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Analysis of high concentrator photovoltaic modules in outdoor conditions: Influence of direct normal irradiance, air temperature, and air mass

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The study of high concentrator photovoltaic (HCPV) technology under real conditions is essential to understand its real behavior. The influence of direct normal irradiance (DNI), air temperature (T_{air}), and air mass (AM) on the maximum power of two HCPV modules was studied for more than three years. Results found are presented in this paper. As expected, the main influence on the maximum power is DNI. Also, T_{air} has been found to have small influence on the maximum power. Regarding AM, two different behaviors have been found. The maximum power could be considered independent of AM for AM ≤ 2, while it decreases with an approximate linear behavior for AM > 2. Also, the maximum power of a HCPV module could be estimated with a linear mathematical fitting based on DNI, T_{air}, and AM. © *2014 AIP Publishing LLC*.
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I. INTRODUCTION

High Concentrator Photovoltaic (HCPV) uses optical devices, lenses, and mirrors that focus the light received on the solar cell surface, usually multi-junction (MJ) solar cells. The aim of this energy production system is to reduce the cost of electricity by increasing the efficiency of the system.[1]

Table I shows the expected forecast for MJ solar cells and HCPV modules for 2015. The high efficiencies expected for HCPV technology mean that it could be profitable in economic and energy terms soon. This fact represents a potential alternative to flat module photovoltaic systems in the energy generation market.[2]

MJ concentrator solar cells are influenced by changes in irradiance and temperature like single-junction solar cells. Additionally, due to the internal series connection of individual sub-cells with different band gap energies, MJ solar cells show a significantly greater sensitivity on the incident spectrum than single-junction solar cells.[3–7] Because of this, HCPV modules are also influenced by these parameters. However, the behavior of HCPV modules cannot only be explained by studying the behavior of MJ solar cells. Other effects such as mismatch losses due to the series-parallel association of MJ solar cells,[8] the reduction of HCPV module efficiency due to optical device losses,[2] the cooling of module[9] or lens temperature[10] under different atmospheric conditions have been demonstrated to have a far from negligible influence on the power generation of a HCPV module. Because of this, the study of HCPV modules under real operating conditions is essential to understand their behavior.

However, one of the problems of HCPV technology is the limited experience in its outdoor evaluation.[11] For this purpose, the *Centre of Advanced Studies in Energy and Environment* located in the south of Spain focused its main activities on HCPV evaluation. Big efforts have been made in this

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TABLE I. Forecast of the efficiencies of MJ cells and HCPV modules in 2015.[2]

Efficiency	Forecast (2015)
MJ solar cells	42%–50%
HCPV modules	30%–40%

center recently to understand and clarify this technology outdoors.[11–15] After more than three years of study of HCPV modules outdoors, the main conclusions obtained are given.

As in any other type of energy production system, it is important to know the behavior of the system in terms of energy. Hence, this paper is focused on the behavior of maximum power under different operating conditions. The goal of this paper is to study the influence on the maximum power (P) of different atmospheric parameters, particularly: direct normal irradiance (DNI), air temperature (T_{air}), and air mass (AM).

The paper is organized as follows. Section II describes the experimental set-up and methodology used to measure and study HCPV modules. In Sec. III, the influence of atmospheric parameters (DNI, T_{air}, and AM) on the maximum power of HCPV modules is presented. Also, a linear mathematical fitting, based on these atmospheric parameters, to estimate the maximum power of HCPV modules under study is introduced and analyzed.

In the last section, Sec. IV, we introduce the main conclusions of our current work and the possible future research lines.

II. EXPERIMENTAL SET-UP

Two different HCPV modules have been measured since 2010 in order to study the behavior of HCPV technology outdoors. Tables II and III show some data of modules under study provided by manufacturers.

In order to study HCPV technology, HCPV modules were measured in the *Centre of Advanced Studies in Energy and Environment* at the University of Jaén. The center is located in the south of Spain, Jaén, which has a high direct annual irradiation level[15] and T_{air} that can easily reach 40 °C in summer and 5 °C in winter. Because of this, Jaén and this solar research center are located in a suitable place for HCPV outdoor evaluation. The center is equipped with all instruments required to perform this task.

To carry out this study, the modules are mounted on a solar tracker designed by BSQ Company on the roof of the research center. A four-wire electronic load PVPM 1000C40 is placed in the laboratory to register the I-V curves of modules; the maximum power (P) is

TABLE II. Characteristics of the high concentrator photovoltaic modules used in the experiment. Every cell is protected with a bypass diode.

Manufacturer	Geometric concentration	Primary optics	Secondary optics	Type of solar cells	Number of solar cells	Cooling
A	500	PMMA Fresnel lens	Refractive truncated pyramid	Lattice-matched GaInP/GaInAs/Ge	6 cells in series	Passive
B	550	PMMA Fresnel lens	Refractive truncated pyramid	Lattice-matched GaInP/GaInAs/Ge	25 cells in series	Passive

TABLE III. Maximum power of modules under study at STC provided by manufacturers.

Manufacturer	P (W)	DNI (W/m^2)	T_{cell} (°C)	Spectrum
A	65	1000	25	1.5d
B	130	1000	25	1.5d

extracted from I-V curves. At the same time, an atmospheric station, MTD 3000C from GEONICA, records other outdoor parameters such as global irradiance, direct normal irradiance, air temperature, or relative humidity. This station is also located on the roof and communicated through Ethernet with a Personal Computer (PC) placed in the laboratory. All parameters have been recorded every 5 min since 2010. It is also important to remark that these modules were cleaned once a week and also after rainy days to avoid possible power losses. Figure 1 shows the scheme of the experimental set-up.

III. RESULTS

In this section the influence of DNI, AM, and T_{air} on the output of HCPV modules under study is analyzed. Also, a linear mathematical fitting to estimate the maximum power outdoors, based on the study of these parameters, is introduced and studied.

A. Influence of direct normal irradiance

The influence of DNI on the maximum power has been studied. Figures 2 and 3 show the behavior of the maximum power measured versus DNI and the linear regression analysis for the modules under study without any corrections either in T_{air} or in spectrum. As can be seen, the maximum power of the HCPV modules is strongly influenced by DNI with a correlation coefficient (R^2) of 0.98 in both cases. This means that, despite the effect of other atmospheric parameters such as temperature or spectrum, the main influence on HCPV modules' behavior comes from DNI. This is an important conclusion because it allows us to understand the main behavior of maximum power taking into account only DNI.

B. Influence of air mass

It is usually assumed that the main reason for spectral changes is AM.[16,17] This is only an approximation of the real spectrum but can be regarded as a good approximation and many

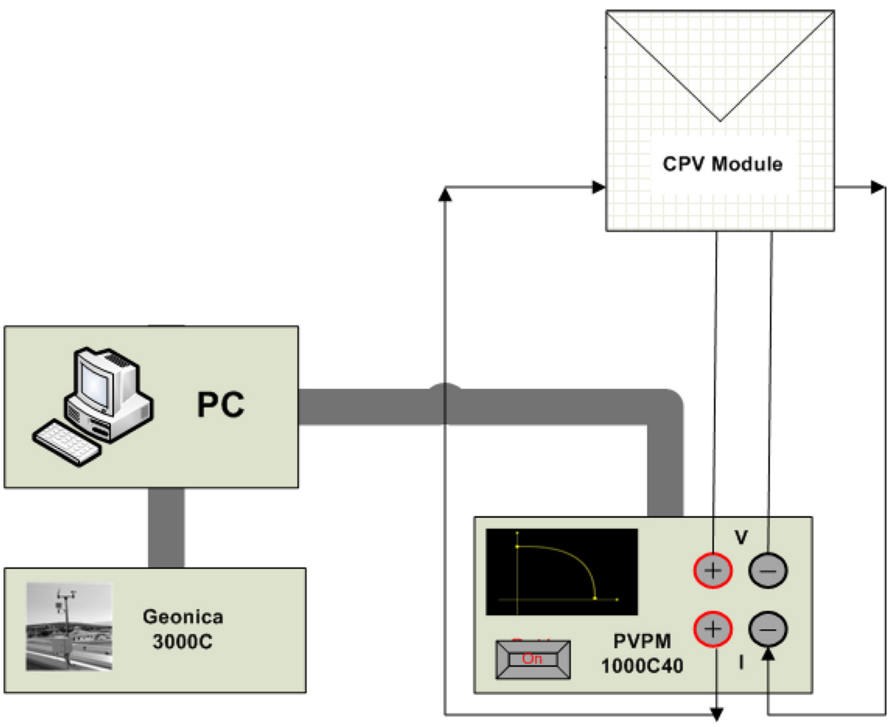

FIG. 1. Experimental set-up used to study the HCPV module behavior at the *Centre of Advanced Studies in Energy and Environment* of the University of Jaén.

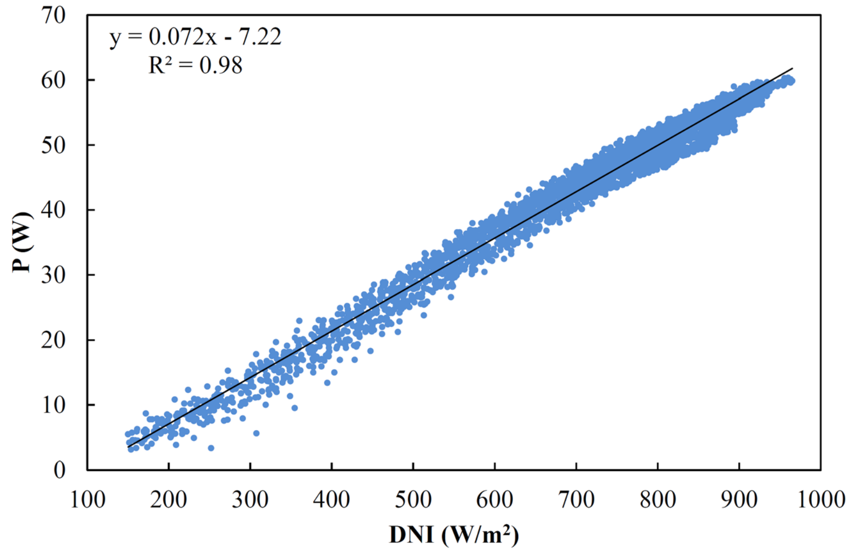

FIG. 2. Maximum power versus direct normal irradiance of module A.

efforts to evaluate the impact of spectrum changes go in this direction.[9,17–20] This is useful because it is not needed to measure AM to obtain it. Other methods based on measurements using spectroradiometers or isotype solar cells are more complex and expensive. In addition, with these methods it is not possible to have direct measurements for the place of interest for long periods of time in all cases. One possibility to know the spectral distribution for the place of interest, without the use of spectroradiometers or isotype solar cells, is based on simulation programs such as SMARTS.[21,22] The problem of these methods is that it is necessary to know atmospheric parameters for the place of interest that are not easy to get. Also, other problems in these methods are that it is necessary to know parameters of MJ solar cells such as external quantum efficiency at different temperatures, or spectral dependencies in focusing, absorption, and/or reflectance introduced by lenses, in order to accurately quantify the influence of incident spectrum.[23,24]

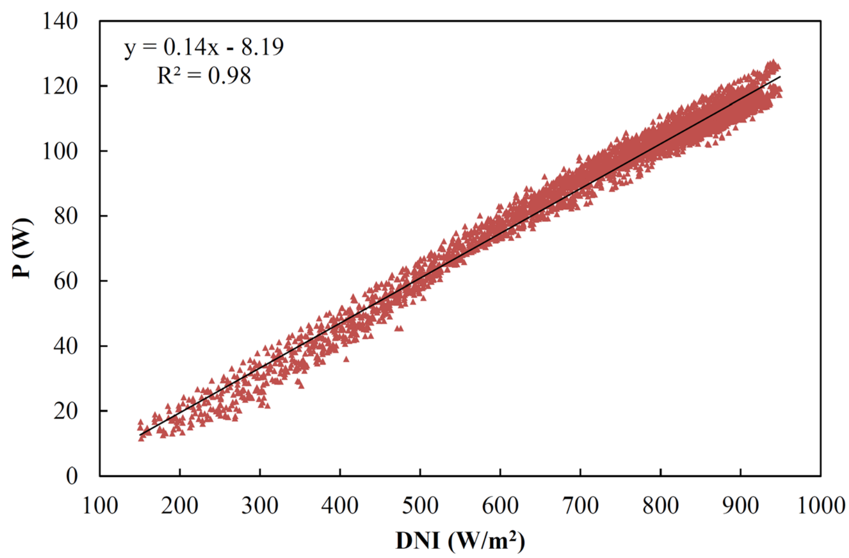

FIG. 3. Maximum power versus direct normal irradiance of module B.

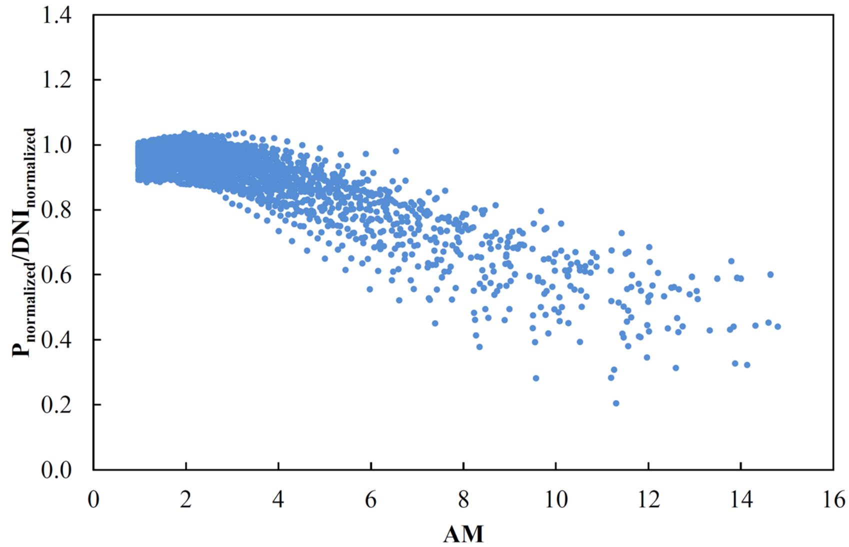

FIG. 4. Maximum power measured normalized to its value at STC divided by DNI measured normalized to its value at STC versus AM for module A.

Because of this, the procedure followed for evaluating the spectral impact in the output of HCPV modules is based on AM:[25,26]

$$\mathrm{AM}(\gamma) = \frac{\exp\left(\frac{-Z}{Z_h}\right)}{\sin(\gamma) + 0.50572 \cdot (\gamma + 6.07995)^{-1.6364}}, \tag{1}$$

where γ is the solar altitude, Z is the site elevation (Z = 452 m at Jaen), and Z_h is the scale height of the Rayleigh atmosphere near the Earth surface, equal to 8434.5 m.

In order to study the influence on the maximum power of AM of HCPV modules under study independently of DNI, the maximum power measured normalized to its value at Standard Test Conditions (STCs) ($P_{normalized}$) divided by the DNI measured normalized to its value at STC ($DNI_{normalized}$) versus AM has been plotted for each module, Figures 4 and 5.

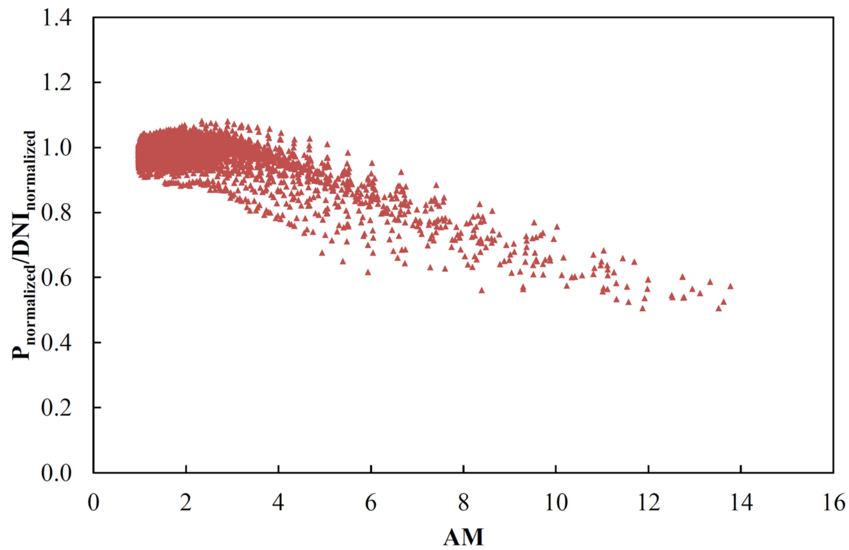

FIG. 5. Maximum power measured normalized to its value at STC divided by DNI measured normalized to its value at STC versus AM for module B.

The first conclusion that can be extracted from Figures 4 and 5 is that the $P_{normalized}/DNI_{normalized}$ decreases for AM > 2 with an approximate linear behaviour. The second conclusion is that for AM ≤ 2, the $P_{normalized}/DNI_{normalized}$ could be considered constant in first approximation. This means that:

- For AM ≤ 2, the maximum power of modules under study could be considered independent of AM in first approximation.
- For AM > 2, the maximum power is influenced by AM decreasing with an approximate linear behavior.

As can also be seen in Figures 4 and 5, there is an important scatter. This scatter could be explained by various reasons. One of them could be due to the working temperature of cells of HCPV modules because no temperature correction has been made. Another possible reason could be due to other atmospheric parameters: aerosol optical depth and precipitable water vapor, which have been demonstrated to have a non-negligible effect in the incident spectrum.[4]

It is also important to remark that MJ solar cells and HCPV modules are optimized to AM1.5d ASTM G-173–03 incident spectrum.[27] This means that a maximum at AM = 1.5 could be expected in Figures 4 and 5. However, this was not found in any case in the outdoor evaluation of HCPV modules under study. This could be explained by the "spectral skewing" introduced by lenses[24] and by the influence of other atmospheric parameters in the incident spectrum[4] among other reasons. This also highlighted the importance of the outdoor evaluation of HCPV technology.

C. Influence of air temperature

The maximum power of a HCPV module are also influenced by T_{air};[9,14,28] however, the study of its effect and the ability to analyze it individually is not easy as it is still under study.[11] As mentioned above, the influence on maximum power of AM could be considered negligible for AM ≤ 2. So that, in order to study the influence of T_{air} on HCPV modules under study independently of DNI and AM, the maximum power measured normalized to its value at STC ($P_{normalized}$) divided by the DNI measured normalized to its value at STC ($DNI_{normalized}$) versus $T_{air,}$ filtered for AM ≤ 2, has been plotted for each module, Figures 6 and 7.

Figures 6 and 7 show $P_{normalized}/DNI_{normalized}$ versus T_{air} and the linear regression analysis for HCPV modules under study. As can be seen, the slope is almost 0 in both cases. This

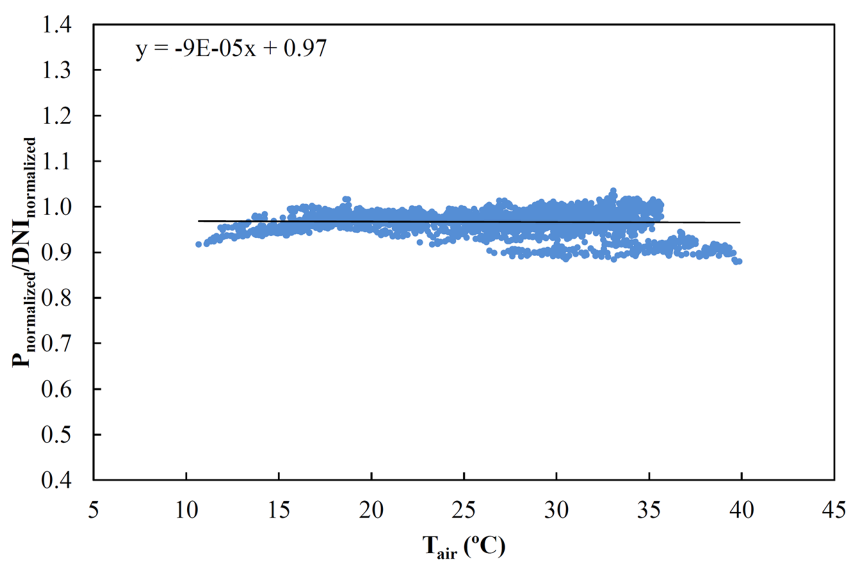

FIG. 6. Maximum power measured normalized to its value at STC divided by DNI measured normalized to its value at STC filtered for AM ≤ 2 versus T_{air} for module A.

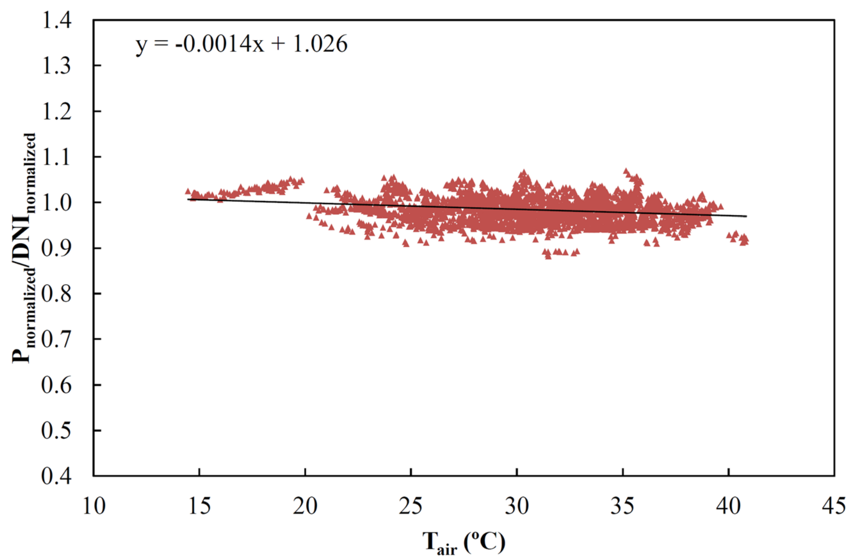

FIG. 7. Maximum power measured normalized to its value at STC divided by DNI measured normalized to its value at STC filtered for $AM \leq 2$ versus T_{air} for module B.

indicates that the influence on T_{air} of a HCPV module is small. This is consistent with the previous work related to the study of the influence of T_{air} on HCPV modules.[11]

D. Linear mathematical fitting of maximum power

Taking into account the above, a linear mathematical fitting of the maximum power point of a HCPV module could be mathematically expressed as a function of

$$P = f(\mathrm{DNI}, T_{air}, \mathrm{AM}). \tag{2}$$

There are two different behaviors in HCPV modules under study depending on AM. Particularly, for $AM \leq 2$, HCPV modules are only influenced by DNI and T_{air}, while for $AM > 2$, HCPV modules are influenced by DNI, T_{air}, and AM, in first approximation.

Hence, a linear mathematical fitting to estimate the maximum power of a HCPV module could be expressed as

$$P = a_1 \cdot \mathrm{DNI} + a_2 \cdot T_{air}; \quad \text{for} \quad \mathrm{AM} \leq 2, \tag{3}$$

$$P = a_1 \cdot \mathrm{DNI} + a_2 \cdot T_{air} + a_3 \cdot \mathrm{AM}; \quad \text{for} \quad \mathrm{AM} > 2, \tag{4}$$

where linear coefficients a_1, a_2, and a_3 are obtained by performing a multiple regression analysis of maximum power as a function of DNI, T_{air}, and AM. Results for each module are shown in Table IV.

Figures 8 and 9 show the linear regression analysis between estimated data using expressions 3 and 4, and actual data for two HCPV modules. As can be seen there is an adequate fit between both

TABLE IV. Linear coefficients for two HCPV modules under study obtained by performing a multiple regression analysis of P as a function of DNI, T_{air}, and AM.

Manufacturer	a_1	a_2	A_3
A	0.063	−0.0032	−0.58
B	0.13	−0.083	−0.42

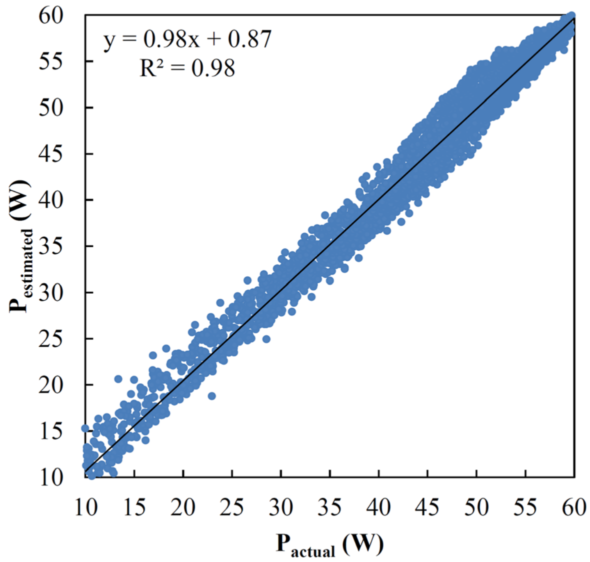

FIG. 8. Linear regression analysis between actual and estimated data using the proposed linear mathematical fitting for module A.

for the two modules under study. Particularly, the slope is close to 1, the offset is close to 0 and correlation coefficient is close to 1 for both modules, which indicates the goodness of the proposed linear mathematical fitting.

Table V shows some statistical parameters that have also been calculated to check the accuracy of the linear mathematical fitting: the root mean square error (RMSE) and the mean bias error (MBE). As can be seen, MBE is close to 0 for both modules. This indicates that the mathematical fitting neither overestimates nor underestimates the maximum power. As can also be seen, RMSE is 3.43% and 3.66% for modules A and B, respectively. This indicates the good accuracy of the linear mathematical fitting in the estimation of the maximum power for HCPV modules under study.

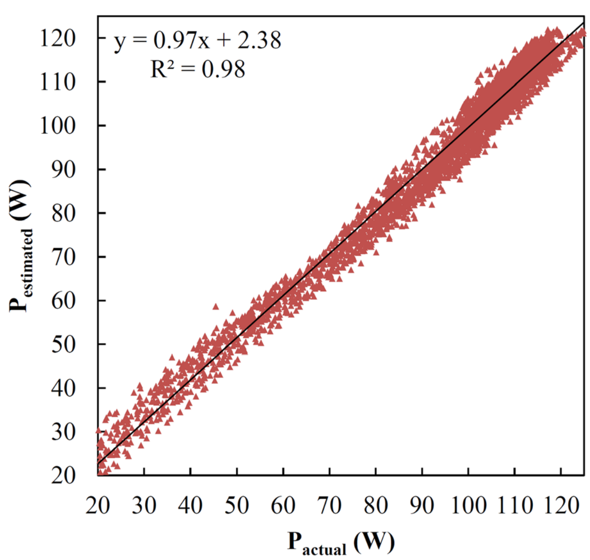

FIG. 9. Linear regression analysis between actual and estimated data using the proposed linear mathematical fitting for module B.

TABLE V. RMSE and MBE obtained for the proposed mathematical fitting.

Manufacturer	RMSE (%)	MBE (%)
A	3.43	−0.16
B	3.66	−0.14

IV. CONCLUSIONS

Two HCPV modules have been measured outdoors since 2010 in the *Centre of Advanced Studies in Energy and Environment* at the University of Jaen located in the south of Spain. This allows us to study and understand the behavior of HCPV technology under real conditions. In particular, the influence of direct normal irradiance, air mass, and air temperature on the maximum power of HCPV modules have been studied. The main parameter that influences the maximum power of a HCPV module is the direct normal irradiance with a great correlation between both. This means that it is possible to understand the main behavior of the maximum power taking into account only the direct normal irradiance. Related to the influence of air mass an important conclusion has been found. The maximum power could be considered independent of air mass for $AM \leq 2$, while it decreases with an approximate linear behavior for $AM > 2$ in first approximation. In the case of the air temperature analysis, it has been demonstrated that the influence of this parameter on the maximum power of HCPV module is small. Also, the maximum power can be estimated as a function of direct normal irradiance, air temperature, and air mass using a linear mathematical fitting with a good accuracy.

The *Centre of Advanced Studies in Energy and Environment* will continue its research in the outdoor evaluation of HCPV technology to understand and clarify its behavior. Also, due to new measurement systems, such as a solar simulator development by Soldaduras Avanzadas company in cooperation with the Instituto de Energia Solar at the Universidad Politécnica de Madrid (IES-UPM), the indoors study of HCPV technology is beginning to be realized. The new conclusions found in the study of HCPV technology under real and controlled conditions will be given in future works.

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