PV performance modelling: A review in the light of quality assurance for large PV plants

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A B S T R A C T

The quality assurance procedures associated with the financing of large PV plants are becoming increasingly more relevant to the PV scene in general. In this context, PV performance modelling is required in order to predict the energy yield and to rate the operating plant performance. Despite the availability of PV performance models since the early days of photovoltaics, the emergence of new proposals and the current debate on the development of an energy rating standard means that this can still be considered an open question. In the specific context of Quality Assurance Procedures, PV performance models must not only be accurate but must also be based on features specifically supported by manufacturers (datasheet information), in order to maintain the chain of responsibility in the event of failure. This paper reviews the currently available PV performance models with regard to accuracy and also compliance with datasheet specifications and guarantees. Accuracy is assessed through a meticulous measurement campaign conducted on PV arrays of four different technologies at a PV plant located in Navarra (northern Spain). The models reviewed are classified into physical models, based on the full I-V curve, and empirical models, which are solely based on the maximum power point (MPP). Despite the fact that physical models and MPP models with more than three parameters are currently widely used, this paper shows that empirical models with just three independent parameters suffice to accurately describe the relationship between PV array performance and operating conditions and are more easily derived from standard datasheet information. This result suggests that 3-parameter empirical models are the best option for PV performance modelling in the context of technical quality assurance procedures.

1. Introduction

The increasing number of large PV plants worldwide has made the specific context of the associated Quality Assurance Procedures increasingly relevant to the PV scene in general. This is due to the fact that, to a large extent, the financing of these PV plants, and return on investment, depends on these procedures. PV performance models are required here in order to predict the energy yield and to rate the operating plant performance, which basically requires comparing observed energy yields with reference values calculated from G and T_C records. This framework usually entails the endorsement of responsibilities in the event of failure. Typically, the EPC (Engineering, Procurement and Construction) is liable to the owner whilst the PV module manufacturer is liable to the EPC. Hence, in order to maintain the responsibility chain, PV performance models must not only be accurate but must also be based on features specifically supported by manufacturers. In other words, as far as possible, they must comply with information given in the datasheets and,

preferably, specifically covered by formal guarantees.

Modelling the maximum output power of a PV generator as a function of the operating conditions requires solving the function given by Eq. (1)

$$P_{\text{MPM}} = P_{\text{MPM}}(G, T_C) \quad (1)$$

Where P_{MPM} is the output power of the PV generator at the maximum power point and G and T_C represent the operating conditions, i.e., the in-plane effective irradiance and the PV module temperature. This response is sometimes termed “performance surface” [1]. It is worth noting that the particular point of this surface corresponding to the so called Standard Test Conditions, STC (irradiance = 1000 W/m²; spectrum AM1.5; cell temperature = 25 °C) is simply the rated power of the PV generator. From now onwards, an asterisk* will be used to refer to parameters measured under these conditions. Hence, $P^*_{\text{MPP}} = P_{\text{MPP}}(G^*, T_C^*)$ and power, efficiency, irradiance and temperature values will be related to STC as shown in Eq. (2):

$$p' = \frac{P_{MPP}}{P_{MPP}^*}; \eta' = \frac{\eta}{\eta^*}; G' = \frac{G}{G^*} \text{ and } T' = T_C - T_C^* \quad (2)$$

Despite the availability of PV performance models since the early days of photovoltaics [2], it can still be considered an open question, as supported by the extensive literature disclosed by corresponding reviews [3–5], by the withdrawal of new proposals and by the current open debate on the development of an energy rating standard. PV performance models are traditionally classified as either “physical”, based on the Shockley and Queisser diode equation, or “empirical”, based on fitting certain predetermined equations to measured efficiency values.

This paper is primarily focused on reviewing models for performance surface construction with regard to accuracy and to compliance with datasheets and guarantees. Accuracy is assessed through a meticulous measurement campaign with four different current commercial PV technologies: c-Si, CdTe, CIGS and a-Si/ μ Si. Five PV arrays (two are a-Si/ μ Si, from different manufactures), each with P^* around 2 kW, were connected to the grid in southern Navarra (Spain) and kept in routine operation in the course of five years. Measured power and energy production values were compared with modelled ones from different sets of equations. On the other hand, compliance with datasheets is assessed by discussing the possibility of extracting the input data required for each model with current datasheet content. Particular attention is given to crystalline silicon, which is by far the dominant technology in the current and near future markets.

Apart from the PV generator components, when modelling the output of entire PV systems, other components (DC/AC inverters, transformers, etc.), and somewhat abnormal situations (shading, inverter saturation, power curtailment and so on) also need to be addressed. However, these issues typically entail low uncertainty and are therefore disregarded in this work.

2. A review of the PV modelling alternatives

2.1. Physical or full I-V curve models

A PV generator is traditionally represented by an equivalent circuit referred to as the five-parameter one-diode model (Fig. 1a). It comprises a current source, an anti-parallel diode and two resistors. Based on the Shockley and Queisser diode equation, the corresponding mathematical model is given by Eq. (3):

$$I = I_L - I_0 \left[\exp \left(\frac{V + IR_S}{V_t} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad (3)$$

where the 5 parameters are: photocurrent, I_L ; diode saturation current, I_0 ; thermal voltage, V_t ; series resistance, R_S ; and shunt resistance, R_{SH} . Good descriptions of this model are available from the early days of photovoltaics [2] and are easily found in basic text books [6–9]. The thermal voltage is given by Eq. (4):

$$V_t = mN_{CS}kT_C/q \quad (4)$$

where m is the so-called ideality factor, N_{CS} the number of solar cells

(a)

associated in series, k is the Boltzmann's constant $-1.381 \times 10^{-23} \text{ J/}^\circ\text{K}$ and q is the absolute value of the charge on an electron $-1.602 \times 10^{-19} \text{ C}$. T_C is expressed as an absolute temperature (K).

The corresponding output I-V curve used to be characterized by values at three points: short-circuit current, I_{SC} ; open-circuit voltage, V_{OC} ; and the current and voltage maximum power point, I_{MPP} and V_{MPP} , respectively (Fig. 1b). Dealing in practice with this model requires solving three different problems:

- Extraction of the parameters at STC from available information
- Extension of the parameters to other than STC values
- Solving the equation for the MPP value.

2.1.1. Extraction of parameters at STC

In principle, in order to determine 5 parameters, 5 independent data items are required. The PV module datasheet shall be assumed to provide the three characteristic points at STC and the open-circuit voltage coefficient, β (Datasheet content is discussed in Section 3.1.1). Then, the first three data items are obtained by writing Eq. (3) for I_{SC}^* , for V_{OC}^* and for (I_{MPP}^*, V_{MPP}^*) . A fourth equation is obtained for imposing the derivative of power at the MPP point as zero and the fifth equation is derived from the open circuit temperature coefficient concept [10]. Details of the equations are given in Annex 1.

The resulting 5 equations form an implicit and non-linear equation system which requires numerical methods demanding extensive computation and also good initial guesses for the iterations to converge. Powerful mathematical tools such as the engineering equation solver (EES) from F-Chart [10] or Lambert functions [11,12] are required. Modified formulations of Eq. (3) have been proposed with the aim of improving convergence [13–15]. Several simulations have been made with the F-solve (MATLAB), obtaining reasonable results for c-Si when using $m=1.06$ and particular R_S and R_{SH} values [16] as initial guesses. However, convergence problems often needed to be addressed.

Such difficulties suggest that the direct extraction of the 5 parameters solely from datasheet information is definitively not a way to develop practical tools for energy yield prediction. Moreover, this way is made even worse by the limited representativeness of the ($I_{SC}^*, V_{OC}^*, I_{MPP}^*, V_{MPP}^*$) set of values given on data sheets, due to corresponding module-to-module variations observed among industrial batches of a same module type, as shown in Section 3.1.1.

Sound assumptions for lessening the task of extracting parameters have been extensively explored. For example, disregarding the short-circuit recombination current [17], i.e. Eq. (5):

$$I_L^* = I_{SC}^* \left(1 + \frac{R_S^*}{R_P^*} \right) \quad (5)$$

Also, assuming the above equation, a value for m and iterating on R_S and R_P until finding the only pair (R_S, R_P) that guarantees only P_{MPP}^* , but not I_{MPP}^* and V_{MPP}^* independently [18]. Widely referred to relationships derive from comparing the fill factor FF^* with the fill factor of an ideal cell (a cell with R_S^* zero and R_{SH}^* infinite), FF_0 , using available semi-empirical expressions for the MPP [7]. The following equations Eqs. (6)–(8) apply:

(b)

Fig. 1. a) Single diode model b) Characteristic points of the IV curve.

$$v_{OC}^* = \frac{V_{OC}^*}{V_t^*} \quad r_{SH}^* = R_{SH}^* \frac{I_{SC}^*}{V_{OC}^*} \quad r_s^* = R_s^* \frac{I_{SC}^*}{V_{OC}^*} \quad (6)$$

$$FF_0^* = \frac{v_{OC}^* - \ln(v_{OC}^* - 0.72)}{v_{OC}^* + 1} \quad (7)$$

$$FF^* = FF_0^* (1 - r_s^*) \left\{ 1 - \left(\frac{v_{OC}^* + 0.7}{v_{OC}^*} \right) \left[\frac{FF_0^* (1 - r_s^*)}{r_{SH}^*} \right] \right\} \quad (8)$$

These equations are valid for cells of reasonable efficiency ($v_{OC} > 10$), as is the case for most commercial cells today, and they become particularly useful when, again, the considered input is only P_{MPP}^* , but not I_{MPP}^* and V_{MPP}^* independently. Combined with reasonable choices for m and R_{SH} , these equations make the I-V curve calculation sequence fully analytical and straightforward. For example, $1.1 \leq m \leq 1.3$ and R_{SH}^* greater than 5 times $V_M^*/(I_{SC}^* - I_M^*)$ represent reasonable ranges for crystalline silicon. A further simplification of this approach is considering R_{SH}^* as infinite. Then Eq. (9) applies:

$$R_s^* = \left(1 - \frac{FF^*}{FF_0^*} \right) \frac{V_{OC}^*}{I_{SC}^*} I_L^* \approx I_{SC}^* \quad \text{and} \quad I_0^* = I_{SC}^* \exp \left(-\frac{V_{OC}^*}{V_t^*} \right) \quad (9)$$

In general, the equivalent circuit for the PV generator can be simplified by assuming R_{SH}^* as infinite, resulting in the so-called “4-parameter model”. This is extensively used for crystalline silicon modules operating in sunny places [9,11,19–24], because it represents a good compromise between accuracy and complexity. Interestingly, even the “3-parameter model” resulting from the ideal cell, where effects of series and parallel resistors are disregarded, leads to reasonably good results, showing P_{DC} errors below 4% for a large range of G and T_C [25–27].

A very different approach consists in extracting the 5 parameters from a measured I-V curve (instead of datasheet values). The literature contains many different variations for this question [12,23,28–45]. Typically, a key step consists in taking R_{SH} as the inverse of the slope around short-circuit point as is shown in Eq. (10):

$$\left. \frac{dI}{dV} \right|_{I_{SC}} = -\frac{1}{R_{SH}} \quad (10)$$

This approach has been adopted by widely-known software such as PVsyst [46] or the CECPV calculator [47]. Such software is user-friendly and has many supporters. However, due to the fact that the I-V curves are obtained from independent testing on a single PV module sample, objections regarding representativeness and also PV manufacturer commitment can arise when predicting energy yield in a contractual context.

2.1.2. Extension of parameters to arbitrary operating conditions

Most typically, I_L is assumed to be almost linearly related to irradiance i.e. Eq. (11):

$$I_L = I_L^* G' [1 + \alpha T'] \quad (11)$$

Where α is the temperature coefficient for the short-circuit current. This value can be found on data sheets and is about one order of magnitude lower than β , so that it can be disregarded with no significant error. The diode saturation current is given by Eq. (12) [48]

$$I_0 = I_0^* \left(\frac{T_C}{T_C^*} \right)^3 \exp \left[\frac{E_g}{k} \left(\frac{1}{T_C^*} - \frac{1}{T_C} \right) \right] \quad (12)$$

where E_g is the material energy band gap (1.121 eV for crystalline silicon). E_g exhibits a small temperature dependence that can be described by Eq. (13) [10]

$$\frac{E_g}{E_g^*} = 1 - 0.0002677 T' \quad (13)$$

m and R_s are generally assumed to be constant, while R_{SH} appears to increase with decreasing irradiance. Inverse [10] and Exponential [49] empirical relationships have been proposed to describe this effect, respectively Eq. (14):

$$R_{SH} = \frac{R_{SH}^*}{G'} \quad (14)$$

and Eq. (15)

$$R_{SH} = R_{SH}^* + (R_{SH0} - R_{SH}^*) \exp(-c_{RSH} G') \quad (15)$$

where the shunt resistance at no irradiance, R_{SH0} , and the exponential coefficient c_{RSH} are empirically adjusted. The observed ratio R_{SH0}/R_{SH}^* ranges from 4 for crystalline silicon to 12 for triple junction amorphous. c_{RSH} ranges from 2 (CdTe) to 5.5 for Si.

It must be noted that the power temperature coefficient is a result and not a data input for these procedures. In fact, if it is necessary to strictly comply with the data sheet, then the resulting γ can be fitted to a predetermined value by adding an adjusting exponent to Eq. (12), but this is at the cost of significantly increasing the calculation complexity. On similar lines, an alternative equation for I_0 , based on the temperature coefficient of voltage data, is obtained by writing Eq. (3) for V_{OC} and imposing the value as Eq. (16)

$$V_{OC} = V_{OC}^* [1 - \beta T'] + V_t \ln G' \quad (16)$$

Finally, considering additional dependences of I_0 on irradiance and of R_s on temperature by means of Eq. (17)

$$I_0 = I_0^* G'^{\tau} \left(\frac{T_C}{T_C^*} \right)^3 \exp \left[\frac{E_g}{k} \left(\frac{1}{T_C^*} - \frac{1}{T_C} \right) \right] \quad (17)$$

and Eq. (18)

$$R_s = R_s^* \exp[\delta T'] \quad (18)$$

where τ and δ are empirical parameters that need to be adjusted with other than STC information, has also been proposed [50,51]. Another empirical and simpler dependence of R_s on temperature has also been proposed by [52]. Obviously, adding empirical parameters potentially improves the model accuracy for reproducing the observed performance of an individual PV module. However, yet again, due to the module-to-module variations among the same batch of industrial PV modules, the representativeness of such a procedure is questionable and, therefore, so is the benefit of adding these two parameters to yield prediction exercises.

2.1.3. Solving the model for MPP value

Eq. (3) is implicit and non-linear and is usually solved by iterative methods (Newton-Raphson, etc.). Ruiz has developed an analytical procedure, based on the Taylor series of the first Newton-Raphson step, which is easy to apply. Although not yet published in peer reviewed journals, it has been extensively used at the IES-UPM and gives excellent results in terms of accuracy, which justifies including the corresponding equations in Annex 1.

Table 1 contains a list of a variety of I-V curve models proposed in the literature.

2.2. Empirical or MPP models

These are empirical descriptions of observed maximum power values in relation to the corresponding operating conditions. The simplest MPP model consists in assuming just a linear relationship between power and irradiance. That is Eq. (19):

$$p' = G' \quad \text{or} \quad \eta' = \text{constant} \quad (19)$$

However, the constancy of efficiency throughout the entire range of operating conditions is hardly realistic. A first refinement consists in

Table 1

Different I-V curve models found in the available literature.

I-V curve models							
$I = I_L - I_0 \left[\exp \left(\frac{V + IR_S}{V_T} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \quad [2,6-9]$							
1. Extraction of parameters at STC				2. Extension to arbitrary operating conditions			3. Solving the model for MPP value
From datasheet				From measured I-V curves	$I_L = I_L^* G' [1 + \alpha T']$ $m = m^*$		Iterative methods (Newton-Raphson, etc.) vs Ruiz analytical method (Annex 1)
Solving 5 equation system	Making several assumptions for I_L , FF , m or R_{SH}^*	Considering R_{SH}^* as infinite (4 parameter model)	Considering $R_{SH}^* = \infty$ and $R_S^* = 0$ (3 parameter model)	[28-30,32-34,35,12,23,36-43-45]	Alternative expressions for I_0	Alternative expressions for R_{SH}	Alternative expressions for R_S
[10-13,14]	[17,18,7]	[9,11,19,22-24,53,54]	[25-27]		[48,10] vs [50,51]	[10] vs [49]	$R_S = R_S^*$ vs [50,51] vs [52]

considering that efficiency is affected by temperature, decreasing at a constant rate, to give Eq. (20):

$$\eta' = (1 + \gamma T') \quad (20)$$

where γ , the power temperature coefficient, is considered to be a constant value. This value is almost always found in datasheets. This formula is well established [55,56] and is still widely used.

Instead of using the lumped coefficient for power, a similar model can be written from the temperature coefficients for short-circuit current, open-circuit voltage and fill factor, α , β (always found in datasheets) and ξ , respectively. It is easy to deduce that Eq. (20) is equivalent to Eq. (21)

$$\eta' = (1 + \alpha T')(1 + \beta T') (1 + \xi T') \quad (21)$$

and that γ meets the following Eq. (22):

$$\gamma = \alpha + \beta + \xi \quad (22)$$

Due to the fact that, in practice, the FF is much less temperature sensitive than V_{OC} , some authors have suggested considering it as a constant, or $\xi = 0$ [57].

With these models, it can be slightly complicated to also consider the irradiance-dependent efficiency. Although this was initially attempted by adding a base 10 logarithm [55], it is better implemented by a model proposed more than ten years ago [58,59] and already used by a number of authors [60,61]. This is Eq. (23):

$$\eta' = (1 + \gamma T')(a_1 + a_2 G' + a_3 \ln G') \quad (23)$$

where a_1 , a_2 and a_3 are empirically adjusted parameters. Due to the fact that the particularization of this equation for STC leads to condition given by Eq. (24)

$$a_1 + a_2 = 1 \quad (24)$$

they can be determined from just two values of the relationship between efficiency and irradiance. Datasheets often give only the value for 200 W/m², $\eta'(0.2)$. It is worth noting that efficiency increases with decreasing irradiance, due to series resistance, represented by the term $a_2 G'$, giving $a_2 \leq 0$, while efficiency decreases with decreasing irradiance, due to shunt resistance, represented by term $a_3 \ln G'$, giving $a_3 \geq 0$. Therefore, a conservative approximation solely based on this value assumes the following Eq. (25)

$$a_1 = 1; a_2 = 0; a_3 = \frac{\eta'(0.2) - 1}{\ln 0.2} \quad (25)$$

However, this must be treated with caution, given the fact that, when c-Si and sunny places are concerned, the positive effect of series resistance can even overcome the negative effect of shunt resistance. Another practical possibility to address this difficulty consists in granting generality to already published values for particular modules. The JRC of ISPRA has published efficiency values at different irradiances for a number of technologies [62]. By way of example, for a poly-Si module they give $\eta'(0.6)=1$ and $\eta'(0.2)=0.96$, which leads to $a_1=1.184$, $a_2=-0.184$ and $a_3=0.118$.

Table 2 contains a chronological list of a variety of MPP models proposed since the mid nineteen-nineties Eqs. (26)–(37). Note that the models differ with regard to the number of empirical parameters involved, ranging from just two – Eqs. (26) and (28) – up to six – Eqs. (31) and (36). The justification for proposals often includes the improvement of accuracy, mainly for Thin Films and low irradiance, and also to deal with the logarithm in the event that $G=0$. However, it is surprisingly disturbing to note that comparisons with previous model proposals are virtually absent in the publications describing most of these models (many models have only been presented at Conferences, but not in peer-reviewed journals). Interestingly, round-robins of different energy prediction methods based on some of these models – in particular, equations [29,30] and [33]–, within the European projects “PV-Catapult” and “Performance”, dealing with setting standards for the PV industry, have concluded that “—all methods were able to predict the energy production of known modules in different environments very well” [63] and “All energy prediction methods showed similar results, which does not allow for any preferred selection” [64].

An immediate idea arising from these comparisons is that only three independent parameters, one for temperature and two for irradiance, suffice to accurately describe the PV performance of PV modules in relative terms to STC. Note that not all the parameters included in the equations in Table 2 are independent. For example, Eq. (23) includes 3 parameters for irradiance but these are not independent, as they must comply with Eq. (24).

It follows that there is little or no justification for the use of more complex models, something that comes as a surprise to many people: “Surprisingly, there doesn’t seem to be a need for overly complicated modelling to achieve this accuracy for most technologies” as stated in the final brochure of the aforementioned Performance European [65] and can help to explain why proposals based on more than three parameters are getting very limited success. It must be understood that increasing the

Table 2

Different MPP models found in the available literature. Formulations for only $\eta'(G')$ and $\eta(G')$ implicitly assume that the efficiency dependence on temperature is given by additional factor $(1 + \gamma T')$. All the letters other than G, T and P represent empirically adjusted, non-dimensional parameters.

Ref.	Formulation	
(Evans [55])	$\eta'(G', T') = 1 + a_1 T' + a_2 I_{g10} G'$	(26)
(Taylor [84])	$\eta'(G', T') = A + BG' + CT'$	(27)
(Randall [58])	$\eta'(G') = 1 + a \cdot \ln G'$	(28)
(Willians [59])	$\eta'(G') = a_1 + a_2 G' + a_3 \ln G'$	(29)
(Willians [80])	$\eta'(G', T') = (1 + \alpha T')(1 + c_0 \ln G' + c_1 \ln^2 G' + \beta T')$	(30)
(Rosell [85])	$P_{DC}(G_{eff}, T_C) = D_1 G_{eff} + D_2 T_C + D_3 (\ln G_{eff})^{d5} + D_4 T_C (\ln G_{eff})^{d5}$	(31)
(Durisch [71])	$\eta(G', T_C) = a[bG' + (G')](1 + d \frac{T_C(oC)}{25} + e)$	(32)
(Heydenreich [86])	$\eta(G) = aG + b \ln(G + 1) + c[\ln^2 \frac{G + e}{G + 1} - 1]$	(33)
(Montgareuil [87])	$\eta'(G') = 1 + a(G' - 1) + b \ln G' + c(G' - 1)^2 + d \ln^2 G'$	(34)
(Reich [61])	$\eta'(G') = a_1 + a_2 G' + a_3 \ln(G' + a_4)$	(35)
(Huld [83])	$P_{MPP}(G', T') = G'(P_{MPP}^* + k_1 \ln G' + k_2 \ln(G')) + k_3 T' + k_4 T' \ln G' + k_5 T' \ln(G') + k_6 (T')^2$	(36)
(Silva [88])	$\eta'(G) = (1 + b \ln G^* - c G^{*1/2})(1 + b \ln G - c G^{1/2})$	(37)

number of module parameters also increases the complexity of the measurements required to determine their values. The IEC 61853 method can serve as paradigm. It is based on first measuring the PV module performance at 23 points of a (G, T_C) matrix, where G and T_C ranges from 100 to 1100 W/m² and 15 to 75 °C, respectively. Then, the PV module is rated at 5 different conditions, called High Temperature Conditions, HTC(1000 W/m², 75 °C); Standard Test Conditions, STC(1000 W/m², 25 °C); Nominal Operating Cell Temperature, NOCT(800 W/m², $T_{ambient}$ = 75 °C), Low Temperature Conditions (500 W/m², 15 °C) and Low Irradiance Conditions, LIC (200 W/m², 25 °C). Finally, the MPP for a particular (G, T_C) pair is calculated by interpolations of these conditions. Despite the fact that the first draft of IEC 61853 was published in 2001 and that it was explicitly recommended by organizations as important as the Solar American Board for Codes and Standards [66], this standard has still never been implemented in practice. Interestingly, the authors of a

detailed validation of the complete IEC 618532 methodology conclude: “The authors feeling is that the complexity of the standard is actually not beneficial for an accurate energy prediction, as it requires data which is actually normally not known and the generation of this... seems to affect the overall agreement more than it would be without this complicated step” [67]. A similar opinion is expressed by the authors of a comparison between the IEC 618523 methodology and Eq. (30): “The two methodologies were found to have comparable accuracy...it is not clear whether the gain in accuracy would justify the cost in complexity of measurements and calculations involved” [68]. On the same lines, a recent Fraunhofer ISE proposal of a method for energy rating [69] is based on the model given by Eq. (33), which is in fact based on three independent parameters. This model has been widely experimentally validated for c-Si and TF technologies [70].

Similar comments can be extended to the Durisch model [71,72] or

the so-called “Loss Factor Model” which requires up to 15 empirical parameters to describe the performance of amorphous silicon modules [73–75].

Similar conclusions in favour of model simplicity have followed MPP models comparisons performed at the University of Jaen (Spain). Concerning the c-Si, the conclusion has been that “... taking an overall view both, FF_K and Osterwald’s models – that have 1 and 2 parameters, respectively – combine simplicity and accuracy best, so they are definitively recommended for PV engineering in Mediterranean climates” [57]. And this conclusion was later extended to thin films, following a testing campaign with four different technologies a-Si, CIGS, CdTe and a-Si:H/ μ Si:H in Jaen, Madrid and Barcelona [76].

Finally, it is interesting to mention that some models have been implemented in popular, open-access energy-prediction tools. The so-called SANDIA or King’s model [77,78] has been implemented in the Solar Advisor Model, developed by NREL [79]. The original version of this model uses broadband irradiance as input and includes a number of equations and many coefficients to cope with spectral and angular responses. However, this is not necessary when using effective irradiance as input and the model can be substantially simplified. This model determines the performance surface by means of empirical equations for both the current and voltage at the maximum power point. Their combination leads to the four parameters Eq. (30) for the relative efficiency [80]. This equation was implemented in the PVGIS (developed by the European JRC [81]) interactive web applications for the estimation of PV production, using empirical values obtained from measurements of a single c-Si module: $\alpha=1.2\times 10^{-3} \text{ }^\circ\text{C}^{-1}$; $\beta=-4.6\times 10^{-3} \text{ }^\circ\text{C}^{-1}$; $c_0=0.033$ and $c_2=-0.0092$ [82]. It was later substituted by the slightly more complex possibility given by Eq. (36) [83]. Coefficients for 18 crystalline PV modules were obtained by means of an extensive measurement campaign (at least 24 power values at corresponding (G_{eff}, T_C) pairs were measured for each module), and the results were combined to generate a model for a generic crystalline silicon module that was included in the online PV estimator in PVGIS. It is given by $k_1=-0.01724$; $k_2=-0.04047$; $k_3=-0.0047 \text{ }^\circ\text{C}^{-1}$; $k_4=1.49\times 10^{-4} \text{ }^\circ\text{C}^{-1}$; $k_5=1.47\times 10^{-4} \text{ }^\circ\text{C}^{-1}$ and $k_6=5\times 10^{-6} \text{ }^\circ\text{C}^{-2}$. Yordanov [52] proposed a set of equations that makes it possible to obtain parameters k_I to k_6 from the I-V curve parameters.

2.3. The case of thin-film technologies

Modelling the performance of thin-film technologies is a slightly more complex issue than modelling that of crystalline silicon. The case of a-Si modules is probably the best example. These modules are subjected to the Staebler-Wronski effect [89], which provokes a decrease in performance upon exposure to light, typically reducing efficiency by 15–20% [90,91] compared with its initial value. Additionally, after reaching stabilization (about 6 months of outdoor exposure), the efficiency of this material exhibits seasonal variations [92] that have been attributed to mainly two effects: spectral effects [93–96], and thermal annealing [97,98]. These seasonal changes can be described very closely with the sinusoidal function [99] which is given by Eq. (38):

$$\frac{\eta(t)}{\eta^*} = A \sin\left(2\pi \frac{t}{T} + \phi\right) + \eta_{AV} \quad (38)$$

where A is the amplitude, t is the time (month) for which the efficiency is to be predicted, T is the total time period (12 months), ϕ is the phase and η_{AV} is the average efficiency.

The spectral effects on the performance of the different PV technologies (mainly on a-Si) have been widely discussed in the literature [94–103]. The published studies point out that disregarding the spectral effects could lead to noticeable errors in annual energy calculations in the case of

a-Si (from 1.5% up to 10%) [100,103] but this is less important in HIT, CIGS and c-Si (less than 1.5%) [102]. The spectral impact on the annual energy for CdTe used to be less than on a-Si but larger than on c-Si modules. [104]. In order to model the spectral influence on the performance of the different PV technologies, some authors use parameters such as the Average Photon Energy [105] or the Useful Fraction [100] to characterize the spectral distribution of incident irradiance and its correlation with the PV module efficiency. However, this procedure requires the use of spectroradiometers, which are not commonly used as measurement instruments. Other authors suggest correlating the PV modules efficiency with the air mass, AM [78,101], or with both the AM and the clearness index, K_T [106]. In these papers, empirical correlations have been proposed for a selection of modules of the different PV technologies, except for CIGS. Nevertheless, it has been pointed out [104] that the spectral behaviour differs not only among different technologies under real outdoor conditions, but also significantly within a single technology. For this reason, most of these empirical correlations do not have a general validity. In this context, because no detailed spectral response data are commonly available for each PV module, and also because spectral distribution of incident irradiance is difficult to obtain, this paper postulates two generalizations:

- CdTe and CI(G)S perform similar to c-Si.
- a-Si/ μ c-Si performs similar to a-Si which, in turns, performs as described in [77] or in [106].

This makes it possible to deal with these technologies in practice, using only available information, however at the cost of increased uncertainty.

Finally, it is worth mentioning that some improvement has also been reported in Cds/CdTe PV module performance modelling if real and non-constant temperature coefficients are used [107]. Nevertheless, empirical measurements are required and the complexity of the performance model is increased. In this paper, maintaining the criteria of using only available information, the constant temperature coefficients provided by manufacturers are used.

2.4. I-V curve versus MPP models

Generally speaking, the PV performance modelling panorama can be understood to have originated in two different areas, each with its own specific mandate. On the one hand, laboratories specializing in photovoltaics, specifically involved in systematic measurements on industrial PV modules, have been the main cradle of MPP models, which are essentially empirical and require relatively easy calculations. On the other hand, universities, often dealing with research and theoretical studies, have been the main cradle of full I-V models, which are essentially physical and require more complex calculations. Not surprisingly, most model comparisons available today have been made within one of these two areas. In fact, among the extensive literature disclosed by PV performance modelling reviews [3,4,108,109], only 2 papers have been found that simultaneously address energy yields predicted by MPP and IV curve models and, even so, in a rather restricted manner:

The first [110] compares the energy yield observed at three c-Si PV arrays located at Albuquerque (USA) with the predictions of three performance modelling alternatives available within the so-called Solar Advisor Model, SAM, a free software program developed by the NREL: the Sandia model given by Eq. (30), a 5-parameter 1-diode model and the simplest MPP that considers only the efficiency dependence on temperature, given by Eq. (20). The coefficients for implementing the SANDIA and 5-parameters models are taken from the database distributed with SAM (derived from particular modules measured at

SANDIA and NREL) while the temperature coefficient for the MPPTD was taken from the manufacturer's datasheet. The PV arrays are of different power outputs (1.1, 1.11 and 2.3 kW) and the same module type but from two different batches (210 and 220 STC nameplate rating). The interesting results is not only that "... all the modules agree within about 2%", but also that the differences of a same model for the three PV arrays are slightly greater than this figure. This suggests that the differences due to module-to-module variations supersede the differences due to model-to-model variations.

The second [61] analyses the low light performance of 41 commercially produced c-Si cells. Due to the fact that the work is made in the context of Product Integrated PV, that are likely to be operated most often indoors than outdoors, this work pays particular attention to the range of very low irradiances ($< 100 \text{ W/m}^2$). Despite the fact that this range is scarcely relevant for standard PV generators, the conclusions of the paper are still useful: the accuracy of diode models in this range can be very high but is very dependent on the parameters used (this is because R_p is of utmost importance in this range, which is not the case at normal irradiance levels); the MPP model given by Eq. (35) performs very well. Note that this equation is an adaptation of Eq. (29) by including an additional parameter in the logarithmic part, simply to avoid negative efficiencies and to improve fitting accuracy at very low light, below 1 W/m^2 ; and that cells from one and the same manufacturer show large differences in cell efficiencies at low irradiance. This helps explain that module-to-module variations also used to be large, as will be seen in section 3.1.

It has been postulated above that only three independent parameters are required to accurately describe the relationship between PV array performance and operating conditions. It follows that 5 parameters, as required by I-V models, are more than is strictly needed for energy yield calculations for PV arrays operating at MPP. Obviously, I-V models allow for studying the performance of the PV array at points other than MPP, which may be useful for analyzing particular problems such as direct coupling to batteries or DC motors. However, it should be mentioned that the output power limitation for PV systems characterized by large array-to-inverter ratios can be easily solved without dealing with I-V curves, and that shading impacts can also be correctly evaluated without I-V curves [111].

3. PV modelling in the context of quality assurance practices

Technical quality assurance procedures are focused on ensuring that actual performance is in line with expectations. For a grid-connected PV plant, prior to construction, expectations are established through a forecast simulation exercise describing the expected site evolution of the operating conditions and the corresponding power response of the PV system. This makes it possible to predict the yearly energy production, of paramount importance for the economic balance and for the bankability of the PV plant. Solar radiation databases and technical specifications of the PV plant components provide input data for this exercise.

It must be noted that predicting the operating conditions unavoidably relies on the available meteorological data, and that this is far from being an exact science [112–114]. Therefore, the corresponding uncertainty is considered to be a source of risk, yet no one can be held responsible for future weather. However, the power response of PV systems is mainly a matter of technical quality and strict responsibilities that need to be endorsed by PV equipment suppliers, who obviously must agree on the corresponding technical specifications that they are requested to guarantee. It follows that the performance models must be based on features specifically supported by manufacturers.

Note that, regarding PV arrays, this applies not only to the P_{MPP}^* value but also to the following function (Eq. (39))

$$P_{MPP} = P_{MPP}(P_{MPP}^*, G, T_c) \quad (39)$$

It is worth noting that P_{MPP}^* can adopt two different values: the "nominal" value, $P_{MPP,NOM}^*$, which is the product of the number of PV modules multiplied by the corresponding nameplate STC power and the "real" value, $P_{MPP,REAL}^*$, which is the power measured at the inverter input. Depending on the contractual conditions, the nominal value is sometimes substituted by the "flash" value $P_{MPP,FL}^*$, which is the sum of the power of all the constituent modules, as measured in the manufacturer's flash tests.

In practice, yield prediction includes the consideration of a baseline loss scenario, agreed among all the parties involved in the project (EPC, investors and independent experts) and establishing the maximum allowable difference between the performance of a hypothetical reference system, whose characteristics are extracted directly from the manufacturer's information and the actual system to be constructed. Such scenario lumps together all the losses that can be properly associated with the concept of technical quality (due to underrating, initial degradation, mismatching, wiring, etc.) and can be adequately quantified by ratio $P_{MPP,REAL}^*/P_{MPP,NOM}^*$ (or $P_{MPP,REAL}^*/P_{MPP,FL}^*$).

At a later date, once the PV plant is operating, its technical quality is typically assessed through a number of performance indices that are derived from comparing the observed energy productions with hypothetical reference values calculated from observed operating conditions. This is first done at the Commissioning Tests, over a relatively short period of a few weeks. In the past, the most widely-used index was the Performance Ratio, PR . This index, defined in IEC 61724 ("Photovoltaic system performance monitoring: guidelines for measurement, data exchange and analysis"), is calculated as Eq. (40)

$$PR = \frac{E_{AC}}{P_{MPP}^* \frac{G_{AT}}{G^*}} \quad (40)$$

where E_{AC} is the energy effectively delivered to the grid and G_{AT} is the annual in-plane irradiation during that period. Note that this PR value can be directly calculated without any kind of modelling, due to the fact that the E_{AC} , $P_{MPP,NOM}^*$ and G_{AT} values are directly given by the billing energy meter of the PV plant, the PV manufacturer receipt and the integration of a solar irradiance signal. However, it entails the fundamental drawback of being time dependent because it includes not only pure technical losses, considered at the baseline loss scenario, but also unavoidable losses due to efficiency variations with operating conditions, which are either time or site dependent but not related to the concept of technical quality. Thus, the rating result of a similar PV plant varies with the climatic conditions for the rating period, which seems contrary to common sense.

Such unavoidable losses need to be removed by more accurate technical assessment procedures. A nice possibility is to consider the so-called Performance Ratio at Standard Test Conditions, PR_{STC} , given by Eq. (41):

$$PR_{STC} = \frac{PR}{\prod_i (1 - \Delta E_i)} \quad (41)$$

Where ΔE represents energy losses during the considered period and subscript "i" extends to all the unavoidable energy loss phenomena (due to operating temperature, irradiance and also to other phenomena inherent in the design such as DC/AC conversion, shading or inverter saturation). All these losses must be calculated from measured G and T_c values, which obviously require some kind of modelling. It is important to realize that the coherence of the full quality assurance

process makes it necessary to use the same PV performance model as for the energy yield forecast. Otherwise, the energy forecast baseline loss scenario is not properly verified. This need for model homogeneity has also been indicated by other authors [115]. It is worth noting that, disregarding other than PV array losses, PR_{STC} is equal to ratio $P_{MPP,REAL}^*/P_{MPP,NOM}^*$.

If P_{MPP} data are available; an equivalent procedure consists in deriving corresponding $P_{MPP,REAL}^*$ values, i.e., solving the inverse of Eq. (39). Then the average result for the period under consideration makes it possible to directly calculate ratio $P_{MPP,REAL}^*/P_{MPP,NOM}^*$.

3.1. Sources of input data

Possible sources of input data for modelling PV performance are manufacturers' datasheets, independent measurements and operating data. Representativeness, guarantee and adequacy for model fitting deserve further comment.

3.1.1. Manufacturers' datasheet content and module-to-module variations

Manufacturers provide data sheets for each PV module type. According to standard EN 50380 ("Data sheet and nameplate information for photovoltaic modules") these must contain characteristic current and voltage values for three points of the I-V curve: short-circuit, open circuit and MPP and for two different (G , T_C) conditions: STC (G^* , T_C^*) and NOCT (800 W/m², ≈ 45 °C); the efficiency reduction from STC to (200 W/m², T_C^*), $\eta'(0.2)$; the NOCT and the temperature coefficients for open circuit voltage, β , and for short-circuit current, α . However, nowadays, this standard is far from being generally observed. Current and voltage at NOCT and low light performance values are sometimes missing [116]. In contrast, although not required by EN 50380, all the data sheets checked include the value of the temperature coefficient for power, γ .

Nowadays, standard guarantees are restricted to the value of P_{MPP}^* while the rest of the data sheet content is given by way of general information, but not particularly intended to support efficiency quality controls. As a result, guarantees on values other than P_{MPP}^* must be agreed with the PV modules manufacturer, prior to the PV modules supply. The IES-UPM experience on the quality control of large PV plants, now spanning PV plants of up to around 300 MW and mainly performed within the context of "due diligences" associated with large PV plant bank financing, includes several cases of PV manufacturers providing guarantees also on γ values.

Datasheet representativeness is limited by module-to-module variations and essentially consistent with guarantees: PV modules are usually marketed with power tolerances of around 3% but the

variability of other than P_{MPP}^* can be significantly larger. As a representative example, observed width ranges at a flash-list of about 14000 crystalline silicon PV modules recently analyzed in our laboratory are 1.9% for P_{MPP}^* , 5% for I_{SC}^* , 2.6% for V_{OC}^* , 5.9% for I_{MPP}^* and 6.3% for V_{MPP}^* .

In the context of checking PV plants, the temperature coefficients and the efficiency variations versus irradiance are often tested on several examples of PV modules of the same type. Fig. 2 shows the results for a c-Si and for a CdTe cases. Table 3 gives the values of γ and $1-\eta'(G')$ for $G'=0.6$ and $G'=0.2$. Note the latter represents the irradiance loss (positive values) or gains (negative values) at G' . Corresponding datasheet information is also displayed. It is noticeable that, firstly, the temperature response is homogeneous (ranging from -3% to +4% around the average) and rather similar to datasheet content and, secondly, the irradiance response is largely non-homogeneous but always better than derived from the $\eta'(0.2)$ value found on the datasheets.

It is worth mentioning that, from our experience, data sheets temperature coefficients are not always fully consistent. For example, there are two ways of deriving P_{MPP}^* values from I-V curves measured at other than STC conditions. One consists in, firstly, extrapolating to STC the full I-V curve in accordance with IEC-6081, which use α and β , and, secondly, obtaining the P_{MPP}^* value. The other consists in, firstly, obtaining the maximum power of the measured curve and, secondly, extrapolating only this value to STC, using γ . Ideally, both results should fully match. However, they usually differ by about 2–3%, and our experience includes differences of up to 5%.

As described above, the 5 i-v curve model parameters can, in principle, be extracted from the I_{SC}^* , V_{OC}^* , I_{MPP}^* , V_{MPP}^* and β values which are all found on datasheets. However, responsibility concerns can arise when using the model for predicting yield, given the fact that the ground information is neither particularly representative nor directly guaranteed by PV manufacturers. In fact, the authors of widely-used software based on this model duly warn users about the lack of PV manufacturers' commitment. Notable examples are the disclaimer in the PVsyst User's Guide: "...for definitive simulations, the user is advised to carefully verify the library data with the last manufacturer's specifications...We drop out any responsibility about the integrity and the exactness of the data and performance including in the library..", and the explanations of the CECPV calculator: "Information presented on this page does not demonstrate performance over time...All parties should perform their own due diligences on all equipment" [117].

On the other hand, the MPP models appear to be closer to the PV manufacturers' guarantees. In fact, P_{MPP}^* is just the main guaranteed value and, as mentioned above, our experience suggests that PV manufacturers are prone to also provide a guarantee for γ . This is

Fig. 2. Efficiency versus Irradiance in a) 7c-Si and b) 6 CdTe PV modules. Values for 200 and 600 W/m² are directly measured. Curves are calculated with Eq. (29). Solid lines correspond to datasheet information.

Table 3

Power temperature coefficient, γ , and efficiency losses at 600 W/m² and 200 W/m² measured in two samples of c-Si and CdTe PV modules. Datasheet information is also presented.

	c-Si			CdTe		
	γ (%/°C)	$1 - \eta'(0.6)$ (%)	$1 - \eta'(0.2)$ (%)	γ (%/°C)	$1 - \eta'(0.6)$ (%)	$1 - \eta'(0.2)$ (%)
M1	-0.428	-0.21	0.47	-0.28	-4.5	-12.9
M2	-0.399	0.56	2.84	-0.25	-4.1	-11.5
M3	-0.41	-0.55	1.89	-0.27	-4.0	-12.1
M4	-0.412	-0.04	1.54	-0.27	-4.0	-11.7
M5	-0.404	1	2.82	-0.29	-3.6	-10.2
M6	-0.422	1.28	3.04	-0.24	-3.6	-10.1
M7	-0.4	1.15	1.34	-0.27	-4.0	-11.4
Average	-0.41	0.46	1.99	-0.27	-4	-11.4
Datasheet	-0.41	1.4 ^(*)	4.50	-0.25	-0.6 ⁽¹⁾	-2

(*) No information is given on datasheet. Eq. (25) has been applied.

important because thermal losses (due to $T_C \neq T_C^*$) are particularly relevant to the energy balance of a PV plant. Concerns regarding low light performance still arise. Related datasheet information is the value of $\eta'(0.2)$ and, when EN 50380 is observed, also $\eta'(0.8)$ which is easily deduced from $P_{MPP}(\text{NOTC})$ and γ values. In principle, this makes it possible to solve the parameters of Eq. (23). In the event that only $\eta'(0.2)$ is known, then the approximation given by Eq. (25) is always conservative, thereby maintaining the chain of responsibility.

3.1.2. Additional independent information

Granting generality to values measured on particular PV specimens or relying on certain assumptions allows for easy fitting of I-V curve models. In fact, this is the path followed by some software that is widely used today, such as PVsyst and CECPV calculator. As mentioned above, such software duly warns users regarding the lack of commitment by PV manufacturers.

On similar lines, independent testing organizations sometimes publish efficiency versus temperature and irradiance values measured on particular specimens. For example, the JRC of ISPRA has published efficiency values at different irradiances for a number of technologies [62]. Again, granting generality to these values permits the fitting of MPP models. However, responsibility concerns arise again when using the model for predicting yield, because this information is likely to be affected by module-to-module variations and it is not directly guaranteed by PV manufacturers.

3.1.3. Operational information

This section refers to possible data from outdoor measurements once the PV plant is in operation. It is worth noting that I-V curves close to 1 MW have been measured [118,119]. However, uncertainty concerns arise with the I-V curves of such large PV arrays, mainly due to the dispersion of T_C in the case of large areas and almost instantaneous observations (I-V sweeps are typically below 30 ms). Interestingly, standard IEC 62446 (Grid connected photovoltaic systems: Minimum requirements for system documentation, commissioning tests and inspection) explicitly mentions that the V_{OC} and I_{SC} tests it prescribes are simply for verifying correct installation but not test performance.

It seems much better to rely on P_{MPP} records for relatively extensive routine operating periods, for example, a minimum of one full day. Due to the fact that the MPP tracking efficiency of current inverters is usually greater than 99%, P_{MPP} can be properly understood as the power at the inverter entry. Moreover, the G and T_C values can also be recorded simultaneously. Then, taking particular precautions regarding irradiance sensors, such as its calibration and stability, leads to low uncertainty P_{MPP}^* measurements [120], which can be used to check

Fig. 3. General view of the PV arrays.

compliance with contractual requirements and also for the routine monitoring of PV plant operation, by comparing real energy production values with the corresponding estimates from the G and T_C records.

Obviously, it is only possible to derive P_{MPP}^* values from (P_{MPP} , G , T_C) records with MPP models, whilst this is not possible with I-V models. This is one of the main reasons why, after achieving similar accuracy (this is discussed later on in this paper), an MPP model and not an I-V one was selected to implement SISIFO, an open access software program under the umbrella of the European project PVCROPS [121]. The same reason has led other authors to adopt MPP models instead of I-V ones [122].

4. Experimental comparison

In order to provide an empirical base for evaluating PV performance models, 5 PV arrays of different technologies (polycrystalline silicon c-Si, CdTe, CIGS, and two double junction a-Si/ μ Si from different manufacturers), each with $P_{MPP,NOM}^*$ between 1890 W and 2400 W, were connected to the grid by 2.5 kW inverters, in Navarra (Spain). All the PV generators are static, tilted 30°, oriented due South and fully free from shading (Fig. 3). Because PV power is always lower than the inverter capacity, it never reaches saturation, so that PV arrays are continuously maintained at the maximum power point. P_{MPP} at the inverter entry, G and T_C are measured at 1 s intervals and recorded as 10 min averages. Moreover, once per month and taking advantage of clear days, the systems are disconnected for a few minutes and PV

Table 4

Main features of the PV arrays tested.

Manufacturer	Generator	P _{Nameplate/module}	Total modules	Total Nameplate Power	γ (%/°C)	β (%/°C)	α (%/°C)
M1	Si	160	14	2240	-0.45	-0.37	0.10
M2	a-Si/ μ Si	130	18	2340	-0.28	-0.33	0.06
M3	a-Si/ μ Si	135	14	1890	-0.24	-0.30	0.07
M4	CIGS	107	18	1926	-0.446	-0.357	-0.003
M5	CdTe	175	30	2250	-0.25	-0.27	0.04

arrays I-V curves are measured. Tables 4 and 5 respectively show the main features of the PV arrays and the instruments used.

Ideally, G is directly given by PV reference devices of the same technology and level of soiling as the corresponding PV arrays. However, due to the stability issue of TF materials, c-Si reference modules entail less uncertainty and are currently more widely accepted by the market actors than TF ones. Taking this into account, it was decided to measure G with only two c-Si reference PV modules, located at the PV arrays surface extremes. Other authors adhere to the same practice [41,64,74,123,124]. Differences between the irradiance measurements of these two reference modules are always lower than 1%, suggesting that dust cover is homogeneous over the entire PV array surface, so that it can be disregarded in the analysis. T_C is measured through thermocouples placed in the centre of the rear side of two modules of each PV array (approximately, 10% of the total number of modules). The temperature differences from these two thermocouples were always lower than 2 °C, suggesting that averages are very representative of the entire PV array operating temperature.

Further equipment included a meteorological station with a horizontal pyranometer, a shaded pyranometer and a thermocouple, which were able to record the following variables: broadband global radiation; diffuse radiation; and air temperature.

4.1. Weather and operating conditions

Measurements were performed over the period from March 2011 to February 2016. Table 6 and Fig. 4 summarize the main characteristics of the observed ambient conditions: broadband horizontal daily irradiation, $G_d^{BB}(0)$, and average ambient temperature during the day, T_A . Roughly, they correspond to a sunny place with larger temperature variations from winter to summer. Operating conditions are also given, in terms of in-plane effective daily irradiation, G_{eff} , and the equivalent PV module temperature, T_{CEQ} , defined as the average of T_C weighted by irradiance. T_{CEQ} values correspond to M1. It is worth mentioning that differences between the different technologies are below 3.5 °C. Fig. 4 shows the annual distribution of these irradiances and temperatures.

4.2. Selected models

Seeking to represent the range of modelling possibilities, the ones described in Table 7 have been selected for MPP models and Table 8 for IV curve models. In addition, Table 9 shows the equations used for the

Table 5

Installed data acquisition equipment, sensors, and uncertainties.

Parameter	Manufacturer	Maximum uncertainty
DC Voltage	Yokogawa	$\pm$ (0.2% of reading + 0.2% of range)
DC Current	Yokogawa	$\pm$ (0.2% of reading + 0.2% of range)
DC Active Power	Yokogawa	$\pm$ (0.3% of reading + 0.2% of range)
IV Characteristic	Photovoltaik Engineering	< 1%
Pt100 Temperature	Omega	B Class = $\pm$ 0.3 °C at nominal resistance (0 °C) B Class = $\pm$ 0.8 °C at nominal resistance (100 °C)
Global Radiation 30° mc-Si reference modules	Yingli Solar	$\pm$ 2% (Calibrated by CIEMAT ^a)

^a CIEMAT: Centre for Energy-Related, Environmental and Technological Research.

Table 6

Main characteristics of both the observed ambient conditions and operation conditions.

	Weather		Operation conditions	
	$G_d^{BB}(0)$ kW h/m ²	T_A (°C)	G_{eff} kW h/m ²	$T_{C,eq}$ (°C)
Average	4.44	16.86	4.79	33.03
Worst month	1.20	6.28	1.96	18.10
Best month	7.86	27.03	7.50	46.21

resolution of the curve and Table 10 shows whether the IV curve was solved using an iterative method or an analytical method.

4.3. Results

Comparison is performed in terms of the daily energy errors, which is relevant for energy yield forecast, and in terms of the weekly PR and PR_{STC} consistency throughout the year, which is relevant for on-site measurement campaigns. The P^* values were the nominal ones, referred to as nameplate values in Table 4.

In order to consider their real impact on energy yield calculations, the errors were weighted by the respective daily irradiation [126]. Therefore, the Error and the Weighted Error at day “i” are respectively given by Eq. (42) and Eq. (43):

$$E_i = \left(\frac{E_{MOD,i} - E_{EXP,i}}{E_{EXP,i}} \right) \quad (42)$$

$$WE_i = E_i \frac{G_{effd,i}}{(\sum_{i=1}^N G_{effd,i})/N} \quad (43)$$

Where E_{MOD} and E_{EXP} represent the daily modelled and experimental PV array energy values, G_{effd} the daily effective irradiation and N extends to the number of days for the considered period. It is worth noting that the Mean Bias Weighted Error, given by Eq. (44), is equal to the error on the energy calculated for such period.

The evaluations metrics that have been considered are:

- Fitting to the experimental measurement, calculated through the relative Mean Bias Weighted Error (MBWE), according to Eq. (44):

Fig. 4. Observed distribution of a) ambient and b) operation conditions.

Table 7
Selected MPP models.

Empirical or MPP models				
Type	Input data (source)	Eqs.	No. of Parameters	Nomenclature
Constant efficiency	P_{MPP}^* (datasheet)	(19)	1	$MPP_{\eta=cte}$
T-dependent efficiency	$P_{MPP,\gamma}^*$ (datasheet)	(20)	2	$MPP_{\eta(T)} \gamma$
	$P_{MPP,\alpha,\beta}^*$ (datasheet)	(21), $\xi = 0$	3	$MPP_{\eta(T)} \alpha\beta$
	$P_{MPP,\alpha,\beta,\xi}^*$ (datasheet)	(21)	4	$MPP_{\eta(T)} \alpha\beta\xi$
G and T-dependent efficiency	$P_{MPP,\gamma,\eta(200)}^*$ (datasheet)	(23), (25)	3	$MPP_{\eta(G,T)} (200)$
	$P_{MPP,\gamma,\eta(200),\eta(800)}^*$ (datasheet)	(23), (25)	4	$MPP_{\eta(G,T)} (200, 800)$
	$P_{MPP,\gamma}^*$ (datasheet), a_1, a_2, a_3 from [62]	(23)	5	$MPP_{\eta(G,T)} (Kenny)$
	$P_{MPP,\gamma}^*$ (datasheet), a_1, a_2, a_3 (experimental)	(23)	5	$MPP_{\eta(G,T)} (exp)$
	P_{MPP}^* (datasheet), $k_1, k_2, k_3, k_4, k_5, k_6$ from [83]	(36)	7	$MPP_{\eta(G,T)} (Huld)$

$$MBWE = \frac{1}{N} \cdot \sum_i WE_i \quad (44)$$

- Dispersion around the fit, through the relative Root Mean Square Weighted Error (RMSWE), according to Eq. (45):

$$RMSWE = \frac{1}{N} \cdot \sqrt{\sum_i WE_i^2} \quad (45)$$

4.3.1. Crystalline silicon

4.3.1.1. Daily energy errors. For explanatory purposes, the particular case of c-Si and model $MPP_{\eta(G,T)}(200)$ is first detailed. Fig. 5 shows the frequency distribution of both the daily energy errors and weighted daily energy errors and its relationship with the daily clearness index, K_{Td} . Corresponding mean bias error, MBE, and mean bias weighted error, MBWE, are -2.11% and 2.39% with corresponding root mean square error, RMSE, and root mean square weighted error, RMSWE, are -3.31% and 1.33% . Note that the radiation weighting factor reduces the general uncertainty of the models and implies a reduction of the error on cloudy days when the energy impact is much lower. The following comments apply:

- The MBE and MBWE errors obviously depend on the difference between the nominal and the actual peak power value. In fact, P^* values deduced from our I-V measurements suggest the actual STC power is 1–2% greater than the nominal value, which is probably due to the positive tolerance (0, +3%) of the PV manufacturing process. This value was further confirmed by testing 2 of the constituent modules at two independent laboratories: CIEMAT (Research Centre on Energy, Environment and Transports) and CENER (National Renewable Energy Centre). The latter means that a good model is expected to underestimate around 1–2%.

The lower K_{Td} is the higher E . Slight differences on the angular response of different PV modules of the same type can help to explain this result. Whatever the case, the impact of cloudy days on total energy error, observable on the WE versus K_{Td} figure, is very low.

Table 8
Selected I-V curve models.

Physical or full I-V curve models (Extraction of parameters at STC)				
Type	Input data (source)	Parameters extraction	Equations	Nomenclature
5 parameters	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*, \beta$ (datasheet)	Solve the implicit and non-linear 5 equations system	(3), (4), (A1)–(A10)	IV _{5p} (5 equations)
	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*$ (datasheet)	R_S^* and R_{SH}^* as described in [125]; I_L^* from Eq. (5); I_0^* from Eq. (A2)	(3)–(5), (A2) $m^* = 1.2$ Ref. [125]	IV _{5p} (Villalva)
	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*$ (datasheet)	R_S^* and R_{SH}^* as described in [16]; I_L^*, I_0^* from Eq. (A1), Eq. (A2)	(3), (4), (A1), (A2) $m^* = 1.2$ Ref. [16]	IV _{5p} (Carrero)
	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*$ (datasheet)	R_S^* from Eqs. (6)–(8); I_L^*, I_0^* from Eqs. (A1), (A2)	(3), (4), (6)–(8), (A1), (A2) $m^* = 1.2$	IV _{5p} (Green)
	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*, R_{SH}^*, R_{S0}^*$ (Experimental)	$R_S^*, R_{SH}^*, m^*, I_L^*, I_0^*$ from [32]	$R_{SH}^* = V_M^*/(I_{SC}^* - I_M^*)$ (3), (4) Ref. [32]	IV _{5p} (Chan)
4 parameters	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*$ (datasheet)	R_S^*, I_L^*, I_0^* from Eq. (9)	(3), (4), (6)–(9) $m^* = 1.2$ $R_{SH}^* = \infty$	IV _{4p}
3 parameters	$V_{OC}^*, I_{SC}^*, V_M^*, I_M^*$ (datasheet)	I_L^*, I_0^* from Eq. (9)	(3), (4), (9) $m^* = 1.2$ $R_{SH}^* = \infty$ $R_S^* = 0$	IV _{3p}

Table 9
Nomenclature for extension to arbitrary operating conditions.

Physical or full I-V curve models (Extension to arbitrary operation conditions)	
Option	Equations $m = m^*, R_S = R_S^*$
E1	R_{SH} from Eq. (14) I_L from Eq. (11) I_0 from Eqs. (12), (13)
E2	R_{SH} from Eq. (14) I_L from Eq. (11) I_0 from Eqs. (3), (16)
E3	R_{SH} from Eq. (15) I_L from Eq. (11) I_0 from Eqs. (12), (13)
E4	R_{SH} from Eq. (15) I_L from Eq. (11) I_0 from Eqs. (3), (16)

Table 10
Nomenclature for solving the I-V curve for MPP.

Physical or full I-V curve models (Solving the model for MPP value)	
Option	Method
S1	Iterative (Newton-Raphson)
S2	Analytical (Annex II)

Tables 11 and 12 give the 5 year MBWE and RMSWE errors for all the considered models. Comments are:

- Regarding to MPP models, those with just three independent parameters perform as well as any other ones.
- The use of published values for polycrystalline modules (MPP_{η(G,T)}_(Kenny)) performs better than the use of a generic c-Si model

(MPP_{η(G,T)}_(Huld)).

- Thermal and low irradiance losses account for about 4.2% and 0.9%, respectively ($\Delta E_{TC \rightarrow TC^*}$ and $\Delta E_{G \rightarrow G}$ are calculated as the MBWE difference between MPP_{η=constant} and MPP_{η(T)_y} models, and between MPP_{η(T)_y} and MPP_{η(G,T)(200)} models, respectively). Obviously, these results are local dependent. Hence, it is appropriate to mention that winter in Navarra is both sunny and cool.
- Somewhat surprisingly, when considering only the variation of the efficiency with T_C but disregarding the effects of G , the MPP_{η(T)_y} performs very well. In order to further explain this result, which is consistent with the energy losses balance mentioned above, Fig. 6 plots ratio $\Delta E_{RP}/\Delta E_{RS}$ versus K_{Td} , as given by MPP_{η(G,T)_(exp)}, where ΔE_{RP} and ΔE_{RS} , respectively, represents the daily energy losses and gains due to R_P and R_S effects. They cancel each other out for $K_{Td} \approx 0.45$ and they perform asymmetrically with respect to K_{Td} : R_S gains for $K_{Td} > 0.45$ are lower than R_P losses for $K_{Td} < 0.45$. The figure also helps to understand that this result is local and PV module dependent.
- In all the IV models simulated with E1-S2 and E2-S2, the results are exactly the same, which is a consequence of using the same V_{OC} values for both E1 and E2.
- IV models simulated with E2 appear to perform better than E1. This is a reasonable occurrence due to the fact that E2 takes into consideration coefficient β of the datasheet module while E1 considers the general silicon E_g value.
- IV models simulated with E3 seem to perform better than E1. This fact implies that the calculation of R_{sh} through Eq. (15) is better than through Eq. (14).
- Similarly, IV models simulated with E4 appear to perform better than E2 which leads to the same conclusion as for the previous point.
- IV models are rather sensitive to R_P assumptions, as shown by the differences between IV_{4p} ($R_{sh}^* = \infty$) and IV_{5p(5 equations)} ($R_P^* = 60 \Omega$), and between E1–E2 (R_P versus G as per Eq. (15)) and E3–E4 (R_P versus G as per Eq. (14)) for IV_{5p(Green)} and IV_{5p(Villalva)} models.
- Models based on experimental measurements (IV_{5p(Chan)}) do not

Fig. 5. a) Observed frequency distribution of the daily energy errors and weighted errors for the $MPP_{\eta(G,T)}(200, 800)$ model. (b) Its relation with the clearness index of the day.

Table 11
MBWE and corresponding RMSWE for the MPP models.

MPP models		
Model	MBWE	RMSWE
$MPP_{\eta_{cte}}$	2.72	6.51
$MPP_{\eta(T)} \gamma$	-1.43	1.25
$MPP_{\eta(T)} \alpha\beta$	0.13	2.81
$MPP_{\eta(T)} \alpha\beta\epsilon$	-1.40	1.26
$MPP_{\eta(G,T)}(200)$	-2.39	1.33
$MPP_{\eta(G,T)}(200, 800)$	-2.05	1.19
$MPP_{\eta(G,T)}(Kenny)$	-1.30	1.09
$MPP_{\eta(G,T)}(exp)$	-1.00	1.08
$MPP_{\eta(G,T)}(Hind)$	-2.61	1.15

seem to be better than the others.

- The model that uses the 5 parameters obtained by solving the implicit and non-linear 5 equations system performs worse than the others.
- The analytical procedure proposed by Ruiz for solving the MPP point of an I-V curve is very convenient. It is extremely easy to implement and the associated errors are insignificant, as revealed by the similarity of IV_{5p_Green} (S1 and S2) results.

Table 13 summarizes the observed errors in daily energy estimates from selected models (the best IV curve models have been selected). In order to consider their real impact on energy yield calculations, the errors are weighted by the respective daily irradiation. Average errors are mainly due to differences between real and nominal STC power ($P_{nominal} - P_{real} = -1$ to 2%). Root mean square weighted errors are due to model uncertainties and to slight differences on the angular response of the PA arrays and the reference module sensing irradiance.

4.3.1.2. Performance indices. Fig. 7a) shows the observed evolution of the weekly PR^{DC} and PR_{STC}^{DC} , again from March 2011 to February 2016. It is worth noting that, in an endeavour to avoid any uncertainty included by the inverters, the PR has been calculated with DC power values. Thermal and irradiance losses have been calculated with the $MPP_{\eta(G,T)}(200)$ model. As expected, the PR_{STC}^{DC} performs significantly more consistently, allowing for a much sounder technical quality evaluation on the basis of the energy production observed in

relatively short periods. Note that the slightly seasonal performance of PR_{STC}^{DC} may be caused by differences between the datasheet value of γ and its real value. Fig. 7b) shows the frequency distribution of the weekly PR^{DC} and PR_{STC}^{DC} . The corresponding mean bias error and root mean square error values are, respectively, 0.99 and 0.05 for the PR^{DC} and 1.02 and 0.01 for the PR_{STC}^{DC} . From our experience and in order to deal with the PR^{DC} , some technical quality evaluations have been made on the basis of observed PR^{DC} values, by considering a different reference value for each month. The 12 reference PR^{DC} values are established by a simulation exercise on the basis of solar radiation and ambient temperature databases. However, the validity of this PR^{DC} monthly correction procedure is probably not general but restricted to particular climatic regions. In fact, our results show weekly PR^{DC} variations of up to 5% for the same month, which seems inadequate for large scale PV plant qualification.

4.3.2. The case of thin-film technologies

As has been seen in the previous section, the performance of simple MPP models with just three independent parameters, such as $MPP_{\eta(T)\gamma}$, $MPP_{\eta(T)\alpha\beta}$ or $MPP_{\eta(G,T)}(200)$, is similar to the most complex models. Therefore, only the three mentioned MPP models were simulated for the thin-film case. Those IV curve models which perform better for the c-Si were also simulated for the thin-film case. Table 14 shows the results for the thin-film cases: $a\text{-Si}/\mu\text{Si}$, CIGS and CdTe. The STC power outputs measured at each PV generator and referred to the nameplate power are shown below each technology in Table 14. It is worth mentioning that average errors are mainly due to differences between real and nominal STC power (except in the CIGS case where it has been experimentally checked that low irradiances losses are higher than the datasheet value). This problem is also addressed in other studies [127,128]. The same comments concerning the Si-x case can be considered. It is worth noting that the higher RMSWE implies that the uncertainty associated with the models is also higher, together with the difficulty of finding typical values of some of the characteristic parameters within manufacturers datasheets or the literature.

5. Conclusions

The review carried out for the currently available PV performance models permits a comparison of full I-V curve and MPP models alike, with regard to accuracy and also compliance with datasheet specifica-

Table 12
MBWE and corresponding RMSWE for the IV curve models.

I-V curve models				
Model	Extension to arbitrary operation conditions	Solving the model	MBWE	RMSWE
IV _{5p} (5 equations)	E1	S1	-5.59	3.36
		S2	-5.62	3.37
	E2	S1	-5.62	3.37
		S2	-7.60	3.47
	E3	S1	-7.71	3.47
		S2	-7.60	3.47
	E4	S1	-7.60	3.47
		S2	-7.60	3.47
IV _{5p} (Villalva)	E1	S1	-1.24	1.53
		S2	-0.42	2.55
	E2	S1	-0.43	2.54
		S2	-0.42	2.55
	E3	S1	-5.64	2.42
		S2	-4.58	3.15
	E4	S1	-4.58	3.15
		S2	-4.58	3.15
IV _{5p} (Carrero)	E1	S1	-1.87	1.26
		S2	-0.94	1.30
	E2	S1	-0.94	1.30
		S2	-0.94	1.30
	E3	S1	-3.77	1.44
		S2	-2.70	1.52
	E4	S1	-2.70	1.52
		S2	-2.70	1.52
IV _{5p} (Green)	E1	S1	-2.30	1.84
		S2	-1.32	1.17
	E2	S1	-1.32	1.17
		S2	-1.32	1.17
	E3	S1	-3.20	1.85
		S2	-2.16	1.23
	E4	S1	-2.16	1.23
		S2	-2.16	1.23
IV _{5p} (Chan)	E1	S1	3.76	4.26
		S2	1.78	1.62
	E2	S1	1.77	1.62
		S2	1.78	1.62
	E3	S1	1.25	4.24
		S2	-0.63	1.61
	E4	S1	-0.63	1.61
		S2	-0.63	1.61
IV4p	E1-E3 ($R_{SH}=\infty$)	S1	-2.27	2.21
		S2	-1.26	1.24
	E2-E4 ($R_{SH}=\infty$)	S1	-1.26	1.24
		S2	-1.26	1.24
IV _{3p}	E1 ($R_{SH}=\infty$ and $R_s=0$)	S1	8.18	5.05
		S2	9.22	6.28
	E2 ($R_{SH}=\infty$ and $R_s=0$)	S1	9.22	6.28
		S2	9.22	6.28

tions and guarantees. Accuracy was assessed through a meticulous measurement campaign conducted on PV arrays of four different technologies at a PV plant. The main conclusions of this comparison are outlined below:

- MPP models with just three independent parameters suffice to accurately describe the relationship between PV array performance and operating conditions. Moreover, these parameters are easily

Fig. 6. Daily ratio between energy losses due to R_p and energy gains due to R_s versus clearness index.

Table 13
Summary of some of the MBWE and RMSWE for the selected models.

Model	Number of input parameters	MBWE	RMSWE
MPP models			
MPP _{η(T)} γ	2	-1.43	1.25
MPP _{η(G,T)} (200)	3	-2.39	1.33
MPP _{η(G,T)} (Huld)	7	-2.61	1.15
I-V curve models			
IV _{5p} (Carrero),E1,S2	5	-0.94	1.30
IV _{5p} (Green),E1,S2	5	-1.32	1.17
IV _{5p} (Chan),E1,S2	5	1.78	1.62
IV4p _{E1-E3} ($R_{SH}=\infty$),S2	4	-1.26	1.24

derived from standard datasheet information. In contrast, physical models and MPP models with more than three parameters do not improve accuracy but increase complexity and move away from the manufacturers' specifications. Hence, their use in engineering practices, despite the fact that they are currently widely used, is scarcely justified.

- Besides, model feedback from actual situations is far easier for MPP models than for physical ones, because records of routine operation of PV plants typically include power records at the inverter entry but not full I-V curves of the PV arrays. Therefore, MPP models provide a direct way for not only advanced operational monitoring but also for linking initial energy yield expectations, which are always at the core of commercial PV plant projects, and further observed performance realities, opening the doors for clear diagnosis and endorsement of responsibilities in the event of underperformance. This represents a great advantage in the context of Technical Quality Assurance Procedures.
- The modelling of the performance of Thin Film technologies using only the standard available information requires particular assumptions regarding seasonal variations and the Staebler-Wronski effect. This paper considers that CdTe and CIGS perform similarly to c-Si and that seasonal variations of a-Si/μc-Si are well described by a sinusoidal function with an amplitude of 3.5% of STC power. In this case, the uncertainty associated with the models is greater, together with the difficulty of finding typical values of some of the characteristic parameters within manufacturer's datasheets or the literature.

Fig. 7. a) Observed evolution of the weekly PR^{DC} and PR^{DC}_{STC} and b) frequency distribution of the weekly PR^{DC} and PR^{DC}_{STC} , during the analyzed period.

Table 14

MBWE and corresponding RMSWE for the selected MPP models for the thin-film cases.

Models		a-Si/ μ Si M1 ($P^*=0.85$)		a-Si/ μ Si M2 ($P^*=0.86$)		CIGS ($P^*=0.99$)		CdTe ($P^*=0.97$)	
		MBWE	RMSWE	MBWE	RMSWE	MBWE	RMSWE	MBWE	RMSWE
MPP Models	$MPP_{\eta(T)} \gamma$	15.94	7.56	16.06	7.35	5.17	3.53	4.41	4.00
	$MPP_{\eta(T)} \alpha\beta$	16.00	7.62	16.10	7.40	5.99	3.69	4.56	4.02
	$MPP_{\eta(G,T)} (200)$	14.78	7.44	14.55	7.19	4.22	3.29	1.54	3.94
IV Models	$IV_{Sp} (Villalva), E1, S2$	19.35	9.79	20.08	9.84	5.51	5.56	1.35	2.70
	$IV_{Sp} (Villalva), E3, S2$	17.06	9.38	18.11	9.45	6.64	7.08	1.22	3.20
	$IV_{Sp} (Green), E1, S2$	18.88	7.17	18.80	7.24	4.53	6.21	1.67	2.80
	$IV_{Sp} (Green), E3, S2$	18.52	7.06	18.49	7.15	4.62	6.07	1.60	2.80
	$IV_{P, E1-E3} (RSH=\infty), S2$	18.89	7.04	18.90	7.16	4.63	6.58	1.82	2.61

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Annex 1. I-V model related equations

A.1. Extraction parameters

Writing Eq. (3) for I_{SC}^* , V_{OC}^* and (I_M^*, V_M^*) gives, respectively Eqs. (A1)–(A3)

$$I_{SC}^* = I_L^* - I_0^* \left(\exp \frac{I_{SC}^* R_S^*}{V_t^*} - 1 \right) - \frac{I_{SC}^* R_S^*}{R_{SH}^*} \quad (A1)$$

$$0 = I_L^* - I_0^* \left(\exp \frac{V_{OC}^*}{V_t^*} - 1 \right) - \frac{V_{OC}^*}{R_{SH}^*} \quad (A2)$$

$$R_S^* = \frac{1}{I_M^* \left[V_{OC}^* - V_M^* + V_t^* \ln \left(1 - \frac{I_M^*}{I_{SC}^*} \left(1 - \frac{R_S^*}{R_{SH}^*} \right) \right) \right]} \quad (A3)$$

Imposing the derivative of power in the MPP point is zero gives Eq. (A4):

$$\frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \quad (A4)$$

dI/dV is obtained by observing that the mathematical model (Eq. (3)) is of the shape $I = f(I, V)$. Then, dI/dV is given by Eq. (A5)

$$dI = dI \frac{\partial f(I, V)}{\partial I} + dV \frac{\partial f(I, V)}{\partial V} \quad (\text{A5})$$

or Eq. (A6)

$$\frac{dI}{dV} = \frac{\frac{\partial f(I, V)}{\partial V}}{1 - \frac{\partial f(I, V)}{\partial I}} \quad (\text{A6})$$

partial derivatives are given by Eq. (A7)

$$\frac{\partial f(I, V)}{\partial V} = -\frac{I_0}{V_t} \exp \frac{V + IR_S}{V_t} - \frac{1}{R_p} \text{ and } \frac{\partial f(I, V)}{\partial I} = -\frac{I_0 R_S}{V_t} \exp \frac{V + IR_S}{V_t} - \frac{R_S}{R_p} \quad (\text{A7})$$

and writing the condition $(dP/dV)_{\text{MPP}}=0$ for STC gives Eq. (A8)

$$I_M^* + V_M^* \frac{-\frac{I_0^*}{V_t^*} \exp \frac{V_M^* + I_M^* R_S^*}{V_t^*} - \frac{1}{R_p^*}}{1 + \frac{I_0^* R_S^*}{V_t^*} \exp \frac{V_M^* + I_M^* R_S^*}{V_t^*} + \frac{R_S^*}{R_p^*}} = 0 \quad (\text{A8})$$

It is worth noting that the same equation is obtained from recognizing that the slope of the I-V curve at MPP is [26,54] and given by Eq. (A9):

$$\left. \frac{dI}{dV} \right|_{\text{MPP}} = -\frac{I_M}{V_M} \quad (\text{A9})$$

The fifth equation derives from writing Eq. (A2) for G^* and T_C , taking into account the dependence on temperature of I_L , I_0 and R_{SH} , as described in (11), (12), and considering that the open circuit temperature coefficient is defined as Eq. (A10)

$$V_{OC}(T_C) = V_{OC}^* [1 + \beta(T_C - T_C^*)] \quad (\text{A10})$$

Giving Eq. (A11):

$$0 = I_L^* [1 + \alpha(T_C - T_C^*)] - I_0^* \left(\frac{T_C}{T_0^*} \right)^3 \exp \left[\frac{E_g}{k} \left(\frac{1}{T_C^*} - \frac{1}{T_C} \right) \right] \left(\exp \frac{V_{OC}^* [1 + \beta(T_C - T_C^*)]}{V_t^* \frac{T_C}{T_C^*}} - 1 \right) - \frac{V_{OC}^* [1 + \beta(T_C - T_C^*)]}{R_{SH}^*} \quad (\text{A11})$$

The particular temperature value is not critical, since any T_C ranging from 1 to 10 K above or below T_C^* gives the same result.

Finally, it is worth mentioning that another alternative item of information derives from establishing a relationship between m and R_p [30]. This is given by Eq. (A12):

$$V_t^* = \frac{V_M^* + I_M^* R_S^* - V_{OC}^*}{\ln \left[\frac{(I_{SC}^* - I_M^*) \left(1 + \frac{R_S^*}{R_p^*} \right) + \frac{V_{OC}^* - V_M^*}{R_p^*}}{I_{SC}^* \left(1 + \frac{R_S^*}{R_p^*} \right) \frac{V_{OC}^*}{R_p^*}} \right]} \quad (\text{A12})$$

A.2. Analytical equations for solving Eq. (3) for MPP. Eqs. (A13)–(A17) apply

$$D_{M0} = \frac{v_{OC} - 1}{v_{OC} - \ln v_{OC}} \quad D_M = D_{M0} + 2r_S D_{M0}^2 \quad (\text{A13})$$

$$i_s = \frac{1 - g_p(1 - r_s)}{1 - \exp(-v_{oc}(1 - r_s))} \quad (\text{A14})$$

$$i_s' = 1 + i_s \exp[-v_{oc}(1 - r_s)] \quad v_s' = 1 - \frac{1}{v_{oc}} \ln(v_{oc} i_s) \quad (\text{A15})$$

$$i_M' = i_s' - \frac{D_M}{v_{oc}} \quad v_M' = v_s' + \frac{1}{v_{oc}} \ln D_M \quad (\text{A16})$$

$$\frac{I_M}{I_{SC}} = i_M' - g_p(v_M' - r_s) \quad \frac{V_M}{V_{OC}} = v_M' - \frac{I_M}{I_{SC}} r_s \quad (\text{A17})$$

where the normalized conductance is $g_p = 1/r_p$ and v_{OC} , r_S and r_p are given by Eq. (6) written without asterisks. For extension of V_{OC} and I_{SC} at arbitrary conditions the following equations Eqs. (A18) and (A19) are used:

$$V_{OC} = V_{OC}^* [1 - \beta T'] + V_t \ln G' \quad (\text{A18})$$

$$I_{SC} = I_{SC}^* G' [1 + \alpha(T_C - T_C^*)] \quad (\text{A19})$$

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