Ethiopian Journal of Science and Sustainable Development

e-ISSN 2663-3205 Volume 10 (2), 2023

Journal Home Page: www.ejssd.astu.edu.et

Research Paper

Analytical Extraction of Physical Parameters of Dye-Sensitized Solar Cells Using Four Points on the Irradiated Density Current-Voltage Curve

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Article Info

Article History:
Received 12 September 2022
Received in revised form 2 March 2023
Accepted 6 March 2023

Keywords:
Power law density current-voltage model, Maximum power point, fill factor, Dye-sensitized solar cells, Physical parameters

Abstract

An exact current density-voltage (J-V) equation of an effective and applicable solar cell is intrinsically implicit, which requires iterative computations to obtain the fill factor and the peak power point. A simple explicit power law J-V model was applied to 14 dye-sensitized solar cells. The model permits an easy prediction of the entire J-V curve, highest power point, and fill factor from four simple measurements of the bias points corresponding to Voc, ~0.6Voc, Jsc, and ~0.6Jsc, where Voc is the open circuit voltage and Jsc is the short circuit current density. Also, the model gives a closed-form description of the J-V curve, maximum power point, and fill factor (FF) in terms of the physical parameters of the single exponential model. The results show that all the model parameters are regular, unlike previous findings that reported parameter irregularities of varying degrees. Furthermore, the DSSCs are grouped into two classes as good or bad based on their FF values such that 12 (86%) with 0.45<<FF<<0.81 are good, while only 2 (14%) with FF<0.45 are bad.

1. Introduction

This study investigates the extraction of the five-model parameters of the single exponential current density-voltage (J-V) equation of irradiated solar cells given by Ibrahim and Anani (2017).

$$J = J_{ph} - J_o\left[e^{\left(\frac{V+JR_s}{a}\right)} - 1\right] - \frac{V+JR_s}{R_{sh}}, \ldots\ldots (1)$$

where all symbols have their usual meanings. The modified diode ideality factor is defined as $a = nV_T$ and the thermal voltage of the diode by $V_T = \frac{kT}{q}$. Therefore, "a" is proportional to "n" and V_T is the constant of proportionality when the temperature is constant. The advantage of using "a" over "n" is that it makes the equation simple and neat.

There are usually two sets of input data required for the analysis of the performance of a solar cell: the input data provided by the manufacturers and the input data extracted from the J-V curve obtained from experimental measurement. Considering the former, an understanding of these parameters of manufactured solar cells is required for cell module/array simulation and efficiency optimization. The five-point analytical calculation method (Chan et al., 1986) requires a detailed mechanism and accurate measurement of

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https://doi.org/10.20372/ejssdastu:v10.i2.2023.547

$\frac{dJ}{dV}|_{v=v_{0c}}$, $\frac{dV}{dJ}|_{J=J_{sc}}$ and the peak power point (J_p, V_p), which is not easy. In the latter set, direct measurement is intricate and is feasible only when the J-V curve has different regions, where parameters other than the one being extracted can be assumed insignificant (Chan et al., 1986; Pallares et al., 2006). It is worth noting that parameter extraction by curve fitting needs observation of a large number of points, previous knowledge of the parameters of interest, that is, suitable initial guesses and rigorous calculations (Bouzidi et al., 2007; Chan et al., 1986; Ortiz-Conde et al., 2006; Pallares et al., 2006; Yerima et al., 2022a).

In the recent past, Karmalkar and Haneefa (2008) discussed an explicit power-law J-V model of irradiated solar cells that allowed extraction of the highest power point & fill-factor from only four simple measurements of "V_{oc}", "J_{sc}", "$V|_{J=0.6J_{sc}}$", and "$J|_{V=0.6V_{oc}}$". It is against this background that we were motivated to study the properties of dyes and the behavior of DSSCs. Recently, Babangida et al., (2022a) developed criteria for selection and screening of single and mixed plant dyes for the fabrication of promising solar cells. Also, Yerima et al., (2022a) derived a matrix method to determine the optical energy band gap of natural dyes. Furthermore, Babangida et al., (2022b) carried out a study on suppressed charge recombination-aided co-sensitization in fabricated dye-sensitized solar cells-based natural plant extracts. In another context, Yerima et al., (2022b) developed analytical methods for mathematical modeling of dye-sensitized solar cells (DSSCs) performance for different local natural dye photosensitizers. Moreover, Yerima et al., (2022c) reported explicit models based on the Lambert W-function used for modeling and simulation of different dye-sensitized solar cells (DSSCS).

In this article, we reported how the model parameters "a", "R_s", "R_{sh}", "J_o", and "J_{ph}" for 14 fabricated dye-sensitized solar cells (Babangida et al., 2022a) were extracted simultaneously from the same four measurements using closed-form equations, neglecting the cumbersome measurements of "$\frac{dJ}{dV}$" gradients and maximum power point. The results were compared with previous works (Babangida et al., 2022b; Yerima et al., 2022b; Yerima et al. 2022c).

2. The power-law model

The J-V curve of irradiated solar cells is represented by the explicit power-law equation given by Karmalkar and Haneefa (2008) and Saleem and Karmalkar (2009).

$$j = 1-(1-\gamma)v-\gamma v^m \quad \text{……………..…(2)}$$

where "γ" and "m" are "$= \frac{J}{J_{sc}}$" is the normalized current density, "$v = \frac{V}{V_{oc}}$" is the normalized voltage while "γ" and "m" are arbitrary dimensionless constants.

The linear term of equation (2) depicts the gradual decrease in current with voltage near the short-circuit point, and the power law term controls the decrease near the open-circuit point. Although "V_{oc}" and "J_{sc}" are measured directly, "γ" and "m" are determined from the measured "$V|_{J=0.6J_{sc}}$", and "$J|_{V=0.6V_{oc}}$" via equations (3) and (4) respectively.

$$\gamma = \frac{j|_{v=0.6}-0.4}{0.6} \quad \text{…………………………...(3)}$$

$$m = \frac{ln\left[\left((0.4-(1-\gamma)v|_{j=0.6}\right)\gamma^{-1}\right]}{ln\left(v|_{j=0.6}\right)} \quad \text{……….……..(4)}$$

The rough estimate resulting in equation (3) is satisfactory for "$0.6^m \ll 0.6$" and the choice for $v = 0.6$ and $j = 0.6$ has been elaborated in Karmalkar and Haneefa (2008). Also, "γ", "m", "V_{oc}" and "J_{sc}" can be calculated roughly from the physical parameters using

$$\gamma \approx 1-\frac{V_{oc}}{J_{sc}R_{sh}} \quad \text{……………………….……..(5)}$$

$$m \approx \left(\frac{V_{oc}}{a+\theta\gamma J_{sc}R_s}\right) \quad \text{…………………….……….(6)}$$

$$J_{sc} \approx J_{ph}\left(\frac{R_{sh}}{R_{sh}+R_s}\right) \text{ or } J_{ph} \approx J_{sc}\left(\frac{R_{sh}+R_s}{R_{sh}}\right) \quad \text{…(7)}$$

$$V_{oc} \approx a\,ln\left(\frac{J_{ph}-\frac{a}{R_{sh}}ln\left(\frac{J_{ph}}{J_o}\right)}{J_o}\right) \quad \text{………………..(8)}$$

where "θ" is a dimensionless empirical parameter and if we assume "$J_o \ll J_{ph}$" and $V_{oc} \approx a\,ln(J_{ph}/J_o)$ while writing the numerator of the term in a bracket of (8). The normalized maximum/peak power voltage (v_p) and the fill factor *(FF)* (Saleem and Karmalkar, 2009) are given by equations (9) and (10) respectively

$$v_p \approx (m+1)^{\frac{-1}{m}} - 0.05(1-\gamma) \quad \text{…………..(9)}$$

$$FF = j_p v_p \quad \text{………………………………..(10)}$$

Therefore, the normalized peak power voltage (v_p) and the fill factor *(FF)* can be calculated from equations (9) and (10) respectively.

3. Four-point extraction method

The expressions of the model adopted in this work are derived from equations (11) and (13) of the five-parameter model (Chan *et al*., 1986) for "m" and "R_s" respectively. This power-law model eliminates the measurements of "$\frac{dJ}{dV}$" slopes and maximum power point by approximating $R_{sho} = dV/dJ_{|V=V_{oc}} \approx R_{sh}$ in terms of "γ" using equation (5), eliminating $dV/dJ_{|J=J_{sc}} \approx R_{so}$ using equation (6) and some equations in Chan *et al*., (1986), and computing (j_p, v_p) using (2), (3), (4), and (9). Following certain algebraic manipulations, we can write terms of this power law model parameter "m" and "γ" as:

$$a = V_{oc}\left[\frac{v_p + j_p(R_{so}J_{sc}/V_{oc}) - 1}{m ln v_p + j_p/\gamma}\right] \quad (11)$$

$$\frac{R_{so}J_{sc}}{V_{oc}} = \frac{R_s J_{sc}}{V_{oc}} + \frac{a}{\gamma V_{oc}} \quad (12)$$

Plugging equation (12) into equation (11) yields

$$R_s = \frac{a m ln(v_p) + (1 - v_p) + V_{oc}}{j_p J_{sc}} \quad (13)$$

Also, we obtain equation (14) by changing equation (6) of this model to

$$\theta R_s = \frac{V_{oc}}{\gamma m J_{sc}}\left(1 - \frac{am}{V_{oc}}\right) \quad (14)$$

Plugging equations (12) and (14) into equation (11), we get

$$a = \frac{V_{oc}}{m}\left(\frac{\theta(\gamma m/j_p)(1 - v_p) - 1}{\theta(\gamma m/j_p) ln(1/v_p) - 1}\right) \quad (15)$$

To determine the value of "θ", Saleem and Karmalkar (2009) calculated this empirical parameter for 19 solar cells operating at about one-sun irradiation, and having various materials, temperatures, and a quality ranging from poor to good (0.45≤FF≤0.81). The model parameters of their solar cells were recorded in Table 1.

For each solar cell, the magnitudes of V_{oc},J_{sc},$V|_{J=0.6J_{sc}}$, and $J|_{V=0.6V_{oc}}$were computed numerically using equation (1), and the values of "γ", "m", "v_p," and "j_p" were determined from equations (2), (3), (4), and (9) and plugging into equation (14) to get "θ". Their computations led to the estimation $\theta \approx \frac{0.77 j_p}{\Upsilon}$, whose substitution in (15) gives

$$a = \frac{V_{oc}}{m}\left(\frac{0.77m(1 - v_p) - 1}{0.77 m ln(1/v_p) - 1}\right) \quad (16)$$

Their value of "a" changes in the range of $0.3(V_{oc}/m)$ *to* $0.9(V_{oc}/m)$ for some solar cells (Saleem and Karmalkar, 2009). Also, their "R_s" was obtained by plugging (16) into (14), in which the value of "θ" was chosen to reduce the extraction error. This value of "θ" was calculated by evaluating the $R_s\theta$ product in (14) for the solar cells, using "a" given by (16), and "γ", "m", "V_{oc}", and "J_{sc}" obtained above. For example, their calculations were fitted using the linear function $\theta R_s \approx 0.6R_s + 0.1\ \Omega cm^2$, whose substitution in (14) gives

$$R_s \approx \left(\frac{V_{oc}}{0.6\gamma m J_{sc}}\right)\left(1 - \frac{am}{V_{oc}}\right) - 0.1\ \Omega cm^2 \quad (17)$$

(Saleem and Karmalkar, 2009).

Their values of "R_s" obtained using (15) vary between$0.1(V_{oc}/\gamma m J_{sc})$ *and* $0.56(V_{oc}/\gamma m J_{sc})$. They obtained (1) at the measured "V_{oc}" point, and setting $J_{ph} - V_{oc}/R_{sh} \approx \gamma J_{sc}$, solve for "$J_o$" as

$$J_o \approx J_{sc} e^{\frac{-V_{oc}}{a}} \quad (18)$$

To obtain "R_{sh}," they used (1) at the measured $0.6V_{oc}$ point and then use (7) to have

$$j|_{v=0.6} = 1 - \frac{0.6V_{oc}}{J_{sc}R_{sh}} - \frac{J_o}{J_{sc}} e^{\left(\frac{0.6V_{oc} + J|_{v=0.6}J_{sc}R_s}{a}\right)} \quad (19)$$

Putting for $j|_{v=0.6}$ in terms of "γ" from (3) and J_o/J_{sc} from (18), "R_{sh}" is solved for as

$$R_{sh} \approx \frac{V_{oc}}{J_{sc}}\left[1 - \gamma - \frac{\gamma}{0.6} e^{\left(\frac{(0.4 + 0.6\gamma)J_{sc}R_s - 0.4V_{oc}}{a}\right)}\right]^{-1} \quad (20)$$

The "R_{sh}" extracted as shown above tends to be more accurate than that extracted using (5), i.e. $R_{sh} \approx (V_{oc}/J_{sc})(1-\gamma)^{-1}$, which is more sensitive to the errors introduced in "γ" by the neglect of the 0.6^m term in the denominator of the RHS of (3).

In this paper, the parameters are extracted in the following sequence: "γ" & "m" from measured "V_{oc}","J_{sc}", $V|_{J=0.6J_{sc}}$, and $J|_{V=0.6V_{oc}}$ using (3) and (4): $FF = v_P j_P$ using (2) and (9): a using (16): "R_s" using 16: "J_o" using (18): "R_{sh}" using (20) and "J_{ph}" using (7).

Nomenclature

a	Modified diode ideality factor ($a = nV_T$)
n	Ideality diode factor
J	Output current of a module (mA/cm^2)
V	Output voltage of a module (V)
FF	Fill Factor
J_{sc}	Short-Circuit Current of the module (mA/cm^2)
V_{oc}	Open-Circuit Current of the PV module (V)
V_T	Thermal Voltage of the PV module (V)
T	Temperature of the PV cell (K)
q	Electron Charge (1.602×10^{-19} C)
J_p	Current Density at the maximum power point (mA/cm^2)
V_p	Voltage at the maximum power point (V)
J_{ph}	Photocurrent current density delivered by the constant current source(mA/cm^2)
J_o	Diode dark or reverse saturation current density (mA/cm^2)
R_s	the series resistor that controls losses in cell solder bonds, interconnection, junction box, etc (Ωcm^2)
R_{sh}	Shunt Resistance of the PV module (Ωcm^2)
k	Boltzmann constant (1.38×10^{-23} JK^{-1})
R_{so}	Reciprocal of slope of the I-V characteristic at $V = V_{oc}(\Omega)$
R_{sho}	Reciprocal slope of the I-V characteristic at $I = I_{sc}(\Omega)$
j	Normalized Current Density
v	Normalized Voltage
m	Dimensionless exponent
γ	Dimensionless constant
θ	Dimensionless empirical parameter
j_p	Normalized maximum/peak power current
v_p	Normalized maximum/peak power voltage

4. Results and Discussion

In this paper, we have verified the validation of the four-point model for 14 DSSCs listed in Table 1. For each DSSC, the values of "V_{oc}", "J_{sc}", $V|_{J=0.6J_{sc}}$, and $J|_{V=0.6V_{oc}}$ were obtained numerically using (1) and the parameters listed in Table 1. Also, the values of $j_{|v=0.6}$ and $v_{|j=0.6}$ were deduced from a typical J-V curve (Fig. 1). For such devices, the parameter "m" is low enough to invalidate the assumption $0.6^m \ll 0.6$ underlying (3), so that "γ" is underestimated, which lowers the "R_{sh}" extracted using (20). An improved estimate of "γ" taking into account the 0.6^m term in (3) improves the extracted "R_{sh}".

Table 2 contains values of the normalized voltage and current, arbitrary constants, and fill factor for 14 DSSCs. The results show that all these quantities are regular, that is, they have positive values. Also, the solar cells with FF in the range $0.45<<FF<<0.81$ are considered to be good while those with $FF<0.45$ are said to be bad (Saleem and Karmalkar, 2009). Thus, in light of this classification, 12 (86%) of the DSSCs are good and only 2 (14%) DSSCs with orange and tomato dye extracts are not.

Using the values of the parameters in Tables 1 and 2 as measured four-point data (J_{sc}, V_{oc}, γ, m), the values of the five physical parameters were extracted and listed in Table 3. Fig. 2 depicts the plot of "θR_s" in equation (14) versus "R_s" in equation (13), which yields the linear function

$$\theta R_s = 0.9413R_s - 6.2555\ \Omega cm^2 \quad \text{………(21)}$$

The values of the model parameters in Table 3 depict that they are all regular, that is, they have positive values unlike previous results (Babangida et al., 2022b; Yerima et al., 2022b; Yerima et al., 2022c) that manifest both negative and positive values. Thus, this method eliminates parameter irregularity as an advantage over previous methods even though parameter irregularity is not a threat to engineers and scientists in their application (Babangida et al., 2022b; Yerima et al., 2022b; Yerima et al., 2022c).

Finally, plugging equation (21) into equation (14) yields the fitting function

$$R_s = \frac{V_{oc}}{0.9413\gamma m J_{sc}}\left(1 - \frac{am}{V_{oc}}\right) + 6.6456\Omega cm^2 \text{……...(22)}$$

Table 1. Characteristic point (J_{sc}, V_{oc}), peak power point (J_P, V_p,), and normalized current density ($j_{|v=0.6}$) and normalized voltage ($v_{|j=0.6}$) measured at STC

Dye extract	***J_{sc} (mA/cm^2)***	***J_p (mA/cm^2)***	***V_p (V)***	***V_{oc} (V)***	$j_{\|v=0.6}$	$v_{\|j=0.6}$
Witch seed flower (Striga hermonthica)	1.97	1.379	0.4	0.639	0.89	0.83
Flamboyant (Delonix regia)	1.717	1.442	0.4	0.61	0.88	0.825
Sunflower (Helianthus)	1.59	1.081	0.4	0.53	0.845	0.80
Rose flower (Rosaceous)	1.69	1.283	0.4	0.563	0.865	0.81
Bitter gourd (Momordica charantia)	9.244	6.435	0.4	0.536	0.85	0.80
Bougainvillea (Bougainvillea)	3.45	2.783	0.3	0.484	0.82	0.78
Wild marigold (Calendulaarvensis)	1.60	0.957	0.3	0.504	0.80	0.79
Red cockscomb (Celosia cristata)	1.58	1.290	0.3	0.49	0.83	0.785
Lantana (Lantana camera)	1.53	1.262	0.4	0.60	0.88	0.82
Hibiscus (Hibiscus rosa sinensis)	1.48	1.090	0.3	0.45	0.81	0.76
Orange peel (Citrus sinensis)	1.40	1.121	0.2	0.37	0.75	0.73
Tomato peel (Lycopersicon esculentum)	0.23	0.135	0.2	0.29	0.69	0.68
Mango peel (Mongifera indica)	2.51	2.13	0.4	0.618	0.89	0.825
Guava peel (Psidium guajava)	0.90	0.669	0.3	0.452	0.81	0.77

Table 2. Model parameters (γ, m), normalized peak power (j_p, v_p) point, and fill factor (FF) for 14 DSSCs measured at STC in the following ranges: 0.406801<<FF<<0.553102, 0.584361<<j_p<<0.765777, 0.690413<<v_p<<0.722276, 5.305353<<m<<6.399813, and 0.48333<< γ <<0.816667

Dye extract	$\boldsymbol{\gamma}$	***m***	$\boldsymbol{v_p}$	$\boldsymbol{j_p}$	***FF***
Witch seed flower (Striga hermonthica)	0.816667	6.399813	0.722276	0.765777	0.553102
Flamboyant (Delonix regia)	0.800000	6.36801	0.720795	0.756384	0.545198
Sunflower (Helianthus)	0.741667	6.025198	0.710653	0.7217	0.512878
Rose flower (Rosaceous)	0.775000	6.024626	0.712307	0.739344	0.52664
Bitter gourd (Momordica charantia)	0.750000	5.923343	0.708831	0.725119	0.513987
Bougainvillea (Bougainvillea)	0.700000	5.792018	0.703380	0.697781	0.490805
Wild marigold (Calendulaarvensis)	0.666667	6.722932	0.721148	0.685586	0.494409
Red cockscomb (Celosia cristata)	0.716667	5.763465	0.703562	0.706197	0.496853
Lantana (Lantana camera)	0.800000	6.151545	0.716287	0.754024	0.540097
Hibiscus (Hibiscus rosa sinensis)	0.683333	5.305353	0.690913	0.685112	0.473353
Orange peel (Citrus sinensis)	0.583333	5.739074	0.696335	0.636773	0.443408
Tomato peel (Lycopersicon esculentum)	0.483333	5.952646	0.696147	0.584361	0.406801
Mango peel (Mongifera indica)	0.816667	6.179607	0.717715	0.763251	0.547796
Guava peel (Psidium guajava)	0.683333	5.647506	0.699210	0.687999	0.481056

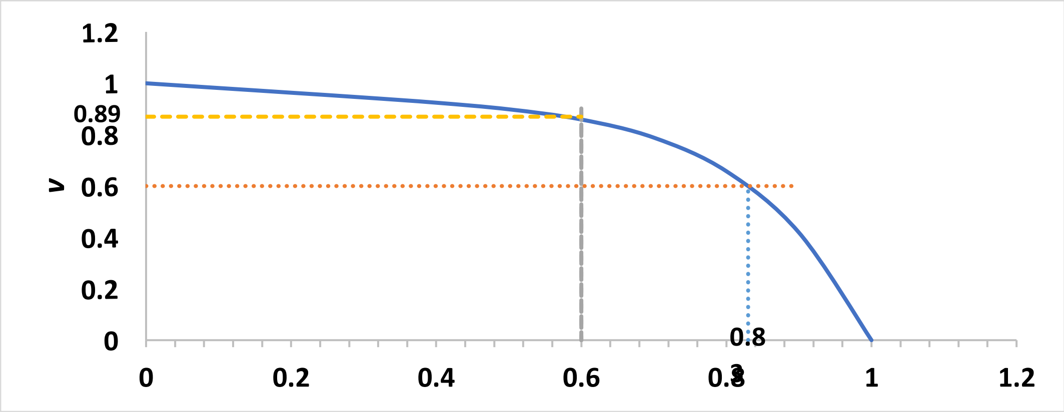

Figure 1. J-V curve used for extracting the physical parameters

Table 3. Physical parameters of 14 DSSCs measured at STC in ranges: 0.028983<<a<<0.061004, 5.305353<<R_s<<6.399813 Ωcm^2, 0.50173×10^{-8}<<J_o<<23.6454×10^{-8} A/cm^2, 467.4028<<R_{sh}<<2646.991 Ωcm^2, 0.93<<J_{ph}<<9.483 mA/cm^2

Dye extract	*a*	R_s (Ωcm^2)	$J_o \times 10^{-8}$ (A/cm^2)	R_{sh} (Ωcm^2)	J_{ph} (mA/cm^2)
Witch seed flower (Striga hermonthica)	0.061004	32.29443	4.54372	2428.858	1.995
Flamboyant (Delonix regia)	0.058397	35.56716	3.99302	2351.752	1.742
Sunflower (Helianthus)	0.051512	39.48390	4.01098	1627.793	1.627
Rose flower (Rosaceous)	0.054498	38.24044	4.27172	1957.712	1.721
Bitter gourd (Momordica charantia)	0.052109	12.52666	23.6454	467.4028	9.483
Bougainvillea (Bougainvillea)	0.047399	22.55439	8.87639	612.289	3.571
Wild marigold (Calendulaarvensis)	0.048027	33.47680	2.95483	1070.087	1.648
Red cockscomb (Celosia cristata)	0.047877	41.49200	4.06572	1379.320	1.625
Lantana (Lantana camera)	0.057775	41.15641	3.78066	2649.104	1.553
Hibiscus (Hibiscus rosa sinensis)	0.043646	49.89697	3.36689	1220.013	1.537
Orange peel (Citrus sinensis)	0.036778	42.66920	3.49045	731.0361	1.477
Tomato peel (Lycopersicon esculentum)	0.028983	195.2414	0.50173	2646.991	0.246
Mango peel (Mongifera indica)	0.059355	27.71379	6.16431	1949.274	2.544
Guava peel (Psidium guajava)	0.044342	68.30240	2.30102	1925.276	0.930

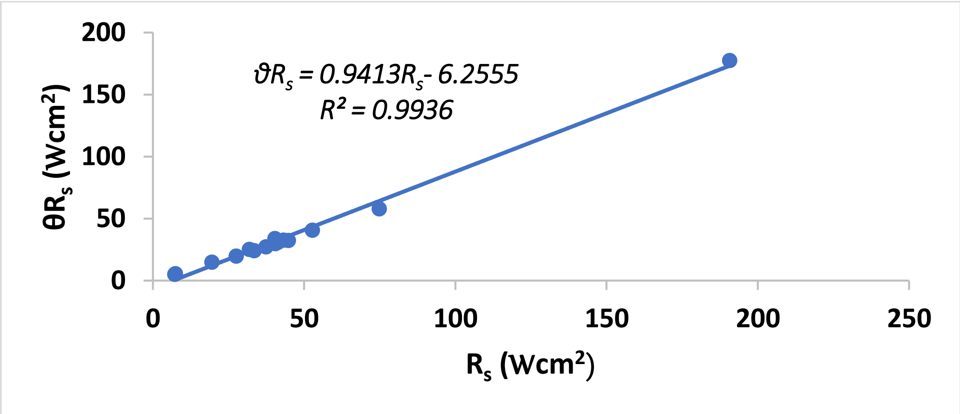

Figure 2. Fitting function used to obtain a simple equation of "R_s" extraction, solid circles represent the computations for the various DSSCs of Table 1.

5. Conclusion

In conclusion, this paper gives a simple explicit J-V five physical parameters of the single exponential model that is useful for the study of the performance of a variety of illuminated DSSCs. The model permits a closed-form estimation of the fill factor and peak power point both from simple J-V measurements and from physical parameters. The model also simplifies the presentation of J-V curves from the physical parameters of the single exponential model. The results reveal that all the physical parameters are regular as opposed to previous findings of parameter irregularities which do not pose any threat to users in their application. Also, the DSSCs studied belong to two classes (good or bad) based on their FF values such that 12 (86%) with 0.45<<FF<<0.81 are good and 2 (14%) with FF<0.45 are bad. Therefore, to ascertain the validity of this method and the authenticity of parameter regularity observed in these DSSC devices, more information on the manufacturer/experimental data for a larger number of such systems should be earmarked.

Reference

Babangida A., Yerima J. B., Ahmed A. D. & Ezike S.C. (2022a). Strategy to select and grade efficient dyes for enhanced phot-absorption. *African scientific reports, 1, 16-22.*

Babangida A., Yerima J. B., Ahmed A. D. & Ezike S. C. (2022b). Suppressed charge recombination aided co-sensitization in dye-sensitized solar cells-based natural plant extracts. *Optik-International Journal for Light and Electron Optics 270 \92022) 170072*

Bouzidi K, Chegar M. & Bohemadou A (2007). Solar cells parameters evaluation considering the series and shunt resistances. *Solar energy mater. Sola. Cells, vol.91, no. 18, pp. 1647-1851*

Chan D. S., Phillips J. R. & Phang J. C. H. (1986). A comprehensive study of extraction methods for solar cell model parameters. *Solid state electron. Vol. 29, no. 3. Pp. 329-337*

Ibrahim H. and Anani N. (2017). Evaluation of analytical methods for parameter extraction of PV modules. *Energy procedia 134, pp 69-78*

Karmalkar S. and Haneefa S. (2008). A physically based explicit J-V model of a solar cell for simple design calculations. *IEEE electron device letters Vol. 29, no. 5, pp449-4521*

Ortiz-Conde A., Sanchez F. J. G. & Muci J. (2006). New method to extract the model parameters of solar cells from the explicit analytic solutions of their illuminated J-V characteristics. *Sol. Energy mater. Solar cells. Vol. 90, no. 3, pp. 352-36*

Pallares J., Cabre R., Marsal I. R. & Schropp R.E.I. (2006). A compact equivalent circuit for the dark current-voltage characteristic of nonideal solar cell. *J. Appl. Phys., vol. 100, no. 8, p. 084513*

Saleem H. and Karmalkar S. (2009). An analytical method to extract the physical parameters of a solar cell from four points on the illuminated J-V curve. *IEEE Electron device lett. Vol. 30, no. 4, pp. 349-352*

Yerima J.B., Babangida A., Ezike S. C., William D. & Ahmed A. D. (2022a). Matrix method of determining optical energy bandgap of natural dye extracts. *J. Appl. Sci. Environ. Manage, 26, 5, 943-948.*

Yerima J. B., Ezike S. C., William D. & Babangida A. (2022b). Analytical methods for mathematical modeling of dye-sensitized solar cells (DDSCs) performance for different local natural dye photosensitizers. *Computational and experimental research in materials and renewable energy (CERIMRE), vol. 5, issue 2, pp. 114-132. DOI 10. 19184/erimre.v5i2.33499*

Yerima J. B., William D., Babangida A. & Ezike S. C. (2022c). Assessment of explicit models based on the lambert w-function for modeling and simulation of different dye-sensitized solar cells (DSSCS). *East* European Journal of Physics. 4. 136-144. DOI:10.26565/2312-4334-2022-4-13