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On the Nature of the One-Diode Solar Cell Model Parameters

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Abstract: The one-diode model is probably the most common equivalent electrical circuit of a real crystalline solar cell. Extensive research has focused on extracting model parameters from measurements performed in standard test conditions (STC), aiming to replicate the current-voltage characteristics (I-V). This study started from finding that, for the same solar cell, different scientific reports yield significantly different sets of parameters, all allowing for highly accurate replication of the measured I-V characteristics. This observation raises a big question: What is the true physical set of parameters? The present study attempts to address this question. For this purpose, a numerical experiment was conducted. The results show that there is an infinity of distinct sets of parameters that can replicate the I-V characteristics at STC via the one-diode model equation. The diode saturation current I_S and the diode ideality factor compensate each other to preserve the open-circuit voltage V_{OC}, always an input data point. Some possible approaches (e.g., the link between V_{OC} and I_S) that can lead to the physical set of parameters are discussed, highlighting their strengths and weaknesses. There is enough room for future research on finding a universal approach able to guarantee the accurate extraction of the one-diode model physical parameters.

Keywords: solar cell; I-V characteristics; one-diode model; parameter extraction

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1. Introduction

The current-voltage (I-V) characteristic of a photovoltaic (PV) module results from the superposition of the I-V characteristics of its constituent solar cells. The I-V characteristics measured in standard test conditions (STC) (normal incoming solar radiation at 1000 W/m^2 under AM1.5G spectrum [1] and a cell temperature T = 25 °C) is the key element in evaluating the performance of a solar cell, being a proxy for computing the cell efficiency and fill factor. Physically, the I-V characteristics of a solar cell depend in a complex manner on the materials' nature and their electro-optical properties, and it is influenced by the technological parameters [2]. Due to its deeply non-linear character, the mathematical modeling of the solar cells' I-V characteristics, even at STC, is far from a trivial task.

For the crystalline solar cells, almost all mathematical models of the I-V characteristics are rooted in the Shockley theory of the illuminated ideal p-n junction (see, e.g., [3]). The one-diode model (Figure 1) is probably the most common equivalent electrical circuit of a real solar cell. The photocurrent I_L is generated by a current source, primarily depending on the solar irradiance level. The diode D, characterized by the saturation current I_S and the diode ideality factor m, models the dark current flowing in the cell. The shunt resistance R_P can arise from the device imperfections as well as from the leakage currents across the edge of the cell. R_P represents a parallel high-conductivity path through the p–n junction and contributes to a decrease in overall cell efficiency. The effective voltage on the parallel group elements is larger than at terminals, being equal to $V + IR_S$. The series resistance R_S encapsulates the ohmic losses in the cell. It is noteworthy that with the development of emerging technology for solar cells [4], new versions of the equivalent circuit are proposed. A good illustration is the double-junction model of the planar p-i-n heterojunction perovskite solar cells [5].

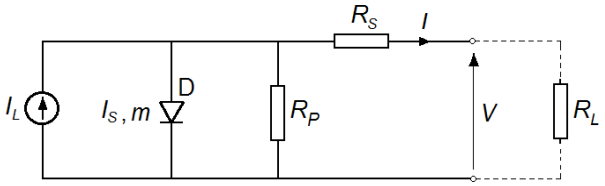


Figure 1. One-diode equivalent circuit of a solar cell.

Based on the one-diode equivalent circuit from Figure 1, the equation of I-V characteristics can be written at different levels of approximation. Probably, the most popular equation for the I-V characteristics of a solar cell is the five-parameter model:

$$I = I_L - I_S\left[\exp\left(\frac{q(V+IR_S)}{mk_BT}\right) - 1\right] - \frac{V+IR_S}{R_P} \quad (1)$$

where q is the electron charge, k_B is the Boltzmann constant, and T is the cell temperature. I_L, I_S, m, R_S, and R_p form a set of five parameters (specific for a cell), which give the name of the model. The five parameters are typically estimated based on the measured I-V characteristic at STC or, even more challenging, based only on the information included in the solar cell datasheet. In practice, further modeling is necessary since the PV modules do not normally operate at STC. The common approach is based on expanding Equation (1) in terms solar irradiance and ambient temperature [6]. A huge effort was paid over time to link the one-diode model parameters to solar irradiance and ambient temperature. For example, Ref. [7] proposed an algorithm based on the I-V characteristics acquired in real operating conditions and the common information from the PV module datasheet.

This paper is focused only on the I-V characteristics of solar cells at STC. There is an overabundance of research reporting on the extraction of the five parameters from Equation (1) at STC. However, currently, a universally accepted approach for extracting the one-diode model parameters still does not exist. During the last few decades, a large diversity of approaches has been proposed, ranging from classic (such as Newton–Raphson [8] or iterative procedures [9]) to exotic artificial intelligence-based techniques (such as the imperialist competitive algorithm [10] or the flower pollination algorithm [11]). For a broad picture of modeling the I-V characteristics of a solar cell, we point the reader to paper [12], where more than 100 methods for extracting the parameters of the solar cell models are classified and reviewed. The strengths and weaknesses of each class are emphasized from various perspectives.

Our experience in dealing with the extraction of the one-diode model parameters led us to the following empirical observation: For a given solar cell, there are many different sets of parameters (I_L, I_S, m, R_S, R_p), which, substituted in Equation (1), accurately replicate the measured I-V characteristics at STC [13]. This study addresses three different facets of this observation, trying to answer the following questions: (1) How many distinct sets of parameters can replicate the I-V characteristics of a given solar cell? Irrespective of its nature, an algorithm for extracting the one-diode model parameters basically deals with highly non-linear equations derived from Equation (1). Apparently, there are many local minima that trap the algorithm and prevent it from finding a global solution. (2) The variation of a parameter must be compensated by changes in the magnitude of the other four. To focus the algorithm on a particular solution, it is critical to understand how the compensation is distributed between the parameters when the solution passes from one local minimum to another. (3) Can criteria be developed so that an algorithm always leads to a physical solution? A physical solution means the set of parameters that result from the measurements. To our best knowledge, this is the first study that approaches from a unitary perspective the problem of multiple solutions for one-diode model parameters of a solar cell.

The rest of the paper is organized as follows. Section 2 presents facts and figures about the extracted one-diode model parameters in the case of three commercial PV modules, based on data reported by scientific publications. The results of a numerical experiment

that address the first two questions above are discussed in the first part of Section 3. The second part is focused on finding solutions to direct an algorithm toward the physical parameters. The main conclusions are gathered in Section 4. The statistical indicators of accuracy used in this study are briefly presented in Appendix A.

2. Facts and Figures

As we already mentioned in the introduction, we were surprised to find that for the same PV module, different authors reported different sets of one-diode model parameters. Table 1 illustrates this observation for three commercial PV modules. For each PV module, a collection of parameter sets (I_L, I_S, m, R_S, R_p), as they were reported by the cited studies, is displayed. These parameters were extracted by very different methods, which are briefly summarized next.

Ref. [10] proposed an approach based on the imperialist competitive algorithm (ICA). This is an evolutionary algorithm that can be thought of as the social counterpart of genetic algorithms (GA). ICA is routed in human social evolution, whereas GA is routed in the biological evolution of species. A meta-heuristic algorithm inspired by the flower pollination process of flowering plants, namely, the flower pollination algorithm (FPA), was proposed by [11]. The authors claimed that FPA is one of the most efficient algorithms to extract the parameters of the one-diode model. Alternatively, a multi-verse optimizer (MVO) algorithm was proposed in [14]. MVO is one of the recent meta-heuristic optimization algorithms, inspired by the multi-verse theory in physics [15]. Ref. [16] reported results on parameter extraction at STC using two very different approaches: an iterative method based on the Newton–Raphson algorithm and an analytical method (LW) based on the Lambert W function. The parameters in Table 1 were extracted with the LW method. Ref. [17] proposed an iterative approach (ITA) for extracting the one-diode model parameters from data provided by manufacturer's datasheets. The method avoids solving implicit equations, which allows a decrease in the algorithm complexity. The wind-driven optimization (WDO) technique was proposed in [18] as a method for accurately extracting the parameters with a smaller number of iterations. Six methods for extracting the one-diode model parameters were reviewed in [19]. The values of the parameters estimated with an iterative method (IT) and a piecewise linear curve-fitting (PLF) technique are inserted in Table 1. The approach proposed in [20], based on the LW function, can extract the five parameters from experimental data or the information available in the cell datasheet. Ref. [21] proposed a procedure based on FPA incorporated with the Neldel–Mead simplex method and the general opposition-based learning mechanism.

A visual inspection of Table 1 shows notable differences between the sets of parameters estimated by different works for a given PV module. We took these parameters and inserted them in Equation (1), thus replicating the I-V characteristics of PV modules at STC. The results reported in the referenced works were confirmed, every set being able to reproduce with reasonable accuracy the measured I-V characteristics (e.g., for M1 the determination coefficient fell in the range $0.943 \leq R^2 \leq 0.991$). The overlap of the two curves, measured and estimated, is not always perfect. The cause is probably our measured I-V characteristics. It was obtained by digitalization of the measured I-V characteristics graphically presented in the manufactures' datasheet. The measured I-V characteristics used in the referenced works may slightly fluctuate around the generic I-V characteristic from datasheet.

Table 1. The one-diode model parameters and the replication performance of the experimental I-V characteristics, reported by different studies for three commercial PV modules at STC.

PV Module	Reference	Method	Parameters					R^2	*nRMSE*
			I_L (A)	I_S (A)	m	R_S (Ω)	R_P (Ω)		
M1 [1]	[10]	ICA	8.21	$1.09 \cdot 10^{-7}$	1.30	0.0039	3.48	0.947	0.108
	[11]	FPA	8.21	$2.07 \cdot 10^{-9}$	1.07	0.0064	13.84	0.939	0.115
	[14]	MVO	8.25	$6.39 \cdot 10^{-8}$	1.28	0.0024	2.49	0.991	0.044
	[16]	LW	8.21	$2.19 \cdot 10^{-9}$	1.07	0.0052	2.92	0.943	0.112
	[17]	ITA	8.21	$9.83 \cdot 10^{-8}$	1.30	0.0042	10.98	0.980	0.066
	[18]	WDO	8.18	$4.42 \cdot 10^{-7}$	1.41	0.0020	13.84	0.980	0.066
	[19]	IT	8.21	$9.89 \cdot 10^{-8}$	1.30	0.0040	10.59	0.982	0.063
	[19]	PWL	8.24	$1.14 \cdot 10^{-15}$	0.65	0.0074	1.52	0.972	0.079
M2 [2]	[14]	MVO	0.76	$3.20 \cdot 10^{-7}$	1.52	0.0365	59.58	0.975	0.052
	[10]	ICA	0.76	$1.46 \cdot 10^{-7}$	1.44	0.0389	41.15	0.980	0.046
	[20]	LW	0.76	$2.09 \cdot 10^{-7}$	1.43	0.0403	61.30	0.936	0.083
	[11]	FPA	0.76	$3.10 \cdot 10^{-7}$	1.47	0.0365	52.87	0.945	0.077
	[18]	WDO	0.76	$3.22 \cdot 10^{-7}$	1.48	0.0367	57.75	0.967	0.060
	[21]	FPA	0.76	$3.23 \cdot 10^{-7}$	1.48	0.0363	53.72	0.966	0.060
M3 [3]	[11]	FPA	3.45	$1.35 \cdot 10^{-7}$	1.37	0.0094	12.53	0.999	0.013
	[21]	FPA	3.40	$1.22 \cdot 10^{-9}$	1.08	0.0124	12.66	0.993	0.028

[1] Kyocera KC200GT, https://www.energymatters.com.au/images/kyocera/KC200GT.pdf (accessed on 22 May 2021), [2] RTC France [22], [3] Shell SM55, https://atlantasolar.com/pdf/Shell/ShellSM55_USv1.pdf (accessed on 22 May 2021).

Looking back at the differences among the parameters listed in Table 1, even a reasonable superposition of both the measured and all the estimated I-V characteristics seems rather weird. For example, in the case of M1, the values identified for the saturation current fell in a range covering several orders of magnitude, 10^{-15} A$< I_S < 10^{-7}$ A, whereas the determination coefficient fell in the range of $0.943 \leq R^2 \leq 0.991$. It is well known that the saturation current I_s of a solar cell can be measured in the dark [23]. There is no guarantee that any method from Table 1 leads to the measured value of I_S. As well, the ideality factor m takes values within a large domain, with a minimum of m = 0.88 (an unphysical value) and a maximum of m = 1.41.

At first glance, one might think that the differences between the different sets of parameters in Table 1 could be caused by the inherent differences between PV module specimens with which the studies were conducted. Indeed, the PV modules of the same type are never perfectly identical. However, the differences between specimens were very small and cannot explain such large differences between the extracted parameters. As shown in Section 3.1, a set of parameters is mostly the consequence of the assumptions made in the development of numerical calculations.

To conclude, the data from Table 1 emphasize that there are many sets of parameters (I_L, I_S, m, R_S, R_p) that, replaced in Equation (1), accurately yield the measured I-V characteristics of the solar cell. This observation raises a big question: Which is the true physical set of parameters? Or, in other words, how can we be sure that we extract exactly the set of parameters that would result from experimental measurements?

3. Results and Discussions

3.1. A Numerical Experiment

In order to confirm and explain the above observations, we conducted a numerical experiment. The aim of experiment was to replicate the measured I-V characteristics of M1 and M2. In brief, we set the diode saturation current I_S at different constant values. For each value I_S, using the successive discretization algorithm (SDA) [24], we extracted the other four parameters $(I_L,\ m,\ R_S,\ R_P)$. The results are summarized in Table 2. Before analyzing these results, a short introduction to SDA is helpful.

Table 2. The one-diode model parameters and the replication performance of the experimental I-V characteristics. I_S was set a priori whereas $(I_L,\ m,\ R_S,\ R_P)$ were estimated with SDA.

PV Module	I_S (A)	I_L (A)	m	R_S (Ω)	R_P (Ω)	R^2	*nRMSE*
M1	10^{-7}	8.2063	1.311	$3.2{\cdot}10^{-3}$	2.54	0.9995	0.011
	10^{-8}	8.2073	1.166	$4.6{\cdot}10^{-3}$	5.04	0.9992	0.013
	10^{-9}	8.2063	1.048	$4.6{\cdot}10^{-3}$	1.90	0.9998	$6.8{\cdot}10^{-3}$
	10^{-10}	8.2064	0.952	$5.3{\cdot}10^{-3}$	2.52	0.9998	$6.9{\cdot}10^{-3}$
	10^{-11}	8.2093	0.873	$5.8{\cdot}10^{-3}$	2.26	0.9996	$9.3{\cdot}10^{-3}$
	10^{-12}	8.2093	0.806	$6.2{\cdot}10^{-3}$	1.80	0.9995	0.011
M2	10^{-7}	0.7592	1.401	0.051	18.5	0.9991	$7{\cdot}10^{-3}$
	10^{-8}	0.7570	1.225	0.062	16.2	0.9980	$8.4{\cdot}10^{-3}$
	10^{-9}	0.7592	1.100	0.094	32.0	0.9973	0.017
	10^{-10}	0.7593	0.980	0.085	20.5	0.9983	0.014

The successive discretization algorithm (SDA) was developed to extract the parameters of the one-diode model [24]. In principle, SDA is an optimization algorithm whose aim is to minimize the sum of squared errors (SSE) of the differences between the estimated $I(V_i)$ (Equation (1)) and measured $I_m(V_i)$ currents:

$$SSE(I_L,\ I_S,\ m,\ R_S,\ R_P) = \sum_{i=1}^{N}[I(V_i) - I_m(V_i)]^2 \quad (2)$$

The subscript i counts the measured points $[V_i\ ,\ I_m(V_i)]$ on the I-V characteristics. The optimization process starts with the calculation of SSE for various sets of parameters $(I_L,\ I_S,\ m,\ R_S,\ R_P)$, obtained by a systematic discrete variation of each parameter in its appropriate domain of values. The set of the parameters, for which SSE reaches the minimum, is picked. Further, the procedure is repeated, at each step the parameters being changed more finely in a smaller domain around the values piked at the previous step. The procedure stops when the desired accuracy is reached. A detailed description of SDA can be read in [24].

Our numerical experiment was conducted as follows. Firstly, the diode saturation current was set at the value $I_S = 10^{-7}$ A. Then SDA was applied to extract the other four parameters $(I_L,\ m,\ R_S,\ R_P)$. The criterion for stopping SDA was an accurate overlapping of the estimated and measured I-V characteristics, i.e., $R^2 > 0.99$. At the next step, the diode saturation current was set at the value $I_S = 10^{-8}$ A and SDA was applied again, providing another set of parameters $(I_L,\ m,\ R_S,\ R_P)$, and so on. The results collected in Table 2 are stunning. In the case of the PV module M1, the diode saturation current covered six orders of magnitude, from $I_S = 10^{-7}$ A to $I_S = 10^{-12}$ A. For each value, *SDA* was able to find a specific set of the other four parameters $(I_L,\ m,\ R_S,\ R_P)$, which led to $R^2 > 0.999$. Similar behavior was experienced by M2. The almost perfect overlapping of the estimated and measured I-V characteristics is presented graphically in Figure 2. The values $m < 1$ can be computationally rejected. We allowed m to take sub-unitary values, aiming to stress that even non-physical sets of parameters in Equation (1) are able to accurately replicate the I-V characteristics.

The analysis of Table 2 led to two remarkable outcomes: (1) There is an infinity of I_S values that can be set between any two discrete values from Table 2. For each of them, SDA will certainly find a set $(I_L,\ m,\ R_S,\ R_P)$, such that Equation (1) accurately replicates the measured I-V characteristics. This answers the first question: Theoretically there is an infinity of distinct sets of parameters $(I_L,\ I_S,\ m,\ R_S,\ R_P)$ that may replicate the I-V characteristics of a given solar cell via the one-diode model equation (Equation (1)). (2) *Is* and m are systematically positively correlated, thus compensating each other to preserve the dark current. This partially answers the second question. More insight on this topic follows.

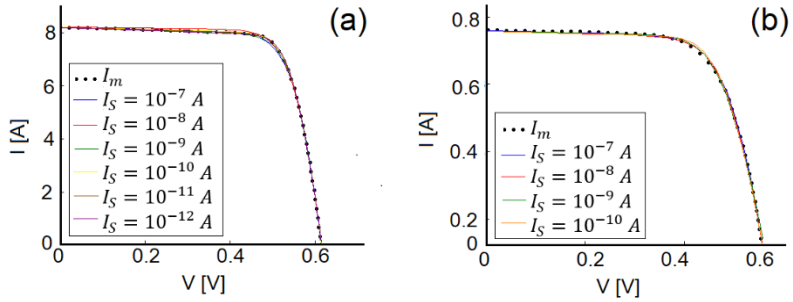


Figure 2. The I-V characteristics of two commercial PV modules: (**a**) M1 and (**b**) M2 estimated with SDA for different values of the diode saturation current I_S (values set a priori) superimposed on the measured I-V characteristics.

Figure 3 shows the relative effect of the parameters on the I-V characteristics of M1. In order to build the figure, the following set of parameters was assumed as reference: I_L = 8.2063 A, $I_S = 10^{-9}$ A, m = 1.048, $R_S = 4.6{\cdot}10^{-3}$ Ω, and R_P = 1.9 Ω. The subsequent I-V characteristics (Equation (1)) were plotted in all four graphs (Figure 3a–d), also as a reference. In each graph, all other curves were plotted, replacing the parameters in Equation (1) with the assumed reference values except one, which was set in turn to the values from Table 2. For example, in Figure 3a the curve parameter is the diode saturation current I_S. Each I-V characteristic was plotted, replacing in Equation (1) the reference parameters excepting I_S, which was set in turn to the values from Table 2. Since the photocurrent I_L was almost constant, it is not displayed in Figure 3.

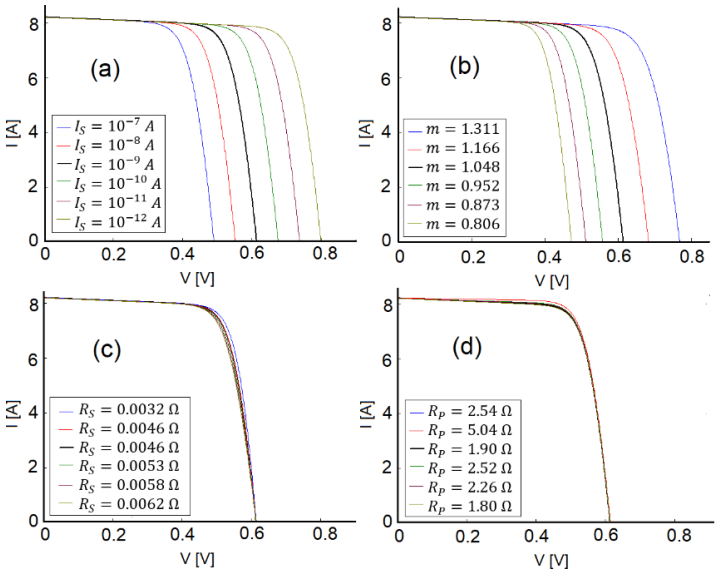


Figure 3. Graphical representation of the I-V characteristics (Equation (1)) of the PV module M1. In each graph, the reference curve (in black) was plotted for the parameters set (I_L = 8.2063 A, $I_S = 10^{-9}$ A, m = 1.048, $R_S = 4.6{\cdot}10^{-3}$ Ω, R_P = 1.9 Ω). The other curves were plotted keeping four parameters at the reference value and varying the fifth one: (**a**) I_S, (**b**) m, (**c**) R_S, and (**d**) R_P.

Figure 3 displays a common picture of the parameters' influence on the I-V characteristics of a solar cell. However, if we keep in mind the peculiarities in building Figure 3, it reveals some relevant features of our numerical experiment. The variation of I_S in the range of $\left[10^{-12}\text{ A},\ 10^{-7}\text{ A}\right]$ changed the I-V characteristics dramatically (Figure 3a). The increase in I_S determined a decrease in the estimated open-circuit voltage. The diode ideality factor m acted exactly in the opposite way (Figure 3b). The serial resistance R_S and the shunt resistance R_P were not meant to change the open-circuit voltage (Figure 3c,d). Overall, the picture in Figure 3 answers the second question: When an algorithm to extract the one-

diode model parameters tends to increase the diode saturation current, the decrease in the open-circuit voltage is compensated by an increase in the diode ideality factor. Taking into account that the open-circuit voltage is always a known input parameter, compensation is a compulsory internal action of any numerical algorithm.

The relationship between I_S and m can be evaluated on the basis of Equation (1). For a given solution $(I_L,\ I_S,\ m,\ R_S,\ R_P)$, Equation (1) models the entire I-V characteristic of the solar cell, including the boundary points: the short-circuit current I_{SC} and the open-circuit voltage V_{OC}. Writing Equation (1) at an open-circuit ($V = V_{OC}$, $I = 0$), under two reasonable approximations $I_{SC} \cong I_L \gg I_S$ and $I_{SC} \gg V_{OC}/R_P$, simple calculations lead to the equation:

$$m \cong \frac{qV_{OC}}{k_B T} \frac{1}{\ln I_{SC} - \ln I_S} \tag{3}$$

Figure 4 displays the relationship between I_S and m given by Equation (3). For a value of the diode saturation current, Equation (3) gives a reasonable approximation of the diode ideality factor, so Equation (1) accurately replicates the I-V characteristics.

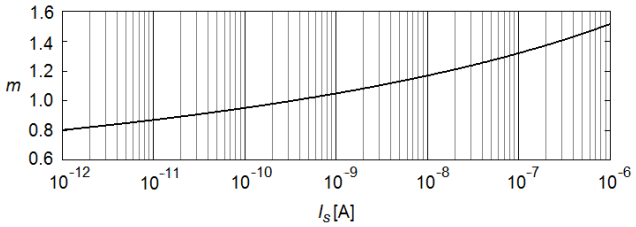


Figure 4. The relationship between the diode ideality factor m and the diode saturation current I_S, approximated by Equation (3). A generic value for the open-circuit voltage, $V = 0.6$ V, has been considered.

3.2. Outlook on Possible Solutions

The simplest and most robust way to avoid non-physical values of the extracted one-diode model parameters is to combine the numerical approach with the measurement of one of the two parameters, the diode saturation current I_S or the diode ideality factor m. Both parameters can be measured in dark conditions with common instruments and without any special or expensive experimental setup. The current I_S can be measured straightforwardly with relatively large reverse bias. Bearing in mind the results of our numerical experiment, if I_S experimentally fixed, there will never be a trade-off between I_S and m: An algorithm to extract the one-diode model parameters will point directly to the value of m for which the I-V characteristics cross the voltage axis at the measured open-circuit voltage. Another beneficial facet is the decrease in complexity of the algorithm; it has to search for only four parameters.

Another possible solution can be developed by taking into account the link between the common electrical specification of a PV module at STC, the short-circuit current I_{SC} and the open-circuit voltage V_{OC}, on one side, and the one-diode model parameters, the diode saturation current I_S and the diode ideality factor m, on the other side. The approach is assessed in detail in [25]. In principle, at $V = V_{OC}$, and considering the above approximations $I_{SC} \cong I_L + I_S$ and $I_{SC} \gg V_{OC}/R_P$, Equation (3) can be rewritten as:

$$V_{OC} \cong \frac{mk_B T}{q} \ln(I_{SC}) - \frac{mk_B T}{q} \ln(I_S) \tag{4}$$

Equation (4) relates V_{OC} to $\ln(I_{SC})$ linearly with the slope $\frac{mk_B T}{q}$, from which m can be retrieved. This procedure also involves a trivial set of measurements of V_{OC} and I_{SC} at different levels of irradiation. However, most PV module datasheets include a graphical presentation of the I-V characteristics at different levels of irradiance, which make the procedure easy to implement.

Finally, some remarks regarding the two diode-model [26] are useful. In addition to the one-diode model, the two-diode model includes a second parallel connected diode that models the generation–recombination process in the space charge region of the p-n junction. The two-diode model is more complex, but also more accurate in modeling the solar cell I-V characteristics. There are many studies dealing with the extraction of two-diode model parameters. Some of these studies consider the diode ideality factors as free parameters, thus facing the same problem as the one-diode model. For example, the studies [10,18,27–29] reported very different sets of parameters for the PV module Kyocera KC200GT operating at STC (e.g., the diode ideality factor fell in the range of 1.0 [28] and 2.98 [27]), all replicating the I-V characteristics with accuracy. However, it is worth noting that the two-diode model may avoid any trade-off between the diode saturation current and the diode ideality factor. In this case, the diode ideality factors can be defined a priori: 1.0 and 2.0 for the diffusion and generation–recombination dark currents, respectively. In this case further investigations are required in order to understand the way in which a numerical algorithm for extraction of the model's parameters deals with the balance between the two dark currents.

4. Conclusions

There are plenty of approaches to extract the parameters of the one-diode model from measurements performed at STC. A scientific literature survey emphasizes that for a specific PV module, a large variety of the parameters is reported. Our short review on this topic shows that for Kyocera KC200GT, the reported values of the diode saturation current I_S differ by several orders of magnitude, from 10^{-15} A to 10^{-7} A. What is really strange is that all values are, in a sense, correct: Generally, irrespective of I_S, the reported sets of parameters are able to replicate the measured I-V characteristics of KC200GT. This result shows that, even if an approach can replicate the I-V characteristics of a solar cell, this does not guarantee the accurate identification of the physical set of parameters. Moreover, the numerical experiment conducted in this study demonstrates the existence of an infinity of distinct sets of parameters that can replicate the I-V characteristics at STC via the one-diode model equation. This is due to the compensation between the diode saturation current and the diode ideality factor to preserve the open-circuit voltage, always an input data point. Some possible solutions were enounced and discussed: (1) Combining the straightforward measurement of I_S with a numerical procedure for extracting the other four parameters, (2) using the link between the common electrical specification of a PV module at STC (short-circuit current and open-circuit voltage) and the one-diode model parameters (the diode saturation current and the diode ideality factor), and (3) replacing the one-diode model with the two-diode model, where the diode ideality factors are defined a priori.

The aim of this study was to draw attention to a red flag regarding the one-diode model parameters reported in the scientific literature. For solar engineering applications, a procedure for extracting the one-diode model parameters is chosen on the basis of two main criteria: accuracy and computational accessibility. As long as a set of parameters accurately replicates the I-V characteristics via Equation (1), it is enough for many applications. However, some parameters from this set may be far from their values resulting from measurements. In order to develop numerical procedures to accurately extract the physical parameters of the one-diode model, further research efforts are necessary.

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Appendix A

This appendix defines the two statistical measures used for evaluating the fit quality of estimated vs. measured I-V characteristics.

(1) The normalized root mean square error *nRMSE* is a very-often-used measure of the differences between the values estimated by a model and the measured values:

$$nRMSE = \frac{\sqrt{N\sum_{i=1}^{N}(e_i - m_i)^2}}{\sum_{i=1}^{N} m_i} \quad \text{(A1)}$$

where e and m denote the estimated and measured quantity, respectively, and *nRMSE* is an indicator suitable for comparing datasets of different scales.

(2) The coefficient of determination R^2 measures the percentage of variability within the estimated values that can be explained by a regression model:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(e_i - m_i)^2}{\sum_{i=1}^{N}(e_i - \overline{m})^2} \quad \text{(A2)}$$

where $\overline{m}$ denotes the arithmetic mean.

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