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A new simplified method for efficient extraction of solar cells and modules parameters from datasheet information

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Abstract

An accurate and straightforward estimation of solar cells and modules parameters from the manufacturer's datasheet is essential for the performance assessment, simulation, design, and quality control. In this work, a simple and efficient technique is reported to extract the parameters of solar cells and modules, namely ideality factor (n), series resistance (R_s), shunt resistance (R_{sh}), photocurrent (I_{ph}) and saturation current (I_o), from datasheet information. The method is based on defining the peak position of the function $f(n, R_{sh}) = n(R_{sh\_max} - R_{sh})$, at which the five parameters are extracted. It was validated on four different technologies of solar cells and modules, including Poly-Si, Mono-Si, thin film and multijunction. Results showed that a simple and efficient extraction of the parameters can be realized by using this technique compared to that of the reported methods in literature.

Keywords: Solar cell, PV module, parameter extraction, simple approach, datasheet information.

1. Introduction

Solar energy is a promising resource to fulfil the future demand of human on energy owing to its diverse utilization, cleanliness, environmentally friendliness and freely abundancy. The conversion of sunlight energy to electricity is implemented by means of solar cells and modules in a technology known as photovoltaic (PV) technology. There are different types of solar modules available on the market, namely mono-crystalline silicon, multi-crystalline and amorphous [1-3]. Modeling of the current-voltage (*I-V*) characteristics of solar modules is essential for the performance assessment, simulation, design, and quality control [4-7]. This can only be achieved if the parameters of these devices are accurately determined. Estimating the parameters of PV modules is also vital to predict the energy yield [8], to build algorithms for maximum power point trackers (MPPTs) [9,10], to develop plug-in hybrid electric vehicles (PHEVs) [11], to address the degradation and aging issues in PV devices [12,13] and to understand the outdoor operation of PV panels in various environmental conditions [14]. The parameters of solar cells and modules are ideality factor (n), series resistance (R_s), shunt resistance (R_{sh}), photocurrent (I_{ph}) and saturation current (I_o). Because these parameters are highly sensitive to the irradiance, light energy, cells temperature and aging [15-17,5,18-20], researchers usually face a big challenge in modelling the *I-V* characteristics of solar modules in different environmental conditions.

Along this line, researchers usually depend on two main datasets to determine the parameters of solar cells and modules. The first dataset is the experimentally measured *I-V* data, while the second dataset is obtained from the datasheet information, which is provided by the manufacturers of the solar cells and modules. It is known that the parameters of solar modules can be accurately extracted from the measured *I-V* data [21-25]. However, the datasheet information does not include the measured *I-V* data of the module. Alternatively, manufacturers of solar cells and modules provide a datasheet information, which includes the short circuit current (I_{sc}), open circuit voltage (V_{oc}), voltage at maximum power (V_m), current at maximum power (I_m) and temperature coefficients of current, voltage and power at standard test condition (STC). Consequently, methods that depend on the datasheet information to determine the solar module parameters are of great importance for the researchers, technicians, end-users and PV designers in order to assess the solar modules under diverse conditions, thereby predicting the performance of PV systems before their real implementation [26].

The challenge is therefore how one simply and efficiently extract the parameters of solar cells and modules from the datasheet information [27,28]. Researchers proposed different analytical and numerical methods to determine these parameters with the help of single-diode model (SDM) [29-31,28,32,27]. Also, evolutionary and heuristic algorithms were utilized to extract the parameters of solar modules [33-44], but these techniques suffer from a high computational cost and reduced stability. We previously reported two computational methods that can be used to efficiently determine the modules parameters from measured *I-V* data [21,22]. However, these methods are not applicable to extract the parameters from datasheet information. A review of literature revealed that iterative approaches can be adopted to achieve a simpler estimation of the parameters compared to that of the computational and deterministic methods. For instance, Sera *et al.* involved R_s, R_{sh} and n iteratively, thereby extracting the rest of parameters [45]. On the other hand, Villalva *et al.* considered a random value for the ideality factor while iterating the values of R_s and R_{sh} to the point where the simulated and experimental power are coincided at STC [46]. Chaibi *et al.* reported a simplified method to extract the PV parameters by iterating only the shunt resistance [47]. However, in order to determine the parameters, minimum and maximum R_{sh} values are required to be selected manually based on the type of the investigated solar module technology. We have observed that the accuracy of simulated current is highly sensitive to the values of n and R_s, but less sensitive to the I_{ph}, I_o and R_{sh} [22]. Taking into account the strong dependency of all the parameters on the ideality factor, we came to the hypothesis that iterating the ideality factor (n), in fine-tuned steps, might be helpful in achieving a simpler, more accurate and computationally cost-effective approach to determine the electrical parameters of solar cells and modules using datasheet information only. Therefore, in the current work, a new method is reported to determine the parameters of solar cells and modules from the datasheet information. The approach is initialized by a fine-tuned iteration of ideality factor through which all other parameters are extracted without any prior initialization or limitations to the values of R_s and R_{sh}.

2. Methodology

The equation of single-diode model (SDM) used to simulate the *I-V* characteristic of solar cells is given by:

$$I = I_{ph} - I_o \left[\exp\left(\frac{V + IR_s}{aV_t}\right) - 1\right] - \frac{(V + IR_s)}{R_{sh}} \dots\dots\dots\dots\dots (1)$$

where a is the ideality factor of the solar cell, I_o is the saturation current in dark condition and V_t is the thermal voltage $(k_B T/q)$. The k_B is Boltzmann's constant, T is the cell's temperature in Kelvin, q is the elementary charge, while R_s and R_{sh} are the series and shunt resistance, respectively. Because PV module is composed of N_s series connected cells, the value of a in Equation 1 is replaced by $n = N_s \times a$ in the subsequent mathematical operations.

Based on the characteristic curve of solar cells, it is possible to derive three formulas from Equation 1, considering the boundary conditions at open circuit voltage (V_{oc}), short circuit current (I_{sc}) and maximum power (P_m) as follows, respectively:

$$0 = I_{ph} + I_o - I_o \exp\left(\frac{V_{oc}}{nV_t}\right) - \frac{V_{oc}}{R_{sh}} \dots\dots\dots\dots\dots (2)$$

$$I_{sc} = I_{ph} + I_o - I_o \exp\left(\frac{R_s I_{sc}}{nV_t}\right) - \frac{R_s I_{sc}}{R_{sh}} \dots\dots\dots\dots\dots (3)$$

$$I_m = I_{ph} + I_o - I_o \exp\left(\frac{R_s I_m + V_m}{nV_t}\right) - \frac{R_s I_m}{R_{sh}} - \frac{V_m}{R_{sh}} \dots\dots\dots\dots\dots (4)$$

Subtracting Equation 2 from 3 and solving for the saturation current (I_o), one can get:

$$I_o = \frac{I_{sc} - \frac{V_{oc}}{R_{sh}} + \frac{R_s}{R_{sh}} I_{sc}}{\exp\left(\frac{V_{oc}}{nV_t}\right) - \exp\left(\frac{R_s I_{sc}}{nV_t}\right)} \dots\dots\dots\dots\dots (5)$$

A safe approximation is to neglect $\exp\left(\frac{R_s I_{sc}}{nV_t}\right)$ due to its very small value [48,31,49,50]. Hence, Equation 3 and 5 can be respectively reduced to:

$$I_{ph} = I_{sc} - I_o + \frac{R_s I_{sc}}{R_{sh}} \dots\dots\dots\dots\dots (6)$$

$$I_o = \frac{I_{sc} - \frac{V_{oc}}{R_{sh}} + \frac{R_s}{R_{sh}} I_{sc}}{\exp\left(\frac{V_{oc}}{nV_t}\right)} \dots\dots\dots\dots\dots \ (7)$$

It is known that when the internal impedance (Z_{in}) of the solar cell is equal to the impedance of the external load (Z_{out}), maximum power (P_m) is delivered, that is where:

$$Z_{in} = Z_{out} = \frac{V_m}{I_m} \dots\dots\dots\dots\dots (8)$$

Moreover, from the single-diode model, the impedance function can be represented by:

$$\frac{R_{sh} r_d}{R_{sh} + r_d} + R_s = \frac{V_m}{I_m} \dots\dots\dots\dots\dots (9)$$

Where r_d is the dynamic resistance of the diode at P_{max}, which can be determined from the first derivative of the diode voltage with respect to its current as follows:

$$r_d = \left.\frac{dV_D}{dI_D}\right|_{P_m} = \frac{nV_t}{I_o exp(\frac{R_s I_m + V_m}{nV_t})} \dots\dots\dots\dots\dots (10)$$

Substituting Equation 10 into 9 and performing some mathematical manipulations, it yields:

$$I_o \exp\left(\frac{R_s I_m + V_m}{nV_t}\right) = \frac{nV_t (I_m - \frac{V_m}{R_{sh}} + \frac{R_s I_m}{R_{sh}})}{V_m - R_s I_m} \dots\dots\dots\dots\dots (11)$$

Furthermore, by subtracting Equation 2 from 4 and inserting Equation 7 one can achieve:

$$I_o \exp\left(\frac{R_s I_m + V_m}{nV_t}\right) = I_{sc} - I_m + \frac{R_s}{R_{sh}}(I_{sc} - I_m) - \frac{V_m}{R_{sh}} \dots\dots\dots\dots\dots (12)$$

Now, from Equation 11 and 12 an explicit formula for R_{sh} is obtained:

$$R_{sh} = \frac{V_m^2 + R_s^2(I_{sc} I_m - I_m^2) + R_s(nV_t I_m - I_{sc} V_m) - nV_t V_m}{R_s(I_m^2 - I_{sc} I_m) + V_m(I_{sc} - I_m) - nV_t I_m} \dots\dots\dots\dots\dots (13)$$

Another explicit form of R_{sh} can be derived from Equation 6 and 4 to achieve:

$$I_{ph} + I_o = I_{sc} + \frac{R_s I_{sc}}{R_{sh}} = I_m + I_o \exp\left(\frac{R_s I_m + V_m}{nV_t}\right) + \frac{R_s I_m}{R_{sh}} + \frac{V_m}{R_{sh}} \dots\dots\dots\dots\dots (14)$$

By substituting Equation 7 into Equation 14 and solving for R_{sh}, one can get:

$$R_{sh} = \frac{R_s I_{sc} A - V_{oc} A - R_s I_{sc} + R_s I_m + V_m}{I_{sc} - I_m - I_{sc} A} \dots\dots\dots\dots\dots (15)$$

where $A = \exp\left(\frac{R_s I_m + V_m - V_{oc}}{n V_t}\right)$.

Now, by equating Equation 13 and 15, an implicit form of R_s can be derived, which is:

$$R_s = \frac{V_{oc} V_m (I_{sc} - I_m) + n V_t (I_{sc} V_m - I_m V_{oc}) - V_m^2 I_{sc} + \frac{n V_t V_m (2 I_m - I_{sc})}{A}}{I_{sc} I_m (V_{oc} - V_m) - I_m^2 V_{oc}} \qquad (16)$$

From Equation 13 and 16, it is obvious that the value of R_s and R_{sh} can be efficiently determined if and only if the ideality factor is accurately identified. A review of literature showed that it is hard to find the accurate value of ideality factor as its value is highly dependent on the parasitic resistances [51,52]. Hence, researchers utilized some approximate equations to determine the value of ideality factor [53-57]. This is ultimately led to inaccurate extraction of the other parameters due to their dependence on the ideality factor. Therefore, in the current work, the value of ideality factor is iterating in fine steps in order to determine the five parameters as accurate as possible, following the detailed procedure which is given in the next subsection.

It is worth to mention that the proposed technique utilizes the main datasheet information provided by the manufacturer, as shown in Table 1. The accuracy and robustness of the proposed method is validated on four different technologies of PV modules, namely mono-crystalline, poly-crystalline, thin film and hybrid/multilayer. One can see that there are three unknown parameters to be determined from Equation 13 and 16, namely n, R_s and R_{sh}. Therefore, the target is to reduce them to two unknown parameters. This is realized by iterating the value of n in Equation 16 and 13 respectively to determine R_s (using fzero function in MATLAB) and R_{sh}. Later on, the values of I_{ph} and I_o can be extracted at the accurate value of n using Equation 6 and 7, respectively.

Table 1. The utilized datasheet information provided by the manufacturer at STC.

PV module (Type)	SM55 (Mono-Si)	KC200GT (Poly-Si)	ST40 (Thin film)
V_m (V)	17.4	26.3	16.6
I_m (A)	3.15	7.61	2.41
V_{oc} (V)	21.7	32.9	23.3
I_{sc} (A)	3.45	8.21	2.68
N_{cell}	36	54	36

An interesting correlation was observed between R_{sh} and n (see Figure 1), from which an empirical formula was derived and used to determine the value of ideality factor and shunt resistance as follows:

$$f(n, R_{sh}) = n\left(R_{sh\_max} - R_{sh}\right) \quad \dots\dots\dots\dots\dots (17)$$

Where R_{sh_max} is the maximum positive value of shunt resistance over the iterated interval of the ideality factor, where $0 < R_{sh} \leq R_{shmax}$ is held. It has been found that at the knee point on the curve of R_{sh} versus n, i.e. at the peak value of $f(n, R_{sh})$, as shown in Figure 1 for the representative SM55 PV module, minimum relative error was obtained between the datasheet and calculated currents. Therefore, the values of n and R_{sh} are first extracted at the peak of $f(n, R_{sh})$ and then they are used to determine the other parameters. The implementation steps of the proposed technique are shown in Figure 2.

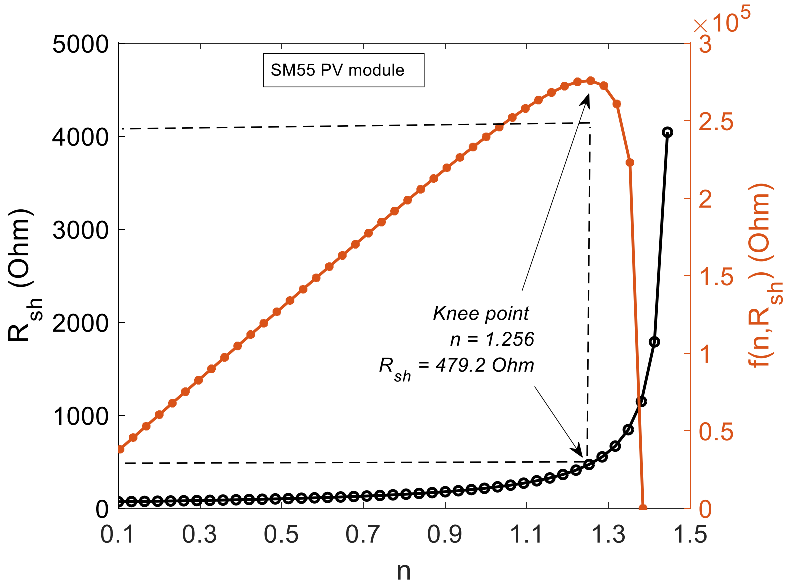


Figure 1. Plot of R_{sh} versus n and $f(n,R_{sh})$ for the representative SM55 PV module.

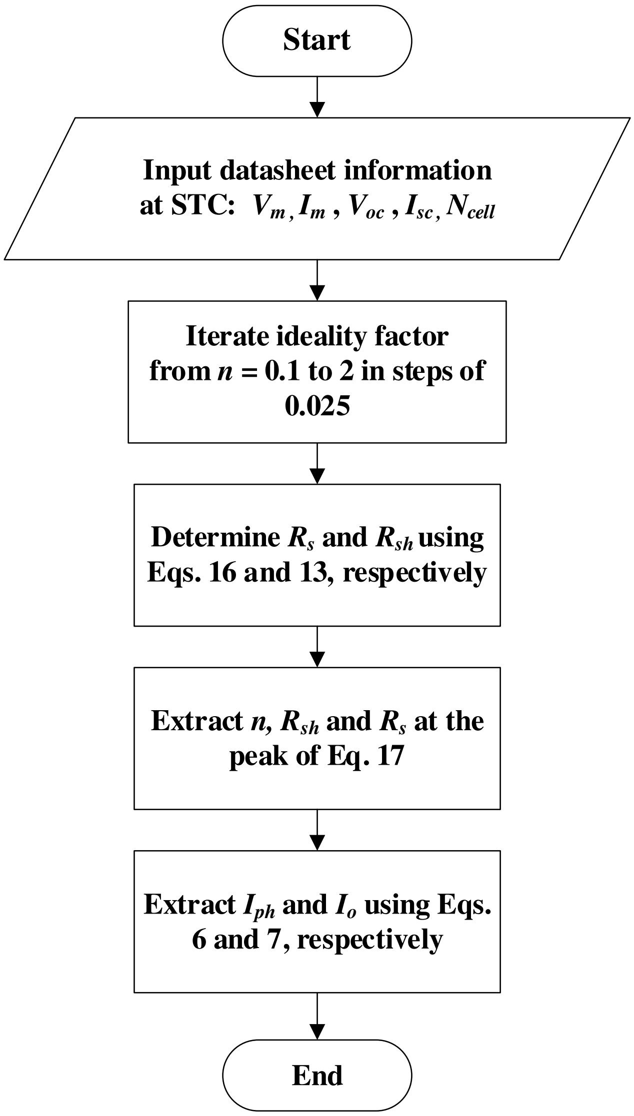


Figure 2. Flowchart of the proposed method to compute the parameters of PV modules.

3. Results and Discussion

Validation of the proposed method was first performed by extracting the parameters of three PV modules, namely mono-Si (SM55), poly-Si (KC200GT) and thin film (ST40), while the obtained results were compared to that of the datasheet information and those reported in literature using different techniques. By considering the datasheet information shown in Table 1 for each of the modules and a simple iteration of ideality factor, the electrical parameters were determined, as shown in Table 2.

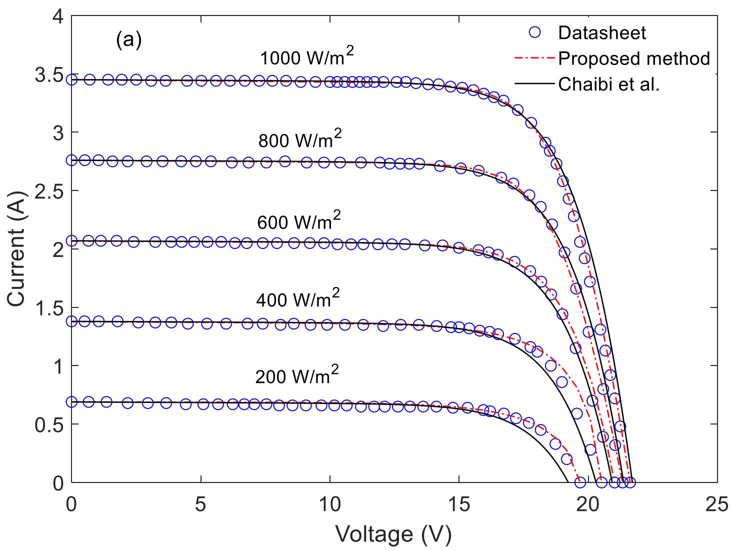
Table 2. Computed parameters using the proposed iterative technique at STC.

PV module (Type)	SM55 (Mono-Si)	KC200GT (Poly-Si)	ST40 (Thin film)
n	1.256	1.192	1.992
R_s (Ω)	0.381	0.212	0.899
R_{sh} (Ω)	479.2	388.6	278.2
I_o (A)	2.816E-8	1.675E-8	6.519E-6
I_{ph} (A)	3.453	8.184	2.687
Relative error	1.040%	1.87%	2.66%

Consequently, the calculated parameters were employed to simulate the *I-V* characteristics for each technology. Later on, the *I-V* curves were compared to that extracted from the manufacturer datasheet [5,58] and those reported in literature by iterative methods under the changes of irradiance and temperature [47,59,19,46]. In order to quantitatively investigate the accuracy of the proposed technique, the maximum relative errors between calculated and manufacturer currents were determined and compared to those achieved by other researchers for the PV modules under different irradiance levels, as shown in Table 3. One can notice from the results that the proposed method has performed very well for both mono- and poly-Si PV modules at low and high irradiance levels. Generally, the calculated results well matched with the datasheet results and outperformed those reported in literature for all types of the PV modules, as shown in Figure 2 and Table 3. However, it was somehow weak against the thin film-based PV module (ST40). Comparably, the parameters determined from the methods proposed by El Achouby et al. and Zaimi et al. [19,59] were found not to be applicable for thin film PV modules due to large errors, while they are more accurate for the mono- and poly-Si technologies.

Table 3. Maximum relative error of the proposed method and those reported in literature applied on different PV technologies at temperature 25 ºC and varied irradiance.

PV module (Type)	Irradiance (W/m^2)	This work	Chaibi *et al.* [47]
SM55 (Mono-Si)	200	**1.71%**	2.38%
	400	4.94%	**2.31%**
	600	**1.71%**	2.02%
	800	**0.44%**	0.89%
	1000	**1.04%**	1.41%
KC200GT (Poly-Si)	200	**3.97%**	4.38%
	400	5.01%	**4.03%**
	600	**3.93%**	4.19%
	800	**1.82%**	2.38%
	1000	**1.87%**	2.19%
ST40 (Thin film)	200	**2.01%**	2.40%
	400	1.24%	**0.98%**
	600	3.01%	1.05%
	800	**1.86%**	2.13%
	1000	**1.66%**	1.73%



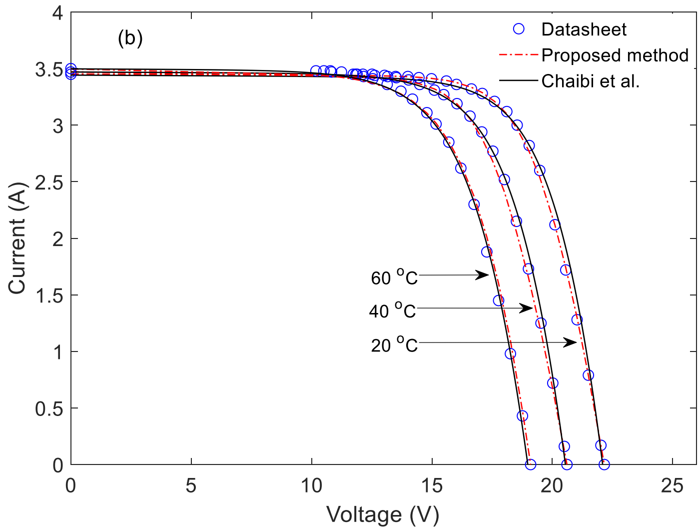


Figure 2. The datasheet and simulated *I-V* curves of the SM55 PV module under (a) uniform change of irradiance and fixed T = 25 °C, and (b) uniform change of temperature and G = 1000 W/m^2.

Figure 3 and 4 show the simulated *I-V* curves for KC200GT and ST40 PV modules that were produced from the parameter's estimation by the proposed approach, the method of Chaibi's et al. and datasheet based *I-V*. It can be seen that the proposed iterative method is well fitting the measured data at varied irradiance and temperature. Noteworthy, there has been less deviation of the calculated curves from those of the measured ones at low temperatures and high irradiances, implying efficient response of the proposed method compared to those reported in literature.

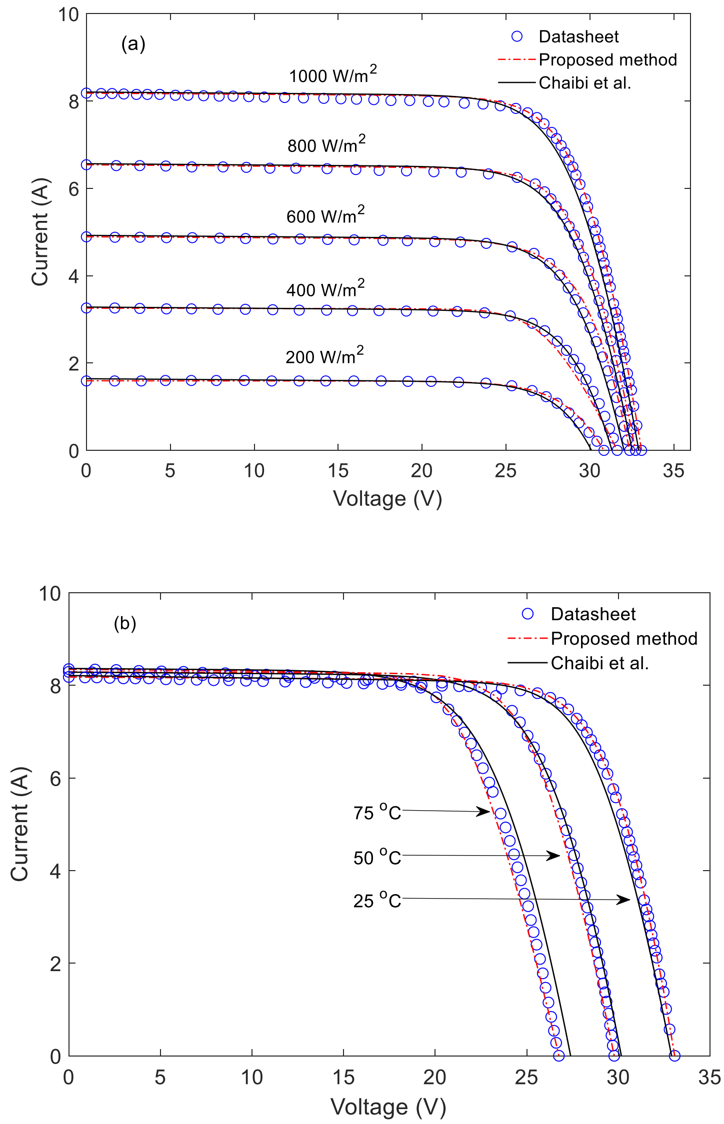
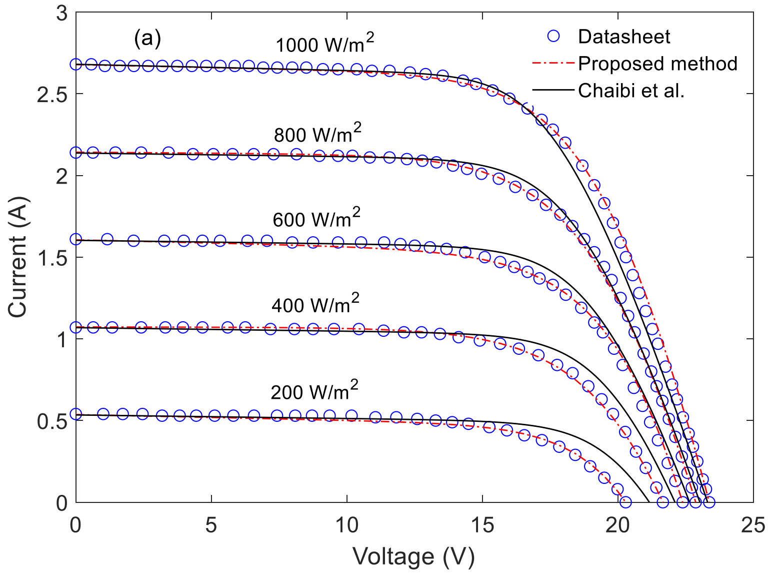


Figure 3. The datasheet and simulated *I-V* curves of the KC200GT PV module under (a) uniform change of irradiance and fixed T = 25 ºC, and (b) uniform change of temperature and G = 1000 W/m^2.



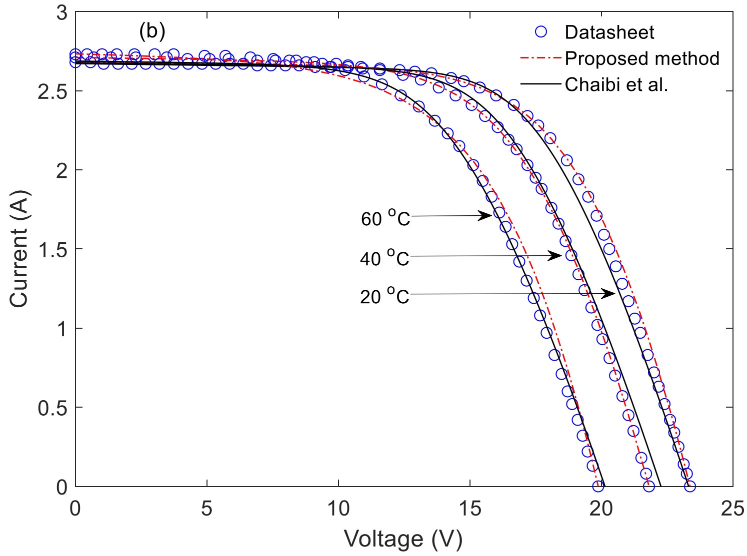


Figure 4. The datasheet and simulated *I-V* curves of the ST40 PV module under (a) uniform change of irradiance and fixed T = 25 °C, and (b) uniform change of temperature and G = 1000 W/m^2.

Table 4 shows the maximum relative error between the datasheet and proposed method for different PV technologies at irradiance 100 W/m^2 and varied temperature. Compared to the other methods, it is noticeable that the proposed method is performing better in the low temperature range of PV modules. However, at high temperatures the Chaibi's et al. method is more efficient. Interestingly, the proposed approach has performed well for thin film PV technology even at relatively high temperatures of about 50 ºC.

Table 4. Maximum relative error of the proposed method and those reported in literature applied on different PV technologies at irradiance 100 W/m^2 and varied temperature.

PV module (Type)	**Temperature (ºC)**	**This work**	**Chaibi *et al.* [47]**
SM55 (Mono-Si)	20	**0.64%**	1.02%
	40	**0.76%**	0.78%
	60	2.75%	**0.62%**
KC200GT (Poly-Si)	20	**1.87%**	2.19%
	40	2.60%	**1.24%**
	60	**1.02%**	1.90%
ST40 (Thin film)	25	3.55%	1.44%
	50	**1.14%**	1.31%
	75	**2.10%**	2.39%

To further validate the proposed method, parameters determination was also performed for a hybrid/multijunction PV module, thin triple-junction CTJ30, which consists of three series cells tested at STC [60]. Table 5 includes the datasheet based *I-V* data, which was extracted by Origin pro digitalize software, and the calculated currents using the proposed method. As such, the electrical parameters of the PV module were determined to be n = 1.028, R_s = 0.055 Ω, R_{sh} = 425 Ω, I_o = 2.83E-15 A and I_{ph} = 0.473 A with the relative error of about 2.86%. Figure 5 shows a comparison of the calculated *I-V* curve to that of the datasheet *I-V* for the CTJ30 PV module investigated at STC. One can see that the simulation result is very well matched with the measured data, where a small deviation can be noticed along the whole dataset except the MPP at which a relatively increased deviation is noticed. Concludingly, the proposed technique is highly effective to determine the parameters of all types of solar cells and modules easily and efficiently by using the datasheet information.

Table 5. Determined parameters of CTJ30 PV module at STC using the proposed technique.

Voltage (V)	Datasheet current (A)	Calculated current (A)	Absolute error
0.000	0.473	0.4730	0.0000
0.139	0.472	0.4728	0.0008
0.297	0.472	0.4727	0.0007
0.445	0.472	0.4726	0.0006
0.577	0.471	0.4724	0.0014
0.722	0.471	0.4723	0.0013
0.880	0.471	0.4721	0.0011
1.022	0.470	0.4720	0.0020
1.189	0.470	0.4718	0.0018
1.344	0.470	0.4717	0.0017
1.489	0.470	0.4715	0.0015
1.640	0.469	0.4714	0.0024
1.779	0.468	0.4712	0.0032
1.940	0.467	0.4708	0.0038
2.078	0.465	0.4694	0.0044
2.204	0.461	0.4644	0.0034
2.314	0.452	0.4487	0.0033
2.385	0.428	0.4223	0.0057
2.420	0.401	0.3997	0.0013
2.458	0.367	0.3637	0.0033
2.484	0.332	0.3297	0.0023
2.504	0.300	0.2969	0.0031
2.520	0.264	0.2658	0.0018
2.539	0.227	0.2223	0.0047
2.552	0.197	0.1880	0.0090
2.561	0.159	0.1618	0.0028
2.574	0.122	0.1203	0.0017
2.587	0.084	0.0741	0.0099
2.600	0.045	0.0229	0.0221
2.610	0.000	-0.020	0.0200
		Average relative error	2.86%

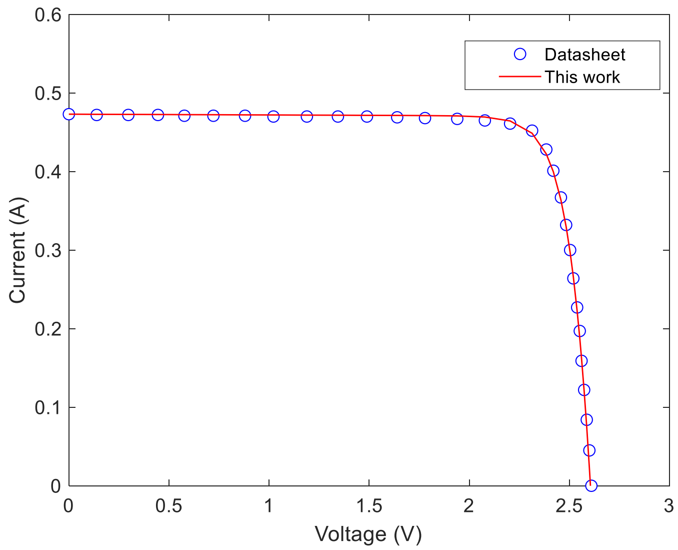


Figure 5. The datasheet and simulated *I-V* curve of the CTJ30 PV module at STC.

In comparison to the reported methods in terms of simplicity, a qualitative assessment was performed considering the required datasheet information as input, the initial values to proceed with the iterations and the applicability of the method to various PV technologies. Table 6 shows the analysis of the investigation, where the proposed approach requires only the iteration of ideality factor with respect to the series and shunt resistances. Besides, it uses a simple mathematical approach to determine the value of ideality factor, while most of the other approaches utilize a complex computation or a reduced equation which leads to underestimate the value of n. In conclusion, the proposed technique can efficiently and simply determine the parameters at different variations of temperature and irradiance.

Table 6: Comparison of the proposed method with other iterative methods reported in literature.

Iterative methods	**Required data**	**Initial values**	**Complexity**	**Module technology**
Chaibi et al. [47]	I_m, V_m, P_m, I_{sc}, V_{oc}, N_{cell}, K_i, V_{th}	R_{sh0}	Low	Poly-Si, Mono-Si, Thin-film
This work	I_m, V_m, I_{sc}, V_{oc}, N_{cell}, V_{th}	n	Very low	Poly-Si, Mono-Si, Thin-film, Hybrid

4. Conclusions

A simple iterative method was successfully implemented on different PV technologies to determine their parameters from datasheet information only. It has been found that with the help of iterating the ideality factor, it is possible to build a fruitful correlation between R_{sh} and n, which has led to derive an empirical formula through which all the parameters were determined at the peak value of the function. It was seen that the proposed method outperformed the other iterative techniques reported in literature, especially at high irradiances and low temperatures which presented a competitive accuracy despite its simplicity. The proposed technique is highly effective to determine the parameters of all types of solar cells and modules easily and efficiently by using the datasheet information.

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Conflicts of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

Author contributions

Conceptualization, Methodology, Formal analysis and investigation, Writing - original draft preparation, Writing - review and editing: Fahmi F. Muhammadsharif

Availability of data and material

The data and material are available within the manuscript.

Compliance with ethical standards

Not applicable

Consent to participate

Not applicable

Consent for Publication

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Figures

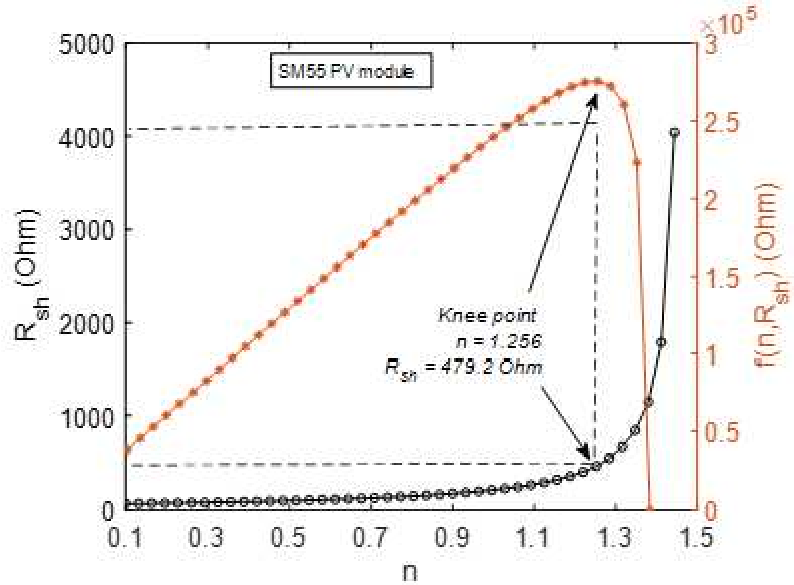


Figure 1

Plot of Rsh versus n and f(n,Rsh) for the representative SM55 PV module.

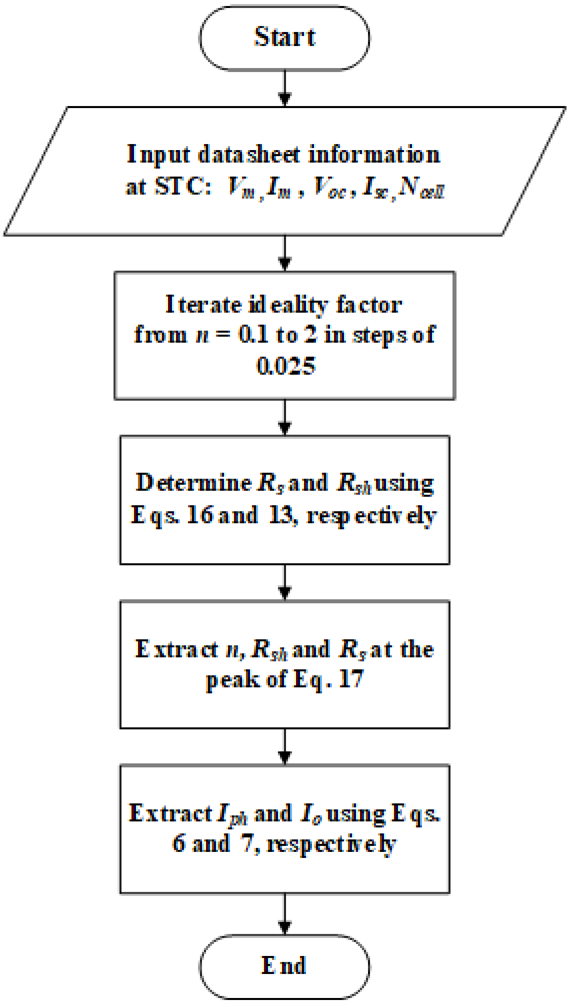
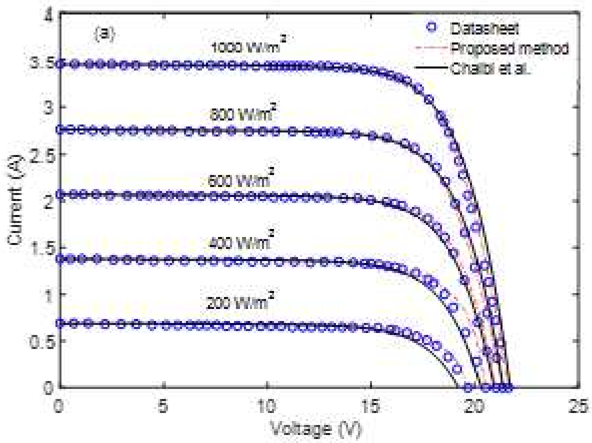


Figure 2

Flowchart of the proposed method to compute the parameters of PV modules.



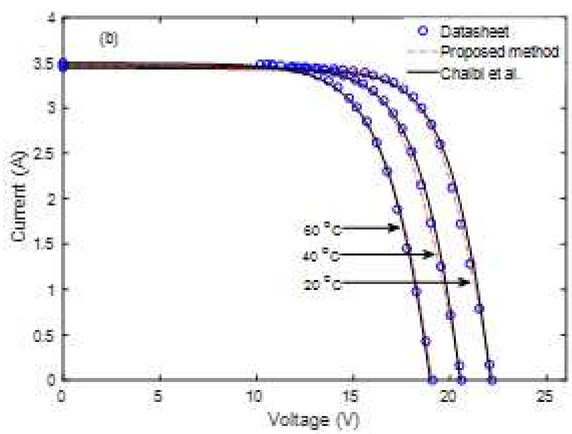


Figure 3

The datasheet and simulated I-V curves of the SM55 PV module under (a) uniform change of irradiance and fixed T = 25 oC, and (b) uniform change of temperature and G = 1000 W/m2.

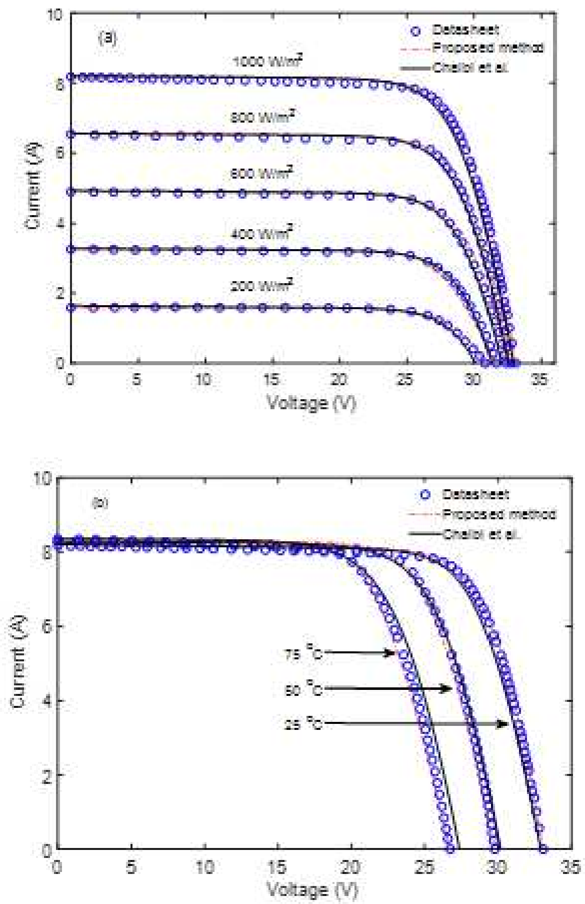
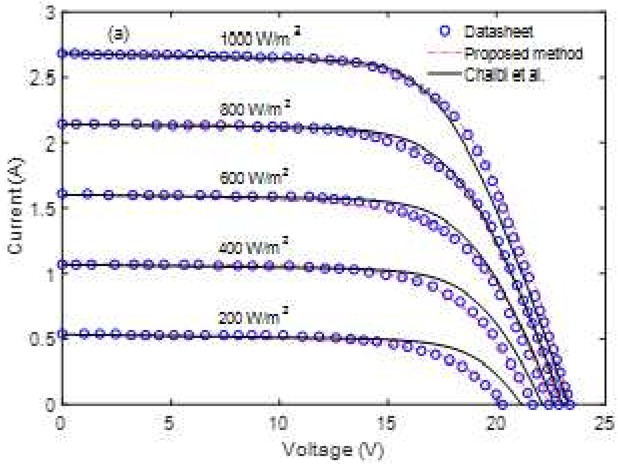


Figure 4

The datasheet and simulated I-V curves of the KC200GT PV module under (a) uniform change of irradiance and fixed T = 25 oC, and (b) uniform change of temperature and G = 1000 W/m2.



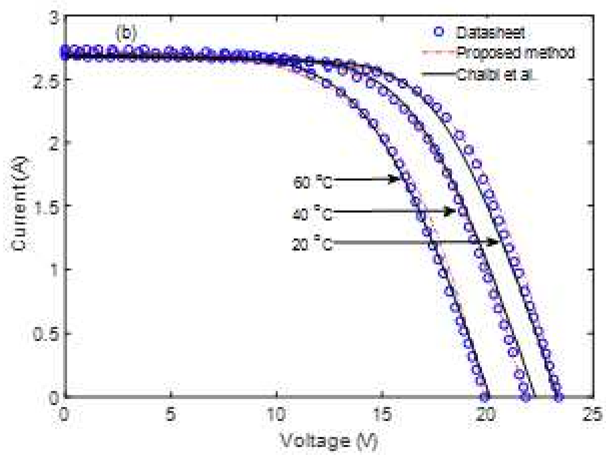


Figure 5

The datasheet and simulated I-V curves of the ST40 PV module under (a) uniform change of irradiance and fixed T = 25 oC, and (b) uniform change of temperature and G = 1000 W/m2.