectral condition (SMR*) considered for optimization.

This kind of modeling also allows to calculate for which SMR* should the CPV system be optimized to maximize the energy harvesting or, in other words, how should be modified the transmittance of the optics to allow that more red light is transmitted as the system will be installed in a place like Madrid that is characterized by a blue-shifted spectra. If the efficiency of the system peaked for SMR=1.11, AEL in Madrid would be reduced to 7.2%. For the high-tolerance system, losses decrease from 7.4% to 5.2% when the system is optimized for Madrid. It is noteworthy that, in the high-tolerance case, the best option is to maximize the system efficiency at SMR*=1.04 as this system makes use of its high temperature tolerance to collect, at a high conversion efficiency, all the irradiance contained, not only at 27ºC, but in the range of 10-32ºC (figure 2).

TABLE 1. Atmospheric losses for different SoG Fresnel lens-based systems

System	SMR* where efficiency peaks	SMR representative of Madrid	Annual energy losses, AEL
"Unoptimized" low-tolerance system	0.94	1.11	17.8 %
"Unoptimized" high-tolerance system	0.94	1.11	7.4 %
Optimized low-tolerance system	1.11	1.11	7.2 %
Optimized high-tolerance system	1.04	1.11	5.2 %

STRATEGIES TO TRIM THE CURRENT RATIO TO MAXIMIZE ENERGY HARVESTING

As a result of the previous section, to maximize energy harvesting in Madrid it would be desirable to optimize the system for a blue-shifted incident spectrum, in other words, to improve the use of red photons in our system. Solar cell designer have proposed mainly two possibilities: to choose the adequate combination of bandgaps between subcells (for example, using metamorphic 3J solar cell [13-14], or quantum dots [15] or tuning the thickness of the top subcell to split the available irradiance between the top and middle subcells [9,21].

In addition to the previous method, we propose three available options the increase the photocurrent produced by the middle subcell by just modifying the optics and we analyze their capacity to impact on the top/middle current ratio of the system. The first studied option consists in taking advantage of the chromatic aberration caused by the Fresnel lens and adjusting the focal distance to trim the top/cell current matching. In this case, we may think in displacing the cell further from the lens to focus the red light. Figure 6 shows the efficiency of the high-tolerance system, its acceptance angle AA (defined as deviation angle where efficiency drops to 90%) and the SMR* of the incident spectrum that maximizes efficiency [26]. All the results were experimentally determined measuring the system indoors with the Helios 3198 solar simulator [25] and a thermal chamber. The conclusion from those measurements is the following: there is not much room to modify the system transmittance while maintaining high efficiency and AA. In fact, SMR* can only be modified from 0.94 to 0.96, far from the desirable value to optimize energy harvesting in Madrid, 1.04 (table I).

The second option under study consists in trimming the antireflection coating (ARC) deposited over the SOE to benefit the transmittance of red light over that of blue light. Assuming a monolayer of MgF_2 evaporated over a glass SOE, the layer thickness can be increased so that reflection losses are minimized for a longer wavelength (in the bandwidth of the middle subcell). Fig. 7 shows the ratio between the integrated transmittance for the top and middle subcells. In this case, results were obtained by simulation using the transmission matrix method, the model and the data reported in [27]. Nevertheless, as a limit with this procedure, the transmittance for the top subcell can be 0.98 of that of the middle subcell. Still, not sufficient to tune current matching as it would be desirable.

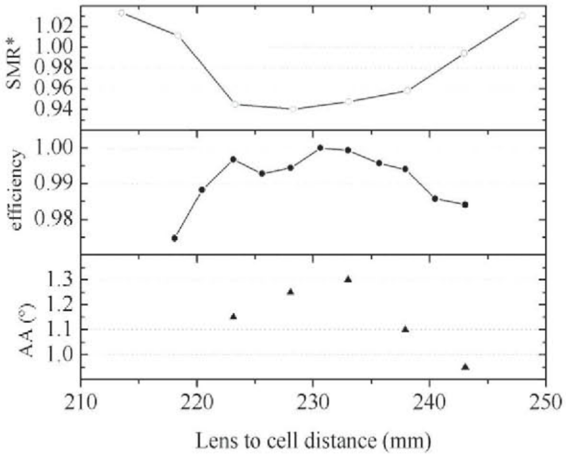

FIGURE 6. Spectral distribution of the incident light that matches top and middle photocurrents (SMR*), normalized efficiency and acceptance angle AA, as a function of the lens to cell distance measured indoors for the high- tolerance system.

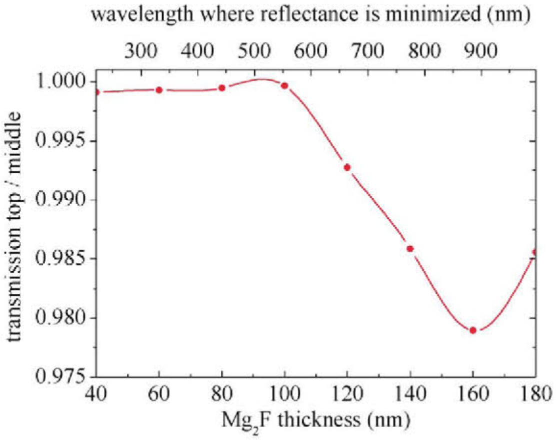

FIGURE 7. Ratio of the integrated transmittance for a top and middle subcells as a function of the thickness of the antireflective coating evaporated over the SOE.

As a last alternative, tuning the ARC evaporated over the 3J solar cell was also analyzed. The ratio of the top and middle integrated transmittance as simulated and calculated by the method described in [27] is shown in fig. 8. Trimming the thicknesses of a two layer ARC made of Al_2O_3/TiO_2 (adequate to couple 3J a solar cell to a glass SOE) allows tuning the top/middle transmission ratio from 0.9 to 1.1. This provides room enough to trim the top/middle current ratio of the system to the desirable value that optimizes energy harvesting in Madrid. In fact, we can envisage the possibility of trimming the thicknesses of the layers of the ARC over the cell to maximize the energy produced by a system depending on the particular location where it will be installed.

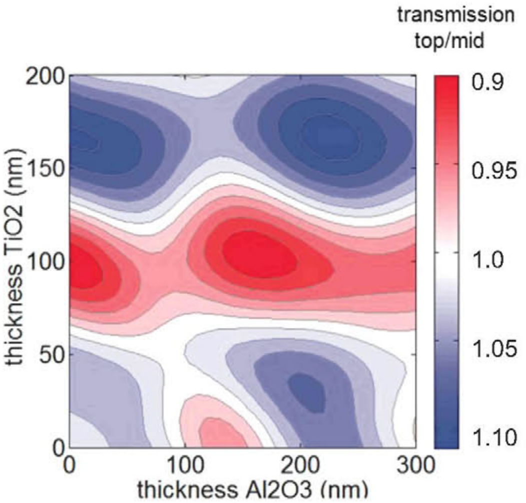

FIGURE 8. Ratio of the integrated transmittance for top and middle subcells as a function of the thicknesses of the layers of the Al_2O_3/TiO_2 antireflective coating evaporated over the solar cell.

CONCLUSIONS

An experimental model to estimate the annual energy losses in a CPV system due to spectral and temperature variations along the year has been presented. It uses as inputs the direct normal irradiance in Madrid as a function of the spectral distribution and ambient temperature, and the thermal and spectral sensitivities of the CPV systems measured indoors using a solar simulator and a thermal chamber. The model estimates annual energy losses equals to 17.8% and 7.4% for a low-tolerance and high-tolerance systems respectively before optimization. These losses are reduced to 7.2% and 5.2% if the current matching of the systems is tuned for the characteristic spectrum in Madrid containing the majority of the irradiance along the year. Among the options to modify the top/middle current matching, trimming the antireflective coating over the cell has been shown to be the one that allows a wider room for trimming the top/middle current matching.

ACKNOWLEDGMENTS

This work was partly supported under the NGCPV project, FP7-ENERGY-2011-JAPAN-283798, and under the SIGMAMODULOS project.

REFERENCES

1. M. A. Gree et al., «Solar cell efficiency tables (version 40)», *Prog. Phot. Res. Appl.*, vol. 20, n.° 5, pp. 606–614, 2012.
2. K. Ghosal et al., «Performance of a micro-cell based transfer printed HCPV system in the South Eastern US», *AIP Conf. Proc.*, vol. 1477, n.° 1, pp. 327-330, 2012.
3. IEC 62670 Concentrator Photovoltaic (CPV) Performance testing
4. T. Schult et al., «Temperature Dependence of Fresnel Lenses for Concentrating Photovoltaics», *2nd International Workshop on Concentrating Photovoltaic Optics and Power*, Darmstadt, 2009.
5. V. D. Rumyantsev et al., «Thermal Regimes of Fresnel Lenses and Cells in "All-Glass" HCPV Modules», in *AIP Conf. Proc.*, pp. 89-92, 2010
6. T. Hornung et al., «Temperature Dependent Measurement And Simulation of Fresnel Lenses For Concentrating Photovoltaics», in *AIP Conf. Proc.*, pp. 85-88, 2010.
7. S. Askins et al., «Effects of Temperature on Hybrid Lens Performance», in *AIP Conf. Proc.*, 2011.
8. P. Faine et al., «The influence of spectral solar irradiance variations on the performance of selected single-junction and multijunction solar cells», *Sol. Cells*, vol. 31, n.° 3, pp. 259-278, 1991.
9. W. E. McMahon et al., «Criteria for the design of GaInP/GaAs/Ge triple-junction cells to optimize their performance outdoors», in *Proc. 29th IEEE Phot. Spec. Conf.*, pp. 931-934, 2002
10. G. Létay, C. Baur, and A. W. Bett, «Theoretical investigations of III-V multi-junction concentrator cells under realistic spectral conditions», in *Proc. of the 19th EUPVSEC, Paris*, 2004.
11. K. Emery, D. Myers, and S. Kurtz, «What is the appropriate reference spectrum for characterizing concentrator cells?», in *Proc. 29th IEEE Phot. Spec. Conf.*, pp. 840-843, 2002.
12. K. Araki and M. Yamaguchi, «Influences of spectrum change to 3-junction concentrator cells», *Sol. Energy Mater. Sol. Cells*, vol. 75, n.° 3-4, pp. 707-714, 2003.
13. S. P. Philipps et al., «Energy harvesting efficiency of III-V triple-junction concentrator solar cells under realistic spectral conditions», *Sol. Energy Mater. Sol. Cells*, vol. 94, n.°5, pp. 869-877, 2010.
14. G. S. Kinsey and K. M. Edmondson, «Spectral response and energy output of concentrator multijunction solar cells», *Prog. Phot. Res. Appl.*, vol. 17, n.° 5, pp. 279–288, 2009.
15. M. P. Lumb et al., «Comparing The Energy Yield of (III–V) Multi-Junction Cells With Different Numbers Of Sub-Cells», in *AIP Conf. Proc.*, pp. 299-302, 2010.
16. J. Jaus and C. A. Gueymard, «Generalized spectral performance evaluation of multijunction solar cells using a multicore, parallelized version of SMARTS», *AIP Conf. Proc.*, vol. 1477, n.° 1, pp. 122-126, 2012.
17. N. L. A. Cha et al., «Validation of energy prediction method for a concentrator photovoltaic module in Toyohashi Japan», *Prog. Photovoltaics Res. Appl.*, 2012.
18. G. S. Kinsey et. al «Energy prediction of Amonix CPV solar power plants», *Prog. Photovoltaics Res. Appl.*, vol. 19, n.° 7, pp. 794–796, 2011.
19. T. Hornung et al., «Estimation of the influence of Fresnel lens temperature on energy generation of a concentrator photovoltaic system», *Sol. Energy Mater. Sol. Cells*, vol. 99, pp. 333-338, 2012.
20. M. Steiner et al., «Realistic power output modeling of CPV modules», *AIP Conf. Proc.*, vol. 1477, n.° 1, pp. 309-312, 2012.
21. S. R. Kurtz, P. Faine, and J. M. Olson, «Modeling of two-junction, series-connected tandem solar cells using top-cell thickness as an adjustable parameter», *J. Appl. Phys.*, vol. 68, n.° 4, pp. 1890-1895, 1990.
22. C. Domínguez, I. Antón, and G. Sala, «Multijunction solar cell model for translating I–V characteristics as a function of irradiance, spectrum, and cell temperature», *Prog. Photovoltaics Res. Appl.*, vol. 18, n.° 4, pp. 272–284, 2010.
23. M. Victoria et al., «Characterization of the spatial distribution of irradiance and spectrum in concentrating photovoltaic systems and their effect on multi-junction solar cells», *Prog. Photovoltaics Res. Appl.*, 2011.
24. C. Domínguez, S. Askins, I. Antón, and G. Sala, «Indoor characterization of CPV modules using the Helios 3198 solar simulator», in *24th EUPVSEC*, Hamburg, pp. 165-169, 2009.
25. C. Domínguez, I. Antón, and G. Sala, «Solar simulator for concentrator photovoltaic systems», *Opt Express*, vol. 16, n.° 19, pp. 14894–14901, 2008.
26. S. Askins et al., «Optimization Of Tolerant Optical Systems For Silicone On Glass Concentrators», in CPV-8, Toledo, 2012.
27. M. Victoria, C. Domínguez, I. Antón, y G. Sala, «Antireflective coatings for multijunction solar cells under wide-angle ray bundles», *Opt. Express*, vol. 20, n.° 7, p. 8136, 2012.
28. M. Muller, B. Marion, S. Kurtz, y J. Rodriguez, «An Investigation into Spectral Parameters as they Impact CPV Module Performance», *AIP Conf. Proc.*, vol. 1277, n.° 1, pp. 307-311, 2010.