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Solar cell parameters extraction based on single and double-diode models: A review

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ABSTRACT

This paper comprehensively describes and discusses the extraction of the DC parameters of solar cells by mathematical techniques based on single-diode and double-diode models. The main parameters of interest are the photocurrent, I_{ph}, the reverse diode saturation current, I_o, the ideality factor of diode, n, the series resistance, R_S, and the shunt resistance, R_{Sh}. This paper reviews the foremost issues of the condition of the methodologies of the extraction of PV solar cell parameters. This paper classifies the reviewed models on the basis of the number of extracted parameters and provides specific comments for each model. Five parameters from different models that have identical attributes are characterized with respect to irradiance and temperature to demonstrate the behavior and characteristics of these parameters. In addition, this article implements two real models, single-diode and double-diode models, and examines the performance of the PV parameters for each model and its effect on the current–voltage (*I–V*) and power–voltage (*P–V*) characteristics. Furthermore, to assess the accuracy of each model with respect to the data provided by the manufacturer, this paper compares the *I–V* and *P–V* curves at standard test condition (STC) and for different parameters for a generic PV panel.

Contents

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1. Introduction

The accurate measurement of current–voltage (I–V) characteristics is essential in controlling the quality of solar cells and evaluating the performance of photovoltaic (PV) systems. However, the accuracy of such measurement is directly related to the number of DC parameters extracted in that model. Furthermore, in addition to its importance for research purposes, the identification and understanding of the impact of DC solar cell parameters on model efficiency have a directly influence on the optimization of the fabrication processes [1,2]. Consequently, the accurate modeling and characterization of a solar cell model are based on the extracted parameters in that model. Previous studies have investigated methods and proposed suggestions regarding the use of nonlinear electrical models to confirm the operating conditions of solar cells and to determine its effective parameters [3–8]. The most imperative DC solar cell parameters are usually calculated and determined from the current–voltage (I–V) and power–voltage (P–V) characteristics. Fig. 1 describes a single-diode model of a PV cell that is used to determine these parameters and its characteristics [1,9]. Another type that can be used is a double-diode model, which can examine the (I–V) and (P–V) characteristics in a wider scope than the single-diode model.

In general, the modeling of a photovoltaic module involves the calculation of the I–V characteristics by using a specific model. However, it is a complex and challenging task to create models that represent various irradiance and temperature conditions that can estimate the parameters in a truly representative way [10,11]. As such, the modeling involves a diversification in the types and methods used, including the number of diodes, the shunt resistance (infinite or finite), the ideality constant, and the most appropriate numerical methods.

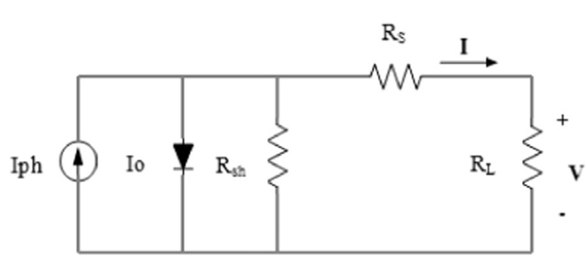

Fig. 1. Single-diode model equivalent circuit.

An entirely accurate benchmarking is somewhat elusive, because researchers test their algorithms and models with respect to different PV systems, such as, environmental conditions, applied technologies, ratings, and size. However, in this study, we summarize and discuss the main equations used in each model to overcome the variety of parameters that can affect the modeling results.

In this review, the presented models consider different parameters that characterize PV solar cells. These parameters include the photocurrent, I_{ph}, the reverse diode saturation current, I_o, the ideality factor of diode, n, the series resistance, R_S, and the shunt resistance, R_{Sh}, and they involve alternative input variables. In addition, the equations and procedures that are adopted to interpret the electrical characteristics are closely related to the specifics of a particular model. In general, the complexity of a model is based on the desired level of accuracy [12]. This review provides an analysis of the characteristics of different models that can be useful for identifying the most relevant type for a specific application. Another contribution of this study is showing that the results can accumulated within one informational source, which could be beneficial for future works on the optimization of fabrication processes.

2. Available PV models

To depict the properties of the existing models, namely, the single-diode and double-diode models, certain assumptions were made in presenting a simplified version of the models for engineering research applications with regard to the solar system. The two models differ in terms of the number of diodes that denote the saturation current.

Nomenclature

STC	standard test condition
G	solar irradiance (W/m^2)
G_{STC}	solar irradiance at standard test conditions (1000 W/m^2)
T	PV cell Temperature (K)
T_{STC}	temperature at standard test conditions (25 °C)
$G^{\triangledown}$	ratio of the generic solar irradiance to the irradiance at STC
$T^{\triangledown}$	ratio of the generic temperature to the irradiance at STC
V_D	voltage across the diode
n	diode quality factor
n, STC	diode quality factor at standard rating conditions
I_o	reverse saturation current of the diode (A)
I_L	photogenerated current (A)
$I_{L,STC}$	photogenerated current at standard rating conditions (A)
I^*mp	coordinates of current at the maximum power point (A)
V^*mp	coordinates of voltage at the maximum power point (V)
I_{mpp}	current corresponding to the maximum power point (A)
V_{mpp}	voltage corresponding to at the maximum power point (V)
I	PV output current
V_{pv}	PV output voltage
I_o	reverse saturation current
Eq	energy gap of solar cell
R_s	series resistance (Ω)
R_{so}	reciprocal of the gradient at the open-circuit point
R_{OC}	inverse of the gradients [(dI/dV)$^{-1}$] under the open circuit conditions
R_{sh}	shunt resistance (Ω)
R_{sho}	reciprocal of the gradient at the short-circuit point
R_{SC}	inverse of the gradients [(dI/dV)$^{-1}$] under the short circuit conditions
V_{oc}	open circuit voltage of the panel (V)
$V_{oc,STC}$	open circuit voltage of the panel at standard test condition (V)
I_{sc}	short circuit current of the module (A)
I_{sc}, STC	short circuit current of the module at standard test condition (A)
μ_{ISC}	coefficient of the short circuit current (A/1C)
μ_{VOC}	coefficient of the open circuit voltage (V/1C)
V_a	denotes a random value of the voltage
V_t	thermal voltage value which equal to (q/nKT)
I_o, STC	reverse saturation current at standard rating conditions (A)
K	Boltzmann constant (1.381e10 – 23 J/K)
n	diode quality factor
P	power generated by the PV panel (W)
q	electric charge of an electron (1.602e10 –19 C)

2.1. Single-diode PV cell model

A solid, single-junction PV cell that is not illuminated behaves very similarly to a semiconductor diode. The conventional equation below describes a simple diode with a distinctive *I–V* curve:

$$I_D = I_o\left[\exp\left(\frac{qV_D}{nkT}\right) - 1\right] \tag{1}$$

The ideality factor (quality factor or emission coefficient), which usually ranges from 1 to 2 but might be higher in certain cases, is determined according to the fabrication process and the semiconductor material. Given that n is generally assumed to be roughly equal to 1, it is often left out.

When the semiconductor diode is illuminated, it will produce a photo-generated current, I_{ph}, which will result in a vertical translation of the *I–V* curve of a quantity that is almost entirely related to the surface density of the incident energy.

Thus, an ideal cell is depicted as a current generator that is linked to a parallel diode with an *I–V* characteristic, which is mathematically defined by Shockley in the following equation as [13]:

$$I = I_{ph} - I_o\left[\exp\left(\frac{qV_D}{nkT}\right) - 1\right] - \frac{V_D}{R_{sh}} \tag{2}$$

where $V_D = V_{pv} + R_S I$

A simple theoretical definition is presented by Eq. (2) because it does not consider the impact caused by the presence of the electrodes, one above and another below the semiconductor layer, which are required to accumulate the charges that cover the intercepting surface to some extent.

2.2. Double-diode PV cell model

Wolf correctly noted in [14] that the photocurrent in a PV cell is generated not only by a single diode but also by the overall effect of multiple elementary diodes that are adjacent to one another and consistently distributed along the surface between the two layers of the semiconductor. A current passes through each basic diode while flowing across the semiconductor layers along a different path, marked by different electric resistance and reduction in voltage.

The transverse element of the current, I_L, which runs parallel to the surface of the cell, should differ for each elementary diode so that each cell will have a different *I–V* characteristic. Given that these diodes are regarded as being in parallel, their combination will determine the overall *I–V* characteristic of the PV cell. The transverse electrical resistance greatly exceeds the electrical resistance in relation to the direct I_L element. The transverse element of the current I_L, which only occurs in an actual photovoltaic cell, generates a high energy dissipation that considerably reduces the conversion efficiency of the solar cell.

In [14], Wolf developed a simplified equivalent circuit, as shown in Fig. 2. This model consists only of double diodes, a current generator, and two resistors, taking into consideration the dissipative effects described above and the existence of any construction flaws. The resolution of the above equivalent circuit resulted in the following implied expression of the

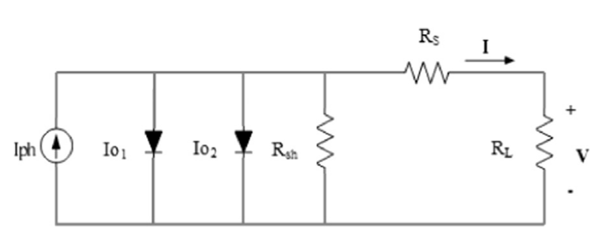

Fig. 2. Double-diode model equivalent circuit.

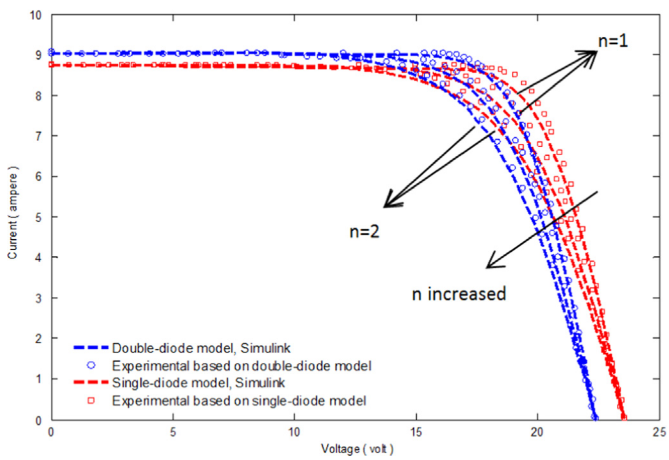

Fig. 3. Influence of diode ideality factor on the I–V characteristic.

current, I:

$$I = I_{ph} - I_{01}\left[\exp\left(\frac{qV_D}{n_1 kT}\right) - 1\right] - I_{02}\left[\exp\left(\frac{qV_D}{n_2 kT}\right) - 1\right] - \frac{V_D}{R_{sh}} \tag{3}$$

As shown in Fig. 2, to solve Eq. (3), the parameters (I_L; n_1; n_2; I_{01}; I_{02}; R_s;and R_{sh}) must be known.

The more comprehensive terms are the slopes of the curve before and after the "knee" of the curve is altered by the resistors R_{sh} and R_s, respectively, while the curvature is changed by the ratio between I_{01} and I_{02} [15]. Although this is not an issue that cannot be solved mathematically, the computation of these parameters is hampered by the implicit form of the equation and by the presence of two exponential terms. In the literature, only a few comprehensive models allow the algorithm to be coded to retrieve these parameters. These models are single-cell models built on specific assumptions that restrict their application.

3. Extraction of parameters for PV model

For the extraction of PV parameters, several researchers prefer the use of different correlations that are not based on an electric model [16,17], whereby there are only five unknown parameters and one or two exponential terms. According to the conventional method, the photocurrent, I_L, is determined by the irradiance, I_o, which is influenced by the temperature of the cell. By contrast, n, R_s, and R_{sh} remain constant. Some researchers have proposed suggestions for improvement and/or simplification that would enable the five parameters (I_L, n, I_0, R_s, and R_{sh}) to be ascertained according to the performance data of the modules that are usually supplied by the manufacturers. In other studies, researchers have concentrated on either four parameters, three, two, or even just one parameter. This study reviews the literature to identify the best-described models for assessing the electrical behavior of single-diode and double-diode models on the basis of the number of DC parameters of PV solar cells. The techniques for extracting solar cell parameters are concisely summarized below.

3.1. Five-parameter models

A solar cell model typically depends on five parameters (I_L, I_o, a, R_s, and R_{sh}) [18]. The parameter extraction procedure is different for each model. Previous studies concerning the extraction of these parameters have utilized either single-diode or double-diode models. Therefore, we review several of the best-described models available in the literature that are designed for the assessment of electrical behavior on the basis of the number of DC parameters of PV solar cells.

3.1.1. Model of Valerio, based on single-diode model.

A method for finding out the parameters of solar cells, according to the single-diode model was devised by Valerio. [19]. Both the computed I–V characteristics and those provided by the manufacturers were employed to get the five parameters, R_s, R_{sh}, n, I_L and I_0. This method, which takes into consideration any changes in external conditions, will result in an accurate approximation of the current produced by the PV panel.

$$I(G^{\nabla}, T) = G^{\nabla} I_L(T) - I_o(G^{\nabla}, T)\left[\exp\left[(G^{\nabla}\{V + \mathrm{KI}(T - T_{STC})\} + \mathrm{IR}_S)/G^{\nabla} nT\right] - 1\right] - \left(\frac{G^{\nabla}\{V + \mathrm{KI}(T - T_{STC})\} + \mathrm{IR}_S}{R_{sh}}\right) \tag{4}$$

where,

$$K = \frac{V_{mp} - V^{*}{}_{mp}}{I^{*}{}_{mp}(T^{*} - T_{STC})} \tag{5}$$

The quantity G^{∇} which is equal to G/G_{STC}represents the ratio of the generic solar irradiance to the solar irradiance at STC, while K is the thermal correction factor similar to the curve correction factor defined by the IEC 891. Hence, the parameters can be evaluated according to the following equation,

$$I_L(T) = I_{L,STC} + \mu_{Isc}(T - T_{STC}) \tag{6}$$

Clearly, $G^{\nabla}$is 1, T is 25 °C at standard test conditions (STC), and Eq. (4) will be equivalent to the conventional five parameters in (2).

$$I_{L,STC} = I_{SC,STC} \text{ and } R_{sh} = R_{sh0} \tag{7}$$

Then, under the common conditions that have been extensively fulfilled, R_s, R_p, *and* n can be found by applying to (8)

$$R_s \langle\langle R_{sho} \frac{I_{o,STC}}{nT_{STC}} \exp(I_{SC,STC} R \quad / nT_{STC} \langle\langle \frac{1}{R_{sho}} \tag{8}$$

S

Another noteworthy observation is with regard to the current I_0 (G, T), whose value for the irradiance and temperature individually can be calculated by the following equation:

$$I_o(G^{\nabla}, T) = \exp\left[\frac{(G^{\nabla} - 0.2)}{(1 - 0.2)} \ln \frac{I_o(1, T)}{I_o(0.2, T)} + \ln I_o(0.2, T)\right] \tag{9}$$

3.1.2. Model of Celik, based on single-diode model

Another model proposed by Celik in [20] for the derivation of the five parameters, I_L, I_o, R_s, R_{sh} and n, are at a certain temperature and solar irradiance level within the limits of V_{oc}, I_{sc}, V_{mpp} and I_{mpp}, according to the following definitions for R_{so} and R_{sho}:

$$R_{so} = -\left(\frac{dV}{dI}\right)_{V = V_{OC}} \tag{10}$$

$$R_{sho} = -\left(\frac{dV}{dI}\right)_{I = I_{SC}} \tag{11}$$

where R_{so} is the reciprocal of the gradient at the open-circuit point, while R_{sho} is the reciprocal of the gradient at the short-circuit point. The module manufacturers normally do not give these resistance values. Blas et al. [21] proposed R_{so} values in the range of 0.30 to 0.33 Ω and R_{sho} values in the range of 50–170 Ω according to the gradients of the experimental curves. According to the sensitivity analysis of the five-parameter model for R_{so} and

R_{sho}, the model is able to adequately predict existing values for an extensive range of R_{so} and R_{sho} values. The five necessary parameters can be calculated by means of the following equations:

$$I_L = I_{SC}\left(1+\frac{R_S}{R_{sh}}\right)+I_o\left(\exp\left[\frac{I_{SC}R_S}{mV_t}\right]-1\right) \tag{12}$$

$$I_o = \left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right)\exp\left[-\frac{V_{OC}}{mV_t}\right] \tag{13}$$

$$R_S = R_{SO}-\left(\frac{mV_t}{I_o}\left(\exp\left[-\frac{V_{OC}}{mV_t}\right]\right.\right. \tag{14}$$

$$R_{Sh} = R_{Sho} \tag{15}$$

$$n = \frac{V_{mp}+I_{mp}R_{so}-V_{OC}}{V_t\left\{\ln\left(I_{SC}-\frac{V_{mp}}{R_{sh}}-I_{mp}\right)-\ln\left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right)+\left(\frac{I_{mp}}{I_{SC}-\frac{V_{OC}}{R_{sh}}}\right)\right\}} \tag{16}$$

where the values of I_{sc} and V_{oc} at a temperature and solar irradiance level besides the reference values can be calculated as:

$$I_{SC} = I_{SC,STC}G^{\nabla}+\mu_{I_{SC}}(T-T_{STC}) \tag{17}$$

$$V_{OC} = V_{OC,STC}+mV_t\ \ln G^{\nabla}+\mu_{V_{OC}}(T-T_{STC}) \tag{18}$$

The model is applied in the following way as (17) and (18) are employed to calculate I_{sc} and V_{oc} based on their reference values, and they are adjusted simultaneously to meet environmental conditions. Eq. (12)–(16) are used to calculate the five parameters, which are then used in succession in Eq. (2), which links the current of the cell to its voltage. And also, the measured voltage values are used to calculate the current of the cell from (2).

3.1.3. Model of Chan, based on single-diode model.

An analytical five-point method was devised by Chan in [22]. In this method, the single-diode model for solar cells is used to find the five parameters, namely I_{ph}, I_o, n, R_s and R_{sh}, under illumination by means of the values of I_{sc}, V_{oc}, I_{mpp}, V_{mpp}, the gradient at the open-circuit point R_{so}, and the gradient at the short-circuit point R_{sho}, which are provided by the I–V characteristic. The values of R_{sho} and R_{so}, which are given by (10) and (11), respectively, can be calculated by fitting the I–V characteristic curve linearly around the short-circuit current point and the open-circuit voltage point, respectively.

The ideality factor of the diode can be calculated via the following equation:

$$n = -\left(\frac{A}{V_t(B+C)}\right) \tag{19}$$

where A, B and C can be derived as follows:

$$A = V_m+R_{So}I_m-V_{OC} \tag{20}$$

$$B = \ln\left(I_{SC}-\frac{V_m}{R_{sh}}-I_m\right)-\ln\left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right) \tag{21}$$

$$C = \frac{I_m}{\left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right)} \tag{22}$$

The other parameters, namely I_o, R_s and I_{ph}, can be obtained from the following equations:

$$I_o = \left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right)\exp\left(-\frac{V_{OC}}{nV_T}\right) \tag{23}$$

$$R_S = R_{So}-\frac{nV_t}{I_o}\exp\left(-\frac{V_{OC}}{nV_T}\right) \tag{24}$$

$$I_{ph} = I_{SC}\left(1+\frac{R_S}{R_{sh}}\right)+I_o\left(\exp\left(\frac{I_{SC}R_S}{nV_T}\right)-1\right) \tag{25}$$

3.1.4. Model of Brano, based on single-diode model.

In [23] Brano developed a method to determine the parameters of the solar cell. The method was free of any simplifications or assumptions for extracting the five parameters of Eq. (2) based merely on the normal technical data (Fig. 2) under standard test conditions (STC) for a single-diode model.

Five separate mathematical equations were formulated for the calculation of the correct values of the five parameters. The five unknown parameters can be extracted by concurrently solving these equations.

The I_{SC} values can be used to derive the first equation. This is assumed that the voltage is zero at the short circuit current point and by substituting these values into Eq. (2) will lead to:

$$f_{n1}: I_L+\left[1-\exp\left(\frac{I_{SC}R_S}{nT}\right)\right]I_o-\frac{I_{SC}R_S}{R_{sh}}-I_{SC}=0 \tag{26}$$

The V_{OC} values can be used to derive the second equation. This is also assumed that the current is zero at the open circuit voltage point, and substituting these values into Eq. (2) will lead to:

$$f_{n2}: I_L+\left[1-\exp\left(\frac{V_{OC}}{nT}\right)\right]I_o-\frac{V_{OC}}{R_{sh}}=0 \tag{27}$$

The data on the MPP, where V is V_{mpp} and I is I_{mpp} can be used for deriving the third equation; and by substituting these values into (2) will lead to:

$$f_{n3}: I_L+\left[1-\exp\left(\frac{I_{mpp}R_S+V_{mpp}}{nT}\right)\right]I_o-\frac{I_{mpp}R_S+V_{mpp}}{R_{sh}}-I_{mpp}=0 \tag{28}$$

Then, the fourth equation can be derived from (2) in terms of V, where V is V_{mpp} and I is I_{mpp}:

$$f_{n4}: \frac{-nT-\left[\exp\left(\frac{I_{mpp}R_S+V_{mpp}}{nT}\right)\right]I_oR_{sh}}{nT.(R_S+R_{sh})+\left[\exp\left(\frac{I_{mpp}R_S+V_{mpp}}{nT}\right)\right]I_oR_{sh}.R_S}+\frac{I_{mpp}}{V_{mpp}}=0 \tag{29}$$

Finally, the fifth equation of the model can be derived from the power of V times (2) in terms of V also, where V is V_{mpp} and I is I_{mpp}:

$$f_{n5}: \frac{V_{mpp}.nT[I_oR_{sh}+I_LR_{sh}-2V_{mpp}+[\exp(\frac{I_{mpp}V_{mpp}R_S+V^2{}_{mpp}}{V_{mpp}nT})]I_oR_{sh}[I_{mpp}V_{mpp}.R_S-V_{mpp}(nT+V_{mpp})}{V_{mpp}\left\{I_o.R_S.R_{sh}.\left[\exp\left(\frac{I_{mpp}V_{mpp}R_S+V^2{}_{mpp}}{V_{mpp}nT}\right)\right]+nT(R_{sh}+R_S)\right\}}=0 \tag{30}$$

The model is constructed on the concept of beginning at a random point and then passing through the neighbors. The initial estimates of I_L, I_0, R_s, R_{sh} and n are selecting from a range of relatively large arbitrary values, and the process can be repeated until the residuals for the equations, f1(I_L, I_0, R_s, R_{sh}, n),…, f5(I_L, I_0, R_s, R_{sh}, n), are virtually zero. The automatic use of a non-linear optimization solver, that ease to be utilized, is now available in almost any spreadsheet software; and open source scripts are also available. The generalized reduced gradient (GRG) algorithm, which is one of the most resilient nonlinear programming methods, is usually employed by these solvers to work out optimization problems [24]. This method is adopted as it can easily be applied in the system in Eq. (31) through the use of a conventional software application without the need to write out a code line.

$$\begin{cases} f_{n1}=0 \\ f_{n2}=0 \\ f_{n3}=0 \\ f_{n4}=0 \\ f_{n5}=0 \end{cases} \tag{31}$$

3.1.5. Model of Merbaha, based on double-diode model

Merbaha devised another technique for extracting the five parameters of solar cells (R_S, G_{sh}, I_L, n_1 and n_2, and I_{01} and I_{02}) by means of the double-diode model [25]. The line of resistance, with a gradient of V_{oc}/I_{sc}, divides the I–V characteristic of a solar cell, measured under illumination conditions, into two regions, with one region being close to the short circuit current and the other being close to the open circuit voltage. Thus, the first region of the I–V characteristic is a function of the current, while the second region is a function of the voltage. Eq. (3) Can be modeled as (32) and (33) for the first and second regions, respectively:

$$I = I_{SC} - G_{sh}^{f} V - a_3 h^{f}(I,V) \tag{32}$$

$$V = V_{OC} - I R_S^{s} - b_3 h^{s}(I,V) \tag{33}$$

where the first region is denoted by the superscript "f" and the second region by the superscript "s", and the curvature of the I–V characteristic is denoted by h^i(I, V), with i being either f or s [26]. To obtain the coefficients (I_{sc} and G_{sh}^{f}) the first region must be fitted close to the short circuit with Eq. (32), while to obtain the coefficients (V_{oc} and R_s^s) the second region must be fitted close to the open circuit with Eq. (33). To determine the set of parameters (I_{ph}, G_{sh1}/R_{sh}, I_{od}, I_{or}, and R_s), the system must be solved with the five non-linear equations obtained for I_{sc}, G_{sh}, V_{oc}, R_s and I_o, with the curve passing through the boundary point, which is approximately the maximum power point [25]. The theoretical values n_d and n_r are assumed by the ideality factors of the diode. To solve the system, the set of parameters must first be equal to zero and the iterative process is conducted once the parameters converge.

3.2. Four-parameter model

Beside the five parameter model, other studies concentrated on the least number of parameters, like four, three, two or even one parameter model. So, four parameters model will be described in the following paragraphs.

3.2.1. Model of Celik, based on single-diode model.

A four-parameter model was constructed by Celik in [20] based on the assumption that R_{sh} in (2), is infinite and thus, can be ignored. As such, this is a single-diode model that can be obtained from (2). Kou et al. in [27] outlined a technique for identifying the four parameters needed for (2). When V assumed to be 0, the short-circuit current can be found by (34),

$$I_{L,STC} = I_{SC,STC} \tag{34}$$

The other parameters under the reference conditions, according to the characteristics of the photovoltaic module can be calculated by means of the following equations:

$$n_{STC} = \frac{\mu_{V_{OC}} T_{STC} - V_{OC,STC} + E_q N_S}{\frac{\mu_{I_{SC}} T_{STC}}{I_{L,STC}} - 3} \tag{35}$$

$$R_{S,STC} = \frac{n_{STC}.\ln\left(1 - \frac{I_{mpp,STC}}{I_{L,STC}}\right) - V_{mpp,STC} + V_{OC,STC}}{I_{mpp,STC}} \tag{36}$$

$$I_{o,STC} = \frac{I_{L,STC}}{\exp\left(\frac{V_{OC,STC}}{n_{STC}}\right) - 1} \tag{37}$$

$$I_L = G^{\nabla}\left[I_{L,STC} + \mu_{I_{SC}}(T - T_{STC})\right. \tag{38}$$

$$I_o = I_{o,STC}\left(T^{\nabla}\right)^3 \exp\left[\frac{E_q N_s}{n}\right]\left(1 - \frac{1}{T^{\nabla}}\right) \tag{39}$$

$$R_S = R_{S,STC} \tag{40}$$

$$n = n_{STC} T^{\nabla} \tag{41}$$

where T^{∇} is T/T_{STC}.

The model is executed in the following way:

The values of the four parameters under reference conditions are found by using Eqs. (34)–(37). Eqs. (38)–(41) are used to adjust these four parameters to match the environmental conditions, and they are then employed in (2) to link the cell current to the cell voltage. Either the cell current or the cell voltage can be calculated from (2), depending on which value is known. On the other hand, both of the cell current and the cell voltage can be computed at the maximum power point.

3.2.2. Model of Tivanov, based on single-diode model.

According to the model devised by Tivanov [28], it is preferable to calculate the parameters of the solar cell, such as R_{sh}, R_s, I_o and n, from the I–V characteristic at a set illumination level. Based on the mathematical equation denoted by (2) for the single-diode model, and by approximating I_{ph} as equal as I_{sc} and analyzing the I–V characteristic of a solar cell at a set illumination level, its parameters can be calculated by means of the following equations:

$$R_S = \frac{1}{2}\left\{\left[(a-b)^2 + \frac{2p}{I_{SC}}(a-b) + \left(\frac{V_{OC}}{I_{SC}}\right)^2\right]^{\frac{1}{2}} + (a+b) + \frac{V_{OC}}{I_{SC}}\right\} \tag{42}$$

$$R_{sh} = \frac{V_{OC}}{\frac{nV_T}{b+R_S} - \frac{nV_T}{a+R_S} + I_{SC}} \tag{43}$$

$$I_o = \frac{I_{SC}}{\lambda} - \frac{V_{OC}}{\lambda R_{sh}}, \text{ where } \lambda = \exp\frac{V_{OC}}{nV_T} - 1 \tag{44}$$

The allotted specific value of n is confirmed by comparing it with the value obtained by using the following equation:

$$n = \frac{\left(V_{mpp} - I_{mpp}R_S\right)\left(I_{SC} + I_o - I_m - V_m/R_{sh}\right)}{V_T\left(I_{mpp} - V_{mpp}/R_{sh}\right)} \tag{45}$$

3.2.3. Model of Chegaar, based on single-diode model.

Chegaar et al. came up with a simple model for the extraction of the parameters R_{sh}, R_s, I_o and n of the solar cell under illuminated conditions using the I–V characteristic of the single-diode model, an auxiliary function $F(v)$ and a fitting routine [1]. Eq. (47) was used to obtain the shunt resistance, while the remaining three parameters were determined by the introduction of an auxiliary function:

$$P(V) = V - V_a \ln\left(I_{ph} - I\right) \tag{46}$$

$$R_{sh} = R_{sho} = -\left(\frac{dV}{dI}\right)_{I = I_{SC}} \tag{47}$$

where V_a denotes a random value of the voltage. By using (3) minus the last term and by replacing V with I, Eq. (48) can be obtained.

$$F(I) = aI + b\ln(I_{ph} - I) + c_o \tag{48}$$

where

$$\mathrm{a} = -R_S, b = nV_T \text{ and } c = -nV_t I_o \tag{49}$$

The curve $F(I)$ vs. I can be used to obtain the series resistance, the ideality factor of the diode and the reverse saturation current. To plot the curve, the values of $F(l)$ were computed for each point (V, I) at a stable temperature and for a value of V_a. Chegaar et al. took into account the integer values for V_a from 1 to 5 [1].The photo-generated current was regarded as being roughly equal to the short circuit current.

3.2.4. Model of Khan, based on single-diode model.

Another model which is based on the single-diode model, was evaluated to predict the influence of the illumination level on the solar cell parameters of a c-Si solar cell in [29]. The PV cell parameters, namely R_{sh}, R_s, n, and I_0, were obtained analytically by employing the values of I_{sc}, V_{oc}, R_{sc}, R_{oc},V_{mpp}, and I_{mpp}.The values of I and I_{mpp}, which had been obtained experimentally, increased linearly at different rates as the P_{in} increased.

$$R_{sh} = R_{SC} \tag{50}$$

$$R_S = R_{OC} - \frac{(V_m + R_{OC} I_{mpp} - V_{OC})}{I_m + [\ln(I_{SC} - I_{mpp}) - \ln(I_{SC})].I_{SC}} \tag{51}$$

$$n = \frac{(V_m + R_{OC} I_{mpp} - V_{OC})}{[\ln(I_{SC} - I_{mpp}) - \ln(I_{SC})].V_T} \tag{52}$$

$$I_o = \frac{nV_T}{(R_{OC} - R_S)} \exp\left(-\frac{V_{OC}}{nV_T}\right) \tag{53}$$

3.2.5. Model of Kaminski, based on double-diode model.

Kaminski et al. used the single-diode model in dark conditions to ascertain the parameters I_{od}, I_{or}, n_d, n_r, R_s and R_{sh} of the solar cell [30]. An analysis of the I–V characteristic of the solar cell in dark conditions is carried out on two regions: the first region denoting the higher section where the series resistance and the diffusion mechanism are significant, and the second region denoting the lower section where the shunt resistance and the recombination mechanism are significant. The parameters I_{od}, n_d and R_s are determined by means of the first section, while the linear regression of (54) is used to define the series resistance and the ideality factor of the diode:

$$y = \frac{1}{n_d V_T}(-R_S + X), y = \frac{\ln(I/I_1)}{I - I_1}, X = \frac{V - V_1}{I - I_1} \tag{54}$$

where (V_1, I_1) represents a point on the first section of the I–V characteristic of the solar cell. If the correlation coefficient is poor, then the value of I_1 must be increased. In order to estimate the saturation current, I_o, $ln\ I$ must be plotted against the function of V- IR_s. The parameters I_{or}, n_r and R_{sh} can be obtained from the second section of the characteristic curve. The linear part of the lower section of the I–V characteristic is obtained by the least square method in (55).

$$I = I_{or}\left(\exp\left[\frac{V_D}{n_r V_T}\right]\right) \tag{55}$$

Eq. (56) is then used to calculate the shunt resistance.

$$R_{sh} = \left[\left(\frac{dI}{dV}\right)_{I = I_{SC}} - \frac{I_{or}}{n_r V_T}\right]^{-1} \tag{56}$$

3.3. Three-parameter model

3.3.1. Model of Zhang, based on single-diode model

Zhang et al. devised a method in [31], based on the single-diode model, for determining the parameters of a solar cell by means of the single I–V characteristic at a stable level of illumination and the Lambert W function. As can be seen, (57) is a straightforward equation with only three parameters, namely n, R_s and R_{sh}, which can be ascertained by employing the numerical fit method. The initial value for the shunt resistance can be obtained by using (58) and the linear dependency dV/dI, while the values of the series resistance and the ideality factor, n, of the diode can be obtained from the intercept and gradient. Eqs. (59) and (60) can be used to calculate the saturation current and the photogenerated current, respectively.

$$I = \frac{nV_T}{R_S} LambertW\left\{\frac{R_S}{nV_T}\left(I_{SC} - \frac{V_{OC}}{R_S + R_{Sh}}\right)\exp\left(\frac{-V_{OC}}{nV_T}\right).\exp\frac{1}{nV_T}\left(R_S I_{SC} + \frac{R_{Sh}V}{R_S + R_{Sh}}\right)\right\}$$
$$+\frac{V}{R_S} - I_{SC} - \frac{R_{Sh}V}{R_S(R_S + R_{Sh})} \tag{57}$$

$$-\frac{dV}{dI} = \frac{nV_T}{I_{SC} - I - [V - R_S(I_{SC} - I) - n} \tag{58}$$

$$I_o = \left[I_{SC} - \frac{nV_{OC} - I_{SC}R_S}{R_{Sh}}\right]\exp\left(-\frac{V_{OC}}{nV_T}\right) \tag{59}$$

$$I_{ph} = \frac{V_{OC}}{R_{Sh}} + I_o\left[\exp\left(\frac{V_{OC}}{nV_T}\right) - 1\right] \tag{60}$$

3.3.2. Model of Kiran, based on single-diode model

Kiran devised a method which is based on the single-diode model, for ascertaining the parameters of a solar cell under illumination conditions [19] by using an approximation equation derived from (2) to eliminate the saturation current, and by regarding the shunt resistance as being infinite, thus formulating (61). Based on this assumption, it is obvious that the results obtained by this method differ from the expected values as the cell ages. This is of significance in studies concerning the aging of PV cells.

$$V = V_{OC} - IR_S + nV_T\ln\left[\frac{I_{SC} - I}{I_{SC}} + \exp\frac{I_{SC}R_S - V_{OC}}{nV_T}\right] \tag{61}$$

Eq. (61) only has three parameters, namely R_s, n and is, which can be calculated from the experimental data. The photo-generated current can be derived as I [32] as equal as I [17].

3.3.3. Model of Arcipiani, based on single-diode model.

The generalized area method was devised by Arcipiani [33]. The solar cell parameters, comprising the ideality factor, the series resistance and the shunt resistance of the diode, can be determined through this method, which involves the calculation of the area between the V and I axes and the I–V characteristic of solar cell using (57). The following expression was used for the single-diode model of the solar cell:

$$A = (I_{ph} + I_o)(V_{OC} - rI_{SC})r + I_{SC}(1 + gr)\left(\frac{rI_{SC}}{2} - V_T n\right) + V_{OC}g\left(V_T n - \frac{V_{OC}}{2}\right) \tag{62}$$

where r denotes the R_s and g the R_{sh}. By taking into account the generally accepted approximation of $gr \ll 1$, $I_o \ll I_{ph}$ and $I_{sc}EI_{ph}$ [29],

(57) becomes

$$y=\frac{I_{SC}}{2V_{OC}}r+\frac{1}{V_{OC}}V_T n+\frac{V_{OC}}{2I_{SC}}g-\frac{1}{I_{SC}}V_T gn, y=\frac{I_{SC}V_{OC}-A}{I_{SC}V_{OC}} \quad (63)$$

3.3.4. Model of Khatib, based on single-diode model.

In another study [34], three parameters (I_o, I_L, and n) were considered and derived experimentally before being compared to the theoretical values. Following this, the mathematical expressions were derived according to the actual parameters in order to come up with a perfect mathematical model for the projected plan. The equation below describes those parameters:

$$I=I_L-I_o\left[\exp\left(\frac{qV_D}{nkT}\right)-1\right] \quad (64)$$

The details of the parameters are then outlined in the following equations:

$$n=\frac{T}{K_1} \quad (65)$$

where K_1–K_5 denotes the coefficients in these equations.

$$K_1=\frac{q}{nk} \quad (66)$$

$$I_L=(K_2+K_3.T)G \quad (67)$$

$$I_o=K_4.T.\exp\left(-\frac{K_5}{T}\right) \quad (68)$$

3.3.5. Model of Garrido-Alzar, based on double-diode model.

Garrido-Alzar devised a new solar cell model in [35], based on the double-diode model, for determining the parameters of the solar cell. The method involves solving the equation system derived from (4) for four points, namely I_{1}, I_{2}, I_{3}, and I_{4}, from the I–V characteristic (VI, Ii), and nd1, in the zero order approximation for n and R_s [35]. Hence, resulting in the calculation of the parameters I_{ph}, I_{od}, I_{or} and R_{sh}. The following equation is used in order to calculate n:

$$n=\frac{V_{OC}}{V_t\left[\ln\left\{I_{or}+I_{ph}-I_{od}\left(\exp\left(\frac{V_{OC}}{V_T}-1\right)\right)-\frac{V_{OC}}{R_{sh}}\right\}-\ln I_{or}\right]} \quad (69)$$

The following equation is utilized to calculate the series resistance:

$$I_5=I_{ph}-I_{od}\left[\exp\left(\frac{V_5+I_5R_S}{V_T}\right)-1\right]-I_{or}\left[\exp\left(\frac{V_5+I_5R_S}{V_t n_t}\right)-1\right]-\frac{V_5+I_5R_S}{R_{sh}} \quad (70)$$

The above steps must be performed repeatedly until, for instance, the value of n, with the desired level of precision, is acquired [35], where n is not equal to 2.

3.4. Two-parameter model

3.4.1. Model of Bowden, based on single-diode model.

Bowden and Rohatgi devised a method for carrying out two parameters of the solar cell, namely n and R_s [36], using two I–V characteristics that one measured for one sun illumination and the other one measured for 0.1 sun illumination or ideally where the level of illumination is such as that the short circuit current of the solar cell is the same as $I_{sc,1}$- $I_{mpp,1}$. The following equation can be used to calculate the series resistance:

$$R_S=\frac{V_{OC,0,1}-V_{mpp,1}}{I_{SC},1-I_{SC,0,1}} \quad (71)$$

where ($V_{mpp,1}$, $I_{sc,1}$) is derived from the I–V characteristic measured for one sun illumination, and ($V_{oc,0,1}$, $I_{sc,0,1}$) are derived from the I–V characteristic measured for 0.1 sun illumination. The following equation can be used to calculate the ideality factor of the diode:

$$n=\frac{V_{OC,1}-V_{OC,0,1}1}{\ln(I_{SC,1}/I_{SC,0,1})V_T} \quad (72)$$

In which, the average between the maximum power point (MPP) and V_{oc} is taken.

Bowden and Rohatgi postulated in this model that the externally apparent R_S is not constant; rather, it varies with illumination level and electrical load. In addition, the ideality factor, n, which should be constant, is affected mainly by variations in temperature level mainly [37]. In practice, a model has to be recalculated, that is, estimate the values of R_S and n again, for every condition of irradiance and temperature. To avoid uncertainty in the application of corrective methods, in [21], De Blas et al. validated their model by using I_{SC} and V_{OC} values known under specific conditions of temperature and irradiance.

3.4.2. Model of Priyanka, based on single-diode model.

As shown in the equation below, the semi-logarithmic I_{sc}–V_{oc} characteristic can be used to attain the ideality factor of the diode and the reverse current. The short circuit current and the open circuit voltage must be established for various levels of illumination. The single-diode model is employed in this method based on the following assumptions and approximations:

$$R_{sh}\to\infty,\ \ I_{SC}\approx I_{ph,}\exp\left(\frac{V_{OC}}{nV_T}\right)\rangle\rangle 1 \quad (73)$$

The semi-logarithmic characteristic can be used to calculate the ideality factor of the diode, while the interception of the characteristic on the Y-axis is used to calculate the saturation current. This method was improved by Priyanka et al., by taking into account for the value of the shunt resistance [38]. Thus, Eq. (73) becomes

$$\ln\left(I_{SC}-\frac{V_{OC}}{R_{sh}}\right)=\ln I_o+\frac{V_{OC}}{nV_T} \quad (74)$$

3.4.3. Model of El-Adawi, based on single-diode model.

El-Adawi suggested a method for ascertaining the series and shunt resistances by means of the single-diode model [39]. Eq. (3) can be used to estimate the series resistance, with the approximations shown in Eq. (75), and by selecting two points, (*Vi, Ii*), $I=1$, 2, around the knee of the I–V characteristic of the solar cell.

$$I_oR_{sh}\exp\left(\frac{V+IR_s}{nV_T}\right)\rangle\rangle V,\ \ \frac{R_SI_i}{R_{sh}}\langle I_{SC}+I_o-I_{i,}i=1,2\ \ I_{SC}\rangle\rangle I_{ph} \quad (75)$$

$$R_{SC}=\frac{nV_T}{I_1-I_2}\ln\frac{I_{SC}-I_2}{I_{SC}-I_1}-\frac{V_2-V_1}{I_2-I_1} \quad (76)$$

The following equation can be used to calculate the shunt resistance:

$$\frac{R_{sh}+R_S}{R_{sh}(I_{SC}-I_1)-R_SI_1}=\frac{V_1-R_S}{nV_TI_1} \quad (77)$$

3.4.4. Model of Ortiz-Conde, based on single-diode model.

Ortiz-Conde devised the integral method [17], which was improved by Kaminski et al. [30]. The linear regression of (79), which is derived from (78) through integration, can be used to obtain the series resistance and the ideality factor of the diode. The single-diode model is employed for the solar cell and the shunt resistance is assumed to be infinite.

$$I = I_o\left[\exp\left(\frac{V_1 - R_S}{nV_T}\right)\right] \tag{78}$$

$$y = nV_T + R_S X,\ X = \frac{I + I_1}{2},\ y = \frac{1}{I - I_1}\int_{V`1}^{V} IdV \tag{79}$$

where (V_1, I_1) is a point on the I–V characteristic of the solar cell, and I is the current under dark conditions. The trapezoidal method can be used to solve the integral issue.

3.4.5. Model of Jia, based on double-diode model.

Jia and Anderson devised a method for ascertaining the series resistance and the ideality factor of diode [40], whereby n is regarded as a variable of the I–V characteristic, thus resulting in n_1 at V_{oc} and n_2 at I_{sc}. The single-diode model was used in this method with the solar cell being illuminated. The series resistance can be computed by means of (59), which is derived by employing the following approximations where I_{ph}, I_{sc}, R_{sh} is infinite and $I_{sc} \gg I_o$.

$$R_S = \frac{(V_m(1/V_T)(I_{SC} - I_m)\{V_{OC} + V_T \ln\left[1 - (I_m/I_{SC})\right]\} - I_m}{(I_m(1/V_T)(I_{SC} - I_m)\{V_{OC} + V_T \ln\left[1 - (I_m/I_{SC})\right]\} + I_m} \tag{80}$$

The following equation can be used to calculate the value of the ideality factor of the diode at the maximum power point:

$$n = (V_m + I_m R_S)/\{V_{OC} + V_T \ln\left[(I_m/I_{SC})/I_{SC}\right]\} \tag{81}$$

3.5. One-parameter model

3.5.1. Model of El-Adawi, based on single-diode model.

A simple method, commonly referred to as the single-diode model, was devised in [39] based on an estimate of the R_s from a single I–V characteristic curve of a solar cell. In this suggested model, which attempts to avoid further graphical manipulation, all the proposed parameters, except for V and I, were considered to be constants. In order to avoid complex calculations, the method was based on the drawing of a curve in relation to the power and the current or voltage, of which two points, (V_1, I_1) and (V_2, I_2), were selected on a single I–V characteristic curve as follows:

$$R_S = \frac{1}{\lambda}\frac{1}{(I_2 - I_1)} = \ln\left[\frac{I_{ph} - I_2}{I_{ph} - I_1}\right] - \frac{V_2 - V_1}{I_2 - I_1} \tag{82}$$

where I_{ph} denotes the photo-generated current, which is proposed as a constant.

3.5.2. Model of Aberle, based on single-diode model.

In this method, the series resistance of the solar cells is ascertained through the use of measurements under both dark and illumination conditions. Aberle et al. [32] suggested the use of Eq. (82) to determine the series resistance:

$$R_S = \frac{\Delta V}{I_{mpp}} = \frac{V_{dark,m} - V_{mpp}}{I_{mpp}} \tag{83}$$

where $V_{dark,m}$ denotes the voltage that is measured under dark conditions, consistent with the current, I_{mpp}, which is measured under illumination conditions [41]. Since the impact of the series resistance in the dark is ignored, the error can be greater than 5%. In order to reduce the error, the corrected equation [8] is used to calculate the series resistance:

$$R_S = \frac{V_{dark,m} - V_{mpp} - (I_{SC} - I_{mpp})R_{S,dark}}{I_{mpp}} \tag{84}$$

where Eq. (85) can be used to calculate $R_{s,dark}$.

$$R_S = \frac{V_{SC} - V_{OC}}{I_{SC}} \tag{85}$$

3.5.3. Model of Cotfas, based on single-diode model.

Cotfas et al. devised this method to ascertain the series resistance based on the single-diode model [42]. Two I–V characteristics are used in this method. One of them which is measured and another one which is ideal. The ideal I–V characteristic can be calculated by means of $n1$ or with the actual values for n and I_o. Eq. (86) can be used to calculate the series resistance.

$$R_S = \frac{\Delta V}{I_{mpp}} = \frac{V_{ideal} - V_{mpp}}{I_{mpp}} \tag{86}$$

3.5.4. Model of Araújo, based on single-diode model.

The area method was devised by Araújo and Sánchez in [43] to ascertain the series resistance of a solar cell through the use of the single-diode model in (2), where R_{sh} is regarded as infinite, while the ideality factor of the diode has a value equal to one. In this method, the series resistance is calculated as follows:

$$R_S = 2\left(\frac{V_{OC}}{I_{SC}} - \frac{A}{I_{SC}^2} - \frac{V_T}{I_{SC}}\right) \tag{87}$$

where A denotes the area between the I–V characteristic curve and the I and V axes.

3.5.5. Model of Polman, based on double-diode model.

Polman et al. devised a method for ascertaining the series resistance of solar cells [44] through the use of the double-diode model to describe the solar cell, and by taking into account the shunt resistance and the ideality factor of the diode. By means of Eq. (88), the series resistance can be computed as the average of the values obtained when n is equal to one and two.

$$R_S = -\left(\left(\frac{\partial I}{\partial V}\right)_{V = V_{OC}}\right)^{-1} - \left(\frac{I_{ph}}{nV_T}\right)^{-1} \tag{88}$$

where $\left(\frac{\partial I}{\partial V}\right)_{V = V_{OC}}$ is derived from the gradient of the linear fitting of several points around V is equal to V_{oc}.

4. Model evaluation criteria

In this review, an efficient evaluation was conducted between the real curves and the models selected from the literature (Table 4). This evaluation was based on many benchmarks to clarify the accuracy of the selected models with respect to the real results. The comparison was made between two different models (a single-diode model and a double-diode model) in the same field (Table 3). All of these criteria showed compared with the single-diode model, the double-diode model exhibits a very small error with respect to real results, as shown in Tables 2 and 4. The model evaluation is based on the most well-known factors, namely, which are the mean absolute percentage errors (MAPE) and the R-square, which is the net of the division of the sum of square due

Table. 1
The specification of the PV module used in the current study.

Parameter	Unit
Maximum power point (P_{MP})	206 W
Maximum voltage (V_{MP})	22.89 V
Maximum current (I_{MP})	8.93 A
Open circuit voltage (V_{OC})	24.5 V
Short circuit current (I_{SC})	9.18 A
Height	1425 mm
Width	652 mm
Thickness	52 mm
Weight	11.9 kg

Table 2
General characteristics of the solar cell parameters and its accuracy measurements with respect to *I*–*V* and *P*–*V* characteristics.

Parameter type	Affect on the *I*–*V* and *P*–*V* characteristics	Depending on the cell temperature mainly	Depending on the irradiance level mainly	Its effect on the maximum power is notable	Its effect on the short circuit (I_{SC}) current is notable	Its effect on open circuit voltage (V_{OC}) is notable	MAPE (%) for *I*–*V* curve with the single-diode model	MAPE (%) for *P*–*V* curve with the single-diode model	MAPE (%) for *I*–*V* curve with the double-diode model	MAPE (%) for *P*–*V* curve with the double-diode model
The photocurrent, I_{ph}	√		√	√	√	√	5.94555	6.54677	1.8977	2.2133
The reverse diode saturation current, I_o	√	√		√	√	√	5.23341	6.11682	1.73352	1.83955
The ideality factor of diode, n	√	√	√	√			4.89332	5.93433	1.54833	1.75548
The series resistance, R_S	√	√	√	√			4.12232	5.8885	1.7577	1.83443
The shunt resistance, R_{Sh}	√	√	√				–	–	–	–

Table 3
General comparisons between the single-diode model and the double-diode model.

Model type	Accurate in the normal condition	Accurate in the shadow condition	High computational effort	More applicable and used for most PV types	Sufficiently describes the PV characteristics	Depending on the cell temperature	Depending on the irradiance	Easy to implement	Applicable for both indoor and outdoor conditions
Single-diode model	√			√	√	√	√	√	√
Double-diode model	√	√	√		√	√	√		√

Table 4
A comparison of different models for the five parameters.

Author	Year	Double-diode model	Single-diode model	No. of parameters used	Type of tested parameter	MAPE (%)	*R*-square
Polman et al.	1986	√		One parameter	Serise resistance (R_s)	11.4	0.94333
Aberle et al.	1993		√	One parameter	Series resistance (R_s)	4.64	0.98667
Garrido-Alzar	1997	√		Three parameters	Diode ideality factor (n)	1.323	0.98879
Jia et al.	1998		√	Two parameters	Diode ideality factor (n)	4.356	0.98667
Kaminski et al.	1999	√		Four parameters	Parallel resistance (R_{sh})	3.895	0.98776
Tivanov et al.	2005		√	Four parameters	Parallel resistance (R_{sh})	13.667	0.87667
Haouari et al.	2005	√		Five parameters	Diode current (I_o)	6.3843	0.92445
Celik AN et al.	2007		√	Five parameters	Diode current (I_o)	8.6667	0.90188
Kaminski et al.	1999	√		Four parameters	Photon current (I_L)	3.4667	0.98667
Khan et al.	2014		√	Four parameters	Photon current (I_L)	6.367	0.93556

to regression (SSR) by the sum of square due to the total average (SST). All of the factors used in the evaluation has the following formula:

$$\mathrm{MAPE} = \left\{ \frac{\left|\frac{(\mathrm{Rv}-\mathrm{Pm})}{\mathrm{Rv}}\right|}{\mathrm{no.}} \right\} * 100\% \tag{89}$$

$$R^2 = \mathrm{SSR}/\mathrm{SST} \tag{90}$$

where *Rv* denote the real values, *Pm* is the proposed model, and *no.* is the number of tested points.

5. Implementation of single-diode and double-diode models

The above analysis reveals that any model adopted to characterize a PV panel involves several parameters that need to be calculated depending on the experimental data. The number of these parameters differs according to the adopted model. A single-diode model provides a good compromise between accuracy and simplicity [45], and this model has been used by several authors in previous works [45,46]. The effectiveness of the single-diode model has been proven, particularly in the simulation of PV modules with power converters. A two-diode model that considers different operation conditions provides a better accuracy under the normal operation conditions of a PV panel, and this model has also been employed by different researchers for modeling PV panels [47].

The approach for calculating the different parameters that characterize the *I–V* and *P–V* curves is as introduced in Eqs. (2) and (3) for the single-diode and double-diode models, respectively. These characteristics can be used to assess the performance of PV parameters by using the general formulas of each model.

5.1. Single-diode model

In calculating solar cell parameters, the analytical approach is commonly used because of its speed and simplicity. By introducing several assumptions, the complex non-linear relationships that define the behavior of a solar cell can be reduced to analytically solvable equations. The performance of these parameters performance can then be assessed through these equations.

The first parameter, the ideality factor, n, accounts for the differential mechanisms responsible for moving carriers across the junction [48]. The parameter n is 1 if the transport process is purely diffusion and approximately 2 if the primary process is recombination in the depletion region. Values are typically selected to be within this range. For example, Carrero [49] suggests a value of unity, whereas another study proposes an empirical approach [50]. One approach is to apply the analytical expression proposed by Phang et al. [51].

$$n = \frac{V_{mp} + R_{S0} I_{mp} - V_{OC}}{V_{th}\left\{ \ln\left(I_{SC} - \frac{V_{mp}}{R_{sho}} - I_{mp}\right) - \ln\left(I_{SC} - \frac{V_{OC}}{R_{Sh}}\right) + \frac{I_{mp}}{I_{SC} - (V_{OC}/R_{Sh0})} \right\}} \tag{91}$$

where V_{mp} is the voltage value at the maximum power point (MPP); R_{S0} and R_{Sh0} are the estimates for R_S and R_{Sh}, respectively; I_{mp} is the current at MPP; V_{OC} is the open circuit voltage; and I_{SC} is the short circuit current. The values of V_{mp}, I_{mp}, V_{OC}, and I_{SC} are typically provided by the manufacturer data sheets. By contrast, the values of R_{S0} and R_{Sh0} must be calculated by examining the current–voltage (*I–V*) curve. The analytical approach put forward by Phang et al. assumes that R_{Sh} is equal to R_{Sh0}.

$$R_{Sh} = R_{Sh0} \tag{92}$$

The value of R_{S0} is adjusted to obtain R_S by using Eq. (4).

$$R_S = R_{S0} - \frac{nV_{th}}{I_0} e^{\left(\frac{-V_{OC}}{nV_{th}}\right)} \tag{93}$$

where the reverse saturation current, I_0, may be calculated by

$$I_o = \left(I_{SC} - \frac{V_{OC}}{R_{Sh}}\right) e^{\left(\frac{-V_{OC}}{nV_{th}}\right)} \tag{94}$$

Physically, R_S and R_{Sh} represent the various ohmic losses that occur within the cell. On the one hand, the series resistance represents the resistances introduced by cell solder bonds, cell-interconnect busbars, cell metallization, and resistances within the emitter base region [52]. On the other hand, the shunt resistance, R_{Sh}, represents any possible high-conductivity paths across the solar cell pen junction that are created as a result of crystal damage and impurities in and near the junction [53].

Finally, the photo-generated current, I_{ph}, must to be determined. One assumption is to assume that I_{ph} is equal to I_{SC} [54]. A more sophisticated method is to use Eq. (6), as suggested by Phang et al.

$$I_{ph} = I_{SC}\left(1 + \frac{R_S}{R_{Sh}}\right) + I_o\left(e^{\left(\frac{I_{SC}R_S}{nV_{th}}\right)} - 1\right) \tag{95}$$

5.2. Double-diode model

The double-diode model equation used is as expressed in the Ishaque model [55], and the main equation model is presented in Eq. (3).

where the diode factors $n1 = 1$ and $n2$ can be derived from:

$$\frac{n1 + n2}{p} \geq 1 \tag{96}$$

where p can be chosen to be greater than 2.2.

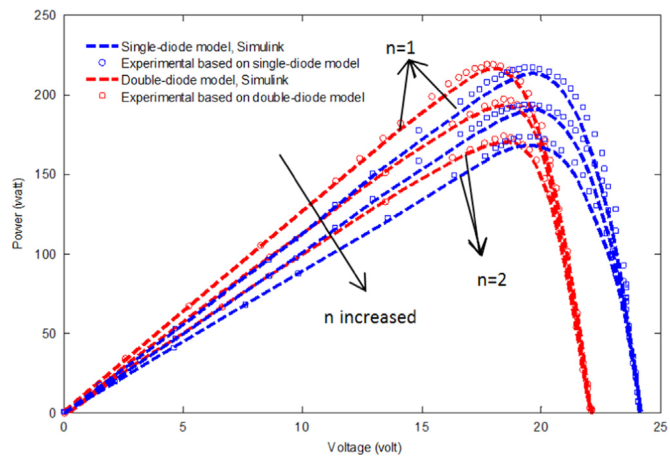

Fig. 4. Influence of diode ideality factor on the *P–V* characteristic.

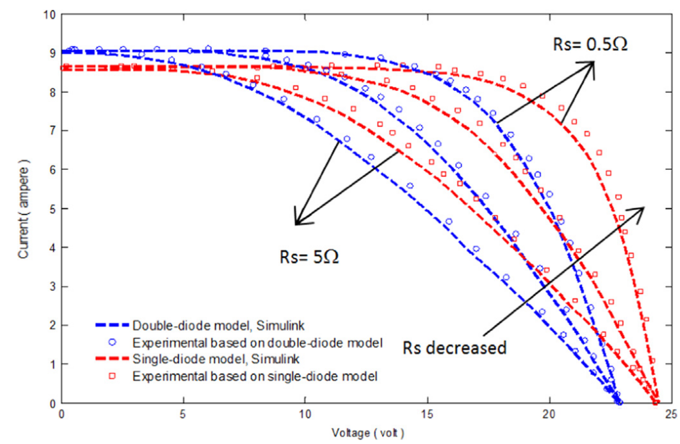

Fig. 7. Influence of series resistance on the *I–V* characteristic.

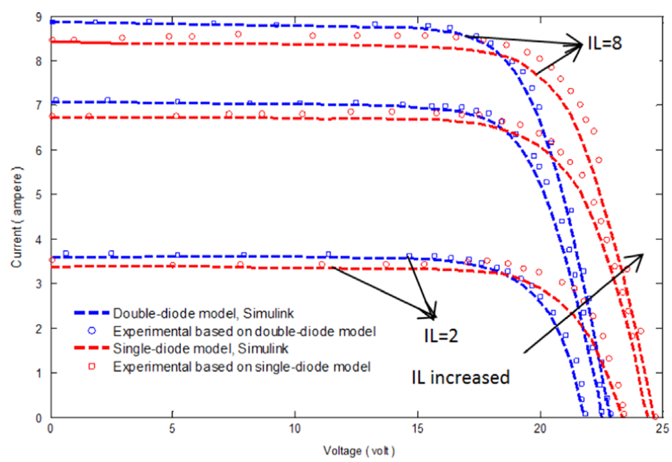

Fig. 5. Influence of photocurrent on the *I–V* characteristic.

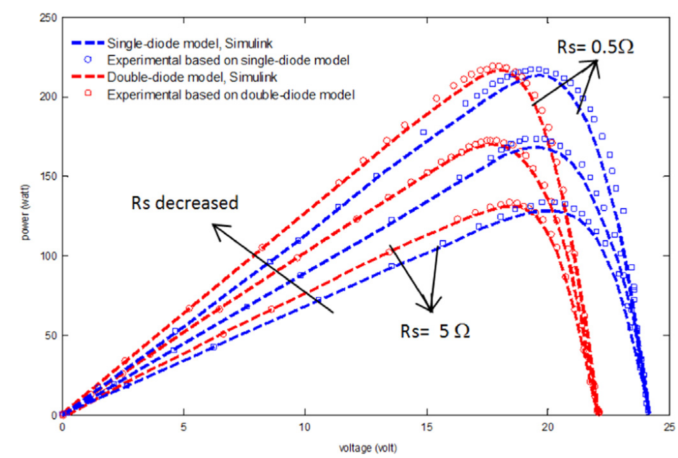

Fig. 8. Influence of series resistance on the *P–V* characteristic.

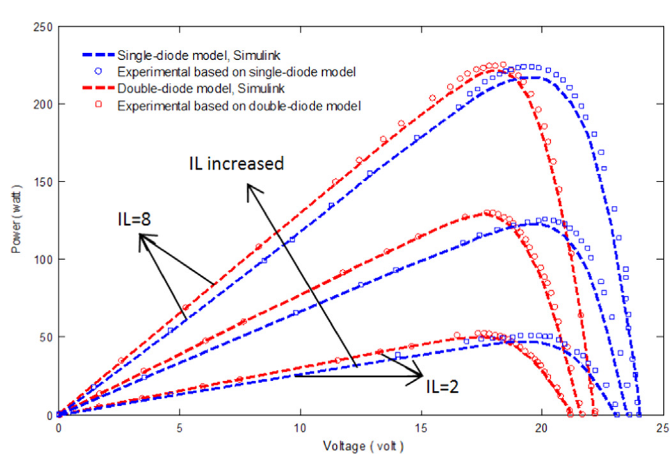

Fig. 6. Influence of photocurrent on the *P–V* characteristic.

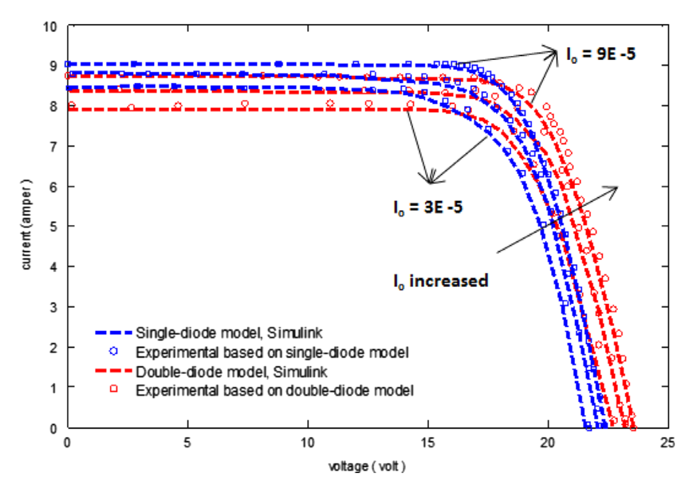

Fig. 9. Influence of the reverse diode saturation current on the *I–V* characteristic.

The rest of the parameters can be deduced from the following equations [55]:

$$I_L = I_{SC} \tag{97}$$

$$I_{o1} = I_{o2} = \frac{I_{SC} + \mu_{I_{SC}} \Delta T}{\exp\left[\frac{q(V_{OC} + \mu_{V_{OC}})\Delta T}{\mathrm{KT}(A_1 + A_2)/p}\right] - 1} \tag{98}$$

R_S and R_{Sh} are calculated by using an iterative method that is similar to the procedure proposed by [45], where the relation between R_S and R_{Sh} is used to verify that the calculated maximum power is equal to the experimental one, that is, ($P_{max,m}$=$P_{max,e}$) at (V_m, I_m) point.

The R_S value is obtained by a slow incrementation by the same manner as that described in the previous subsection. The expression of R_{Sh} can be written as

$$I_{o1} = I_{o2} = \frac{V_m + I_m R_S}{I_{Ph} - I_{o1}\left[\exp\left(\frac{qV_m + I_m R_S}{\mathrm{KT}}\right) + \frac{qV_m + I_m R_S}{\mathrm{KT}(p-1)}\Big) + 2\right] - \frac{P_{max\_e}}{V_m}} \tag{99}$$

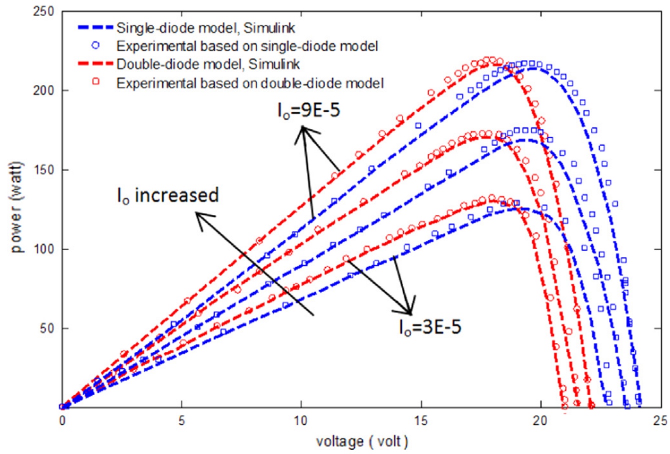

Fig. 10. Influence of the reverse diode saturation current on the *P–V* characteristic.

5.3. Effect of solar cell parameter variation on PV performance

In this section, the single-diode and double-diode models were compared with respect to the Monocrystalline PV cell technology (Kyocera (KC200GT) panel) to analyze the performance of the parameters. Table 1 lists the data obtained from the manufacturer data sheets for Monocrystalline PV module at 25 °C and 1000 W/m^2. Figs. 3–10 compare the results obtained for different parameters with the use of the single-diode and double-diode models for both the Simulink and the real results.

In constructing the decision vector, varying different variables have different effects on the characteristic curves of the PV module, and the effect of varying the ideality factor on the *I–V* and *P–V* is shown in Figs. 3 and 4, respectively. As shown in these figures, increasing the ideality factor decreases the values of voltage and current, and in turn decreases the power at the maximum point. Figs. 5 and 6 show the effect of varying the series resistance on the *I–V* and *P–V* curves, respectively. This figures illustrate that as R_S increases, the voltage, the current, and the power at the maximum point decrease. In addition, varying the values of both the ideality factor and the series resistance caused a noticeable effect on the region of the maximum power point. Figs. 7 and 8 show the effect of varying the photocurrent on the *I–V* and *P–V* curves, respectively. This figures illustrate that as IL increases, the voltage, the current, and the power at the maximum point also increase. In addition, the effect of the reverse diode saturation current, Io on the *I–V* and *P–V* characteristic curves also studied and the performance results noticed as in Figs. 9 and 10, it shows that as the Io increases, the voltage, the current, and the power at the maximum point also increase. Finally, the effect of varying RSh on the *I–V* and *P–V* curves of a PV module were also studied, and this effect was found to be barely noticeable. Moreover, general characteristics and specifications of the solar cell parameters and its accuracy measurements with respect to *I–V* and *P–V* characteristics shown in Table 2. The results of the comparison between these parameters accuracies showed that the double diode model, in general, exhibit better accuracy compared with the single-diode model and for all DC parameters used. The comparisons were performed on a Kyocera (KC200GT) panel under standard test conditions. This panel was also selected for the validation of the results of the slected models.

The analysis shows that the parameters of the double-diode model exhibit the best match with experimental data, a general comparison listed in Table 3. The reason is that the double-diode model expresses a better accuracy than the single-diode model under normal and shadow operating conditions.

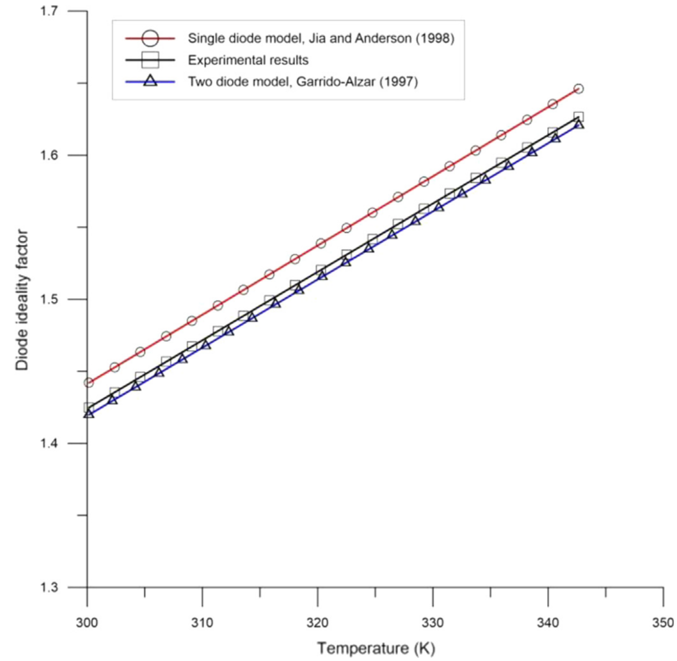

Fig. 11. A comparison between single-diode and double-diode model with real results based for the parameter (a).

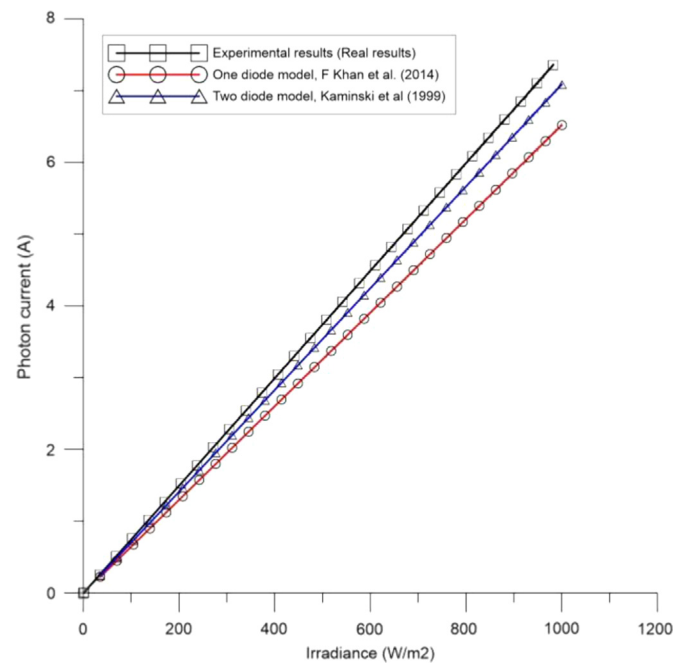

Fig. 12. A comparison between single-diode and double-diode model with real results based for the photocurrent (I_L).

6. Discussion

This review discusses and classifies the extraction of DC parameters (I_L, I_o, R_s, R_{sh}, and n) of solar cells based on single-diode or double diode models. This discussion explores both theoretical and experimental approaches to determine the importance of the DC parameters of solar cells. The *I–V* characteristic is an important tool for determining the above quantities, and it can be measured under both illumination and darkness conditions. The majority of existing methods use the *I–V* characteristic obtained under illumination

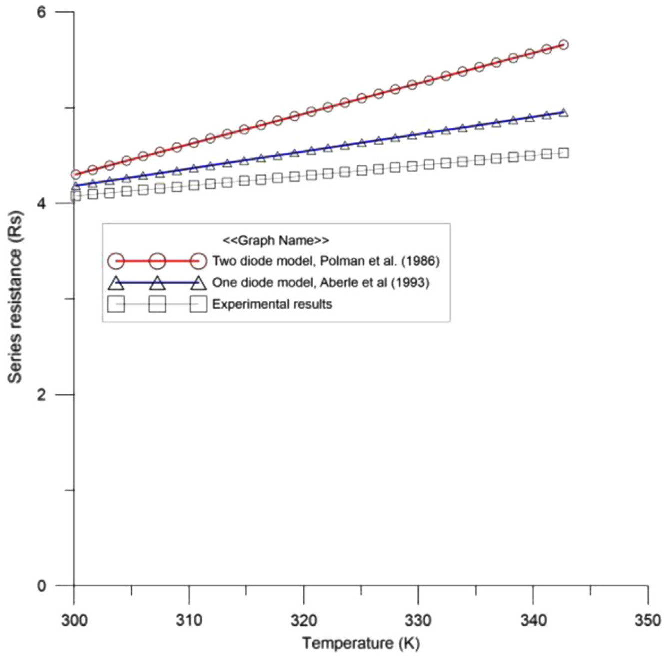

Fig. 13. A comparison between single-diode and double-diode model with real results based for the series resistance (R_s).

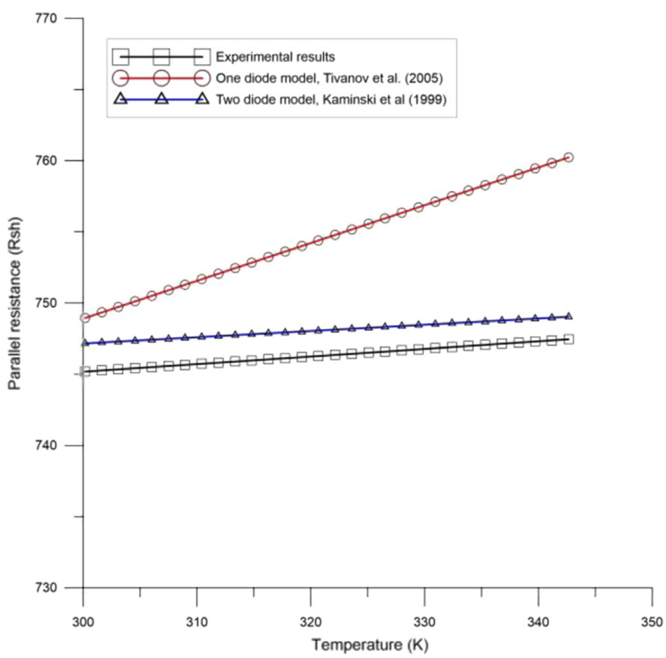

Fig. 14. A comparison between the single-diode and double diode model with real results based for the parallel resistance (R_{sh}).

conditions, as these are the real operating conditions for a solar cell. Few works have applied the methods that utilize the dark measurements. One such method is Model no. 5, which is the four-parameter model developed by Jia and Anderson. By contrast, Model no. 2, which is the one-parameter model developed by Aberle et al., uses both dark conditions and illumination conditions.

The equation that mathematically describes the behavior of solar cells depends on the model chosen for the solar cell. The most widely used model is the single-diode model because of its simplicity. Moreover, this model describes well the characteristics of the majority of solar cell behaviors. However, the double-diode model exhibits better accuracy (in terms of DC parameter

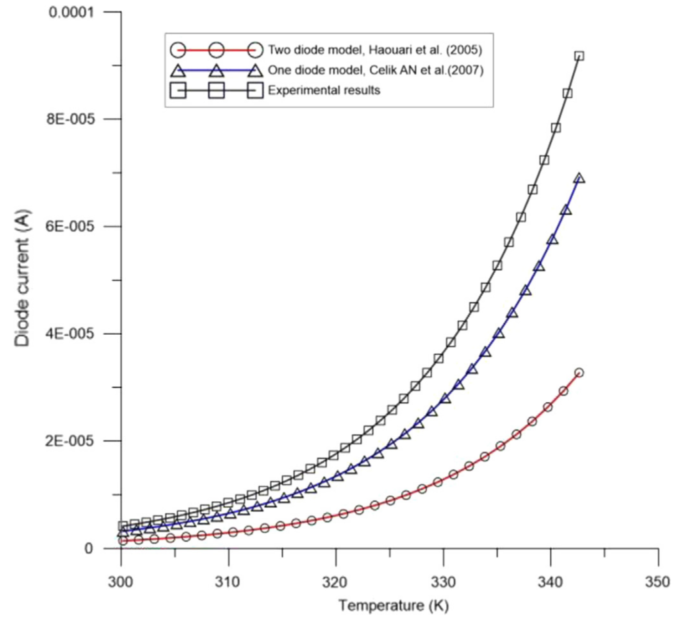

Fig. 15. A comparison between single-diode and double-diode model with real results based for the diode current (I_o).

characteristics) than the single-diode model, as shown in Figs. 11–15 [4,47].

The first five models that are presented in this paper allow the determination of the five parameters: I_{ph}, I_o, R_s, R_{sh}, and n. The subsequent models then allow the determination of a part of these parameters, such as four, three, two, or even only one parameter (i.e., series resistance, which is the most commonly taken parameter of solar cells). The values of I_{sc} and V_{oc}, and implicitly V_{mpp} and I_{mpp}, can be determined from the experimental data [56].

Most of the models that allow the determination of all five parameters use the least-squares numerical techniques suggested in Eqs. (2) and (3). Consequently, the non-linear fitting procedure becomes complex. With the approximation $R_sI \ll V$, Eq. (2) becomes a direct equation, and the fitting procedure becomes simpler. Such approximation holds for a solar cell with small area, which implies that the current is small for low-level illuminations. By using Lambert W-function, Eq. (2) becomes an explicit equation where I is $I(V)$, [57] and the fitting procedure simplifies the approach. The extraction process is easier when implemented on consecrated software such as MATLAB, among other software. In MATLAB, only a few lines of code are necessary for such purpose [34].

The accuracy of the fitting procedure depends on the selected fitting algorithm, particularly on the initial values of the fitting parameters and the confidence interval. The models in which the ideality factor of the diode gives a value of one and the shunt resistance is considered infinite must be carefully used. Model no. 3 is a one-parameter model that shows how the value of the series resistance changes when the value of n takes the real value or the theoretical value ($n = 1$).

Solar cell parameters such as R_s, n, R_{sh}, and I_L depend on the irradiance levels [58-60]. However, some researchers [10,34] claim that these parameters also depend on the operating temperature of the solar cell. The series resistance obtained under dark conditions is underestimated. The series resistance is higher because of the larger lateral electron flow in the emitter under illuminated conditions, which is the normal operating mode for solar cells.

To obtain a clear understanding of these five parameters, they are tested and evaluated for different levels of illumination and temperatures, as shown in Figs. 11–15. The outcomes of these five figures clarify that the double-diode model is more accurate than the single-diode model for all test parameters. However, as stated, the single-diode model is the most widely used model because it is simple and can adequately describe the characteristic behavior of most solar cells.

Thus, some suggestions based on the discussion are provided in the following abridged points:

1. The five-parameter model is the most widely used model, particularly for outdoor condition tests. Thus, it should be equipped with better accuracy by taking into consideration all of the available DC parameters. However, this could increase the complexity of the model.
2. The easiest extraction model is the one-parameter model. However, the lack of parameters may affect the accuracy of the model. Therefore, an appropriate equation, such as the widely used R_s equation, must be built and selected carefully.
3. The single-diode model is the simplest approach for building a solar cell model because it can sufficiently describe the PV characteristics of most solar cells. Therefore, it can be applied in the majority of built models, particularly for the case of rapidly changing weather conditions [21].
4. In the normal weather condition test, the double-diode model is the most preferred because it exhibits a better result than the single-diode model.

7. Conclusions

This review discussed, summarized, and classified the techniques for DC parameter extraction. These DC parameters that compose the *I–V* characteristics of the PV solar cells were reproduced in this review either with a single-diode model or a double-diode model. In this review, all of the available five parameters (I_L, I_o, R_s, R_{sh}, and n) were extracted by using different reviewed models.

The extraction techniques were categorized into five main groups. The first group comprised the approaches that extracted five parameters, of which the first four models are based on single-diode model and the last model is based on a double-diode model. The second, third, fourth, and fifth groups consists of the techniques that extracted four, three, two, and one parameter, respectively. These techniques were organized in such a way that they might be efficiently presented in the most appropriate models to afford the values for the five DC parameters of the solar cells. Thus, considering the results of the evaluation of the techniques delineated in this article, the researcher might select the appropriate model on the basis of the structure of the experiment and the selected implements.

Acknowledgments

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