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MODESTUM

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Influence of the ideality factor on the series resistance for some analytical methods of parameters extraction of PV panels

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ABSTRACT

This paper revisits classical problem of PV cell parameters extraction based only on three points of their characteristics. Given the dispersion and discrepancy of the results provided by the various extraction methods, the goal is to examine and compare some analytical methods for reconstruction of I-V curves while stressing in particular on the influence of the ideality factor on the series resistance. These methods are tested on two commercial types of PV panels: monocrystalline and polycrystalline ones. Among some results, the performed analysis has shown the profile of the series resistance with respect to the ideality factor as well as their influence on I-V characteristics. In addition, a contribution proposes an explicit expression that links the series resistance to the ideality factor derived from Cubas' formula upon an approximation of Lambert W-function.

Keywords: parameters extraction, series resistance, diode ideal factor, one-diode model, I-V characteristics, photovoltaic panel

INTRODUCTION

To promote the intended energetic shift from hydrocarbon-based energies into renewable energies, an intense effort is continuously and increasingly supported since about these last 50 years. One main goal is to generalize and extend the use of PV systems by optimizing their performances and reducing their relative high cost to make them competitive with other source of energy and thus let them becoming affordable for popular use. In this context, many avenues of research are explored both scientifically and technologically (Dambhare et al., 2021; Pastuszak & Węgierek, 2022). Among all these efforts, identifying intrinsic parameters and estimating the influence of external factors on PV cells such as the illumination and the temperature are of great importance. In particular, finding easy and accurate methods for identifying PV cell parameters is a necessary condition for modeling, simulating, and optimizing the efficiency of such systems.

To this end, several methods have been proposed to identifying PV cell parameters based on some data measurements supplied by their manufacturers. According to the literature, among the developed PV cell models, the one-diode-two-resistance model (1D-2R) is the most popular one that offers a good compromise between simplicity and accuracy (Rezaee Jordehi, 2016; Sabadus & Paulescu, 2021; Villalva et al., 2009). Nevertheless, this model contains five parameters that need to be extracted, which are namely the photocurrent, the saturation current, the series resistance, the shunt resistance and the diode ideality factor. Usually, all PV array data sheets provide information concerning three remarkable points that belong to I-V curves: the short-circuit point, the open-circuit point, and the maximum power point. This information is always provided with reference to nominal conditions or standard test conditions of temperature and solar irradiation.

Therefore, based on only this three points, many methods are developed to addressing the issue of extracting the five parameters of ID-2R model. But some difficulties raise because of the following reasons. Firstly, the equation of this model is transcendental; secondly, the established set of equations related to the provided data are nonlinear and are initially fewer than the parameters to extract. Thus, to overcome these difficulties, several numerical (Elhammoudy et al., 2023), analytical (Batzelis, 2019; Taouni et al., 2015), optimization (Elkholy & Abou El-Ela, 2019), meta-heuristic (Oliva et al., 2019), and hybrid (Gupta et al., 2023) approaches and methods are proposed. However, the comparative examination of the literature reveals a dispersion and a discrepancy concerning the obtained results outputted by the different used methods (Bashahu & Nkundabakura, 2007; Cotfas et al., 2021; Ndegwa et al., 2020; Yerima et al., 2022).

Regarding this multiplication of approaches, some authors have compared various ones aiming to find out the best method that outputs the more accurate parameters values

(Appelbaum & Peled, 2014; Rawat & Thakur, 2019). To quantify the accuracy of the compared models, criteria such as the mean absolute difference and the maximum difference for current and power are used (Cubas et al., 2013; Orioli & Di Gang, 2016). Ultimately, up to date, there is no definite conclusions supporting the superiority of one specific method over the others in the general case when using a limited set of experimental data such as the use of only the three points given by the manufacturers (Ibrahim & Anani, 2017).

Nevertheless, the non-analytical methods even in cases they are claimed to be more accurate, they do not by nature allow an explicit examination of the influence of data on the extracted parameters. In addition, they do not allow an explicit examination of the interdependency between the parameters to be extracted. In the contrary, analytical methods, although they use approximations, they remain more suitable for enabling examination of the influence of the data on the parameters to be extracted and on their interdependency (Ibrahim & Anani; 2017; Ndegwa et al., 2020). In this direction, it is worthy to note that Lambert W-function has attracted much attention as it enables to express the transcendental I-V equation in an explicit analytical form, as shown by Jain and Kapoor (2005). Consequently, it has leaded to a family of interesting methods of parameters extraction (Batzelis et al., 2019; Sharma et al., 2014). On the other hand, the dispersion and the discrepancy of the results persists also among analytical methods even when they are exclusively based on the three points and excluding, for instance, those involving the short-circuit and open-circuit slopes as input data and, those including any iterative process.

If one considers 1D-2R model from the parameters extraction viewpoint, one notices some typically adopted assumptions. The reverse diode current I_0 is usually considered as very small and negligible compared to the saturation current I_{sc}. The photocurrent I_{ph} is usually considered as approximately comparable to the short-circuit current Isc. The series resistance R_s is usually considered as negligible compared to the shunt resistance R_{sh}. Finally, the ideality factor M is considered by many authors to belong to the interval [1; 2] for silicon diodes (Bashahu & Nkundabakura, 2007; Faulkner & Buckingham, 1968; Sah et al., 1957) while others consider it as an independent parameter that has to be adjusted in a limited interval of [1; 1.5] (Tossa et al., 2014; Villalva et al., 2009). Because of these assumptions and some simplifications, the number of parameters to be extracted can be of three, four or five depending on the used analytical method (Batzelis et al., 2019).

Concerning the extracted parameters issued from the numerous analytical methods, our review of literature has shown that they are generally expressed with respect to the data related to the three via points when they are decoupled but for some methods they are also related to one or more other parameters (Ibrahim & Anani; 2017; Ndegwa et al., 2020). It has also shown that there are many theoretical and some experimental studies dedicated to analyzing the influence of the extracted parameters on different quantities such as the current, voltage, temperature, illumination and to some data related to the three points (Bashahu & Nkundabakura, 2007; Dandoussou et al., 2015; El Tayyan, 2015; Singh & Ravindra, 2011; Venkateswari & Rajasekar, 2021). On the other hand, very few experimental studies can be found that highlight the interdependency between parameters such as the series resistance and the ideality factor (Park et al., 2018; Rana et al., 2018). This lack justifies our interest to carry out this study.

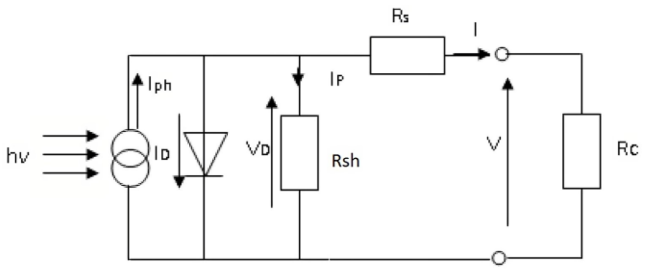

Figure 1. Equivalent electric 1D-2R model of a photovoltaic cell (Source: Author's own elaboration)

In this paper, we revisit the question of parameters extraction by an examination of some selected analytic methods, which provide explicit analytical expressions of the parameters by using exclusively the three given via points. A special attention is devoted to analyzing the relationship between the ideality factor and the series resistance for each invoked methods (Aldwane, 2014; Batzelis et al., 2019; Cubas et al., 2014; Ibrahim & Anani, 2017; Kumar et al., 2023; Sera et al., 2007; Zaatri & Belhour, 2009). These methods are tested, compared, and simulated for reconstituting I-V characteristics of two types of PV panels: monocrystalline and polycrystalline silicon cells. The influence of the series resistance and the ideality factor and their interdependence is simulated and visualized on the plots of the characteristics of PV panels. Moreover, an approximate expression linking the series resistance to the ideality factor derived from the expression that involves the Lambert W-function in Cuba's method is proposed (Cubas et al., 2014).

MODELLING PV CELLS

Figure 1 presents equivalent electrical circuit of photovoltaic solar cell model (1D-2R) under illumination by photons of energy *hv* (Sabadus & Paulescu, 2021). This model includes a current generator I_{ph} delivering a photocurrent generated by light into cell. It also includes a diode, representing silicon junction. This junction induces a potential barrier, which absorbs a current I_o called reverse saturation current. A parallel resistance R_{sh} and a series resistance R_s represent ohmic losses in cell. Current I is delivered by solar cell to supply a load R_c under voltage V.

Equation of PV Cell Characteristics

By applying the Kirchhoff and Shockley's laws to the equivalent electrical circuit of the photovoltaic cell 1D-2R (**Figure 1**), one obtains the equation of I-V characteristics:

$$I = I_{ph} - I_o\left(\exp\left[\frac{V+R_sI}{MV_{th}}\right] - 1\right) - \frac{V+R_sI}{R_{sh}}. \quad (1)$$

Here, V_{th} is the "thermal voltage" of a cell, which is given by: $V_{th}= kT/q$; k is Boltzmann constant (1.38×10^{-23} JK^{-1}); T is the absolute temperature (K); q is the electron charge (1.61×0^{-19} C) and M is the ideality factor of a cell (unitless).

For 1D-1R model, the shunt resistance is considered as infinite and thus is removed from **Figure 1**. Its corresponding equation derived from Eq. (1) can be expressed in an I(V) form, as follows:

$$I(V) = I_{ph} - I_0\left(\exp\left[\frac{V+R_sI}{MV_{th}}\right] - 1\right). \quad (2)$$

Inversely, it can also be expressed in an explicit V(I) form, as follows:

$$V(I) = -R_sI + mV_{th}ln\left(1 + \frac{I_{ph}-I}{I_o}\right). \quad (3)$$

If one consider a panel, then *n* represents the number of cells.

Eq. (1) is a transcendental equation that corresponds to I-V curve of characteristics of 1D-2R model. To exploit this equation, it is necessary to determine the five parameters involved in which are (M, Rs, Rsh, Io, and Isc).

Analytical I-V Expressions Using Lambert W-Function

The transcendental nature of Eq. (1) makes it difficult to extract the cell parameters from 1D-2R model. However, by using Lambert W-function, it is possible to convert Eq. (1) into explicit analytical expressions in the form of I(V) or V(I), where the arguments of W-function contains only the corresponding variable and the model's parameters (Jain & Kapoor, 2004; Jain et al., 2006). An exact explicit form for V(I) is, as follows:

$$V(I) = -I(R_s + R_{sh}) + (I_{ph} + I_o)R_{sh} - MV_{th}W_o(X) \ldots, \quad (4)$$

with $X = \left\{\frac{I_oR_{sh}}{MV_{th}} exp\left[\frac{R_{sh}}{MV_{th}}(I_{ph} + I_o - I)\right]\right\}$.

It can also be written in the form of *I(V)*, as follows:

$$I(V) = -\frac{V}{R_s+R_{sh}} + (I_{ph} + I_o)\frac{R_{sh}}{R_s+R_{sh}} - \frac{MV_{th}}{R_s}W_o(Y), \quad (5)$$

with $Y = \left\{\frac{R_sR_{sh}I_o}{MV_{th}(R_s+R_{sh})} exp\left[\frac{R_{sh}(R_sI_{ph}+R_sI_o)+V}{MV_{th}(R_s+R_{sh})}\right]\right\}$.

For 1D-1R model, Eq. (2) of I(V) can be also expressed in an explicit analytic form by using the Lambert W-function. It can be written as shown in Zaatri and Belhour (2009):

$$I(V) = I_{sc} - I_o\left(exp\left[\frac{V+R_sI}{MV_{th}}\right] - 1\right) = (I_o + I_s) - \frac{V_{th}}{R_s}W_0\left(Ae^{\frac{V}{V_{th}}}\right), \quad (6)$$

with $A = \frac{R_sI_o}{V_{th}} exp\left(\frac{R_s}{MV_{th}}(I_o + I_{sc})\right)$.

In this paper, we will consider two methods (method 1 and method 2) using 1D-1R model (Ibrahim & Anani, 2017; Sera et al., 2007; Wang et al., 2011; Zaatri & Belhour, 2009) and two methods (method 3 and method 4) using 1D-2R model (Cubas et al., 2014; Kumar et al., 2013).

DETERMINATION OF PARAMETERS BASED ON 1D-1R MODEL

The methods used for determining the parameters (M, I_{ph}, I_o, R_s, and R_{sh}) exploit the experimental data provided by the manufacturers, which correspond to the three remarkable points (I_{sc}, V_{co}, and P_m).

Method 1: Simple Method for Extracting Three Parameters

We will start by using the simplest method that estimates only three parameters, which are (I_{ph}, I_o, and R_s) of PV panels. This method uses 1D-1R model while considering Rsh as infinite and assigning a constant value to ideality factor *M*. According to the literature, the value of *M* varies for silicon junctions in the interval [1; 1.5] (Villalva et al., 2009). This method is described by Eq. (2) and Eq. (3) (Aldwane, 2014; Wang et al., 2011; Zaatri & Belhour, 2009). It requires only the three equations corresponding to the three given points.

Determination of photonic current I_{ph}

To estimate the photonic current, we consider the short circuit situation (I=I_{sc} and V=0). Since M is considered as constant and with the assumption that the series resistance is negligible (Rs→0), therefore imposing these assumptions to (2) leads to estimate the photonic current, as follows (Aldwane, 2014; Saloux et al., 2011; Zaatri & Belhour, 2009):

$$I_{ph} = I_{sc}. \quad (7)$$

Determination of saturation current Io

To estimate the saturation current, we consider the open circuit situation (I=0 and V=V_{oc}). By imposing this condition to (2), the saturation current is estimated, as follows (Aldwane, 2014; Saloux et al., 2011; Zaatri & Belhour, 2009):

$$I_o = I_{sc}\left[e^{\frac{V_{oc}}{MV_{th}}} - 1\right]^{-1} \cong I_{sc}e^{-\frac{V_{oc}}{MV_{th}}}. \quad (8)$$

The determination of the current *Io* based on Eq. (8) is in general negligible, in the order of 10^{-6} to 10^{-10} A.

Determination of series resistance Rs

Under the assumption that *M* belongs to the interval [1; 1.5] and by extracting I_{ph} and I_o from Eq. (7) and Eq. (8), we can estimate the remaining parameter *Rs* by two techniques. The first one is by graphical simulation and the second one by matching Eq. (3) with the maximum point $P_m(V_{mpp}, I_{mpp})$.

By graphical simulation: Rs is roughly estimated by trial and error technique. Starting with an arbitrary small value of Rs, which is about tens of Ω, and plotting the I(V) curve corresponding to Eq. (3). Thus, by adjusted the value of Rs so that I(V) curves matches Pm, a rough estimation is obtained (Zaatri & Belhour, 2009).

Approximation of Rs from Eq. (3): By expressing Eq. (3) at PM, we can have an estimate of the series resistance, which is, as follows:

$$R_s = -\frac{V_{mpp}}{I_{mpp}} + M\frac{V_{th}}{I_{mpp}}log\left(1 + \frac{I_{sc}-I_{mpp}}{I_o}\right). \quad (9)$$

Introducing *Iph* and *Io* respectively from Eq. (7) and Eq. (8) into Eq. (9), it is possible to estimate *Rs* with respect to *M* by using only the values provided by the datasheet. By considering also that *Io* is negligible, Eq. (9) can be approximated by the following expression:

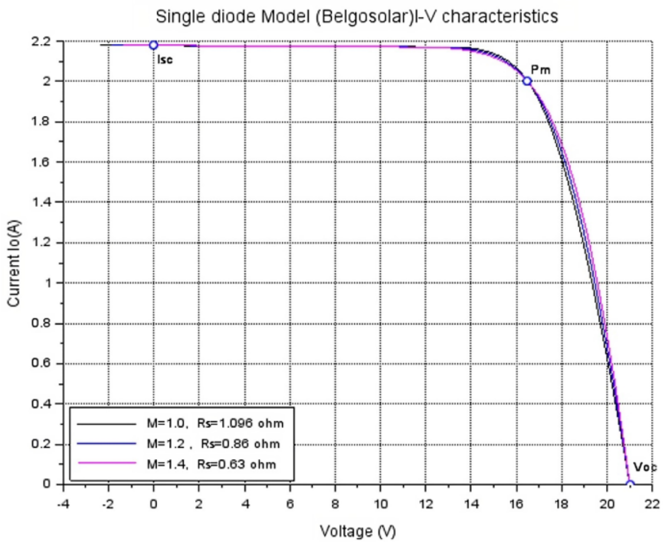

Figure 2. I-V characteristics obtained for different values of *M* for a Belgosolar panel (Source: Author's own elaboration)

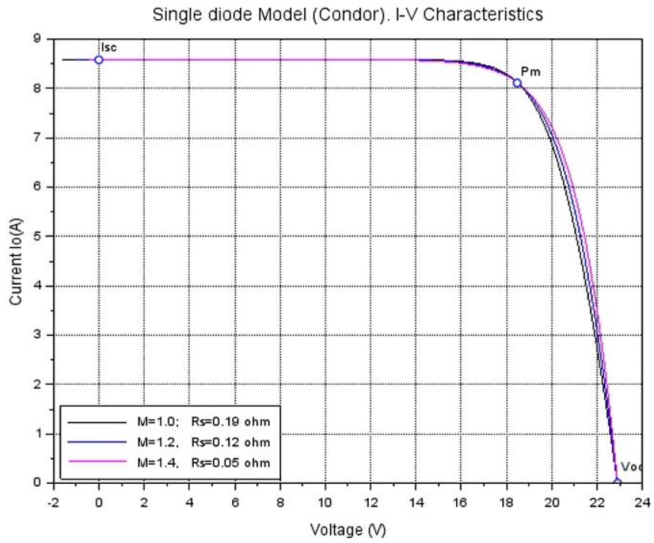

Figure 3. I-V characteristics obtained for different values of *M* for a Condor panel (Source: Author's own elaboration)

$$R_s(M) \cong \frac{(V_{oc}-V_{mpp})}{I_{mpp}} + M\frac{V_{th}}{I_{mpp}} ln\left(\frac{I_{sc}-I_{mpp}}{I_{sc}}\right). \quad (10)$$

According to Eq. (10), the relationship between *Rs* and *M* is linear and *Rs* decreases as *M* increases and vice-versa.

Influence of Ideality Factor on Series Resistance

We examine here the relation of *Rs(M)* and its influence on the profile of I-V curve of characteristics. According to Eq. (10), any variation of *M* induces a variation on *Rs*. This relation provides a degree of freedom between *Rs* and *M*. Therefore, it is always possible, in the defined interval of *M*, to find a couple (*M*; *Rs[M]*) that can compensate each other in order to keep the simulated I-V curve crossing the three via points. Consequently, by assigning a value to *M* and extracting its corresponding Rs value one can reconstitute I-V curves of characteristics related to Eq. (2).

I-V characteristics of a monocrystalline solar panel

The first type of panels (Belgosolar) we examine are made up of 36 monocrystalline silicon cells arranged in series. The three points of the solar panel provided by the manufacturer at standard conditions are, as follows: P_C=33 Watts, V_{OC}=21.0 V, I_{CC}=2.18 A, and P_m(V_{MPP}=16.5 V, I_{MPP}=2.0 A).

By considering *M=1*, the estimated other three parameters are: $I_{ph}=I_{sc}$=2.18A and $I_o=3.03\times10^{-10}$ A. The value of the series resistance roughly estimated by graphical adjustment is about R_S=1.2 Ω while the value estimated by Eq. (9) is about 1.096 Ω. A graphical representation of *I=f(V)* for this panel is given in **Figure 2** with black color. We can observe that the curve matches the three via points.

In fact, for the interval [Mmin, Mmax], we can determine from Eq. (10) a corresponding interval [Rsmax, Rsmin], where compensation can be met. For the Belgosolar panel, if the range of *M* is [Mmin=1; Mmax=1.5], we get the corresponding range of Rs [Rsmax=1.096; Rsmin=0.52]. In this case, for each value of M*, we can obtain the corresponding value Rs* by means of Eq. (10). As a result, the simulation of I-V curves obtained with the couple (M*, Rs*) matches the three via points but the shapes can be slightly different outside of these points. **Figure 2** presents three I-V curves obtained with three different values of M(1; 1.2; 1.4), which correspond to Rs(1.096 Ω; 0.86 Ω; 0.63 Ω). We notice that the variation in shapes affects essentially the right region from the Pm to the open circuit point. When M increases, then Rs decreases, and I-V curves move right up.

I-V characteristics of a polycrystalline solar panel

The second type of panel (Condor) is made up of 36 polycrystalline silicon cells. The manufacturer data are, as follows: P_C=150 Watts, V_{OC}=22.9 V, I_{CC}=8.59 A, and P_m(V_{MPP}=18.5 V, I_{MPP}=8.11 A) at a temperature of T=25 °C.

By considering *M=1*, the estimated other three parameters are: I_{ph}=8.59 A, $I_o=7.27\times10^{-10}$ A. The value of Rs estimated by graphical adjustment is about 0.2 Ω while the value estimated by Eq. (9) is about Rs=0.19 Ω. A graphical representation of I=f(V) is given in **Figure 3**. We can observe that the curve matches the three via points. Similarly, for Condor panel, if the range of *M* is [Mmin=1, Mmax=1.5], we get the corresponding range of Rs [Rsmax=0.191 Ω, Rsmin=0.016 Ω]. In this case, for different values of *M*, the simulated I-V curves match the three via points but the shapes are slightly different outside these points. **Figure 3** simulates three I-V curves obtained with three different values of M(1; 1.2; 1.4) corresponding to Rs(0.19 Ω; 0.12 Ω; 0.05 Ω). We notice that the variation in shapes affects essentially the region from the Pm to the open circuit point Pc. When M increases then Rs decreases, and I-V curves move right up.

For *M=0*, from Eq. (10), the maximal value of Rs is, as follows:

$$R_s max = \frac{(V_{oc}-V_{mpp})}{I_{mpp}}. \quad (11)$$

Inversely, if Rs is very small (Rs=0), then M is given by:

$$M_o = \frac{1}{V_{th}} \frac{(V_{mpp}-V_{oc})}{ln\left(1-\frac{I_{sc}}{I_{mpp}}\right)}. \quad (12)$$

As a conclusion, one can assert that the simplest model of 1D-1R, with an assigned value to M and with estimation of the three parameters I_o, I_{ph}, and Rs obtained through respectively Eq. (7), Eq. (8), and Eq. (10) can provide an acceptable approximation of I-V characteristics since they match the three via points with shapes resembling to the experimental ones. According to performed simulation, this fact is verified for both types of PV panels from **Figure 2** and **Figure 3**.

Method 2: Sera's Method for Extraction of Four Parameters

Let us consider an analytical method that uses 1D-1R model with the possibility to extract four parameter, and which is described in (Sera et al., 2008). To do so, a fourth equation that is the derivative of power with respect to voltage is added to the three equations corresponding to the given three points in Eq. (2). The derivative of power should be zero at the maximum Pm points of P-V curves of characteristics. This method enables to estimate the ideality factor M with respect to the data related to the three points instead of assigning to it a constant value as in method 1. Within this method, the parameters I_{pv}, I_o, and R_s are computed by the same formulas used in the previous simple method, which correspond to Eq. (7), Eq. (8), and Eq. (10). The only difference is that this method proposes to extract the ideality factor M prior to calculating R_s from Eq. (7) and I_o from Eq. (6). The four parameters have thus to be extracted in the following order:

$$I_{ph} = I_{sc} \ \& \ M = \frac{\frac{2V_{mpp}-V_{oc}}{V_{th}}}{ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)+\frac{I_{mpp}}{I_{sc}-I_{mpp}}}. \quad (13)$$

$$R_s(M) \cong \frac{(V_{oc}-V_{mpp})}{I_{mp}} + M\frac{V_{th}}{I_{mp}}\ln\left(\frac{I_{sc}-I_{mp}}{I_{sc}}\right). \quad (14)$$

$$I_o = I_{sc}exp\left(\frac{-V_{oc}}{MV_{th}}\right). \quad (15)$$

Based on this formulation, Rs can be artificially written as a function of M as in Eq. (14). In fact, M and Rs are decoupled and can be expressed independently from each other using only the coordinates of the three via points. The independent relation of Rs from M can be expressed, as follows:

$$R_s(M) = \frac{(V_{oc}-V_{mpp})}{I_{mpp}} + \frac{(2V_{mpp}-V_{oc})\ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)}{I_{mpp}\left(ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)+\frac{I_{mpp}}{I_{sc}-I_{mpp}}\right)}. \quad (16)$$

By applying method 2 to the two types of PV panels, we obtain the following results:

For Condor PV panels: I_{ph}=I_{sc}=8.59 A; M=1.02; R_s= 0.185 Ω; I_o=1.12×10^{-9} A. For Belgo PV panels: I_{ph}=I_{sc}=2.18 A; M=1.505; R_s=0.513 Ω; I_o=6×10^{-7} A.

Simulations of I-V characteristics for the two types of PV panels is performed with the four extracted parameters based on method 2. They are compared to that obtained by method 1 and reported graphically in **Figure 4** and **Figure 5**.

Concerning the Belgosolar panels, one can observe a remarkable difference between the two methods. This is caused by the new estimate of M, which is significantly different in the two methods (M=1 in method 1 and M=1.5 in method 2). The influence of M can be seen in **Figure 4**, where

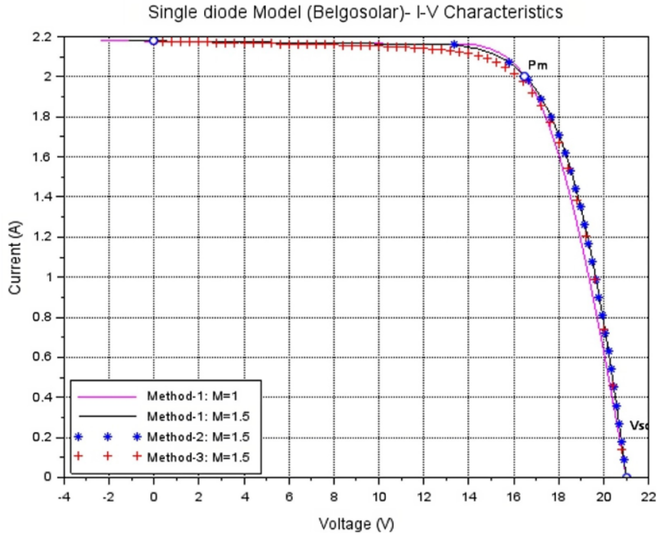

Figure 4. I-V curves (Belgo) obtained with method 1, method 2, & method 3 (Source: Author's own elaboration)

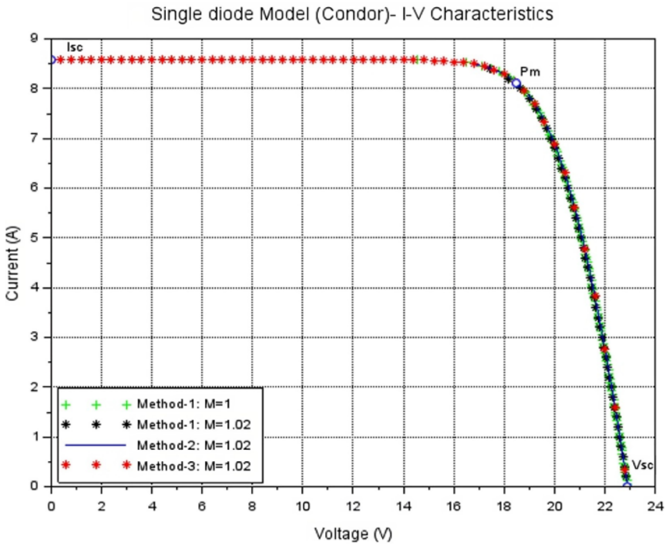

Figure 5. I-V curves (Condor) obtained with method 1, method 2, & method 3 (Source: Author's own elaboration)

the two curves show some differences in shapes. Concerning the Condor PV panels, one can observe a good similarity in I-V shapes obtained with the two methods since M did not change significantly (M=1 in method 1 & M=1.02 in method 2).

DETERMINATION OF PARAMETERS BASED ON 1D-2R MODEL

Method 3: Method for Extraction of Five Parameters

This method is presented in (Ezike et al., 2023; Kumar et al., 2023). Method 3 is based on 1D-2R model and is designed to extract five parameters. Within this method, M and Rs are decoupled. The four parameters I_o, I_{ph}, M, and Rs are extracted similarly to method 2. A fifth equation is added to the four equations used in Sera's method for enabling to extract the shunt resistance R_{sh} parameter. Technically, this fifth equation approximates the slope of I-V characteristics at the short-circuit points (Hejri et al., 2016; Kumar et al., 2023). The parameters are extracted according to the following order:

$$M = \frac{(2V_{mpp}-V_{oc})/V_{th}}{ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)+\frac{I_{mpp}}{I_{sc}-I_{mpp}}} \;\&\; R_s = \frac{V_{mpp}}{I_{mpp}} - \frac{2V_{mpp}-V_{oc}}{(I_{mpp}-I_{sc})\left[ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)+\frac{I_{mpp}}{I_{sc}-I_{mpp}}\right]}. \tag{17}$$

$$R_{sh} = \sqrt{\frac{R_s}{\frac{I_{sc}}{MV_{th}}exp\left(\frac{R_sI_{sc}-V_{oc}}{MV_{th}}\right)}}, \tag{18}$$

where $I_{ph}=I_{sc}$ and $I_o=I_{sc}exp(-V_{oc}/MV_{th})$.

Within this formulation, *M* and *Rs* are decoupled and are expressed independently only in terms of the coordinates of the three via points. Nevertheless, *Rs* can be artificially written as a function of *M*, as follows:

$$R_s = \frac{V_{mpp}}{I_{mpp}} + M\,\frac{I_{sc}-I_{mpp}{}_{th}}{I_{sc}-I_{mpp}}. \tag{19}$$

By applying method 3 to the two types of PV panels, we obtain the following results:

For Condor PV panels: I_{ph}=8.59 A; *M*=1.02; *Rs*=0.185 Ω; $I_o=1.12\times10^{-9}$ A; R_{sh}=5146 Ω.

For Belgosolar PV panels: I_{ph}=2.18 A; *M*=1.505; *Rs*=0.513 Ω; $I_o=6\times10^{-7}$ A; R_{sh}=440 Ω.

Based on the results obtained from method 1, method 2, and method 3, we can simulate and compare their corresponding I-V characteristics. The simulation of I-V characteristics for method 1 and method 2 are based on Eq. (2) of 1D-1R model while the simulation of I-V characteristics of method 3 are based on Eq. (5) of 1D-2R model.

Figure 4 presents I-V characteristics resulting from the three methods for the Belgosolar PV panel. In **Figure 4**, I-V shape (in magenta color) is the one obtained initially with the method 1 with *M* arbitrarily chosen (*M*=1). We can notice that this I-V shape is significantly different compared to the two other I-V shapes obtained with method 2 (blue stars) and method 3 (red +), which have the same values of (*M*=1.5 and *Rs*=0.51) and therefore the same profile. By adjusting method 1 with the value determined by the two other methods, which is *M*=1.5, we obtain the corresponding I-V plot (black line) that becomes superimposed with those given by method 2 and method 3.

Figure 5 presents I-V characteristics resulting from the three methods for the Condor PV panel. In this case, one can observe almost similar I-V shapes since *M* and *Rs* did not change significantly for the three methods. I-V shape obtained from method 1 (green color +) with *M* arbitrarily chosen (*M*=1) is almost superimposed to the other shapes, which are practically undistinguishable since their four parameters are the same. A blue line represents I-V shape obtained from method 2 while that of method 3 is represented with red stars. The influence of the shunt resistance R_{sh} in method 3 is negligible as its effect is not observable in the shapes of **Figure 5**.

Moreover, by adjusting method 1 with the value determined by the two other methods, which is *M*=1.5, we obtain the corresponding I-V shape (black stars) that becomes superimposed with those given by method 2 and method 3.

Method 4: Cubas' Method of Four Parameters Using Lambert W-Function

Method 4 uses 1D-2R model in order to estimate four parameters including R_{sh} while *M* is considered as an independent parameter with a value that has to be assigned. The extraction of the four parameters is based on Eq. (4) and (6) involving Lambert W-Function. This method, described in Cubas et al. (2014), is an easy and straightforward explicit analytical method that requires simple calculations. It also adds a fourth equation that is the derivative of the power withrespect to voltage, which should equals zero at PM. However, to solve this problem with five variables, the method still assumes the ideality factor *M* as a parameter with a value assigned in the interval [1; 1.5]. Therefore, the four other parameters will be determined as functions of *M*. According to this method, the calculations have to be performed in the following sequence.

Firstly, *Rs* is calculated, as follows:

$$R_s = A(W_{-1}(Bexp(C)) - (D + C)), \tag{20}$$

where W_{-1} is the negative branch of the Lambert W function and A, B, C, and D are the following coefficients:

$$A = \frac{MV_{th}}{I_{mpp}},$$

$$B = \frac{-V_{mpp}(2I_{mpp}-I_{sc})}{(V_{mpp}I_{sc}+V_{oc}(I_{mpp}-I_{sc}))},$$

$$C = -\left(\frac{2V_{mpp}-V_{oc}}{MV_{th}}\right) + \frac{(V_{mpp}I_{sc}-V_{oc}I_{mpp})}{(V_{mpp}I_{sc}+V_{oc}(I_{mpp}-I_{sc}))},$$

$$D = \frac{V_{mpp}-V_{oc}}{MV_{th}},$$

Secondly, R_{sh} is calculated by:

$$R_{sh} = \frac{(V_{mpp}-R_sI_{mpp})[V_{mpp}-R_s(I_{sc}-I_{mpp})-MV_{th}]}{(V_{mpp}-R_sI_{mpp})(I_{sc}-I_{mpp})-MV_{th}I_{mpp}}. \tag{21}$$

Thirdly, I_o is calculated by:

$$I_o = \frac{(R_s+R_{sh})I_{sc}-V_{oc}}{R_{sh}exp\left(\frac{V_{oc}}{MV_{th}}\right)}. \tag{22}$$

Fourthly, I_{ph} is calculated by:

$$I_{ph} = \frac{(R_s+R_{sh})}{R_{sh}}I_{sc}. \tag{23}$$

Assuming *M*=1, the application of this method generates the following values:

For Condor panel: *M*=1; R_s=0.189 Ω; R_{sh}=2,185.15 Ω; $I_o=7.263\times10^{-10}$ A; I_{ph}=8.591 A.

For Belgosolar panel: *M*=1; R_s=0.935 Ω; R_{sh}=287.94 Ω; $I_o=2.94\times10^{-10}$A; I_{ph}=2.187 A.

By substitution of the obtained values in Eq. (6), we obtain a graphical representation of I(V) characteristics respectively

Table 1. Estimated parameters with different used methods for Condor panel

Method/model (Condor)	M	I_{ph} (A)	I_o (A)	R_s (Ω)	R_{sh} (Ω)
Method 1: 1D-1R	1.000	8.590	7.27×10^{-10}	0.196	-
Method 2: 1D-1R	1.019	8.590	1.50×10^{-9}	0.184	-
Method 3: 1D-2R	1.019	-	1.50×10^{-9}	0.184	5,146
Method 4: 1D-2R	1.000	8.591	7.26×10^{-10}	0.189	2,185

Table 2. Estimated parameters with different used methods for Belgosolar panel

Method/model (Belgosolar)	M	I_{ph} (A)	I_o (A)	R_s (Ω)	R_{sh} (Ω)
Method 1: 1D-1R	1.0	2.180	3.03×10^{-10}	1.096	-
Method 2: 1D-1R	1.5	2.180	6.00×10^{-7}	0.510	-
Method 3: 1D-2R	1.5	2.180	6.00×10^{-7}	0.510	440
Method 4: 1D-2R	1.0	2.187	2.94×10^{-10}	0.935	287

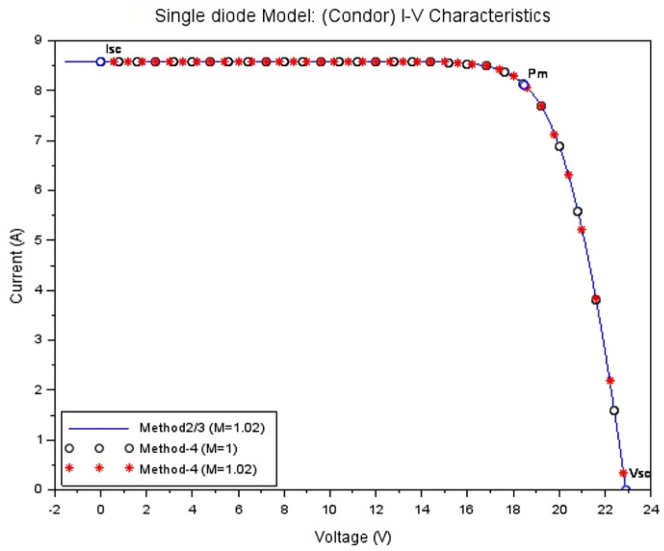

Figure 6. I-V curves of characteristics (Condor panel) (Source: Author's own elaboration)

for Condor and Belgosolar panels. Both characteristics cross the three via points.

Comparison of Methods

The obtained results by the different methods are summarized in **Table 1** for Condor panel and in **Table 2** for Belgosolar panel.

To synthesize this analysis, a graphical presentation of I-V characteristics of PV panels is simulated with the three different last methods. **Figure 6** represents I-V characteristics for the Condor panel. I-V characteristics, defined by the blue line, corresponds to method 2 and method 3 for (M=1.02), which are superimposed. The plot of I-V characteristics corresponding to method 3 is not represented because it is almost similar to that of method 2. I-V characteristics represented by black dots corresponds to method 4 with extracted parameters based on the assumption for M=1. I-V characteristics defined by the red stars corresponds to method 4 with extracted parameters adjusted for M=1.02 as determined with method 2 and method 3. We can notice that all plots are almost superimposed because the value of M did not change significantly from 1 to 1.02.

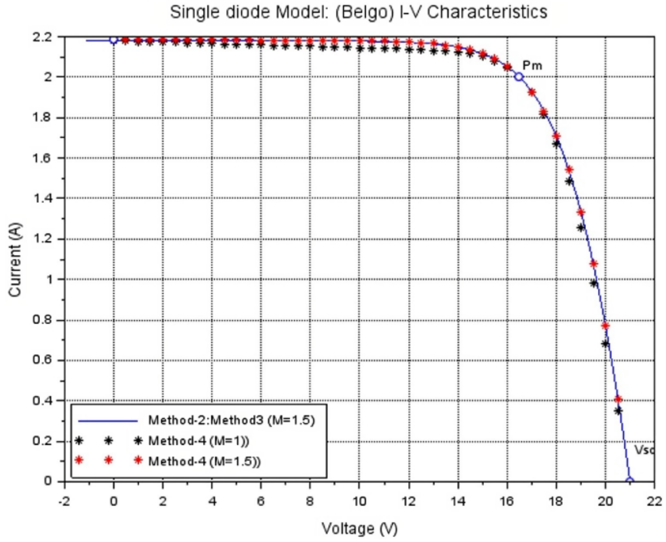

Figure 7. I-V curves of characteristics (Belgosolar panel) (Source: Author's own elaboration)

On the other hand as explained in the description of the relation *Rs(M)* of method 1, the same phenomenon of compensation exists with *Rs(M)* with method 4. For different values of M, using their corresponding parameters, all I-V curves of characteristics cross the three via points.

Similarly, **Figure 7** represents I-V curves of characteristics of Belgosolar panel. The curve of characteristics defined by the blue line corresponds to method 2 with (M=1.5). The curve represented by black dots corresponds to method 4 with extracted parameters based on the assumption that M=1. The curve defined by the red stars corresponds to method 4 with extracted parameters adjusted for M=1.5 as extracted by method 2 and method 3. It can be noticed that the adjusted curve is almost superimposed with the curve of method 2 while the curve with black dots is situated with some discrepancy with respect to the other curves. This is due to the difference on values of M from the initial assigned value of 1 to the adjusted one that is 1.5.

The comparison on the graphical representations reveals that, for Condor panel, the different methods have provided similar results leading to almost similar I-V curves (**Table 1**). For Belgosolar panel, the results show a slight discrepancy that is visible in the graphical representation and in **Table 2**.

APPROXIMATION OF *Rs* VERSUS *M* FROM CUBAS' METHOD

Approximation of Rs(M)

In order to highlight explicitly the complex interdependency between cell parameters, we consider the expression *Rs(M)* as given by method 4 in Eq. (20). To have an approximation of *Rs(M)*, we have tested several approximations of the Lambert W_{-1} function (Alvarez et al., 2021; Borsch-Supan, 1961). In our context, the most appropriate approximation of $W_{-1}(x)$ reveals to be the one given by (Batzelis, 2019; Borsch-Supan, 1961). It is defined, as follows:

$$W_{-1}(e^{a+x}) \cong x\left(1 - \frac{\log(x)-a}{1+x}\right), \quad (24)$$

and which is applicable for x large and $a \ll x$.

By applying Eq. (24) to $W_{-1}(B.e^{C})$ in Eq. (20) and after some elementary mathematical transformations, it becomes:

$$W_{-1}(Be^{C}) = W_{-1}\left(e^{\log(B)+c_1+c_2}\right) \cong c_1\left(1 - \frac{\log(c_1)-a}{1+c_1}\right), \quad (25)$$

where C=c_1+c_2, $c_1 = -\left(\frac{2V_{mpp}-V_{oc}}{MV_{th}}\right)$, and $c_2 = \frac{V_{mpp}I_{sc}-V_{oc}I_{mpp}}{(V_{mpp}I_{sc}+V_{oc}(I_{mpp}-I_{sc}))}$.

If we consider a=$log(B)$+c_2 and x=c_1=a_4/M, then, by substituting Eq. (25) into Eq. (20), we obtain an explicit approximation of the series resistance Rs with respect to the ideality factor M in the following form:

$$R_s(M) = AW_{-1}(Bexp(C)) - A(C+D) \equiv a_1 + a_2M + a_3\left(\frac{log\left(\frac{a_4}{M}\right)-a}{1+\frac{a_4}{M}}\right), \quad (26)$$

where the coefficients a_i depend only on data provided by the manufacturers: $a_1 = -AD = -\frac{(V_{mpp}-V_{oc})}{I_{mpp}}$, $a_2 = -\frac{A}{M}c_2 = -\frac{V_{th}}{I_{mpp}}c_2$, $a_3 = -Ac_1 = -\frac{(2V_{mpp}-V_{oc})}{I_{mpp}}$, and $a_4 = -\frac{(2V_{mpp}-V_{oc})}{V_{th}}$.

Eq. (26) enables to analyze the series resistance in function of the ideal factor as a variable while considering the data provided by the manufacturer as input parameters.

Comparison of *Rs(M)* Expressions to Approximation

To evaluate the proposed approximation of *Rs(M)* obtained in Eq. (26), we compare it with the original Cubas' formula of 1D-2R given in Eq. (20), and with the expression of Rs(M) obtained in Eq. (10) from 1D-1R model. We plot these three expressions in **Figure 8** and **Figure 9**, which are corresponding respectively to Condor and Belgosolar PV panels.

For both **Figure 8** and **Figure 9**, the curves with black + color correspond to the relation Eq. (20) of *Rs(M)* obtained from Cubas formula with Lambert W function. The curves with magenta + color represent its approximation as given by Eq. (26). The curves with red star color correspond to Eq. (10) of *Rs(M)*. We represent also the coordinates of *Rs* and *M* inferred from method 3 and method 4, which are indicated by a blue square dot (Sera's method).

We can notice graphically that the approximation of (26) is very close to the Cubas formula in Eq. (20) for both PV panels and thus it can be used instead. The expression *Rs(M)* obtained with method 1 intersects the curves of Eq. (26) and Eq. (20) and then diverges from them. From the three plotted curves, one can observe that the relations *Rs(M)* are practically linear in the defined range. However, it is worth to notice that for both PV panels, *Rs(M)* plots intersect in a point that is close to the blue one that corresponds to the value obtained by method 2 and method 3.

Some Comments on *Rs* & *M*

The examination of the state of the art concerning the analytical methods leading to explicit expressions of Rs and M can be classified in two classes. The first class provides decoupled expressions of *Rs* versus *M* (Jia & Anderson. 1988; Ndegwa et al., 2020; Sera et al., 2007). Examples of this class

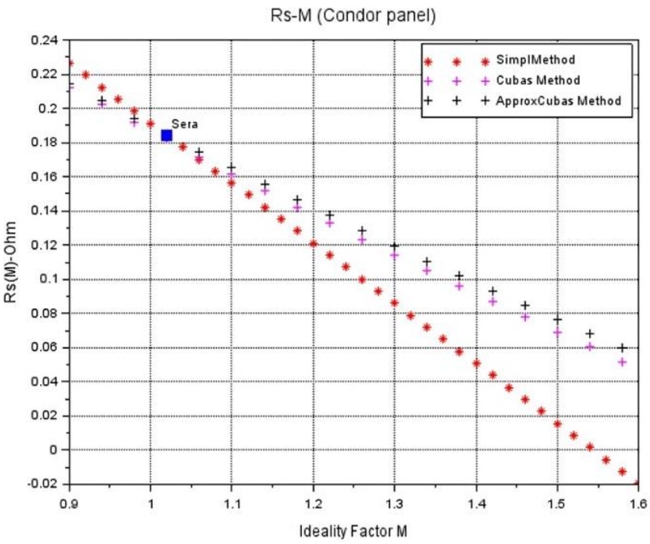

Figure 8. Comparison of *Rs(M)* for Condor panel (Source: Author's own elaboration)

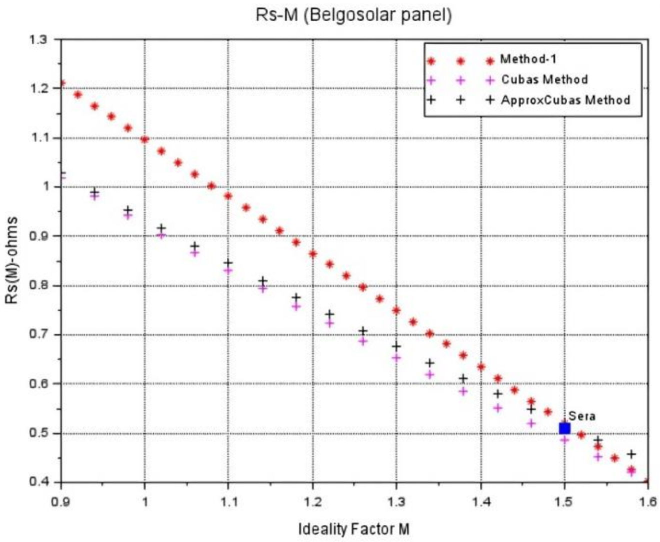

Figure 9. Comparison of *Rs(M)* for Belgosolar panel (Source: Author's own elaboration)

are method 2 and method 3, where *Rs* and *M* depend on the same input data, which are the coordinates of the three via points. However, it is possible to artificially express *Rs* with respect to *M* as done in Eq. (14) for method 2 and Eq. (19) in method 3. Within this class and according to the used methods, explicit expressions of *Rs* and *M* can be expressed differently.

The second class provides expressions of *Rs* as a function of *M*, where *M* is considered as an independent variable. This is the case for method 1 and method 4, where the value of *M* is assumed as a constant to be adjusted so that the three points fit I-V curves (Carrero et al., 2010; Rana et al., 2018; Stornelli et al., 2019; Wang et al., 2011). Within this class, most methods generate *Rs(M)* profiles that are practically linear in the considered interval of *M*. It is worthy to notice that the expressions of *Rs(M)* given by the second class intersect each other almost closer to the values of *Rs* and *M* given by the methods of the first class, as shown in **Figure 1** and **Figure 2** (points located by blue squares in **Figure 8** and **Figure 9**). It seems meaningful to consider the point, where intersection of *Rs(M)* plot occurs and which is close to the values of *Rs* and *M* given by the expressions of the first class as an acceptable estimation of *Rs* and *M*.

Moreover, available experimental studies expressing graphically the relation between *Rs* and *M* show rather a linear relation between them (Park et al., 2018; Rana et al., 2018). This fact proves also that the profile of *Rs(M)* given by (method 1 and method 4) is qualitatively in agreement with the few available experimental results. However, more experimental studies need to be carried out in order to precisely confirm the interdependency between the extracted parameters and their influence on I-V characteristics.

CONCLUSIONS

This paper revisits the classical problem of PV cell parameters extraction based only on the three points of their characteristics as provided by the manufacturers. The objective is to reconstitute I-V characteristics of PV panels based on the one diode model and to analyze the influence of the ideality factor on the series resistance. To this end, four selected analytical methods generating explicit expressions of PV parameters have been applied to a polycrystalline silicon and to a monocrystalline silicon panels.

The performed theoretical analysis based on the expressions of parameters extracted from the four selected analytical methods has led to assess that there is rather a linear relation between *Rs* and *M*. This fact has been also qualitatively corroborated by the few available experimental studies of the literature. The series resistance decreases linearly with the increase of the ideality factor in the range, where *M* is defined in [1; 2]. This analysis also reveals that different values of Rs and their corresponding values of *M* can compensate each other providing I-V shapes that always match the three via points.

In addition, an expression that links the series resistance to the ideality factor derived from Cubas' formula is proposed. It is obtained by means of a particular approximation of the Lambert W-function and enables to express *Rs(M)* with coefficients depending only on data provided by the manufacturers. The comparison of the graphical representation of *Rs(M)* for method 1, Cubas' method and the proposed approximation shows that the proposed approximation is very close to the Cubas' formula in the assumed range of *M*, which is [1; 2].

The application of the four selected methods to extracting PV parameters has given results enabling simulation of their I-V curves that cross the three via points for the two types of PV panels. However, I-V curves corresponding to the polycrystalline silicon panels are very close to each other for all the four tested methods but there was some observable discrepancy concerning the monocrystalline silicon panels. The difference could originate from the specific physical structure of PV cells, the used technology, their present state such as aging, etc. Let's remind that the polycrystalline panel were provided since 2015 while the monocrystalline are much older from the 1980.

Regarding this multiplication of approaches in order to find out a method that provides the most accurate extracted parameters, but up to date, there is no definite conclusions supporting the superiority of such specific method in the general case while using a limited set of experimental data. But, to get more accurate results, there is a need for a larger amount of experimental data with appropriate techniques of optimal adjustments. However, qualitatively, the tested methods can be satisfying for simulation purposes of PV panels in general applications since they generate I-V curves of characteristics that fit the three given points. Moreover, in most cases, it was noticed that analytical methods could also produce results, which are comparable with those obtained using other non-analytical techniques.

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Data sharing statement: Data supporting the findings and conclusions are available upon request from author.

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