Outdoor evaluation of concentrator photovoltaic systems modules from different manufacturers: first results and steps

Eduardo F. Fernández[1]*, Pedro Pérez-Higueras[1], Antonio J. Garcia Loureiro[2] and Pedro G. Vidal[1]

[1] Centre of Advanced Studies in Energy and Environment, University of Jaén, Jaén, Spain
[2] University of Santiago de Compostela, Santiago de Compostela, Spain

ABSTRACT

For the behavior of concentrator photovoltaic systems technology under real conditions to be understood, different modules from different manufacturers were measured in a new research center in Jaén. The influence in the power and the efficiency of irradiation levels, air temperature, and the influence of air mass were under study for 6 months. $P_{\max}$ shows a linear behavior with direct normal irradiance, and efficiency was constant to a first approximation for a wide range of irradiance levels. The effect of air temperature was negligible for the temperatures under study. At the same time, efficiency shows a maximum around AM1.5 and decreases aside this point.

KEYWORDS
concentrator photovoltaic; outdoor measures; characterization

*Correspondence
Eduardo F. Fernández, University of Jaén, Spain.
E-mail: fenandez@ujaen.es

1. INTRODUCTION

Concentrator photovoltaic systems (CPV) using triple-junction solar cells could achieve lower cost than conventional flat panel PV systems in a few years [1]. CPV uses optics that increase the light received on the solar cell surface. Lenses and mirrors concentrate light on small and high-efficiency photovoltaic solar cells, reducing the cell area, which is the most expensive material, and also mounting cheaper optical devices. The idea is to reduce the costs of electricity production increasing the efficiency of the system [2].

One of the problems of CPV technology is the difficulty to find data from modules and power plant efficiencies, or from the influence of outdoor parameters. This is due to the fact that companies are still learning and they need more operative experience with their new designs, and at the same time, such data are strategic and confidential for their commercial purposes. In addition to that, most of the information disclosed is uncompleted, as it does not indicate measuring conditions, the laboratory involved, or if the values obtained come from commercial systems or prototypes. The efficiency of the current CPV modules ranges from 20% to 30%, and the efficiency of the present CPV power plants is around 20%. Such data have been collected from different articles and only give an idea about the current efficiency of modules or power plants, Figure 1 [3,4].

Moreover, multi-junction (MJ) concentrator solar cells are influenced by changes in irradiance, spectrum, and temperature [5–7], and as a consequence, such parameters have also an impact on CPV. Likewise, other parameters such as wind speed or cooling at high irradiance levels are also important to understand the real output of a CPV module [8,9]. Thus, outdoor evaluation is critical to understand the actual behavior of the system. However, there is little experience in CPV technology, and the way to estimate the influence of atmospheric parameters is still challenging.

The real efficiency and the behavior of a CPV module cannot only be explained through the study of MJ solar cells. The serial-parallel association of these cells causes mismatch problems. The cell with worst quality and performance determines the operational behavior of the rest, and this reduces the global efficiency of the module. The optical devices mounted also introduce losses in the transmission of light, reducing the efficiency of the module

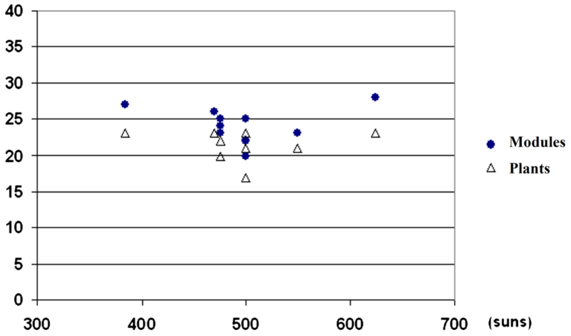

Figure 1. DC modules and AC power plants efficiencies for different commercial concentrator photovoltaic systems technologies. All modules and power plants are equipped with monolithic III–V triple-junction solar cells and Fresnel lenses or mirrors to concentrate light.

even with the high efficiencies achieved by the current optical technology, set at around 85% [3]. At the same time, the “spectral skewing” introduced by the concentrator optics could change the spectrum received by the MJ solar cell and therefore change the current-matched condition of the device [10]. All these factors introduce differences and losses that reduce the final efficiency of the module.

For the CPV technology to be understood and clarified, it is necessary to investigate and carry out important efforts in this respect. Because of this, a new research center, *Centre of Advanced Studies in Energy and Environment*, has been created in the University of Jaén. The center is equipped with different instruments, namely an atmospheric station, a solar tracker, and a complex system to measure *I*–*V* curves and temperatures to understand the behavior of CPV technology.

The center is located in the south of Spain, Jaén, which has a high direct annual irradiation level per year, more than 2.000 kWh/m^2 [11]. Figure 2 shows the distribution of direct annual radiation in Jaén versus direct normal irradiance (DNI). The maximum contribution to the annual energy comes from irradiance levels between 800 and 900. In particular, 95% of the total direct energy received is located in the range 400–1000 W/m^2, and this will be the focus of our study. The temperature of air can easily reach 40° C in summer and 5°C in winter. Because of this, Jaén and its new solar research center are located in an excellent place for flat panel or CPV outdoor evaluation.

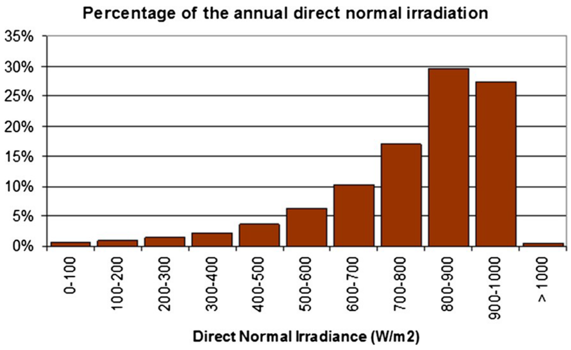

Figure 2. Distribution of direct annual radiation in Jaén versus direct normal irradiance level.

The goal of this paper is to study the influence of atmospheric parameters (direct irradiance levels, air temperature or air mass) in CPV technology to understand the behavior of the system under realistic conditions. For this purpose, the *I*–*V* curves of three modules from different manufacturers were measured during the last 6 months, and the impinging atmospheric parameters were recorded.

2. A BRIEF OVERVIEW OF CPV MODULES

A typical CPV module contains a particular number of solar cells, usually monolithic MJ solar cells, interconnected in series, with one Fresnel lens per cell that concentrates light. The most critical element of a CPV module is the solar cell because it is the one that has more influence in the final efficiency of the system.

Frequently, III–V triple-junction solar cells display the highest efficiencies and are used in CPV technology to reduce the total area of CPV modules through a reduction in the amount of solar cells required. Many efforts are being made to increase the efficiency of MJ solar cells and CPV modules. New materials and MJ solar cells with more junctions are currently under study to increase the final efficiency of the devices [12–14].

Such electronic devices consist of a monolithic III–V triple-junction solar cell with three different subcells. MJ solar cells are rated under AM1.5 d ASTM G-173-03, defined by the *American Society for Testing and Material*, and they are optimized for this spectrum [15]. Because of the internal series connection of the individual subcells with different band gap energies, MJ solar cells show a significant dependence on the spectral distribution of the incident light [16–18]. This dependence needs to be studied to understand the power output of a CPV module that uses MJ solar cells.

The influence of irradiance and temperature is also paramount. As an example, Figure 3 shows the efficiency of a III–V monolithic InGaP/InGaAs/Ge triple-junction solar cell 3C40C by AZURSPACE under different effective concentration ratios and under different temperatures [19]. The device was designed for an operation between 400× and 500 ×. Depending on the temperature of the cell and at higher irradiance levels, efficiency decreases due to series resistance losses. As a result, the study of the influence of spectrum, temperature, and irradiance are necessary to understand the *I*–*V* characteristics of an MJ cell and a CPV module [20].

In accordance to what is stated previously, the power output of an MJ solar cell could be written in a general way as follows:

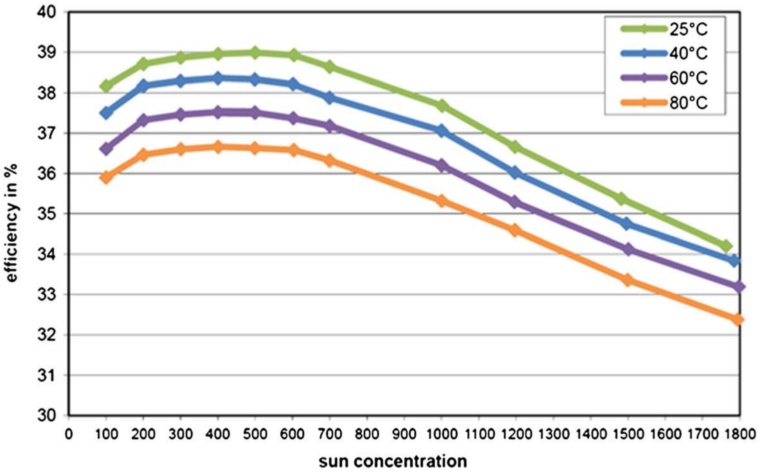

Figure 3. Efficiency versus effective concentration ratio for different cell temperatures of an III–V monolithic InGaP/InGaAs/Ge triple-junction solar cell 3C40C by AZURSPACE.

$$P_{\mathrm{cel}} = (B; T_{\mathrm{cel}}; S) \quad (1)$$

where B is the direct radiation, T_{cel} is the cell temperature and S is the incident spectrum. Similar to solar cells, CPV modules are influenced by these parameters and others. An additional problem in CPV technology is that T_{cel} is difficult to measure and there is not enough experience in the study of the relation among T_{cel}, T_{air}, and B. Some authors try to find general relations in these parameters but the dependence on the internal characteristic of each module makes the problem complex [21,22]. So, several methods use air temperature to simplify the problem [23,24]. Thus, following the ASTM standard E2527 [23], the power output of CPV modules could be described as follows:

$$P_{\mathrm{mod}} = (B; T_{\mathrm{air}}; V) \quad (2)$$

where V is the wind speed. As it is shown, this method also introduces wind speed but does not consider the influence of the spectrum. A more complete model to describe CPV modules may be the following one:

$$P_{\mathrm{mod}} = (B; T_{\mathrm{air}}; V; S) \quad (3)$$

In our study, however, all the data considered have been measured at wind speeds below 1 m/s, which make the influence of wind negligible [8]. Therefore, the power output could be described as follows [24]:

$$P_{\mathrm{mod}} = (B; T_{\mathrm{air}}; S) \quad (4)$$

3. EXPERIMENTAL PROCEDURE

Three different CPV modules from different manufacturers have been measured during the last 6 months to shed light on this technology. Tables I and II show some data from the modules under study provided by the companies. As mentioned previously, it is difficult to find data from manufacturers. Tables I and II contain the information that was possible to gather from the companies. Table II shows that data have not been provided at the same measurement conditions. In the case of manufacturer B, some important data were unavailable, namely cell temperature and incident spectrum.

For this study, modules are mounted in a solar tracker designed by the BSQ company in the roof of the research center. A four-wire electronic load PVPM 1000 C40 and an Agilent 34970A (Agilent Technologies, Inc., Santa Clara, CA, USA) data logger are located in the laboratory to register the I–V curves and to measure the temperature

Table I. Characteristics of the concentrator photovoltaic systems modules measured in Jaén.

Manufacturer	Geometric concentration	Optics	Type of solar cells	Number of solar cells	Cooling	Area of the module (m^2)
A	550	Fresnel lens with secondary optic	Lattice-matched GaInP/GaInAs/Ge	16 cells in series	Passive	0.44
B	500	Fresnel lens with secondary optic	Lattice-matched GaInP/GaInAs/Ge	6 cells in series	Passive	0.39
C	625	Fresnel lens with secondary optic	Lattice-matched GaInP/GaInAs/Ge	6 cells in series	Passive	0.47

All the cells are protected with bypass diodes.

Table II. Electrical data from manufactures of the concentrator photovoltaic systems modules under study.

Manufacturer	Efficiency (%)	P_{max} (W)	DNI (W/m^2)	T_{cel} (°C)	spectrum
A	21.8	96.0	1000	25	AM1.5 d
B	17.9	57.9	850	—	—
C	19.4	90.2	1000	25	AM1.5 d

Efficiencies have been calculated using expression 5.
DNI, direct normal irradiance.

of the module. The distance between CPV modules and instruments is 50 m. To measure temperature, we placed two 4-wire PT100 as close as possible to the solar cell, on the concentrator receivers inside the module. This temperature will be defined as module temperature. At the same time, an atmospheric station, MTD 3000 from *Geonica* (GEÓNICA S.A., Madrid, Spain), records other outdoor parameters such as global irradiance, direct normal irradiance, wind speed or direction, air temperature, and humidity. This station is also located in the roof and communicated through Ethernet with a pc located in the laboratory. All parameters were recorded daily and were compared every 10 min during 6 months, from July to December 2010. The current study only accounts for the data collected in clear days and with wind speed below 1 m/s. It is also important to remark that the modules were cleaned once a week and also after rainy days to avoid possible power losses. With what is mentioned previously, we are able to give the first conclusions of our research.

4. RESULTS AND DISCUSSION

4.1. Normalization of measurement conditions

As it was presented in Table II, some data from manufacturers are provided at different conditions. This makes the comparison between them difficult, and therefore, it is necessary to analyze the *I*–*V* curves under the same conditions. For this, the stratified method defined by K. Araki [8] has been used because of its proved high accuracy in translating CPV to particular outdoor conditions. In this case, the particular outdoor conditions defined were 850 W/m^2 for DNI, 20° C of air temperature and optical air mass of 1.5 corrected in altitude calculated with the formula given by Kasten and Young in 1989 [25]. These conditions have been considered as the standard values to use the stratified method. Table III shows the results obtained with the stratified method and also for wind speed less than 1 m/s because only data with this speed were considered, as mentioned previously. The stratified method needs an important set of measurements to be applied because it requires lower and higher values of air mass and air temperature than the defined standard conditions and a combination of these for a fix value of DNI (850 W/m^2) [8]. As it has been commented, the data were recorded from July to December 2010. Because of this, it is possible to have enough data with low and high air temperatures and air mass for the standard DNI that let us use this method.

Table III. Efficiency and maximum power of different concentrator photovoltaic systems modules at 850 W/m^2, air mass AM1.5, wind speed <1 m/s and 20° C of air temperature calculated from measurements.

Manufacturer	Efficiency (%)	P_{max} (W)	DNI (W/m^2)	T_{air} (°C)	Air mass
A	20.2	75.7	850	20	1.5
B	20.3	66.6	850	20	1.5
C	17.9	70.9	850	20	1.5

Efficiencies have been calculated using expression 5.
DNI, direct normal irradiance.

4.2. Influence of DNI and air temperature in P_{max}

The main conclusion found is that the relation between maximum power point and DNI is, to a first approximation, linear despite other outdoor parameters as, for example, the important influence of spectrum in MJ solar cells. Figure 4 shows the good linear fitting for the modules under study with an R^2 from 0.91 to 0.97 for a wide range of DNI and temperatures from 400 to 1000 W/m^2 and 10 to 40° C, respectively.

The maximum power point of a solar cell and therefore of a CPV module depends on the DNI levels. However so, other parameters such as air temperature or cell temperature may play an important role in the *I*–*V* curves [26,27]. Figures 5 and 6 display maximum power versus DNI for manufacturers A and B, classified by temperatures. The first conclusion is that air temperature did not play a very important role in the power output for the modules under study, which may indicate that the main heat source of solar cell is DNI. The influence of air temperature in P_{max} was negligible for the air temperatures of our study, this means from 10 to 40°C. Important efforts are needed to quantify the influence of air temperature in CPV modules.

When the behavior of both modules is compared, there are some differences. Module B has bigger dispersion in the data than module A. It is probably because module B has a worse acceptance angle, which introduces an additional tracking error due to the fluttering of the structure during tracking. This produces losses and must be considered by manufacturers to increase the generation and justify the big efforts in optic design to increase the acceptance angle of modules [28,29].

If the three different modules are compared (Figure 4), module A has the best linear behavior and the smallest dispersion of data. At lower DNI, the three have a similar maximum power. When the DNI is increased, module A

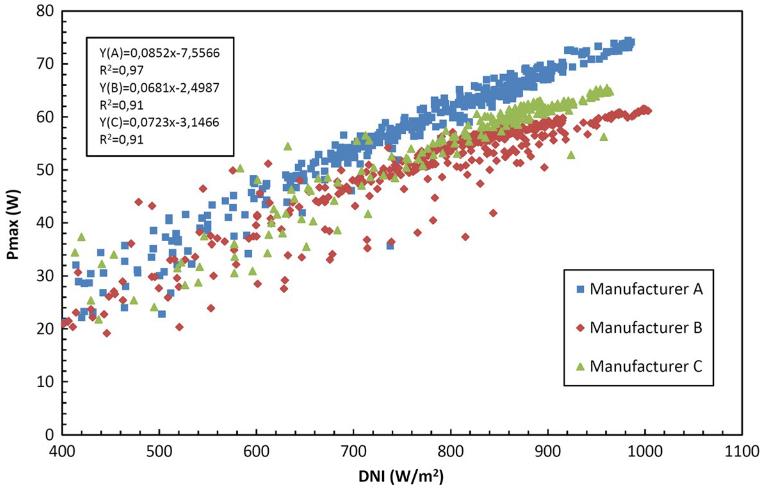

Figure 4. P_{max} versus direct normal irradiance (DNI) of modules from three manufacturers.

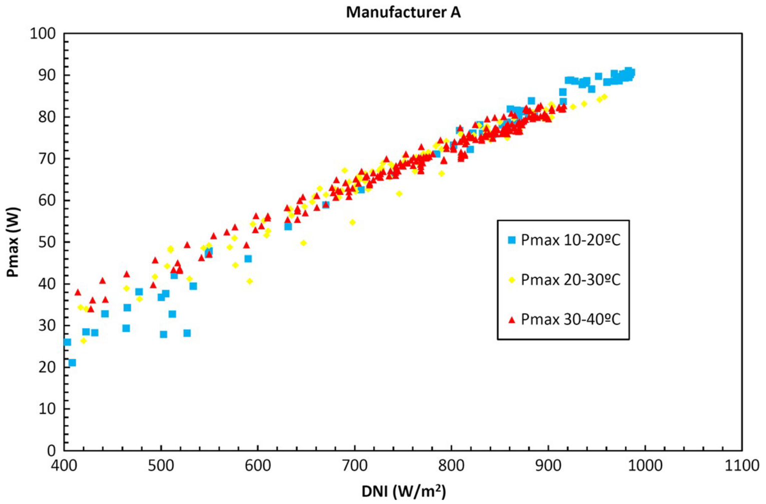

Figure 5. P_{max} versus direct normal irradiance (DNI) of module from manufacturer A for different air temperature ranges.

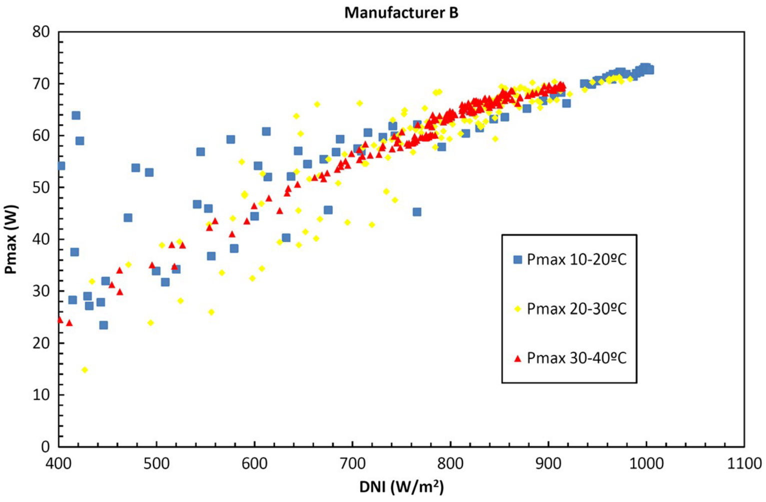

Figure 6. P_{max} versus direct normal irradiance (DNI) of module from manufacturer B for different air temperature ranges.

increases its power linearly with the best slope, module C increases its power linearly too but with a lower slope, whereas module B shows the worst results.

4.3. Influence of DNI and air temperature in Efficiency

Taking into account the area of a given module (A) and the average irradiance on its surface, efficiency (Z) will be

$$\eta = \frac{P(W)}{B\left(\frac{W}{m^2}\right)\cdot A(m^2)} \tag{5}$$

As it has been commented, modules show efficiencies between 20% and 30%. In this study, efficiencies calculated using expression 5 are slightly smaller (Tables II and III). One possible explanation is that the total area of modules was used in our calculations although, usually, data from manufactures only include the active area (the area of the lens that concentrates light) [30].

It is possible to compare the efficiencies of modules using both the data from the manufacturer (Table II) and our own measurements (Table III). Module B is not taken into account because the data provided by the manufacturer are scarce to draw conclusions. As shown, the efficiencies calculated with the data provided by the manufacturers are better for modules A and C, probably because the temperature of the cell is lower and the spectrum and irradiance levels are exactly adjusted to reach the highest efficiencies. Further possible explanations could be found in optical losses [27,31], various resistance losses, wires between cells, resistance losses at the cell metal connection, or current mismatch losses. Other possible influences (such as tracking errors, for example) do not have any influence because the measurements were carried out under controlled conditions.

With the use of expression 5, it is possible to make a similar analysis to that of power. This involves the study of the influence of air temperature and DNI levels. As shown in Figures 7–9, module efficiency reaches its maximum at certain irradiance levels and then decreases following the same behavior of MJ solar cells (Figure 3). Despite this, it could be considered as constant to a first approximation for the DNI of our study. The decreased efficiency of solar modules at high radiation levels may have different origins: series resistance losses of the MJ solar cell at higher irradiance levels, spectral effects originated in the fact that one of the cells of the MJ could be limiting the current, and high temperatures reached by the MJ at higher irradiance levels that could have and important influence on power and efficiency [26,27]. The study of these effects and the ability to quantify them individually is still under study. Figures 7 and 8 represent efficiencies versus DNI for modules A and B. For the influence of DNI and air temperature to be studied, efficiencies are represented, sorted out by air temperatures. Again, the effect of air temperature could be considered negligible because it does not have a critical influence. When comparing the three modules (Figure 9), we can see that module A shows the best results because it reaches the highest efficiencies for a wider range of DNI levels, then come modules B and C. Table III displays the results of the modules under the same output conditions, in which the efficiencies of modules A and B are similar. When the DNI is increased, module B losses efficiency as opposed to module A. This could be explained by different reasons: a possible worse cooling of module B that could increase the temperature of the cell reducing its efficiency, a higher series resistance of the MJ at higher irradiance levels, or a bigger influence of spectrum. It is not easy to separate these effects; it is one of our current research lines and more conclusions regarding it will be given in future studies.

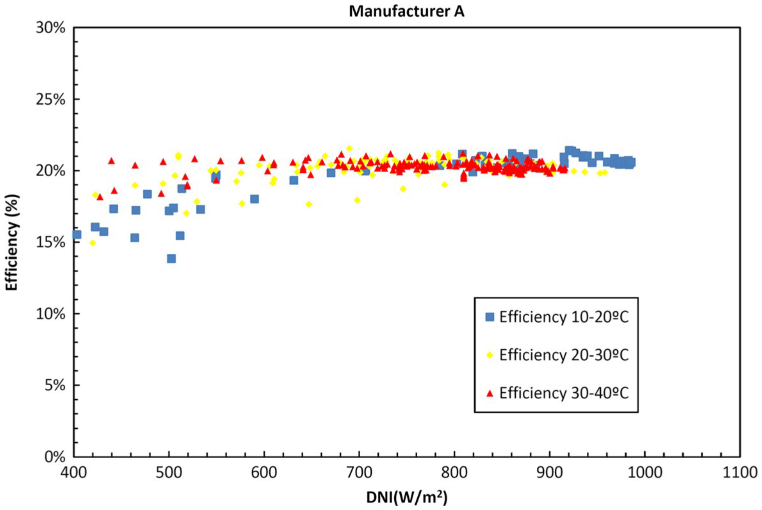

Figure 7. Efficiency versus direct normal irradiance (DNI) of module from manufacturer A for different air temperature ranges.

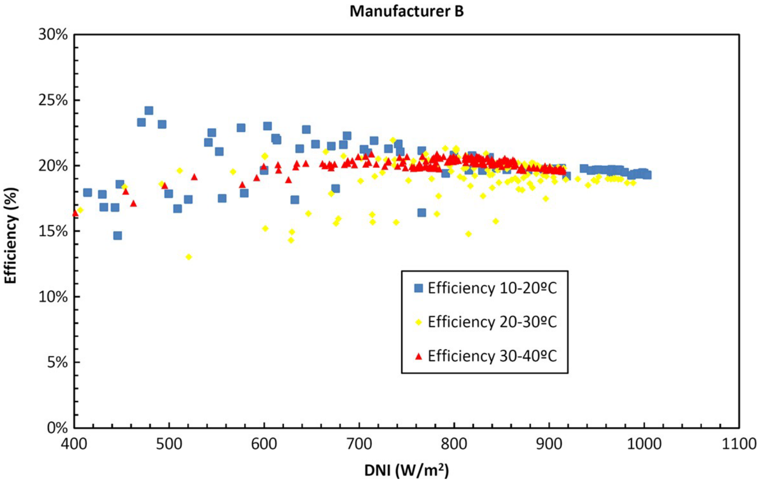

Figure 8. Efficiency versus direct normal irradiance (DNI) of module from manufacturer B for different air temperature ranges.

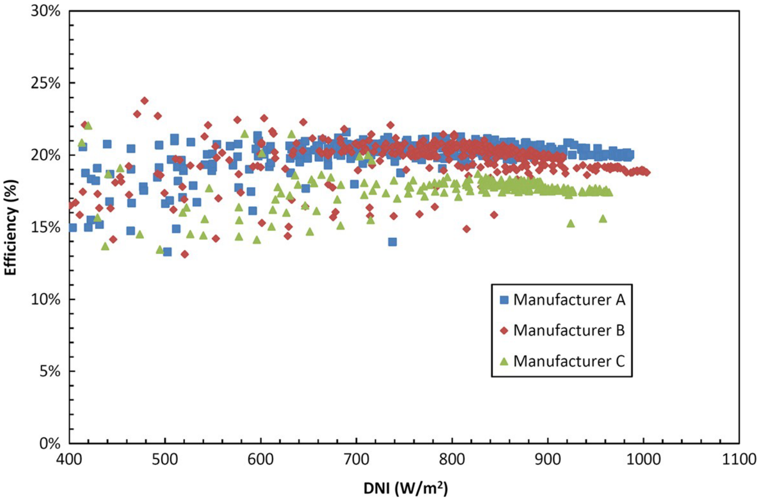

Figure 9. Efficiency versus direct normal irradiance (DNI) of modules from three manufacturers.

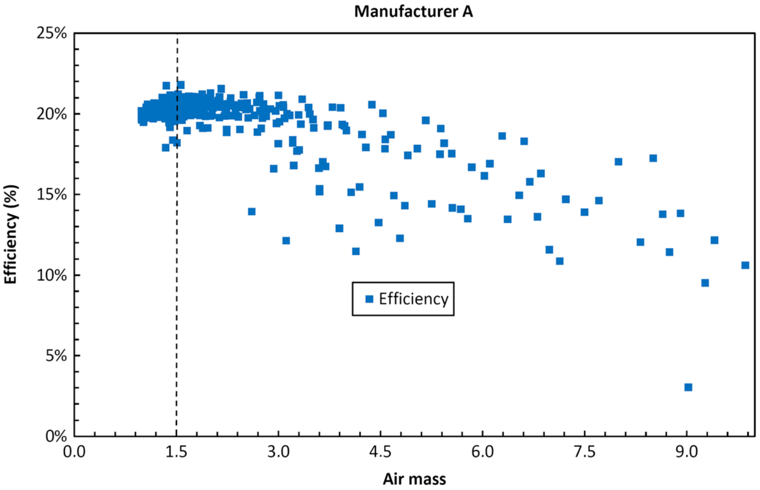

Figure 10. Efficiency versus air mass of module from manufacturer A.

4.4. Influence of air mass

The main reason for spectral changes is the optical air mass. This is only an approximation of the real spectrum but can be regarded as a good approximation and many efforts to evaluate the impact of spectrum changes go in this direction [32,33]. This is useful because it is simpler than measuring the spectral distribution with spectroradiometers and it is an important tool to evaluate spectral impacts. The method based on spectroradiometers is more complex and expensive, and at the same time, it is not possible to have direct measurements of the place of interest during 1 year in all the cases. On the other hand, the "spectral skewing" introduced by the concentrator optics changes the real spectrum that the cell is receiving; thus, this method has also some errors apart from an important complexity. As it was commented previously, MJ solar cells are currently optimized for AM1.5 direct and therefore CPV modules too. During the day, however, the spectrum changes, and the efficiency and power output of the device change too. Thus, the efficiency of the MJ or CPV modules loses power or efficiency per air mass unit where AM1.5 represents the maximum[34,35].

Figure 10 shows the correlation between efficiency and air mass for one of the modules under study, the results are equivalent for all of them. The maximum efficiency is reached at an air mass around 1.5. Aside this point, efficiency decreases with nonlinear behavior probably because of the effect of other parameters such as humidity or morning dew that introduce other external influences that are still under study. As discussed throughout this study, the effect of air temperature could be negligible for the temperatures under study. So, when the efficiency versus air mass is represented, the influence of air temperature can be expected not to have an important role. Anyway, limiting the effects of air or cell temperature, spectrum, or humidity in CPV modules is still a challenge.

5. CONCLUSIONS

Modules from different manufacturers are currently being measured in outdoor conditions in a new solar research center in Jaén. The aim is to investigate the behavior of CPV modules under realistic conditions. In particular, this paper has focused on the study of CPV modules with a geometric concentration between 500 and 625 suns equipped with Fresnel lens and with lattice-matched GaInP/GaInAs/Ge solar cells in Jaén. Some conclusions could be extracted from this first analysis of data. $P_{\max}$ shows a linear behavior with DNI from 400 to 1000 W/m^2. Regarding efficiency, we can conclude that, for such irradiance levels, it is constant to a first approximation. At the same time, the effect of air temperature can be considered negligible under a wide range of temperatures for $P_{\max}$ and efficiency. Furthermore, the influence of air mass in efficiency is also shown. In particular, there is a maximum around AM1.5, and aside this point, it decreases. This work must be considered as the first step of the study of CPV modules and other parameters such as wind. A deeper study of the influence of air mass or cell temperature and how to quantify them individually will be carried out in the future.

ACKNOWLEDGEMENTS

This work forms part of project *Sigmasoles: La Innovacion en Concentracion Fotovoltaica en España* (Sigmasoles: Innovation in Concentrator Photovoltaic in Spain), PSE-440000-2009-8, supported by the Spanish Science and Innovation Ministry, and by European Union (European Regional Development Fund). This work has been also supported by Consejería de Innovación, Ciencia y Empresa de la Junta de Andalucía within the frame of the Project "Análisis y caracterización de un sistema fotovoltaico de concentración a sol real. Comparativa con otras tecnologías fotovoltaicas (P09-TEP-5045)".

The authors would like to express their deep appreciation to Juan Ignacio Fernández Carrasco and Florencia Almonacid Cruz for their technical support and generous assistance.

REFERENCES

1. Pérez-Higueras P, Almonacid G, Gómez P, Muñoz E, Luque-Heredia I, Banda P, Valera P, Cabrerizo M. *Proposal of Regulatory Framework for Concentration Photovoltaics in Spain*. ASIF: Madrid, 2010. ISBN: 978-84-692-9987-6.
2. Luque AL, Andreev VM. Concentrator Photovoltaics. Springer-Verlag 2: New York, 2007. ISBN 978-3-540-68796-2.
3. Perez-Higueras P, Muñoz E, Almonacid G, Vidal PG. High concentrator photovoltaics efficiencies: present status and forecast. *Renewable and Sustainable Energy Reviews* 2011; **15**: 1810–1815.
4. Rubio F, Martínez M, Hipólito A, Martín A, Banda P. Status of CPV technology. *25th European Photovoltaic Solar Energy Conference and Exhibition*, 2010.
5. Siefer G, Abbot P, Baur C, Schleg T, Bett AW. Determination of the temperature coefficients of various III–V solar cells. *20th European Photovoltaic Solar Energy Conference*, 6–10 June 2005, Barcelona, Spain.
6. Siefer G, Baur C, Meusel M, Dimroth F, Bett AW, Warta W. Influence of the simulator spectrum on the calibration of multi-junction solar cells under concentration. *29th IEEE Photovoltaic Specialist Conference*, New Orleans, May 20-24th, 2002; Paper No 302.6.
7. Fernández EF, García Loureiro AJ, Pérez Higueras PJ, Siefer G. Monolithic III–V triple-junction solar cells under different temperatures and spectra. 8th IEEE CED 2011, Palma de Mallorca, ISBN 978-1-4244-7863-7.
8. Araki K, Kemmoku Y, Yamaguchi M. A simple rating method for CPV modules and systems. 978-1-4244-1641-7 IEEE, 2008.

9. Bett AW, Jaus J, Peharz G, Siefer G. Outdoor evaluation of flatcon modules and systems. 978-1-4244-1641-1641-7, IEEE, 2008.
10. McMahon WE, Emery KE, Friedman DJ, Ottoson L, Young MS, Ward JS, Kramer CM, Duda A, Kurtz S. Fill factor as a probe of current matching for GaInP/GaAs tandem cells in a concentrator system during outdoor operation. *Progress in Photovoltaics: Research and Applications* 2008; **16**: 213–224.
11. Šúri M, Remund J, Cebecauer T, Hoyer-Klick C, Dumortiert D, Huld T, Stackhouse PW, Ineichen P. Comparison of direct normal irradiation spatial products for Europe. Solar Paces 2009. Conference, Berlin, Germany, 2009.
12. Law DC, King RR, Yoon H, Archer MJ, Boca A, Fetzer CM, Mesropian S, Isshiki T, Haddad M, Edmondson KM, Bhusari D, Yen J. Future pathways of terrestrial III–V multijunction solar cells for concentrator photovoltaic systems. *Solar Energy Materials & Solar Cells* 2010; **94**: 1314–1318.
13. Yamaguchi M, Nishimura K-I, Sasaki T, Suzuki H, Arafune K, Kojima N, Ohsita Y, Okada Y, Yamamoto A, Takamoto T, Araki K. Novel materials for high-efficiency III–V multi-junction solar cells. *Solar Energy* 2008; **82**: 173–180.
14. Yamaguchi M, Takamoto T, Araki K, Ekins-Daukes N. Multi-junction III–V solar cells: current status and future potential. *Solar Energy* 2005; **79**: 78–85.
15. ASTM. ASTM G173-03e1 standard tables for reference solar spectral irradiances: direct normal and hemispherical on 370 tilted surface, 2003.
16. Philipps SP, Peharz G, Hoheisel R, Hornung T, Al-Abbadi NM, Dimroth F, Bett AW. Energy harvesting efficiency of III–V multi-junction concentrator solar cells under realistic spectral conditions. *Solar Energy Materials & Solar Cells* 2010; **94**: 869–877.
17. Meusel M, Adelhelm R, Dimroth F, Bett AW, Warta W. Spectral mismatch correction and spectrometric characterization of monolithic III–V multi-junction solar cells. *Progress in Photovoltaics: Research and Applications* 2002; **10**(4): 243–255.
18. Kurtz SR, Olson JM, Faine P. The difference between standard and average efficiencies of multijunction compared with single-junction concentrator cells. *Solar Cells* 1991; **30**(1–4): 501–513.
19. http://azurspace.de/index.php?mm=129.
20. Kinsey GS, Stone K, Brown J, Garboushian V. Energy prediction of amonix CPV solar power plants. *Progress in Photovoltaics: Research and Applications* 2011; **19**(7): 794–796.
21. Kemmoku Y, Egami T, Hiramatsu M, Miyazaki Y, Araki K. Modelling of module temperatura of a concentrator PV systems. *19th European Photovoltaic Solar Energy Conference*, 7–11 June 2004, Paris, France.
22. ISFOC. Specifications of general conditions for the call for tenders for concentration Photovoltaic Solar Plants for the Institute of Concentration Photovoltaic Systems (ISFOC), 2007.
23. ASTM standard E2527. Standard test method forelectrical performance of concentrator terrestrial photovoltaic modules and systems under natural sunlight, 2009.
24. Gombert A, Gerstmaier T, Heile I, van Riesen S, Röttger M, Wüllner J. Analysis of long term operation data of FLATCON CPV systems. *25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion*, 6–10 September 2010, Valencia, Spain.
25. Kasten F, Young AT. Revised optical air mass tables and approximation formula. *Applied Optics* 1989; **28**(22): 4735–4738.
26. Aronova ES, Shvarts MZ, Soluyanov AA. The effect of temperature on the efficiency of concentrator PV modules with MJ SC. 978-1-4244-2950, 2009, IEEE.
27. Peharz G, Ferrer Rodríguez JP, Siefer G, Bett AW. Investigation on the temperature dependence of CPV modules equipped with triple-junction solar cells. *Progress in Photovoltaics: Research and Applications* 2011; **19**(1): 54–60.
28. Luque A, Araújo GL. Solar Cells and Optics for Photovoltaic Concentration. Adam Hildger: New York, 1989. ISBN 0-85274-106-5A.
29. Winston R, Miñano JC, Benítez P. Nonimaging Optics. Elsevier Inc: Amsterdam, 2005. ISBN 978-0-12-759751-5.
30. Pujol L, Perona A, Bouriel JR, Landart E, Dollet A. Outdoor characterization and performance evaluation of integra-sun prototype CPV module. *6th International Conference of CPV Systems*, 2010.
31. Hornung T, Steiner1 M, Nitz P. Estimation of the influence of Fresnel lens temperature on energy generation of a concentrator photovoltaic system. *Proceedings of 7th International Conference on Concentrating Photovoltaic (CPV-7)*, Las Vegas, USA, 2011.
32. Emery K, Del Cueto J. Spectral correction based on optical air mass. *29th IEEE PV Specialists Conference*, New Orleans, Louisiana, 2002.
33. Verlinden PJ, Lasich JB. Energy rating for CPV systems using III–V solar cells. ICSC5, Palm Desert, 18 November 2008.
34. Aronova ES, Grilikhes VA, Shvarts MZ, Timoshina NH. On correct estimation of hourly power output of solar photovoltaic installations with MJ SCs and sunlight concentrators. 978-1-4244-1641-7 IEE, 2008, IEEE.
35. Araki K, Kumagai I, Nagai H. Theory and experimental proof loss multy-trackers CPV system. *5th World Conference on Photovoltaic Energy Conversion*, 6–10 September 2010, Valencia, Spain.