



# Validation of an outdoor efficiency model for photovoltaic modules

## Validación de un modelo de eficiencia exterior para módulos fotovoltaicos

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**ABSTRACT:** The study of the efficiency of photovoltaic modules in outdoor conditions allows determining their correct operation and to detect abnormal behavior. Most efficiency models developed use experimental data that are difficult to obtain as they require specialized equipment and a long measurement time under laboratory conditions to identify or adjust the model parameters. In this article, we propose a linear equation that estimates the efficiency of photovoltaic modules using irradiance and back panel temperature measurements as input variables. The main contribution is that the parameters of the proposed model can be obtained directly from the reference information (IEC61853-1 power values) without any data regression. The proposed model was validated using experimental data obtained from three different climatic zones during a whole year. The model shows the best fit to the data of four analyzed models, and its normalized root mean square deviation for all photovoltaic modules is less than 3.6%; this dispersion could be explained by the fact that the outdoor data have an uncertainty of around 3.0%

**RESUMEN:** El estudio de la eficiencia de los módulos fotovoltaicos en condiciones exteriores permite determinar su correcto funcionamiento y detectar comportamientos anómalos. Los modelos de eficiencia que están disponibles en la literatura utilizan medidas ad-hoc que son poco prácticas ya que requieren equipos especializados y un largo tiempo de medición usualmente en condiciones de laboratorio para identificar o ajustar los parámetros del modelo. En este artículo, proponemos una ecuación lineal que estima la eficiencia de los módulos fotovoltaicos, usando las mediciones de temperatura del panel y la irradiancia como variables de entrada. La principal contribución es que los parámetros del modelo propuesto se pueden obtener directamente de la información de referencia, en nuestro caso usando la matriz de potencia de según la norma IEC61853-1, con la ventaja que no se requiere ninguna regresión con los datos. El modelo propuesto se validó utilizando datos experimentales obtenidos de tres zonas climáticas diferentes durante todo un año. El modelo muestra el mejor ajuste a los datos de cuatro modelos analizados, y su desviación cuadrática media normalizada para todos los módulos fotovoltaicos es inferior al 3.6%; esta dispersión podría explicarse por el hecho de que los datos del exterior tienen una incertidumbre de alrededor de 3.0%.

## 1. Introduction

The operation and maintenance activities in photovoltaic (PV) plants can benefit from an accurate model of the expected PV plant's power or current efficiency. PV operators can identify underperformance due to failures or soiling with this efficiency model, proposing new

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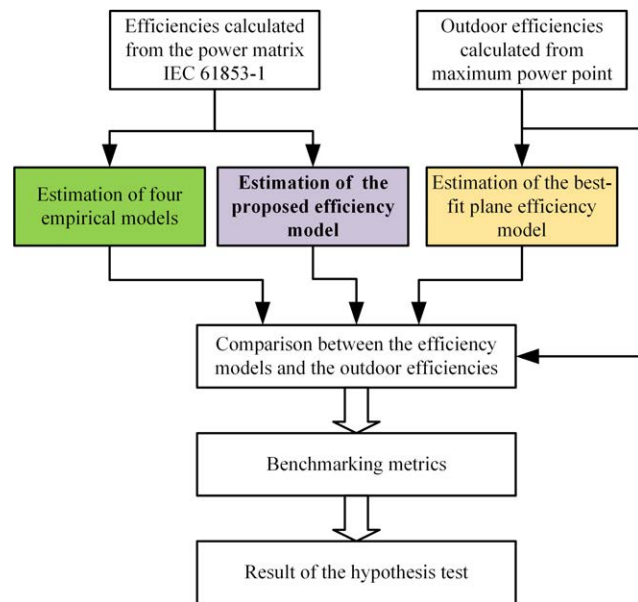
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techniques such as [1–3]. Even though a PV module datasheet provides information that can be used to get an idea of the electrical characteristics of a PV plant, that information has been obtained under laboratory conditions which, in several cases, are different from outdoor conditions. Hence, measured experimental efficiency differs considerably from the efficiency reported in the PV panel datasheet, as has been verified in [4]. The difference above is not suitable for a PV plant's proper maintenance and operation. Several PV efficiency models have been developed, i.e., Fifty-three models are presented in [5] and twenty-three are presented in [6]. Also in [7], an extensive study on empirical models is presented, which presents the errors comparison among 15 models. Several models are based on the model presented in [8] that defines the efficiency as a function of the temperature of the cell and the irradiance. Other types of models also incorporate the air mass ( $AM$ ), such as the one proposed in [9]. Empirical models such as the one proposed in [10], or the one proposed in [11] have been accurate. But, the main disadvantage of the models mentioned above is that they require data sets and fitting algorithms to find optimal parameters. On the other hand, the efficiency models based on physical parameters, such as the one proposed in [12], have demonstrated a high accuracy with the IEC 61853 data. Still, also it requires a complex procedure to obtain the five fitting parameters.

It would be more appropriate to obtain an efficiency model that is accurate for outdoor conditions and calculated from reference points without any type of regression. In this regard, the present paper proposes an outdoor efficiency model that can be constructed with the standard data provided by the PV module datasheet or other efficiency points provided by norms, i.e., IEC 61853-1.

The proposed model is inspired by the fact that PV efficiency values plotted in a temperature, irradiance, and efficiency space resemble a surface when low irradiance values are not considered. In this regard, we demonstrate in this paper that it is possible to obtain a best-fit plane equation (BFPE) that estimates the efficiency of a PV module using irradiance and temperature measurements with reasonable accuracy. In addition, this paper also derives a simpler efficiency plane equation (PE) that can be obtained using the datasheet values of the PV module and that does not require the use of best-fitting techniques.

This article used several data sets obtained with different methodologies. The reference efficiencies obtained according to the IEC 61853-1 and the outdoor efficiencies were obtained by the National Renewable Energy Laboratory (NREL), which carried out all the data acquisition. In summary, we prove that a proposed PE model calculated from the power matrix is equivalent



**Figure 1** Summary of the validation process

to the BFPE model calculated from a data set gathered during a whole year for several locations.

The methodology followed can be summarized in the following steps: First, we calculate the BFPE model from outdoor efficiency measurements. We selected six locations and a panel technology; then, we filtered the efficiency records in specific ranges of temperature and irradiance. The second step was to calculate our plane model, which was calculated from an efficiency dataset obtained from the power matrix according to the IEC 61853-1. Then, four models were used to compare their estimations with the proposed model. We used Evans' model, Ransome's model, Heydenreich's model, and Durish's model because they are widely referenced, as indicated above. The fourth step consisted of studying the fitting of the models and then hypothesizing about the similarities between the PE and BFPE models. The process mentioned above is summarized in Figure 1. The authors believe that the simplicity of the proposed PE model, along with obtained accuracy, makes this model an appropriate tool for fault detection and PV power production estimation when there are no historical efficiency measures available.

This work is an extension of the research presented at the Ibero-American Congress of Smart Cities (ICSC-CITIES 2021) [13], to which three new efficiency models were added to contrast with the data and our model. The use of more models changed the original structure of the work, adding, for example, new sections, new graphics, updating tables, etc. The rest of the document is structured as follows: section 2 presents a short review of the efficiency models and the proposed model, and section 3 explains

the metrics used in the analysis, section 4 describes the experimental data analysis, and section 5 explains how the coefficients of the efficiency models were calculated. Section 6 explains the methodology for testing whether the proposed plane cuts the efficiency point cloud, and the analysis and result are presented in section 7. Finally, the main conclusions of this work are presented in section 8.

## 2. Efficiency models for PV modules

The efficiency of a PV module is the ratio between the output electrical power,  $P_{pv}$ , and the received solar irradiance on its surface,  $P_i$ , as indicated in Equation (1).

$$\eta = \frac{P_{pv}}{P_i}. \quad (1)$$

The input power is  $P_i = G_i A$ , where  $G_i$  is the sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the PV module and  $A$  is the area of the PV module.

PV module datasheet provides rated efficiency values at given conditions, being the most common the efficiency at standard test conditions (STC),  $\eta_{STC}$ , as indicated in [2], where the considered output power,  $P_{mpp,STC}$ , is the maximum power that the PV module can produce at a temperature in the PV module of  $T_{STC} = 25^\circ\text{C}$  (298.15 °K), and incident irradiance of  $G_{STC} = 1000\text{ W/m}^2$  and an air mass of 1.5.

$$\eta_{STC} = \frac{P_{mpp,STC}}{AG_{STC}} \quad (2)$$

The STC efficiency of a 72-cell crystalline PV module ranges from 18 % to 22.8 % [14]. The efficiency of a PV module is not a constant value but depends on several variables and parameters, as shown next.

To illustrate the PV module efficiency dependence on environmental variables consider the ideal three-parameter model for a PV model shown in Equation [3], i.e.,

$$i_{pv}(T, G) = I_{ph}(T, G) - I_s(T) \left( \exp \left( \frac{q v_{pv}}{N_s k T a} \right) - 1 \right) \quad (3)$$

where the photocurrent  $I_{ph}$  is defined according to [4], and the diode saturation current  $I_s$  is defined according to [5]. The variables and parameters used are defined in Table 1. According to [15] and [16], the influence of the temperature ( $T$ ) and irradiance ( $G$ ) in [3] can be expressed as,

$$I_{ph}(T, G) = (I_{ph,n} + K_i \Delta T) \frac{G}{G_{STC}} \quad (4)$$

$$I_s(T) = \frac{I_{ph,n} + K_I \Delta T}{\exp \left( \frac{q(V_{oc,n} + K_V \Delta T)}{akTN_s} \right) - 1} \quad (5)$$

**Table 1** Parameters used in the PV model. Standard Test Conditions (STC): Irradiance of  $1000\text{ W/m}^2$ , a temperature  $298.15^\circ\text{K}$  and an air mass of 1.5

Parameter	Description
$I$	Current generated by the PV module
$V$	Voltage drop across the PV module
$a$	Ideality factor
$N_s$	Number of cells in series in the PV module
$k$	Boltzmann constant ( $1.38 \times 10^{-23}\text{ J/K}$ )
$q$	Charge of the electron ( $1.6 \times 10^{-19}\text{ C}$ )
$T$	Cell temperature
$T_{STC}$	Temperature at Standard Test Conditions(STC) (298.15° K)
$I_{ph,n}$	Photocurrent measured at STC
$K_I$	Short circuit current thermal coefficient
$G$	Plane of Array Global Irradiance
$G_{STC}$	Irradiance at STC (1000 W/m <sup>2</sup> )
$K_V$	Thermal coefficient for the open circuit voltage
$V_{oc,n}$	Open circuit voltage measured at STC

where  $\Delta T = T - T_{STC}$ .

Based on [2] and [3], it is possible to infer that the efficiency varies concerning the temperature. Even though the input power,  $P_i$ , of the efficiency expression (1) does not vary with  $T$ , according to the simplified model shown in [3], the PV-generated power changes with respect to  $T$ . The aforementioned reasoning explains several efficiency models based on physics, such as [12, 17].

### 2.1 Empirical models of efficiency

The empirical efficiency models define a function in terms of the PV module temperature,  $T$ , and the in-plane irradiance,  $G$ , i.e.,  $\eta = f(T, G)$ . In this regard, several authors [e.g., [18] and [6]] have proposed temperature-dependent efficiency models most of them derived from the seminal models presented in [8, 17], where, in all cases, as the temperature in the PV module increases, the efficiency decreases reaching zero value at  $270^\circ\text{C}$  as indicated in [5]. It is important to highlight that the STC efficiency is an optimistic value given that a PV module temperature of  $25^\circ\text{C}$  occurs at low ambient air temperature. The Evans' model [6] defines an expression for the efficiency as follows,

$$\eta = \eta_{STC} \cdot (1 - \beta \cdot \Delta T + \zeta \cdot \log_{10}(G/G_{STC})), \quad (6)$$

where  $\eta$  and  $\eta_{STC}$  are the estimated efficiency and the efficiency at Standard Test Conditions (STC), and  $\beta$  and  $\zeta$  are the temperature and irradiance coefficients, respectively. It is suggested that constant values for silicon panels of  $\beta = 0.0048$  and  $\zeta = 0.12$  [8], but [6] shows that there might be a large variation in both parameters, i.e.,  $\beta$  usually varies between [0.0026, 0.0060] depending on the technology of the PV cell/module.

As mentioned previously, the efficiency reported in a PV module datasheet is obtained from measurements with a

constant air mass (AM) of 1.5. In photovoltaics, AM is used to approximate the effects of spectral responsivity in PV modules. Nevertheless, air mass changes according to the relative position of the sun and the molecules present in the atmosphere. According to [19], there is a 2% difference between the efficiency measured at AM 1.5 and AM 0. These other effects that take place in the PV module affect efficiency and they have been studied by some authors. For instance, the Durisch's model [9] shows the efficiency expression as a function of the in-plane irradiance, PV module temperature, and air mass. Nevertheless, it is not uncommon that the majority of the PV efficiency models neglect the Air Mass; doing so for Durish's model (7) yields the following simplified expression,

$$\eta = p \left[ s \frac{G}{G_{STC}} + \left( \frac{G}{G_{STC}} \right)^m \right] \cdot \left[ 1 + r \frac{T}{T_{STC}} \right] \quad (7)$$

where  $T_{STC}$  and  $G_{STC}$  are the temperature and the irradiance at STC, respectively. The authors establish that the parameters  $p, r, s$  and  $m$  have to be identified for each type of solar cell/module.

Another empirical model used in this work is the Heydenreich's model [10]; the efficiency model [8], is expressed as,

$$\eta = \left( aG + b \cdot \ln(G + 1) + c \left( \frac{\ln^2(G + e)}{G + 1} - 1 \right) \right) \cdot (1 + \gamma \Delta_T) \quad (8)$$

where  $\{a, b, c\}$  are the fitting parameters, and  $\gamma$  is the temperature coefficient at the maximum power point.

Ransome's model [11] is normally called Mechanistic Performance Model (MPM), which is formed by six parameters. Still, we could neglect the parameter associated with the wind speed and the constant related to the inverse of the irradiance. In this way, the simplified expression [9] is the following,

$$\eta = c1 + c2 \cdot \Delta_T + c3 \cdot \log_{10}(G) + c4 \cdot G \quad (9)$$

where  $\{c1, c2, c3, c4\}$  are the constants linked to the efficiency, temperature and irradiance.

## 2.2 Proposed efficiency model

The simplest expression for the PV module efficiency  $\eta = f(T, G)$  is a linear function [10], i.e.,

$$\eta = K_1 T + K_2 G + K_3 \quad (10)$$

where  $K_1, K_2$  and  $K_3$  are constants. The parameters  $K_1, K_2$  and  $K_3$  can be obtained from at least three points from the efficiency space, i.e., each efficiency point is defined by

three values which are  $\eta, T$  and  $G$ . Assume that such three points are named as:  $P = \langle T_p, G_p, \eta_p \rangle, Q = \langle T_q, G_q, \eta_q \rangle$  and  $R = \langle T_r, G_r, \eta_r \rangle$ , then an efficiency expression can be derived from the following set of equations,

$$\begin{aligned} \mathbf{P} \cdot (\overrightarrow{PQ} \times \overrightarrow{PR}) &= 0 \\ \mathbf{P} &= \langle (T - T_p), (G - G_p), (\eta - \eta_p) \rangle \\ \overrightarrow{PQ} &= \langle (T_q - T_p), (G_q - G_p), (\eta_q - \eta_p) \rangle \\ \overrightarrow{PR} &= \langle (T_r - T_p), (G_r - G_p), (\eta_r - \eta_p) \rangle. \end{aligned} \quad (11)$$

The solution of Equations (11) is obtained by solving the following determinant

$$\det \begin{bmatrix} (T - T_p) & (G - G_p) & (\eta - \eta_p) \\ (T_q - T_p) & (G_q - G_p) & (\eta_q - \eta_p) \\ (T_r - T_p) & (G_r - G_p) & (\eta_r - \eta_p) \end{bmatrix} = 0 \quad (12)$$

however, choosing special points where  $T_r = T_p$  and  $G_q = G_p$  allow us to solve Equation (12) easier. Then, comparing [10] with [12], it can be seen that parameters  $K_i$  are equal to [13],

$$\begin{aligned} K_1 &= (\eta_q - \eta_p) / (T_q - T_p) \\ K_2 &= (\eta_r - \eta_p) / (G_r - G_p) \\ K_3 &= \eta_p - K_1 T_p - K_2 G_p. \end{aligned} \quad (13)$$

The constants  $K_1, K_2$ , and  $K_3$  can also be obtained from a set of experimental points using multivariate nonlinear regression techniques yielding a best-fit plane efficiency (BFPE) model.

In [20], the efficiency expression [10] was derived from values readily available in PV modules datasheets. By employing simulations, the authors were able to verify that the efficiency values obtained from the proposed model at different temperatures and irradiances had at most 2.6% difference with respect to more complex and validated models such as the Evans efficiency model, e.g. [8]. Nevertheless, in [20], no experimental analysis or validation was provided.

## 3. Metrics to compare the efficiency estimations

The metrics to evaluate the accuracy and precision of the models are based on the analysis of the residues. We consider the residue  $r_i$  as the difference between the  $i_{th}$  value of observed efficiency ( $\eta_i$ ) and the estimated result by the model  $\hat{\eta}$  for the outdoor conditions ( $T_i, G_i$ ) as follows,

$$r_i = \eta_i - \hat{\eta}(T_i, G_i). \quad (14)$$

Notice that from [14], it is possible to obtain a relative error [15], i.e.,

$$r.e_i = \frac{r_i}{\eta_i} \cdot 100. \quad (15)$$

This metric explains how far the efficiency point is, predicted by the model from the point of view of the experimental data.

Another metric used to compare the models is the normalized root mean square deviation (nRMSD) which is the RMSD value divided by a nominal value [21], and nRMSD [16] is defined as,

$$nRMSD = \frac{1}{\eta_p} \sqrt{\frac{\sum_{i=1}^n r_i^2}{n}}, \quad (16)$$

where  $n$  represents the number of elements to analyze.

Also, the coefficient of determination,  $R^2$  [17], is used to determine if the variability of the data is captured by the model [22], and it is calculated as follows,

$$R^2 = 1 - \frac{\sum_{i=1}^n r_i^2}{\sum_{i=1}^n (\eta_i - \bar{\eta})^2} \quad (17)$$

where  $\bar{\eta}$  is the average of the observed efficiency values  $\eta_i$ . The adjusted  $R^2$  ( $R_{adj}^2$ ) is shown in (18) and it is obtained as in [23],

$$R_{adj}^2 = 1 - \frac{(n-1) \cdot \sum_{i=1}^n r_i^2}{(n-p) \cdot \sum_{i=1}^n (\eta_i - \bar{\eta})^2} \quad (18)$$

where  $p$  is the number of coefficients in the estimation model. Also, the mean of the relative error,  $\bar{x}_r$  [19], a type of percentage bias is calculated as,

$$\bar{x}_r = \frac{\sum_{i=1}^n r \cdot e_i}{n} \quad (19)$$

and the standard deviation of the relative error,  $\sigma_r$  [20], which is calculated as follows,

$$\sigma_r = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (r \cdot e_i - \bar{x}_r)^2}. \quad (20)$$

It should be noticed that the value of  $\bar{x}_r$  indicates on average how far the data are from the estimations of the selected model, and this value can be associated with the accuracy of the models. The other metric, the value  $\sigma_r$  represents the dispersion of the relative error, and it can be related to the precision.

## 4. Experimental data used for validation

The data set used for validation was obtained from measurements made on four multi-crystalline PV modules, all of them having a surface of 0.3429 m<sup>2</sup> and consisting of 36 cells connected in series. The data above was facilitated by the NREL [24] in the US, and it was taken in three different locations with distinct climates

as indicated in Table 2. The data used for validation was taken with high-precision equipment as detailed in [24], and the measured variables were: plane-of-array (POA) irradiance with an uncertainty of 2.42% , the PV module back-surface temperature with an uncertainty of 1.76%, and the maximum power produced (MPP) with an uncertainty of 0.41%. This means that outdoor efficiency data have an uncertainty of around 3.02%.

The outdoor data used in this analysis were limited to PV module back-surface temperatures greater than 298.125 °K and less than 338.125 °K, a POA irradiance greater than 200 W/m<sup>2</sup> but less or equal to 1050 W/m<sup>2</sup>, and a PV module soiling derate equal to one (clean panels). The cloud of points comprising the aforementioned range can be seen in Figure 2 for the case of a PV panel in Cocoa, Florida.

**Table 2** Identification (ID) of the PV modules and the climate region from which the experimental data were obtained

ID	Climate Region	File
C-mSi0166	Subtropical	Cocoa_mSi0166.csv
C-mSi0188	Subtropical	Cocoa_mSi0188.csv
E-mSi0166	Marine West Coast	Eugene_mSi0166.csv
E-mSi0188	Marine West Coast	Eugene_mSi0188.csv
G-mSi0247	Semi-arid	Golden_mSi0247.csv
G-mSi0251	Semi-arid	Golden_mSi0251.csv

With the measurements of temperature and POA irradiance, an experimental efficiency ( $\eta$ ) has been calculated for each data point according to (1). In this way, a point located in a three-dimensional space ( $T, G, \eta$ ) has been obtained for each PV panel and each geographical location. For instance, these efficiency values for module C-mSi0166 are shown as light-brown circles in Figure 3.

The NREL database also includes for every panel its power matrix following the IEC 61853-1: Irradiance and Temperature Performance Measurements and Power Rating [25], which describes requirements for evaluating PV module performance in terms of power rating over a range of irradiances and temperatures. These data are represented as blue asterisks in Figure 3, and later we used them as a reference to calculate the plain equation (PE) (10), and the four empirical efficiency model: Evans' model [6], Durish's model [7], Heydenreich's model [8], and MPM [9].

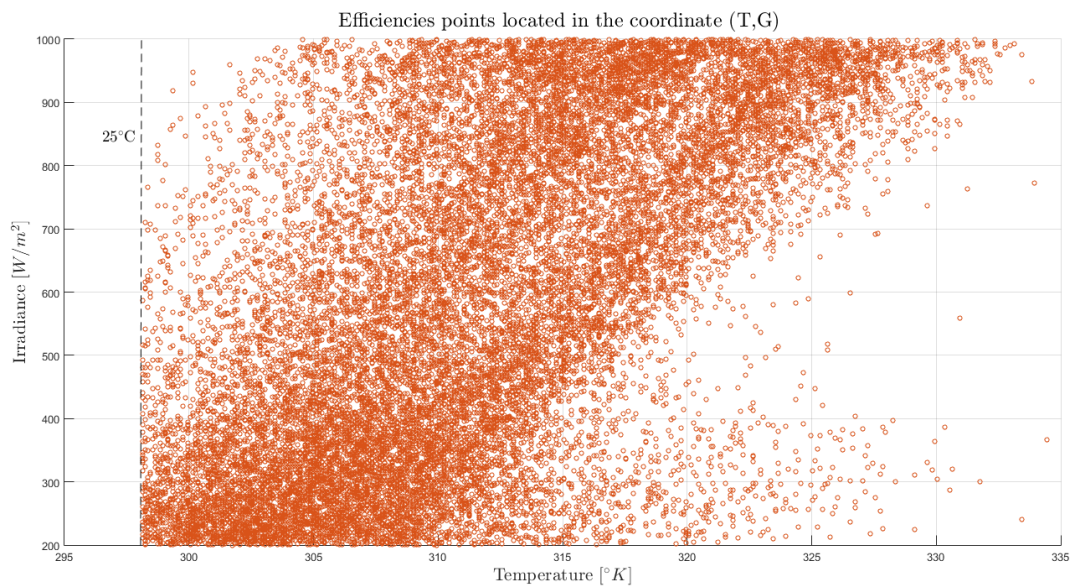
## 5. Efficiency models

### 5.1 Proposed plane equation

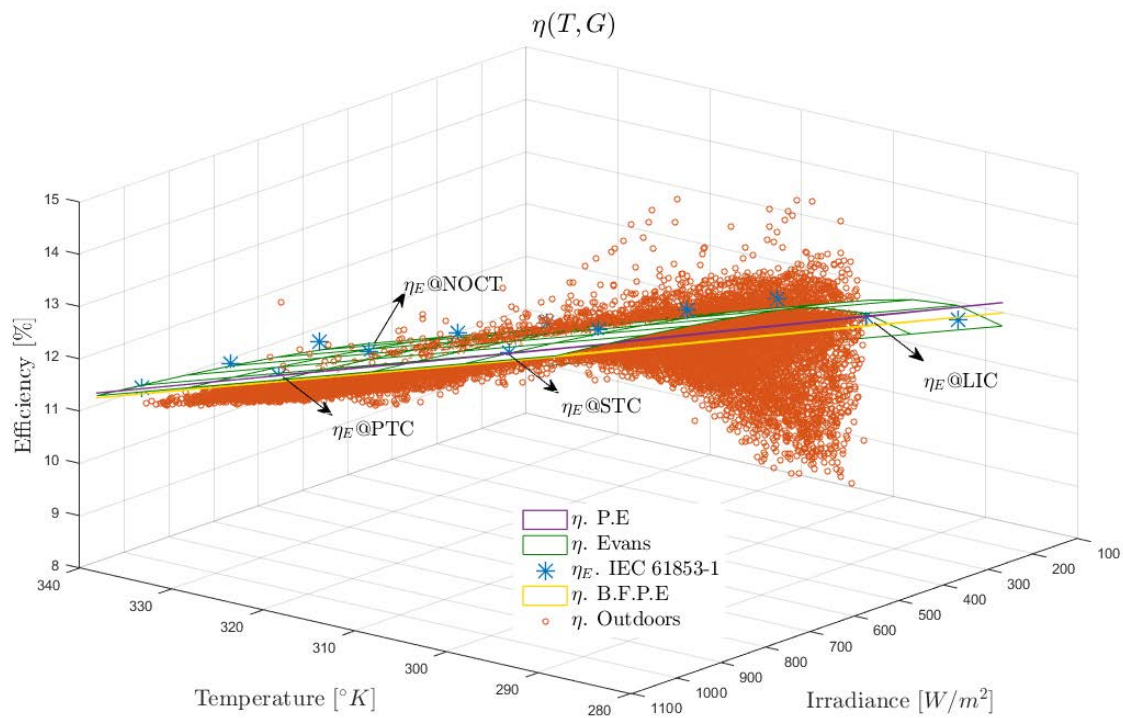
The efficiency surface expression (10) is constructed using the following three points in the efficiency space:

- The point  $P$  is the equivalent efficiency obtained at the





**Figure 2** Data cloud considered for the validation of the efficiency expression. Case of module ID C-mSi0166 in Cocoa Florida



**Figure 3** Efficiency values obtained at outdoors conditions (light-brown circles) and with IEC 61853-1 procedure (blue asterisks) for the PV module *C – mSi0166*. The presented efficiency models are: Evans efficiency expression (green surface), the proposed plane expression calculated from three reference points (purple line) and the best-fit plane model (yellow line) calculated from the outdoor efficiency measures

Standard Test Conditions (STC) point. This efficiency data point,  $\eta_E@STC$ , has an incident irradiance of  $G_{STC} = 1000 \text{ W/m}^2$  and a back panel temperature of  $T_{STC}=25^\circ\text{C}$ .

- The point  $Q$  is the efficiency obtained at the high-temperature condition point and for this model, we selected the efficiency obtained at the PV-USA Test Condition (PTC) equivalent point. This efficiency data point,  $\eta_E@PTC$ , has an incident irradiance of  $G_{PTC} = 1000 \text{ W/m}^2$  and a back panel temperature of  $T_{PTC} = 50^\circ\text{C}$ . This point has been selected due to the possibility of pairing it with the PV-USA Test Condition (PTC) point reported in some PV manufacturer data sheets, which is a US-standard that was developed in collaboration with the U.S Department of Energy [26].
- The point  $R$  is the equivalent efficiency obtained at the Low Irradiance Condition (LIC) point. This efficiency data point,  $\eta_E@LIC$ , has an incident irradiance of  $G_{LIC} = 200 \text{ W/m}^2$  and a back panel temperature of  $T_{LIC}=25^\circ\text{C}$ .

These reference points are calculated from the matrix powers given by IEC 61853-1 in the NREL database. Table 3 shows the experimental efficiency values obtained for the aforementioned three points for the panels under study.

**Table 3** Experimental efficiency measures  $\eta_E$  calculated with the IEC 61853-1 for the standard conditions

Module	$\eta_E@STC$ [ $\eta_p$ ]	$\eta_E@PTC$ [ $\eta_q$ ]	$\eta_E@LIC$ [ $\eta_r$ ]
C-mSi0166	13.48%	12.06%	11.83%
C-mSi0188	13.39%	11.92%	11.90%
E-mSi0166	13.48%	12.06%	11.83%
E-mSi0188	13.39%	11.92%	11.90%
G-mSi0247	13.36%	12.04%	11.78%
G-mSi0251	13.32%	12.01%	11.68%

Using the efficiency measures in Table 3 and the expressions in (13), the constants of the Table 4 are obtained. The following example shows the calculus (21) for module C-mSi0166,

$$\begin{aligned}
 K_1 &= (\eta_E@PTC - \eta_E@STC)/(T_{PTC} - T_{STC}) \\
 K_1 &= -0.0568 \\
 K_2 &= (\eta_E@LIC - \eta_E@STC)/(G_{LIC} - G_{STC}) \\
 K_2 &= 0.0021 \\
 K_3 &= \eta_E@STC - K_1 T_{STC} - K_2 G_{STC} \\
 K_3 &= 28.3485. \quad (21)
 \end{aligned}$$

### 5.2 Empirical models of efficiency

Following the procedure presented in Figure 1, we adjusted four empirical models to the efficiencies calculated with

**Table 4** Constants for the proposed model

Modules	$K_1$	$K_2$	$K_3$
C-mSi0166	-0.0568	0.0021	28.3485
C-mSi0188	-0.0586	0.0019	28.9854
E-mSi0166	-0.0568	0.0021	28.3485
E-mSi0188	-0.0586	0.0019	28.9854
G-mSi0247	-0.0528	0.0020	27.1420
G-mSi0251	-0.0524	0.0020	26.8869

the power standard IEC 61853-1. In total, six panels and four empirical models were adjusted. The fitting algorithm used was the nonlinear least-squares with a trust region (NLS-TR) of the Matlab Curve Fitting Toolbox [27]. Figure 4 shows the efficiencies derived from the IEC standard versus the efficiency estimation for all six panels. The diagonal blue line represents the perfect estimation, and data in the lower triangle means the sub-estimation of the models. On the other hand, data in the top triangle mean overestimation of the models. It can be observed that models with four parameters, such as MPM, HEY, and Durish, fit better than models with fewer parameters, such as Evans, with one fitting parameter. The goodness of the fit defined by Equations (16) to (20) for all the efficiency models and PV modules is presented in Table 5. Notice in general that the MPM model is the one with the best fit to the IEC data; for example, the normalized RMSD is less than 0.4%, this metric is shown in Figure 5.

### 5.3 Best Fit Plane Equation

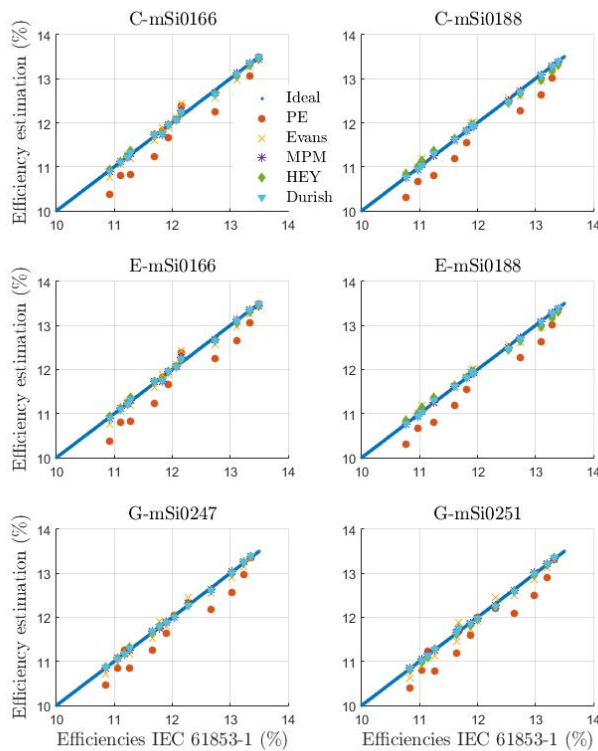
The best-fit plane efficiency (BFPE) model is obtained by fitting the constants  $\{K_1, K_2, K_3\}$  to the outdoor efficiency data. This procedure was done with using the nonlinear least-squares with a trust-region (NLS-TR) algorithm of the same toolbox [27]. The results are shown in Table 6.

### 5.4 Visualization of the data: example

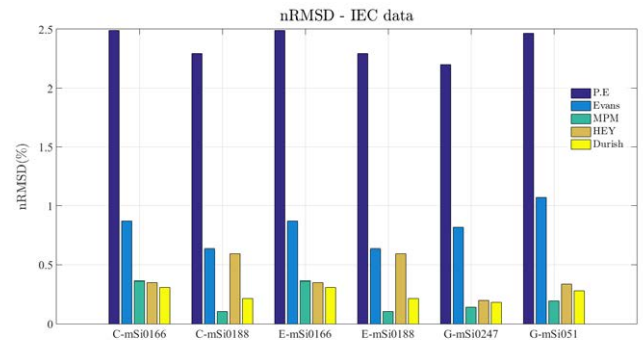
As an illustrative example of the data and some models, Figure 3 shows the aforementioned representations for the module C-mSi0166. In that figure, the outdoor efficiency values are presented as light-brown circles; the experimental efficiency values obtained with the power matrix according to IEC 61853-1 are presented as blue asterisks; the surface that estimates the efficiency using the model (10), with the three reference points, is the purple mesh and here it looks like a line. The BFPE model that estimates the efficiency using (10), with the parameters obtained from the data cloud (light-brown circles), is presented as a yellow mesh. Finally, the Evans' efficiency model adjusted to the efficiency values obtained according to IEC 61853-1 (blue asterisks) is presented as a green mesh. In Figure 3, only the Evans' model was presented to keep the readability of the figure.

**Table 5** Metrics of the models calculated from the efficiency values using IEC61853-1

Panel	Model	<i>n</i>	<i>nRMSD</i>	$R^2$	$R^2_{adj}$	$\bar{x}_r$ (%)	$\sigma_r$ (%)	
C-mSi0166	P.E.	13	0.0249	0.8369	0.8043	1.9728	2.1142	
	E-mSi0166	Evans	13	0.0087	0.9800	0.9800	0.2767	0.9716
		MPM	13	0.0036	0.9965	0.9954	-0.0014	0.4216
		HEY	13	0.0035	0.9967	0.9961	-0.0284	0.4082
		Durish	13	0.0031	0.9975	0.9975	-0.0010	0.3596
C-mSi0188	P.E.	13	0.0292	0.8762	0.8518	1.999	1.7261	
	E-mSi0188	Evans	13	0.0063	0.9905	0.9905	-0.0445	0.7274
		MPM	13	0.0010	0.9997	0.9997	-0.0001	0.1212
		HEY	13	0.0059	0.9916	0.9899	-0.0844	0.6862
		Durish	13	0.0021	0.9989	0.9989	-0.0010	0.2512
G-mSi0247	P.E.	13	0.0220	0.8689	0.8427	1.7872	1.7546	
	E-mSi0247	Evans	13	0.0082	0.9818	0.9818	0.4243	0.8493
		MPM	13	0.0014	0.9995	0.9993	-0.0004	0.1588
		HEY	13	0.0020	0.9989	0.9887	-0.0135	0.2319
		Durish	13	0.0018	0.9991	0.9991	-0.0012	0.2044
G-mSi0251	P.E.	13	0.0246	0.8346	0.8015	2.0860	1.8677	
	E-mSi0251	Evans	13	0.0107	0.9686	0.9686	0.6510	1.0833
		MPM	13	0.0019	0.9990	0.9987	-0.0008	0.2194
		HEY	13	0.0034	0.9969	0.9963	0.1782	0.3510
		Durish	13	0.0028	0.9979	0.9979	-0.0021	0.3185



**Figure 4** IEC 61853-1 Efficiencies versus estimation efficiencies by the models for all panels

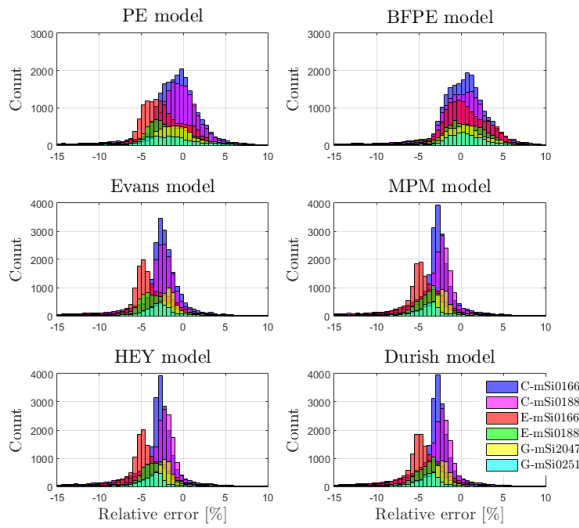


**Figure 5** Normalized Root mean squared deviation between the IEC standard and the models

**Table 6** Constants for the BFPE

Modules	$K_1$	$K_2$	$K_3$
C-mSi0166	-0.0557	0.0021	27.8336
C-mSi0188	-0.0557	0.0021	27.8336
E-mSi0166	-0.0652	0.0022	30.4959
E-mSi0188	-0.0650	0.0020	30.5986
G-mSi0247	-0.0425	0.0018	23.8447
G-mSi0251	-0.0431	0.0015	24.1377





**Figure 6** Histogram of the relative errors for each efficiency model and PV panels

The MPM, HEY, and Durish models are closer to the asterisk data. Therefore, these good fits, in some cases, hide the asterisks, and the models cannot be distinguished.

## 6. Validation methodology

In order to prove that the plane equation behaves as well as the best-fit plane equation, the following steps have been developed:

1. For every PV panel, comparing the efficiency models estimated with the IEC 61853-1 data and, the outdoor data.
2. For every data set selected, proving using the hypothesis test if the efficiency plane models could have equivalent precision and if they could have equivalent accuracy.

Table 7 shows the metrics calculated for the six efficiency model: the proposed plane efficiency (PE) model, the best-fit plane efficiency (BFPE) model, the Evans' models, the Mechanistic Performace Model (MPM), the Heydenreich model (HEY), and the Durish's model. The graphical distribution of the relative errors for all the efficiency models and PV modules is presented in Figure 6. Each subfigure is associated with a specific efficiency model, and inside there are six histograms related to each PV module. The mean and the standard deviation of these error distributions are equivalent to the ones calculated with Equations (19), (20), and are presented in Table 7.

## 6.1 Establishment of the hypothesis test

To quantify the similarity between the BFPE model and the PE model, 12 hypothesis tests are made with the data provided. The Minitab Software [28] was used to process the data. The hypothesis tests, formulated in Equation (22) were analyzed with the Bonetts' method, and according to [28], this method is more rigorous than the Fisher or Levene methods. Another benefit is that Bonetts' method can be used with data that do not have a normal distribution, therefore the normality test is not required. The hypothesis test proves if the standard deviation of the relative errors of the studied models can be considered equivalent. Thus, the formalization of the hypothesis is presented as follows,

$$\forall \mathbf{p} \in \{C - mSi0166, C - mSi0188, E - mSi0166, E - mSi0188, G - mSi2047, G - mSi0251\}$$

$$\mathbf{H}_0^{\mathbf{p}} : \sigma_r^{PE} / \sigma_r^{BFPE} = 1$$

$$\mathbf{H}_1^{\mathbf{p}} : \sigma_r^{PE} / \sigma_r^{BFPE} \neq 1$$

$$\alpha = 0.05$$
(22)

where  $\sigma_r$  is the standard deviation of the relative errors.

For the second hypothesis expressed in [23], the analysis method uses the two-sample t-test without the assumption of equal variances, which measures the distance between the two planes as follows,

$$\forall \mathbf{p} \in \{C - mSi0166, C - mSi0188, E - mSi0166, E - mSi0188, G - mSi2047, G - mSi0251\}$$

$$\mathbf{H}_0^{\mathbf{p}} : \bar{x}_r^{PE} - \bar{x}_r^{BFPE} = 0$$

$$\mathbf{H}_1^{\mathbf{p}} : \bar{x}_r^{PE} - \bar{x}_r^{BFPE} \neq 0$$

$$\alpha = 0.05$$
(23)

where the mean of the relative errors is expressed as  $\bar{x}_r$ . In both hypothesis equations, the superscript  $^{PE}$  means plane equation, and  $^{BFPE}$  means best-fit plane equation.

## 7. Analysis and results

According to the results seen in Table 5 and Figures 4 and 5, it is clear to the authors that models with a high number of fitting parameters adjust the IEC efficiency data better. Table 5 shows the metrics for all PV modules, and the MPM represents better the behavior of the efficiencies derived from the power matrix. MPM models present the highest values of  $R_{adj}^2$  more than 99.5%, and the lowest values of  $nRMSD$  lower than 0.36% concerning the other models. It is seen that the efficiency values calculated from the IEC standard are better described by MPM, Durish, and

**Table 7** Metrics of the efficiency models calculated with the outdoor efficiency values

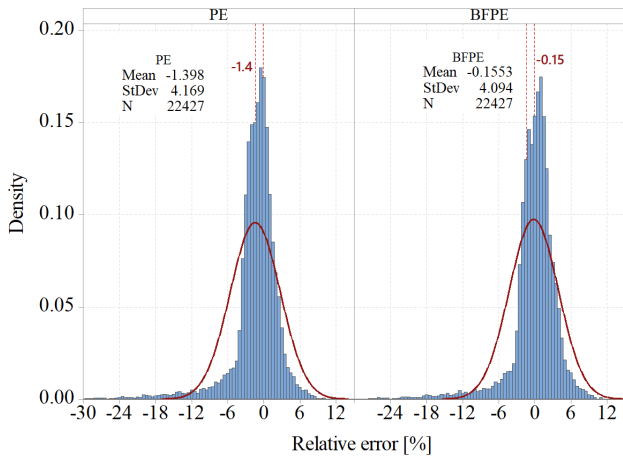
Panel	Model	$n$	$nRMSD$	$R^2$	$R^2_{adj}$	$\bar{x}_r$ (%)	$\sigma_r$ (%)
C-mSi0166	P.E.	22427	0.0342	0.4669	0.4668	-1.3975	4.1689
	BFPE	22427	0.0324	0.5208	0.5207	-0.1553	4.0944
	Evans	22427	0.0408	0.2408	0.2408	-3.2483	4.0690
	MPM	22427	0.0425	0.1736	0.1735	-3.6148	3.9619
	HEY	22427	0.0434	0.1377	0.1376	-3.7221	4.0477
	Durish	22427	0.0431	0.1500	0.1499	-3.6943	4.0069
C-mSi0188	P.E.	18678	0.0372	0.4107	0.4106	-1.4229	4.6362
	BFPE	18678	0.0352	0.4725	0.4725	-0.1831	4.4648
	Evans	18678	0.0455	0.1189	0.1189	-3.5920	4.6404
	MPM	18678	0.0460	0.1006	0.1004	-3.6872	4.5995
	HEY	18678	0.0473	0.0483	0.0482	-3.8055	4.7562
	Durish	18678	0.0467	0.0721	0.0719	-3.7697	4.6623
E-mSi0166	P.E.	14726	0.0426	0.1978	0.1977	-3.1917	4.4908
	BFPE	14726	0.0333	0.5104	0.5103	-0.1689	4.3244
	Evans	14726	0.0524	-0.2104	-0.2104	-4.8944	4.4820
	MPM	14726	0.0552	-0.3459	-0.3462	-5.3238	4.4263
	HEY	14726	0.0552	-0.3442	-0.3444	-5.2917	4.4997
	Durish	14726	0.0555	-0.3580	-0.3582	-5.3509	4.4529
E-mSi0188	P.E.	7689	0.0399	0.3196	0.3194	-2.6817	4.3759
	BFPE	7689	0.0329	0.5376	0.5374	-0.1606	4.2319
	Evans	7689	0.0504	-0.0867	-0.0867	-4.5038	4.4685
	MPM	7689	0.0524	-0.1757	-0.1761	-4.7961	4.4617
	HEY	7689	0.0511	-0.1165	-0.1168	-4.5299	4.5949
	Durish	7689	0.0526	-0.1857	-0.1861	-4.8190	4.4864
G-mSi0247	P.E.	6179	0.0381	0.3047	0.3045	-1.7857	4.6315
	BFPE	6179	0.0348	0.4186	0.4184	-0.1807	4.4895
	Evans	6179	0.0445	0.0482	0.0482	-3.2290	4.7840
	MPM	6179	0.0473	-0.0750	-0.0755	-3.7510	4.7351
	HEY	6179	0.0477	-0.0924	-0.0927	-3.8246	4.7612
	Durish	6179	0.0475	-0.0811	-0.0816	-3.7897	4.7390
G-mSi0251	P.E.	3337	0.0374	0.2079	0.2074	-2.1379	4.1730
	BFPE	3337	0.0315	0.4372	0.4369	-0.1463	4.0295
	Evans	3337	0.0446	-0.1255	-0.1255	-3.6960	4.1982
	MPM	3337	0.0493	-0.3760	-0.3773	-4.4257	4.1724
	HEY	3337	0.0486	-0.3371	-0.3379	-4.3283	4.1895
	Durish	3337	0.0494	-0.3803	-0.3815	-4.4690	4.1517

HEY models than the proposed PE model. Actually, the proposed PE presents the worse fitting for the IEC data. However, when thousands of outdoor efficiencies are used, the PE model performs much better than the other parameter fitting models, as it is shown in Table 7. Notice that outdoor efficiency values are not taken at specific conditions (temperature, irradiance), as opposed to the case in which the IEC 61863-1 standard is used.

In Table 7, the  $nRMSD$  column presents results in the range of  $[3.15 - 5.55]\%$  which represents how the outdoor efficiency values are scattered around the efficiency models. Notice that the plane-based models have the best-adjusted coefficient of determination,  $R^2_{adj}$ , i.e., the plane models capture much better the variability of the error than efficiency models calculated from IEC 61853-1. In summary, the efficiency prediction model based on a plane in which parameters were calculated using a best-fit algorithm (BFPE) performs better than

the model-based which parameters have been calculated using only three points (PE) or the other efficiency models: Evans, Hey, Durish, MPM. Nevertheless, as stated before, the three-point plane-based model is more practical due to the possibility of constructing it just with three reference values which may be taken from IEC references or datasheets without fitting procedures.

A relevant characteristic to consider is that the BFPE and PE models differ only by an offset value that is on average  $-1.94\%$  as can be appreciated graphically in Figure 3. The displacement between the models is measured with the mean relative error ( $\bar{x}_r$ ) and for the plane models do not vary significantly in all the modules analyzed (see Table 7). Actually, this displacement is observed in the histograms for the PE and the BFPE presented in Figure 6. In order to show a specific example, we selected the PV module C-mSi0166. The histograms in Figure 7 show the relative error distribution for both efficiency models. The results



**Figure 7** Histograms of the R.E. for panel C-mSi0166 a) *r.e.* distribution for the proposed equation b) *r.e.* distribution for the BFPE

presented in this figure are confirmed in Table 7 where it can be seen that the average of the relative error ( $\bar{x}_r$ ) for the PE is  $-1.39\%$ , while for the BFPE is  $-0.1533\%$ , i.e., the difference between these averages is only  $1.24\%$ . Therefore, the hypotheses established in [23] are rejected because those averages are not equal. On the other hand, the standard deviation of the *r.e.* ( $\sigma_r$ ) presents similar results for both models indicating that the hypothesis in Equation (22) may be accepted or rejected.

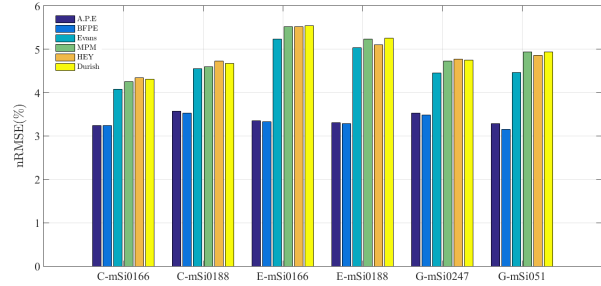
Based on observation of the previous results, we hypothesized that the three-point plane efficiency model could give the same prediction results as the best-fit plane model if the former is rewritten as,

$$\eta^{BFPE} \approx \eta^{APE} = \eta^{PE} \cdot (1 + f), \quad (24)$$

where  $f = \bar{x}_r^{PE} - \bar{x}_r^{BFPE}$ .

The previous model [24] is called the adjusted plane equation (APE). Notice that according to Table 7  $\bar{x}_r^{BFPE}$  is at least one order of magnitude smaller than  $\bar{x}_r^{PE}$  and therefore  $f \approx \bar{x}_r^{PE}$ . This equation means that if we multiply one PE model by a constant  $(1 + f)$  it is possible to displace the plane equation and obtain an equivalent plane to BFPE.

The new APE model has similar metrics to the BFPE model calculated from the outdoor data. For example, the *nRMSD* is almost the same for these two models and this can be observed in Figure 8. Notice that the APE model and the BFPE have the lowest *nRMSD* and could be considered equivalent models from the statistical point of view as we show next. Table 8 shows the results obtained when the hypothesis tests [22] and [23] are tested with the adjusted plane equation, where the P-Valued is the criteria used to accept or reject the null hypothesis  $H_0$ .



**Figure 8** Normalized RMSD for each PV panel and efficiency model

The results in Table 8 are quite satisfactory. First of all, the standard deviation of the APE can be considered equivalent to the standard deviation generated by the BFPE. Second, both models generate an equivalent average of the relative error. It should be noticed that for all the tests made, the P-value is always higher than the acceptance value of  $0.05$ ; therefore, for all the six modules, it can be confirmed that both planes can be considered “parallel” and with equivalent error distributions.

## 8. Conclusions

This work has proposed a simple plane efficiency model to predict the efficiency value of PV modules using back-panel temperature and POA irradiance for outdoor conditions. The proposed PE model is calculated from three reference efficiency values obtained from the power matrix using the IEC 61853-1 standard. It was validated with outdoor efficiency values in three locations with data collected during one year. All the efficiency values data taken from the NREL database correspond to clean PV panels, with a temperature and irradiance in the ranges  $[25 - 65]^\circ C$  and  $[200 - 1050] W/m^2$ .

The proposed PE mode can be considered “parallel” to the best-fit-plane equation obtained from nonlinear regression of the efficiency data, and on average, the PE model is more optimistic with the predictions than the BFPE model. This means that the PE gives on average  $1.94\%$  higher efficiency predictions for all the modules ( $f = -0.0194$ ). However, when the PE is adjusted by the factor  $(1 + f)$ , the adjusted plane equation generates, statistically speaking, equivalent results to the BFPE as demonstrated with the hypothesis test.

The usefulness of the proposed efficiency plane expression hinges on the possibility of constructing it with only three points. Even though a more accurate expression can be obtained by applying a best-fit algorithm to a set of measurements; these are not always available or desirable to obtain. A cloud of data, such as the one used in this

**Table 8** Results of the hypothesis test

Tag	Number $n$	Ratio $\sigma_r^{APE} / \sigma_r^{BFPE}$	P-value	Difference [%] $\bar{x}_r^{APE} - \bar{x}_r^{BFPE}$	P-value
C-mSi0166	22427	1.00556	0.745	0.0174	0.654
C-mSi0188	18678	1.02551	0.188	0.0176	0.706
E-mSi0166	14726	1.00709	0.758	0.0965	0.056
E-mSi0188	7689	1.00797	0.817	0.0676	0.324
G-mSi2047	6179	1.01508	0.656	0.0287	0.725
G-mSi0251	3337	1.01501	0.743	0.0426	0.668

paper for validation, requires measuring each PV module for months with high-precision equipment, which makes it impractical to determine the parameters of an efficiency model. Therefore, the main advantages of the proposed model are the simplicity of calculating the model constants and that the PE model describes the efficiency behavior also like the best-fit plane efficiency model for a cloud of efficiency points, this without experiments nor data regression.

## 9. Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

## 10. Acknowledgements

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## 12. Author contributions

L.D.M.S. Conceived and designed the analysis. L.D.M.S. and C.M. Contributed data or analysis tools. L.D.M.S. Performed the analysis. L.D.M.S. and C.M. Wrote the paper.

## 13. Data availability statement

The database used in this article is described in [24], and for access to the data, please contact Bill

Marion at bill.marion@nrel.gov for the ftp instructions. The user's manual may be viewed at this link: <http://www.nrel.gov/docs/fy14osti/61610.pdf>.

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