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ASSESSMENT OF EXPLICIT MODELS BASED ON THE LAMBERT W-FUNCTION FOR MODELING AND SIMULATION OF DIFFERENT DYE-SENSITIZED SOLAR CELLS (DSSCs)[†]

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In this paper, the characteristic points were used as input data in five different explicit models based on Lambert W-function for the extraction of model parameters of three DSSCs. Moreover, these model parameters for given values of voltages were used to obtain the corresponding currents for the simulation of the DSSCs. The results show that the sign of the model parameter does not matter for methods that do not have series resistance and shunt resistance. However, when R_{sh} was negative the five-parameter single-diode model failed to yield good curve fit except when R_{sh} was neglected and four-parameter model used. Moreover, all the model parameters for DSSCs with bitter gourd dye were regular and yielded good curve fit for all the models. On the hand, DSSCs with R_{sh} values negative were handled with four-parameter model to obtain good curve fit. Thus, the sign of model parameter matters in simulation of DSSC using single-diode model.
Keywords: Model parameter, Explicit model, Lambert W-function, Characteristic points, DSSC, Curve fit
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INTRODUCTION

Nowadays, renewable energy plays a great role in reducing fossil resources consumption [1] due to problems arising from the use of fossil resources such as global warming, climate change, and air pollution [2] to mention a few. Presently, among the various renewable energy sources, solar energy is likely the most applicable, as it is clean, safe, and unlimited [3,4]. In one year, the amount of solar energy received from the sun is 10^4 times greater than the world's energy consumption [4]. It has been revealed the installed photovoltaic power increased from 100.9 GW in 2012 to 230 GW in 2015, rising to 400 GW in 2017 [1, 5]. This rate of increase has been feasible due to a new brand of solar cells that permit production growth while reducing costs and environmental impact [6].

Modeling has become a crucial step for photovoltaic system design and development, as it permits appropriate and accurate energy production forecasts [7]. The modeling of solar cells/panels is usually performed by using equivalent circuit models represented with mathematically implicit equations which are not easy to solve. However, the Lambert W-function has been identified as a useful tool to solve these equations.

The purpose of this paper is to present simplified model expressions in terms of the Lambert W-function, which is usually applied in photovoltaic devices, and depicts how this function is needed to solve equations connected to these systems. The desired model expressions were obtained by matching famous mathematical equations (exponential functions, polynomials, hyperbolic functions) to points on the Lambert W-function calculated numerically with the highest available accuracy.

The approach presented in this paper is to apply simplified model equations based on the Lambert W-function that can be solved easily with a pocket calculator, to model and simulate DSSC systems behavior.

MATERIALS AND METHODS

Modeling and simulation of solar cells

A host of researchers have reported that ideal solar cells behave like a current source connected in parallel with a diode [7-9]. This ideal model is achieved with resistors to represent the losses and sometimes with additional diodes that takes into account other phenomena [10,11]. The most common circuit equivalent to a solar cell consists of a current source, one diode and two resistors; one in series and one in parallel [12-19]. It is worth noting each of the element in the equivalent circuit one parameter has to be calculated except two in the case of the diode whose behavior is represented by the Shockley equation [20]. Thus, five parameters are required to be determined when applying this method [21-33]. This simple equivalent circuit has been used quite well to reproduce the current-voltage curve or simply I-V curve. Three important points of the I-V curve known as characteristic points namely: short circuit, maximum power, and open circuit points are used as input data. These representative points depend on temperature, irradiance of the photocurrent source, characteristic points and usually the normal information included in the manufacturer's datasheets.

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The conventional equation (1) describes a simple diode with a distinctive I-V curve

$$I = I_o\left(e^{\frac{V}{a}} - 1\right), \tag{1}$$

where a is the modified ideality diode factor (quality factor or emission coefficient) which varies with the nature of diode is determined according to the fabrication process and the semiconductor material.

When the semiconductor 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. The equivalent circuit solar cell containing series resistance R_s, shunt resistance R_{sh}, photocurrent I_{ph}, diode saturation current I_o, modified diode ideality factor, a is depicted in Fig. 1.

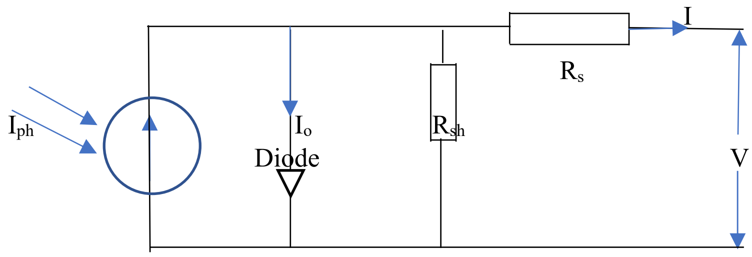


Figure 1. Electrical equivalent circuit of the single-diode solar cell

The single-diode model assumes an ideal cell is pictured as a current generator that is linked to a parallel diode with an I-V characteristic which is mathematically defined by Schokley equation (2)

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{a}} - 1\right) - \frac{V+IR_s}{R_{sh}}, \tag{2}$$

where I and V are the terminal current and voltage respectively, I_o the junction reverse current, a is the modified junction ideality factor, R_s and R_{sh} are the series and shunt resistance respectively.

Equation (2) is transcendental in nature hence it is not possible to solve for V in terms of I and vice versa. However, explicit solutions can be obtained using the principal branch of the Lambert W-function W_o [21, 34-37].

$$I = \frac{R_{sh}(I_{ph}+I_o)-V}{R_{sh}+R_s} - \frac{a}{R_s}W_o\left(\frac{R_{sh}R_sI_o}{a(R_{sh}+R_s)}e\left(\frac{R_{sh}R_s(I_{ph}+I_o)+VR_{sh}}{a(R_{sh}+R_s)}\right)\right), \tag{3}$$

$$V = R_{sh}(I_{ph}+I_o) - (R_s+R_{sh})I - aW_o\left\{\frac{R_{sh}I_o}{a}e^{R_{sh}\left(\frac{I_{ph}+I_o-I}{a}\right)}\right\}. \tag{4}$$

One can directly find the current for a given value of voltage using equation (3) or the voltage via (4), which makes the computation easy and robust in contrast to (2). The Lambert W function is readily available in all computation procedures [21, 35]. Finally, for simulation purpose the current can be calculated for each model by plugging the appropriate model parameters for any given value of V into equation (3) and vice versa for V for any given value of I in equation (4). However, if the curve fit fails due to parameter irregularity, for example R_{sh} negative or complex we neglect $R_{sh}=\infty$, the last term in equation (2) vanishes reducing the five-parameter model to four-parameter model. Therefore, equation (3) reduces to equations (5)

$$I = I_{ph} + I_o - \frac{a}{R_s}W_o\left(\frac{R_sI_o}{a}e\left(\frac{R_s(I_{ph}+I_o)+V}{a}\right)\right). \tag{5}$$

Furthermore, if equation (5) fails to yield good curve fit then R_s is neglected and equation (2) reduces to the ideal diode equation (1) representing a three-parameter model. Thus, equations (1), (3) and (5) can be used for simulation of three-, four- and five-parameter models respectively.

The explicit model equations based on the Lambert W-function

There are many explicit models to study the current-voltage behavior of a solar cell [38]. Notwithstanding, the results do not sustain any of the physical appearance of the photovoltaic conversion process, they are attracting great attention and accurate enough to produce recent discoveries from time to time [39]. Some of the explicit models with solutions based on the Lambert W-function include:

I. The El-Tayyan model [40]. The proposed El-Tayyan model equation for generating I-V characteristics of solar cell or PV module is in the form

$$I = I_{sc} - C_1e^{\left(\frac{-V_{oc}}{C_2}\right)}\left(e^{\left(\frac{V}{C_2}\right)} - 1\right), \tag{6}$$

where C_1 and C_2 are coefficients of the model equation. These coefficients are given by [41]as

$$C_1 = \frac{I_{sc}}{1-e^{\left(\frac{-V_{oc}}{C_2}\right)}}, \tag{7}$$

and, if $V_{oc}/C_2 >> 1$:

$$C_2 = \frac{V_{mp}-V_{oc}}{W_{-1}\left(\left(1-\frac{V_{oc}}{V_{mp}}\right)\left(\frac{I_{mp}}{I_{sc}}\right)\right)}. \tag{8}$$

However, Babangida [42] have shown that the relationships between the conventional model parameters (I_o and a) and the El-Tayyan coefficients (C_1, C_2) are given by equations (9) and (10)

$$I_o = C_1 e^{-\frac{V_{oc}}{C_2}}, \tag{9}$$

$$a = C_2. \tag{10}$$

Thus, a and I_o in equations (9) and (10) are the two model parameters for the El-Tayyan model.

II. The Karmalkar and Haneefa model [43]. This model presents the current-voltage relation as

$$I = I_{sc}\left\{1-\left(1-\gamma\left(\frac{V}{V_{oc}}\right)\right)-\gamma\left(\frac{V}{V_{oc}}\right)^m\right\}, \tag{11}$$

where the model parameters are:

$$\gamma = \frac{2\left(\frac{I_{mp}}{I_{sc}}\right)-1}{(m-1)\left(\frac{V_{mp}}{V_{oc}}\right)^m}, \tag{12}$$

$$m = \frac{W_{-1}\left[\left(\frac{V_{oc}}{V_{mp}}\right)^{\frac{1}{K}}\left(\frac{1}{K}\right)ln\left(\frac{V_{mp}}{V_{oc}}\right)\right]}{ln\left(\frac{V_{mp}}{V_{oc}}\right)} + \frac{1}{K} + 1, \tag{13}$$

$$K = \frac{1-\left(\frac{I_{mp}}{I_{sc}}\right)-\left(\frac{V_{mp}}{V_{oc}}\right)}{2\left(\frac{I_{mp}}{I_{sc}}\right)-1}. \tag{14}$$

III. The Das model [44]. The current-voltage for this model is given by

$$\mathrm{I} = I_{sc}\left[\frac{1-\left(\frac{V}{V_{oc}}\right)^k}{1+h\left(\frac{V}{V_{oc}}\right)}\right], \tag{15}$$

where the coefficients are:

$$k = \frac{W_{-1}\left[\left(\frac{I_{mp}}{I_{sc}}\right)ln\left(\frac{V_{mp}}{V_{sc}}\right)\right]}{ln\left(\frac{V_{mp}}{V_{oc}}\right)}, \tag{16}$$

$$h = \left(\frac{V_{oc}}{V_{mp}}\right)\left(\frac{I_{sc}}{I_{mp}} - \frac{1}{k} - 1\right). \tag{17}$$

IV. The Saetre [45] and Das model [44]. This model was proposed independently by Das [41] and Saetre [42] given by the following equation

$$I = I_{sc}\left[1-\left(\frac{V}{V_{oc}}\right)^f\right]^{\frac{1}{g}}, \tag{18}$$

where the model parameters f and g are estimated with output current measurements at $V=0.8V_{oc}$ and $V=0.9V_{oc}$.

Using the maximum power point conditions, $(v,i) = (\alpha,\beta)$ and $\frac{\partial i}{\partial v}|_{mp} = -\frac{\beta}{\alpha}$, such that $\alpha = \frac{V_{mp}}{V_{oc}}$ and $\beta = \frac{I_{mp}}{I_{sc}}$, the following equations are obtained:

$$\beta^g = 1 - \alpha^f, \tag{19}$$

$$g\beta^g = f\alpha^f. \tag{20}$$

Assuming α^f<<1, then

$$g ln\beta = -\alpha^f. \tag{21}$$

Therefore, plugging equation (21) into equation (20), the equations for f and g are finally given by

$$f = W_{-1}\left(\frac{-\alpha}{ln\beta}\right), \tag{22}$$

$$g = \frac{-\alpha^f}{ln\beta}. \tag{23}$$

V. The 1-diode/2-resistors equivalent circuit model. The mathematical form of this model is already defined by equation (2) whose solution for I or V in terms of Lambert W-function is given by equation (3) or (4) respectively. Many researchers like [35] have published a solution of equation (2) based on the Lambert W-function which requires the diode ideality factor n as an input, say n=1.1 for the silicon cells studied and R_s is determined via equation (24).

$$R_s = A[W_{-1}(Be^C) - (C + D)]. \tag{24}$$

where W_{-1} is the lower branch of the Lambert W-function and A, B, C, and D auxiliary parameters defined as:

$$A = \frac{a}{I_{mp}}, \quad B = \frac{V_{mp}(I_{sc}-2I_{mp})}{[V_{mp}I_{sc}+V_{oc}(I_{mp}-I_{sc})]}, \tag{25}$$

$$C = \frac{V_{oc}-2V_{mp}}{a} + \frac{V_{mp}I_{sc}-V_{oc}I_{mp}}{[V_{mp}I_{sc}+V_{oc}(I_{mp}-I_{sc})]}, \quad D = \frac{V_{mp}-V_{oc}}{a}. \tag{26}$$

Most often the modified diode ideality factor a in terms of n and the thermal voltage V_T is defined by equation (27)

$$a = nV_T \tag{27}$$

such that V_T is also defined by equation (27)

$$V_T = \frac{kT}{q} \tag{28}$$

where k is the Boltzmann constant, T is the absolute temperature and q is the electron charge. In another vein, [43] avoided the assumption of the value of n instead he deduced that the modified diode ideality factor *a* is equal to the second El Tayyan coefficient C_2 i.e he set a=C_2 given by equation (29)

$$a = \frac{V_{mp}-V_{oc}}{W_{-1}\left(\left(1-\frac{V_{oc}}{V_{mp}}\right)\left(\frac{I_{mp}}{I_{sc}}\right)\right)}. \tag{29}$$

Furthermore, the parameter R_{sh} is calculated via [21] equation (30)

$$R_{sh} = \frac{(V_{mp}-I_{mp}R_s)\{V_{mp}-R_s(I_{sc}-I_{mp})-a\}}{(V_{mp}-I_{mp}R_s)(I_{sc}-I_{mp})-aI_{mp}}. \tag{30}$$

Finally, the remaining parameters I_o and I_{ph} are found by equations (31) and (32) respectively

$$I_o = \left[I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right) - \frac{V_{oc}}{R_{sh}}\right] e^{\frac{-V_{oc}}{a}}, \tag{31}$$

$$I_{ph} = I_{sc}\left(1 + \frac{R_s}{R_{sh}}\right). \tag{32}$$

In this paper, equations (24) and (29-32) are used to extract the five model parameters (a, R_s, R_{sh}, I_o, and I_{ph}) to study the performance of DSSCs.

RESULTS AND DISCUSSION

Table 1. The characteristic points for three DSSCs

Source of natural dye		Characteristic points			
English Name	Scientific Name	I_{sc} (mA)	I_{mp} (mA)	V_{mp} (V)	V_{oc} (V)
Bitter gourd	Momordica charantia	9.244	6.450	0.4	0.536
Bougainvillea	Bougainvillea	3.450	2.783	0.3	0.484
Mango peel	Mongifera indica	2.51	2.130	0.4	0.618

In Table 1, the characteristic or representative points namely the short circuit point (I_{sc}, 0), open circuit point (0, V_{oc}) and the maximum power point (I_{mp}, V_{mp}) were obtained from the I-V curves of measured currents and voltages for three DSSCs are included. These points were used as input data for the modeling and simulation of the DSSCs studied.

Table 2. The El Tayyan model parameter for three DSSCs

Source of natural dye		Parameter model	
English Name	Scientific Name	C_1	C_2
Bitter gourd	Momordica charantia	0.009245	0.060353
Bougainvillea	Bougainvillea	0.003927	0.229684
Mango peel	Mongifera indica	0.002760	0.257501

Table 2 contains the two parameters for the 2-parameter El Tayyan model and both parameters are positive and less than unity. This means the parameters are regular parameters. The two parameters are inversely proportional to each other.

Table 3. The Karmalkar and Haneefa model parameter for three DSSCs

Source of natural dye		Parameter model		
English Name	Scientific Name	ϒ	m	K
Bitter gourd	Momordica charantia	0.758887	9.611764	-1.12783
Bougainvillea	Bougainvillea	1.846619	1.777069	-0.69538
Mango peel	Mongifera indica	1.394703	2.453534	-0.71120

Table 3 depicts the three parameters of the Karmalkar and Haneefa 3-parameter model. Two of the parameters, $\gamma\ and\ m$, have positive values whereas the parameter K has all values negative. This implies that $\gamma\ and\ m$ are regular parameters and K is irregular parameter. The three parameters are inversely proportional to one another.

Table 4. The Das model parameter for three DSSCs

Source of natural dye		model parameter	
English Name	Scientific Name	k	h
Bitter gourd	Momordica charantia	8.584082	0.428833
Bougainvillea	Bougainvillea	2.024451	-0.410257
Mango peel	Mongifera indica	2.293207	-0.398095

Table 4 contains the two parameters (k and h) for the 2-parameter Das model. The parameter k has positive values for all DSSCs while h negative value for DSSC with bitter gourd dye and positive values for DSSCs with bougainvillea and mango peel dyes. This means k is regular parameter for all dyes whereas h is regular for bitter gourd dye and irregular for bougainvillea and mango dyes. The parameters are directly proportional to one another.

Table 5. The Saetre and Das model parameter for three DSSCs

Source of natural dye		model parameter	
English Name	Scientific Name	f	g
Bitter gourd	Momordica charantia	2.746442	1.235772
Bougainvillea	Bougainvillea	0.990796	2.897765
Mango peel	Mongifera indica	0.393542	5.133096

In Table 5, the Saetre and Das model parameters f and g are included. Both parameters are positive and therefore they are regular. Also, f and g are inversely proportional. However, the DSSCs with bougainvillea and mango dyes exhibit parameter irregularity in R_{sh} and I_{ph}.

Table 6. The Single diode circuit 5-parameter model for three DSSCs

Source of natural dye		model parameter				
English Name	Scientific Name	A	R_s (W)	R_{sh} (W)	I_o (mA)	I_{ph} (mA)
Bitter gourd	Momordica charantia	0.060353	11.2	189.6	9.6755×10^{-4}	9.7879
Bougainvillea	Bougainvillea	0.229684	35.5	-18.6	2.7823×10^{-3}	-3.1223
Mango peel	Mongifera indica	0.257501	34.6	-99.5	7.1220×10^{-4}	1.6378

In Table 6, the single-diode model parameters (a, R_s, R_{sh}, I_o, and I_{ph}) are included. The DSSC with bitter gourd dye have all the parameters positive and hence they are regular. Similarly, the other DSSCs show parameter irregularity in R_{sh}

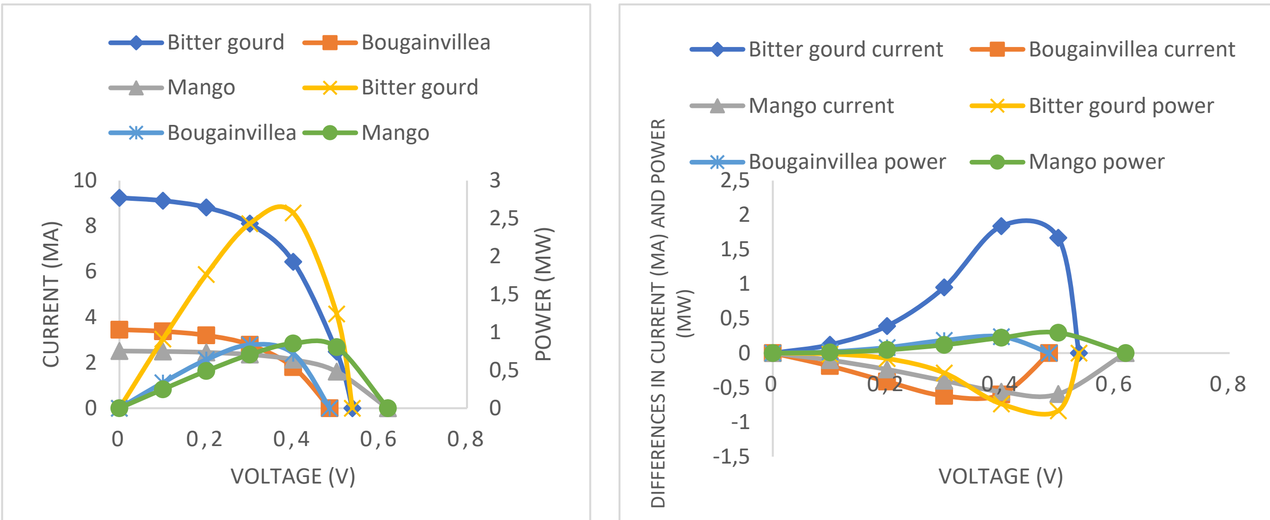
and I_{ph} for DSSC with bougainvillea dye and only R_{sh} for DSSC with mango dye. Also, a and I_{ph} are inversely proportional to R_{sh} and R_s respectively.

Table 7. Some common features of the five models studied

Model	Year	MP	OB	PI	SM ($R_{sh}=\infty$)
El Tayyan	2006	2	6	0	2-parameter model
Karmalkar & Haneefa	2008	3	9	3	3-parameter model
Das	2011	2	6	2	2-parameter model
Saetre and Das	2011	2	6	0	2-parameter model
Shockley single-diode	1949	5	15	3	4-parameter model

Table 7 depicts the 2wnumber of model parameters (MP), observations (OB), parameter irregularities (PI), and simulation model (SM) that produced good curve match for all the DSSCs studied.

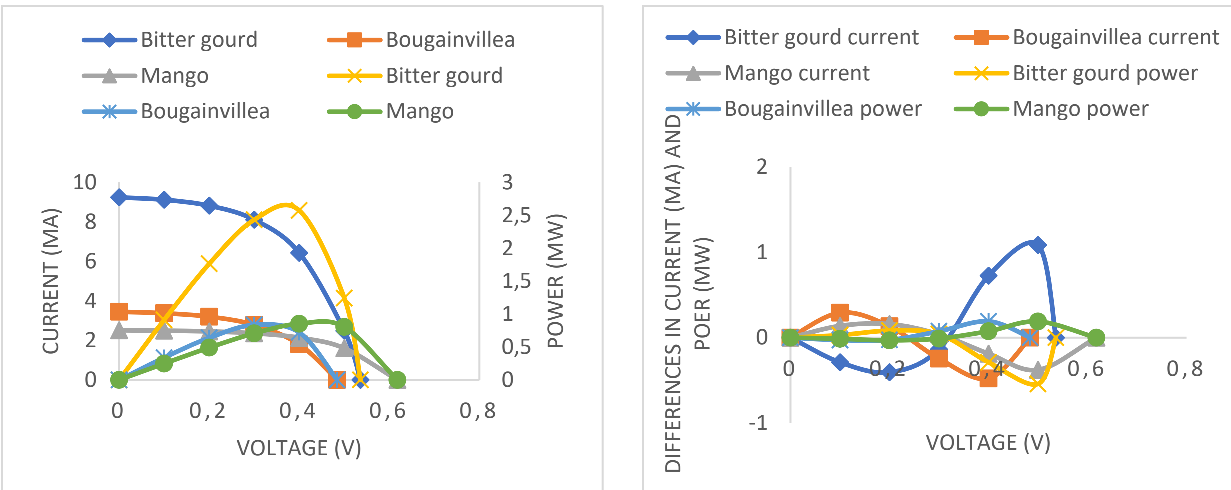
In all cases, the model parameters were used in appropriate model equations for the simulation of the DSSCs investigated. In this work, the five-parameter model was used to simulate DSSC with bitter gourd dye with regular parameters whereas the four-parameter model for the remaining DSSCs with irregular parameters yielded good curve fits Figs. (2a-6a) on the left and their corresponding error distributions in Figs.(2b-6b) on the right.



(a) Characteristic I-V/P-V curves

(b) Differences in Current and power

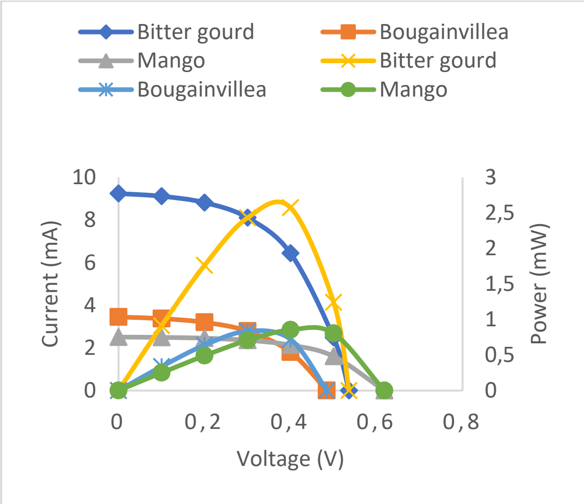
Figure 2. El Tayyan model
(a) characteristic curves and (b) differences between measured and simulated currents and powers



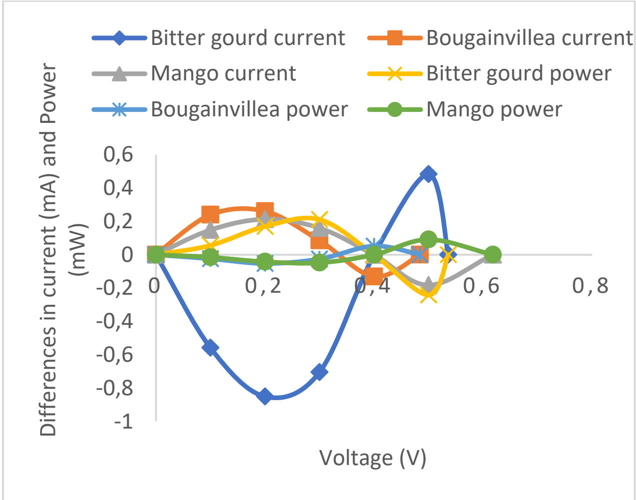
(a) Characteristic I-V/P-V curves

(b) Differences in Current and power

Figure 3. Karmalkar and Haneefa model
(a) characteristic curves and (b) differences between measured and simulated currents and powers

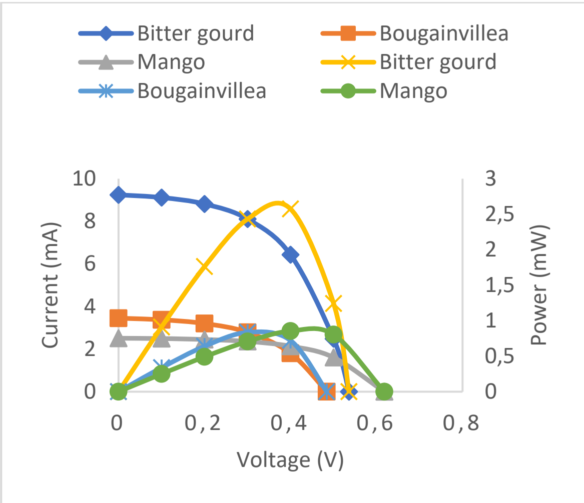


(a) Characteristic I-V/P-V curves

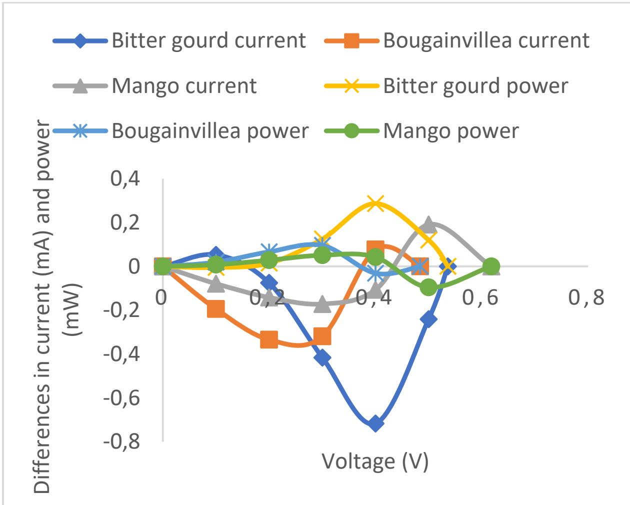


(b) Differences in Current and power

Figure 4. Das model
(a) characteristic curves and (b) differences between measured and simulated currents and powers

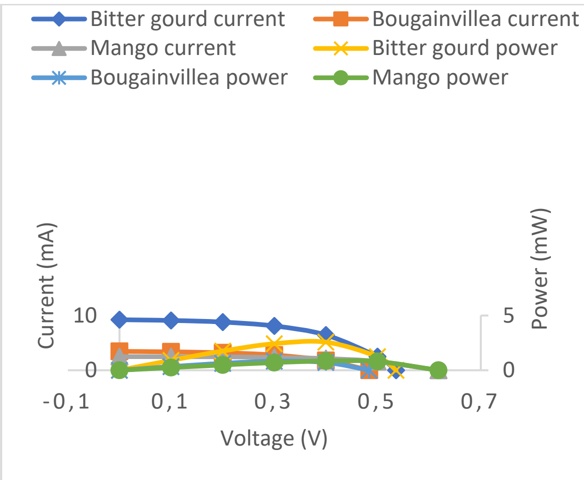


(a) Characteristic I-V/P-V curves

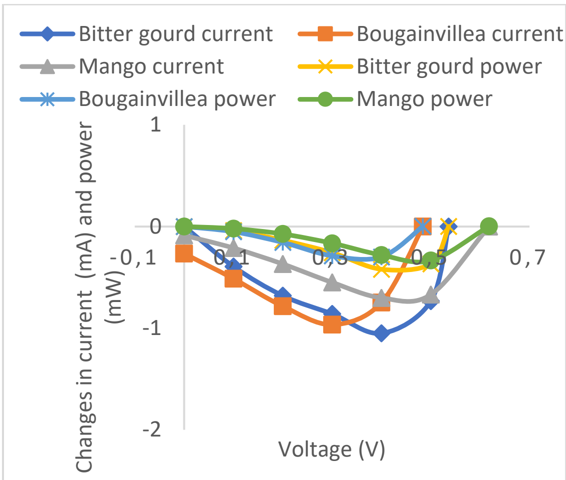


(b) Differences in Current and power

Figure 5. Saetre and Das model
(a) characteristic curves and (b) differences between measured and simulated currents and powers



(a) Characteristic I-V/P-V curves



(b) Differences in Current and power

Figure 6. Single-diode model
(a) characteristic curves and (b) differences between measured and simulated currents and powers

CONCLUSIONS

In this study, solutions of five explicit model equations based on the Lamber W-function were used to model and simulate the behavior of three DSSCs. The major conclusions resulting from this work are:

• The input data was the experimental data (short-circuit, maximum power and open circuit) of three DSSCs.

• The nature or sign of model parameters did not affect curve fit for models that neglect resistances (R_s and R_{sh}) as opposed to those depending on the resistances.

• The five-parameter single-diode model relies on resistance with poor curve fit when R_{sh} was negative.

• If n is the number of irregular model parameters, then the model that produced good curve fit is 5-n parameter single-diode model i.e., if R_{sh} is neglected we have 4-parameter single-diode model; if R_s and R_{sh} neglected we have 3-parameter single-diode model; etc.

• The single-diode model is more rigorous, time consuming, higher number of model parameters and hence provide more information about the system than the other models.

• The proposed models have provided overall curve fits between the simulated and experimental data.

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ОЦІНЮВАННЯ ЯВНИХ МОДЕЛЕЙ НА ОСНОВІ W-ФУНКЦІЇ ЛАМБЕРТА ДЛЯ МОДЕЛЮВАННЯ ТА ВІДТВОРЕННЯ РІЗНИХ СЕНСИБІЛИЗОВАНИХ БАРВНИКАМИ СОНЯЧНИХ ЕЛЕМЕНТІВ (DSSC)

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У цій статті використовувалися характерні точки як вхідні дані в п'яти різних явних моделях на основі W-функції Ламберта для вилучення параметрів моделі трьох DSSC. Крім того, ці параметри моделі для заданих значень напруг були використані для отримання відповідних струмів для моделювання DSSC. Результати показують, що знак параметра моделі не має значення для методів, які не мають послідовного опору та опору шунта. Однак, коли R_{sh} був від'ємним, 5-параметрична однодіодна модель не дала хорошої відповідності кривої, за винятком випадків, коли нехтували R_{sh} та використовували 4-параметричну модель. Більше того, усі параметри моделі для DSSC з гарбузовим барвником були регулярними та дали хорошу відповідність кривій для всіх моделей. З іншого боку, DSSC з негативними значеннями R_{sh} оброблялися за допомогою чотирипараметричної моделі для отримання хорошої відповідності кривої. Таким чином, знак параметра моделі має значення при моделюванні DSSC з використанням однодіодної моделі.

Ключові слова: параметр моделі, явна модель, W-функція Ламберта, характерні точки, DSSC, підгонка кривої