Various Modeling Approaches of Photovoltaic Module: A Comparative Analysis

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ABSTRACT:
Solar energy serves as one of the promising resources of renewable energy due to its abundance availability and clean nature. Climatic data such as irradiation level and temperature are essential as input variables while designing the photovoltaic-based system. This research paper presents an extensive comparative analysis of modeling approaches of photovoltaic modules using a 1-diode and 2-diode solar models studied under varying irradiation levels and temperature values. 8 different cases of solar models based on 1-diode and 2-diode models have been incorporated. Its effect on 10 performance indexes of the photovoltaic module is comprehensively investigated. Based on these parameters, these solar models are compared in detail. MATLAB/Simulink tool is applied to explore the results. Extensive results have been taken under various operating conditions. The results show that the 2-diode model exhibits excellent performance as it maximizes the efficiency by 5.41% against the 1-diode model. Also, the 2-diode model has a greater performance ratio of 41.70% than the 1-diode model. Hence, it is revealed that the performance of 2-diode models in terms of smooth output curves, increased maximum power, fill factor, and efficiency are much closer to the actual performance as compared to the 1-diode model.

KEYWORDS: Irradiation Level, Mathematical Modelling, Power-Voltage Curve, Photovoltaic Module, Voltage-Current Curve, 1-diode Model, 2-diode Model.

1. INTRODUCTION

Due to the increase in population, the need for electricity is in more demand. Renewable energy resources are employed to meet the power shortage satisfactorily. Among all the available renewable resources, solar energy is more utilized due to its abundance of availability and clean nature [1]. At the minimum, by 2050 the production of this kind of solar energy is estimated to be 42% [2]. Irradiance obtained from the sun and the temperature is two vital constraints on which this energy is dependent [3]. The solar module comprises numerous series and shunt-connected solar cells. By measuring various parameters such as current, voltage, and power, the solar photovoltaic system is assessed [4].

Mathematical modelling of the solar module plays a key role in determining the behavior of the solar cell under various climatic conditions [5]. In past years, several studies have been proposed related to solar cell modeling using several software [6, 7]. A source of photocurrent, series and parallel resistances, diode ideality factor, and reverse saturated current density are the five most important specifications by which the non-linearity of a 1-diode model's current-voltage characteristics can be brought into the picture [8, 9]. This study lacks the incorporation of various cases for the 1-diode model (D-1 to D-3) and is oriented towards the study of an equivalent model of the solar cell (D-4). In [10], the authors have prepared the output curves of the solar array using the data-sheet values in MATLAB. The limitation of this study is that it does not calculate various performance parameters due to which precise outcome is not obtained. Also, D-1 to D-3 and D-5 to D-8 are missing in it. Temperature-based maximum power extraction was studied for a 1-diode model. It does not include the detailed modeling of the 1-diode model under varying irradiations and temperature levels [11]. A 1-diode model is deeply studied using the iterative procedure and it reports the least error for output curves. But the main drawback is that, it does not evaluate the performance parameters and a 2-diode model study is missing it [12]. Seven parameter evaluation was done using an analytical approach. It reported accurate output curves irrespective of the type of material used for the solar cell modeling. But the major limitation is that the deep analysis of the 2-diode model (D-1 to D-8) and evaluation of performance parameters are missing in it

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[13]. The 2-diode model leads to greater performance under 100-1000 W/m^2 irradiance level with the least error [14]. Different methods were used to study the equivalent circuit model of solar cells using 1 and 2-diode models. It reported least mean absolute error. The major limitation associated with it is it does not calculate various performance parameters due to which precise outcome is not obtained. Also, various sub-cases (D-1 to D-3, and D-6 to D-8) are missing due to which deep analysis of the 1 and 2-diode models are not well explained [15, 16]. A 2-diode model was employed to extract the parameter under 200-1000 W/m^2 irradiation levels. It reported the least mean square error of 15.26% [17]. Authors have used MATLAB solar module to demonstrate the outcomes of various parameters. It gave accurate output curves. No analysis is done for in-depth modeling of the solar model (D-1 to D-8) and performance parameter calculation is missing. Thus, this does not provide an authentic real-time output [18]. Solar cell modeling leads to in-depth knowledge of performance parameters and it is highly recommended because solar energy accounts for the least cost [19]. A 2-diode model using monocrystalline and polycrystalline material was reported. It provided improved results under various varying irradiations and maximized the power up to 23.56%. The drawback of the study includes the missing of various sub-cases (D-1 to D-3 and D-5 to D-8) due to which deep analysis of the-diode models is not well understood [20, 21]. Several nature-inspired metaheuristics were reported in the literature to detect the unknown parameters of solar photovoltaic systems. It leads to exact parameter values for 1 and 2-diode models [22-28]. All these studies reported in the literature rely on the mathematical modelling of the solar cell using directly the equivalent solar circuit (D-4 or D-8). Step-by-step modeling of the solar cell is not incorporated (D-1 to D-3 and D-6 to D-8). Also, several performance parameters like fill factor, performance ratio, capacity utilization factor, efficiency, etc. are missing in the literature due to which the accurate behavior of the solar model is not well understood under varying irradiations and temperature levels.

The novelty and contributions of the proposed work are as follows:

(1) This paper deals with the in-depth comparative analysis of modeling approaches of photovoltaic modules using 1-diode and 2-diode solar models respectively. It is an improved work over [6-11].

(2) 8 distinct cases (D-1 to D-8) of solar diode models are extensively explored to clearly understand the step-by-step mathematical modeling of the solar cell. It is an improved work over [12-15].

(3) The extensive study is explored based on 10 parameters namely maximum voltage, maximum current, maximum power, efficiency, fill factor, performance ratio, capacity utilization factor, series resistance, shunt resistance, and diode ideality factor to deeply understand the solar modeling under varying climatic factors. It is an improved work over [16-25].

The literature consists of the direct incorporation of the equivalent model of 1-diode (D-4) and 2-diode (D-8) solar models. Various sub-cases (D-1 to D-3 and D-6 to D-8) in modeling from basics to reaching the equivalent model are missing in the literature. Hence, the main idea of this paper is to extensively understand the mathematical modelling of solar modules from its root and fill this gap in the literature. Also, the existing literature lacks extensive performance parameter evaluation based on maximum voltage, maximum current, maximum power, efficiency, fill factor, performance ratio, capacity utilization factor, series resistance, shunt resistance, and diode ideality factor. So, in this work, authors have incorporated this area and filled the literature gap. To the best of the authors' knowledge, such an extensive and novel work has yet not been reported under one piece of literature.

Followed by the introduction in section 1, section 2 deals with the in-depth mathematical modeling of a photovoltaic system related to 1 and 2-diode solar models. Section 3 extensively discusses parameter evaluation. Section 4 elaborates results and discussion. Section 5 compares the results of circuit models and finally, section 6 concludes the work reported in this paper.

2. MATHEMATICAL MODELLINGS OF PHOTOVOLTAIC SYSTEMS

Photovoltaic (PV) cell technologies serve as promising tools for several commercial operations. Its classification includes multi-crystalline, mono-crystalline, and thin film. To model the output characteristics of a PV module, 1 and 2-diode models are used extensively. The current source is connected in shunt with the diode for a 1-diode model which is the simplest form of the solar cell as shown in Fig. 1. One series resistance (R_S) is included in this model which enhances its structure. It is depicted in Fig. 2. Although its structure is uncomplicated, but it has a drawback, in that it gets affected by temperature deviations very fast. This model is further improved by incorporating the shunt resistance (R_{sh}) into it which is shown in Fig.3. The complete equivalent model of a 1-diode solar cell is represented in Fig. 4.

2.1. 1-diode Model of Solar Photovoltaic Cell

In this section, the 1-diode solar model is elaborately discussed under several cases as D-1 to D-4. This helps to understand clearly the step-by-step modeling of the 1-diode solar model. Eq. (1) to Eq.

(15) helps in the mathematical modelling of the 1-diode solar cell. From Fig. 1 using Kirchoff's current law,

$$I_{cell} = I_{ph} - I_D \tag{1}$$

The Shockley equation for an ideal diode is given by:

$$I_D = I_0[exp^{\frac{qV_{cell}}{nkT}} - 1] \tag{2}$$

$$I_D = I_{ph} - I_0[exp^{\frac{qV_{cell}}{nkT}} - 1] \tag{3}$$

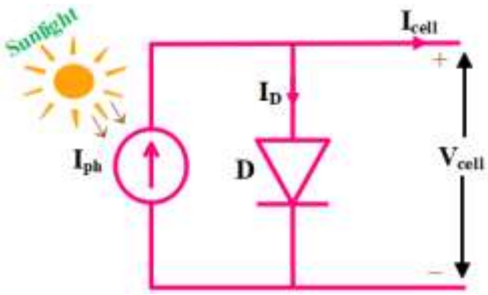


Fig. 1. Ideal 1-diode model (D-1).

For the n_S number of cells,

$$I_D = I_{ph} - I_0[exp^{\frac{qV_{cell}}{nn_SkT}} - 1] \tag{4}$$

A solar photovoltaic cell can be distinguished by employing open circuit voltage (V_{OC}) and short circuit current (I_{SC}). The I_{SC} is obtained when $V_{cell} = 0$ in (4). Thus,

$$I_{SC} = I_{ph} = I_{cell} \tag{5}$$

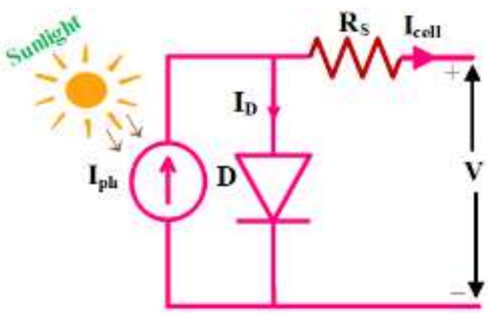


Fig. 2. 1-diode model with series resistance (D-2).

The V_{OC} is obtained when $I_{cell} = 0$ in (4).

$$I_{ph} = I_0[exp^{\frac{qV_{cell}}{nkT}} - 1]$$

$$V_{OC} = \frac{nn_SkT}{q} ln[\frac{I_{ph}}{I_0} + 1] \tag{6}$$

$$\text{Power, } P = I_{cell}V_{cell} = [I_{ph} - I_0[exp^{\frac{qV_{cell}}{nn_SkT}} - 1]]V_{cell} \tag{7}$$

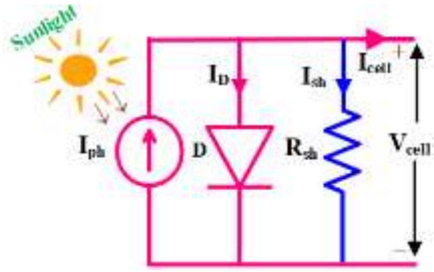


Fig. 3 1-diode model with shunt resistance (D-3).

Using similar procedures in Equations (1) - (7) in the analysis of Fig. 2, we obtain,

$$I_{cell} = I_{ph} - I_D$$

$$I_{cell} = I_{ph} - I_0[exp^{q[\frac{V_{cell} + I_{cell}n_SR_S}{nn_SkT}]} - 1] \tag{8}$$

$$I_{SC} = I_{ph} - I_0[exp^{\frac{qI_{SC}R_S}{nkT}]} - 1] \tag{9}$$

$$V_{OC} = \frac{nn_SkT}{q} ln[\frac{I_{ph}}{I_0} + 1] \tag{10}$$

Power,

$$P = I_{ph} - I_0[exp^{q[\frac{V_{cell} + I_{cell}n_SR_S}{nn_SkT}]} - 1]]V_{cell} \tag{11}$$

$$I_{cell} = I_{ph} - I_D - I_{SH} \tag{12}$$

$$I_{SH} = \frac{V_{cell} + I_{cell}R_S}{R_{SH}} \tag{13}$$

$$I_{cell} = I_{ph} - I_0\left[exp^{q[\frac{V_{cell} + I_{cell}R_S}{nkT}]} - 1\right] - \frac{V_{cell} + I_{cell}R_S}{R_{SH}} \tag{14}$$

For the n_S number of cells,

$$I_{cell} = I_{ph} - I_0\left[exp^{q[\frac{V_{cell} + I_{cell}n_SR_S}{n_SnkT}]} - 1\right] - \frac{V_{cell} + I_{cell}n_SR_S}{n_SR_{SH}} \tag{15}$$

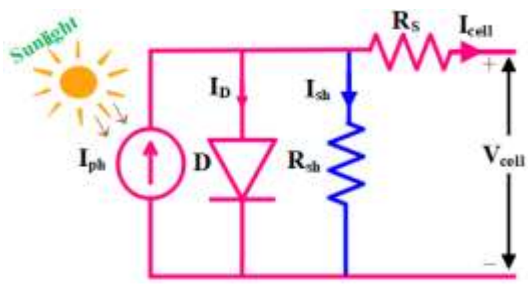


Fig. 4. Equivalent circuit of the 1-diode solar cell (D-4).

2.2. 2-diode Model of Solar Photovoltaic Cell

In the region of open-circuit voltage (V_{OC}), the reliability falls off at values of low irradiation levels for a 1-diode solar model. Thus, for greater precision, a 2-diode model comprising R_S and R_{sh} is put forward.

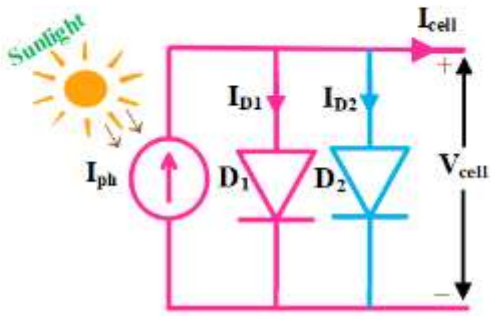


Fig. 5. Ideal 2-diode model (D-5).

In this section, 2-diode solar model is elaborately discussed under several cases as D-5 to D-8 as shown in Fig. 5 to Fig. 8. This helps to understand clearly the step-by-step modelling of the 2-diode solar model. Similar equations as derived under section 2.1 are used for 2-diode solar model. Additionally, Equation (16) and Equation (17) help in complete mathematical modelling of 2-diode solar cell.

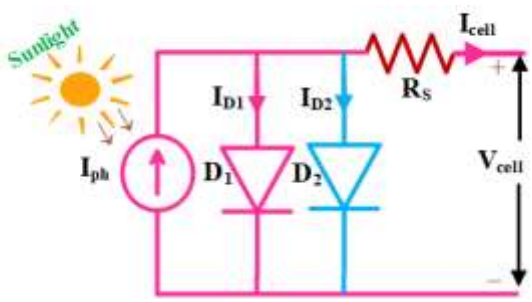


Fig. 6 2-diode model with series resistance (D-6).

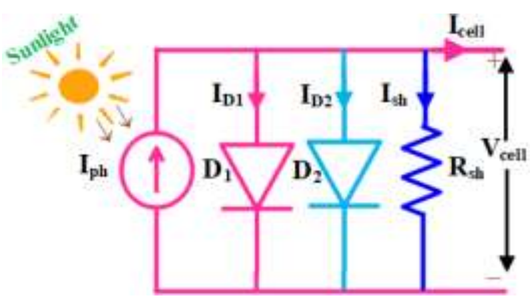


Fig. 7. 2-diode model with shunt resistance (D-7).

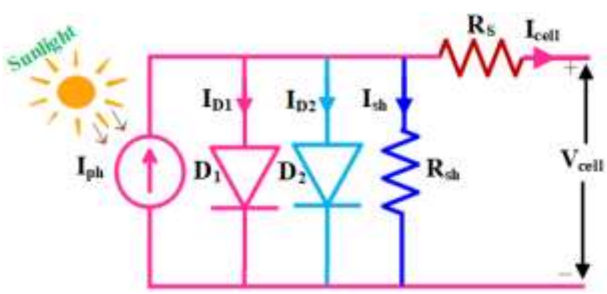


Fig. 8. Equivalent circuit of 2-diode solar cell (D-8).

From Fig. 5, applying KCL, Equation (16) is obtained.

$$I_{cell} = I_{ph} - I_{D1} - I_{D2} - I_{SH} \quad (16)$$

$$I_{cell} = I_{ph} - I_{01}\left[exp^{q\left[\frac{V_{cell}+I_{cell}R_S}{n_1kT}\right]} - 1\right] - I_{02}\left[exp^{q\left[\frac{V_{cell}+I_{cell}R_S}{n_2kT}\right]} - 1\right] - \frac{V_{cell}+I_{cell}R_S}{R_{SH}} \quad (17)$$

Thus, with the help of above Equations (1)-(17), the deep mathematical modeling of the solar 1-diode and 2-diode models under D-1 to D-8 is obtained satisfactorily.

3. PARAMETER EVALUATION

3.1. Short-circuit current (I_{SC})- In a solar photovoltaic cell, the peak current encircling the loop is termed as a short circuit current [8].

3.2. Open-circuit voltage (V_{OC})- When the dark current compensates the photocurrent, corresponding to it is a forward-biased voltage which is referred to as the open circuit voltage [9].

3.3. Maximum Power (P_{max})- It corresponds to the maximum voltage and maximum current in the power-voltage plot of the solar photovoltaic system [4].

3.4. Standard test condition (STC)- The STC for a solar cell are solar irradiation level of 1000W/m^2, a temperature of 25^{0}C, and an atmospheric pressure of 1.5 [9].

3.5. Fill-Factor (FF)- FF is the ratio of the maximum power to the product of V_{OC} and I_{SC}. It is calculated by Equation (18). To yield precise output, FF is desired to be closer to unity [31].

$$FF = \frac{P_{max}}{V_{OC} \times I_{SC}} \quad (18)$$

3.6. Efficiency (η)- The ratio of maximum power to the product of various solar irradiation levels and the area enclosed by the solar panel are known as efficiency [30]. It is calculated by Equation. (19).

$$\eta = \frac{P_{max}}{L \times A} \quad (19)$$

Where P_{max} is the initiated maximum power, "L" is the sun's rays falling on the solar cell, and "A" is the surface area of assembled sun structures.

3.7. Performance Ratio (PR)- The performance ratio of a solar module is the quotient of energy measured in kilowatt hour to the product of irradiation on the panel, active area of assembled sun's structures, and corresponding efficiency. It is calculated by Equation (20) [4].

$$PR = \frac{Energy\ Measured(kWh)}{Irradiation\ (kWh/m^2)\ X\ Active\ area\ of\ PV\ module(m^2)\ X PV\ module\ \eta} \quad (20)$$

3.8. Capacity Utilization Factor (CUF)- The fraction corresponding to the photons emitted by the sun's rays for the entire calendar year and the analogous output of power at its computed range are termed CUF. It is calculated by equation (21) [29].

$$CUF = \frac{Energy\ Measured(kWh)}{365\ X\ 24\ X\ Installed\ Capacity} \quad (21)$$

4. RESULTS AND DISCUSSION

Table 1. shows the data corresponding to several parameters that are employed during the comparative approaches of solar photovoltaic modules for 1 and 2-diode solar models respectively.

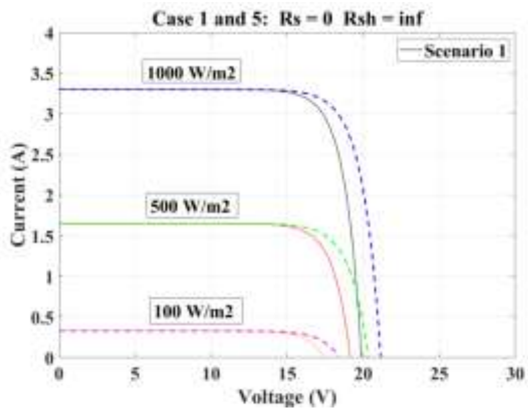
Table 1. Specifications for 1-diode and 2-diode model (Module-TATA SOLAR GOLD 55).

Parameters	1-diode	2-diode
Power (P_{max})	55 W	55 W
Voltage (V_{mp})	18.20 V	18.2 V
Current (I_{mp})	3.02 A	3.02 A
Open Circuit Voltage (V_{OC})	21.8 V	21.8V
Short Circuit Current (I_{SC})	3.26 A	3.26 A
Solar-generated current for measurements (I_{PV})	3.33 A	3.33 A
Diode Saturation Current (I_0) ie I_{01} = I_{02}	2.5e-8 A	2.5e-8 A
Quality Factor (N_1)	1.15	1.25
Quality Factor (N_2)	-	1.30
Resistance attached in series (R_S)	0.04 Ω	0.04 Ω
Resistance attached in shunt (R_{sh})	320.96 Ω	320.96 Ω
Number of Series Solar Cells (n_S)	36	36
Minimum Bypass Diode	9 A	9 A
Maximum Series Fuse	8 A	8 A
Area	0.4 m^2	0.4 m^2

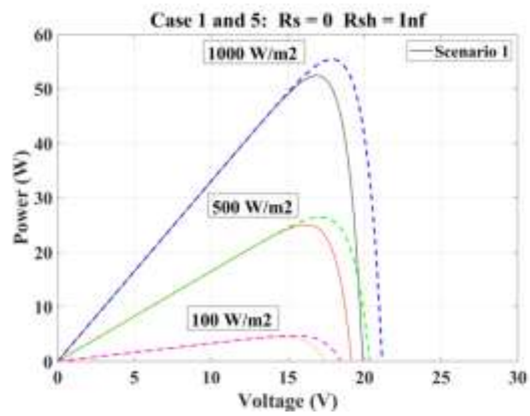
4.1 End Result of a Change in Irradiance

Figs. 9-12 correspond to the consequence of varying solar irradiation levels on different models of solar photovoltaic modules both for 1 and 2-diode models. 100 W/m^2, 500 W/m^2, and 1000 W/m^2 are the three different irradiation levels being considered to study the behaviour of varying irradiation levels by keeping the temperature constant at 25^{0}C. The diode ideality factor is 1.15 for the 1-diode model and n_1= 1.25 and n_2= 1.3 for the 2-diode solar model. It is observed that, maximum power increases when there is a gradual increase in the irradiation level which in turn also increases short-circuit current.

This modeling is done under scenario 1 which includes three different irradiations: 1000W/m^2, 500W/m^2, and 100W/m^2 with constant temperature values of 25^{0}C for a 1 and 2-diode solar models respectively as shown in Fig. 9. Under 1000W/m^2, we recognize that maximum voltage for 1-diode model is 16.82V and for 2-diode model it is 17.86V which indicates that 2-diode solar model is 5.82% better concerning 1-diode model. Maximum power for 1 and 2-diode models is 52.41W and 55.39W, respectively which clearly shows that 2-diode model is 5.38% higher than 1-diode model.



(a)



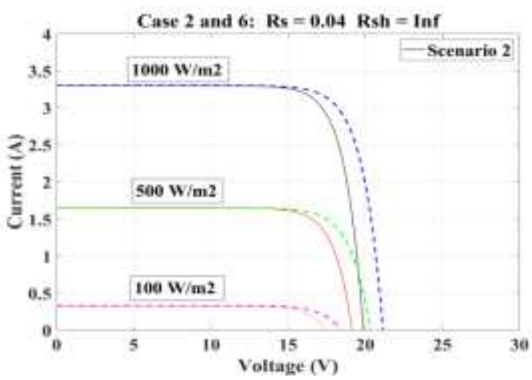
(b)

Fig. 9. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) model (a) I-V and (b) P-V characteristics.

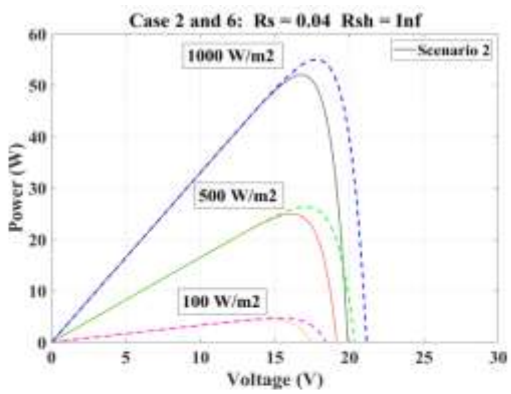
For 500W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 16.24V and 17.18V which denotes that a 2-diode solar model is 5.47% better than 1-diode model. Maximum power attained is 25.06W and 26.44W respectively for 1 and 2-diode models which account for 2-diode's betterment of 5.21% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 14.64V and 15.44V which denotes that a 2-diode solar model is 5.18% better than 1-diode model. Maximum power attained is 4.48W and 4.71W respectively for 1 and 2-diode solar models which account for 2-diode's betterment of 4.88% over 1-diode model.

Under scenario 2, three different irradiation levels of 1000W/m^2, 500W/m^{2,} and 100W/m^2 with constant temperature values of 25^{0}C is considered for 1 and 2-diode models. It is shown in Fig. 10. Under 1000W/m^2, we recognize that the maximum voltage for 1-diode solar model is 16.76V and for 2-diode model it is 17.93V which indicates that 2-diode model is 6.52% better with respect to 1-diode model. Maximum power for 1 and 2-diode models is 52.03W and 55.01W, respectively which clearly shows that the 2-diode model is 5.41% higher than the one-diode model.



(a)



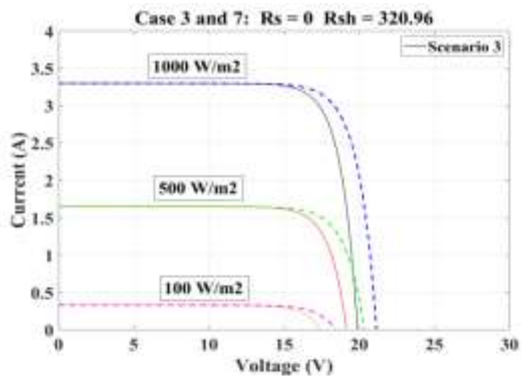
(b)

Fig. 10. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) model (a) I-V and (b) P-V plots.

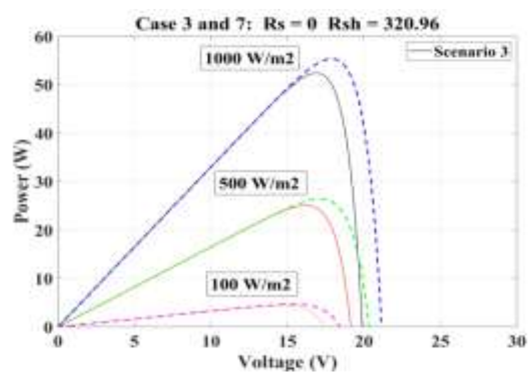
For 500W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 16.14V and 17.15V which denotes that a 2-diode solar model is 5.88% better than a 1-diode solar model. Maximum power attained is 24.97W and 26.35W respectively for 1 and 2-diode solar models which account for the 2-diode's betterment of 5.24% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 14.57V and 15.51V which denotes that a 2-diode solar model is 6.06% better than a 1-diode solar model. Maximum power attained is 4.48W and 4.70W, respectively for 1 and 2-diode models which account for the 2-diode's betterment of 4.68% over the 1-diode model.

In this scenario 3, three different irradiation levels 1000W/m^2, 500W/m^2, and 100W/m^2 with constant temperature values of 25^{0}C for 1 and 2-diode models are incorporated. It is shown in Fig. 11. Under 1000W/m^2, we recognize that the maximum voltage for the 1-diode model is 16.01V and for the 2-diode model, it is 17.05V which indicates that the 2-diode model is 6.09% better with respect to the 1-diode model. Maximum power for 1 and 2-diode models is 52.41W and 55.37W respectively which clearly shows that the 2-diode model is 5.34% higher than the 1-diode model.



(a)

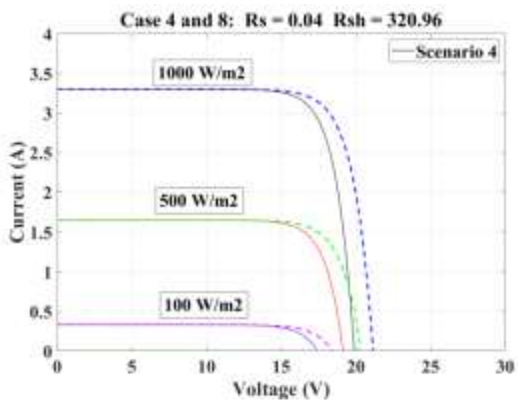


(b)

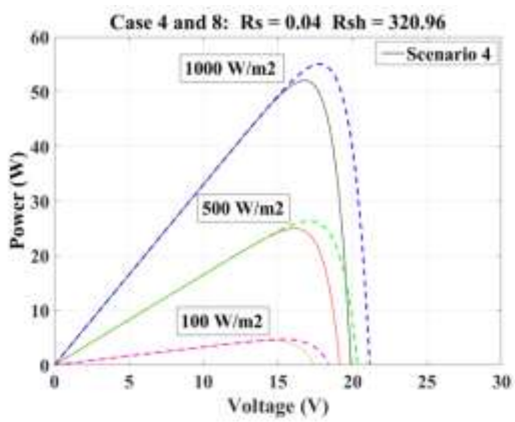
Fig. 11. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) model (a) I-V and (b) P-V plots.

For 500W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 17.1V and 16.14V which denotes that a 2-diode solar model is 5.61% better than a 1-diode model. Maximum power attained is 25.06W and 26.42W, respectively for 1 and 2-diode solar models which account for the 2-diode's betterment of 5.14% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for 1 and 2-diode models is 14.12V and 15.01V which denotes that a 2-diode model is 5.92% better than a 1-diode solar model. Maximum power attained is 4.48W and 4.69W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 4.47% over the 1-diode model.



(a)



(b)

Fig. 12. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) model (a) I-V and (b) P-V plots.

Under scenario 4, three different irradiation levels of 1000W/m^2, 500W/m^{2,} and 100W/m^2 with constant temperature values of 25^{0}C are used for 1 and 2-diode model of the solar cell. It is shown in Fig. 12. Under 1000W/m^2, we recognize that the maximum voltage for the 1-diode model is 16.76V, and for 2-diode models, it is 17.80V which indicates that the 2-diode model is 5.84% better with respect to the 1-diode model. Maximum power for 1 and 2-diode models is 52.03W and 54.98W, respectively. It clearly shows that the 2-diode model is 5.36% higher than the 1-diode model.

For 500W/m^2, the maximum voltage attained for 1 and 2-diode models is 16.14V and 17V which denotes that the 2-diode model is 5.05% better than a 1-diode model. Maximum power attained is 24.96W and 26.32W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 5.16% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for the 1 and 2-diode models is 14.57V and 15.39V which denotes that the 2-diode model is 5.32% better than the 1-diode model. Maximum power attained is 4.48W and 4.68W, respectively for 1 and 2-diode models which account for the 2-diode's betterment of 4.27% over one diode model.

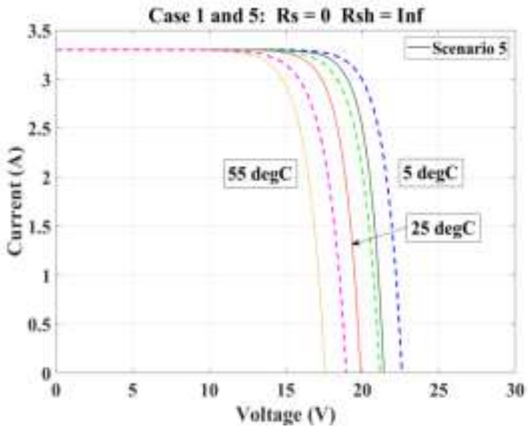
4.2 End Result of a Change in Cell Temperature

To bring the outcome of the studied variation in temperature data on the proposed models of the solar photovoltaic module, simulation was performed in MATLAB. It is concluded that the 2-diode solar model gives a precise value under values of temperature as shown in Figs. 13-16. Power has an inverse relationship with temperature. The amount of energy encapsulated by the sun and the amount of power being generated leads to temperature variation. It can be noted from power-voltage plots as shown in Fig. 13(b)-16(b) that the 2-diode solar model extracts maximum power than the 1-diode model.

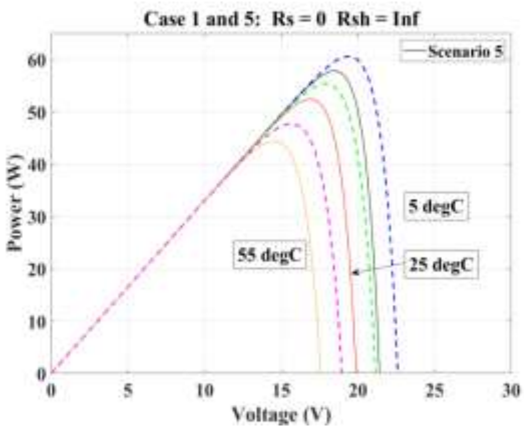
Under scenario 5, three different temperature values of 50C, 250C, and 550C with constant irradiation level 1000W/m2 is studied for the 1 and 2-diode model, respectively. It is shown in Fig. 13. For 50C, we recognize that the maximum voltage for the 1-diode model is 18.39V and for the 2-diode model, it is 19.4V which indicates that the 2-diode model is 5.21% better with respect to one diode model. Maximum power for 1 and 2-diode models is 57.81W and 50.58W, respectively which clearly shows that the 2-diode model is 4.57% higher than 1-diode model.

For 500W/m2, the maximum voltage attained for the 1 and 2-diode models is 16.82V and 17.86V which denotes that the 2-diode model is 5.82% better than the 1-diode model. Maximum power attained is 52.4W and 55.39W, respectively for 1 and 2-diode models which account for the 2-diode's betterment of 5.39% over the 1-diode model.

For 100W/m2, the maximum voltage attained for the 1 and 2-diode models is 14.55V and 15.64V which denotes that the 2-diode model is 6.96% better than the 1-diode model. Maximum power attained is 44.39W and 47.71W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 6.95% over the 1-diode model.

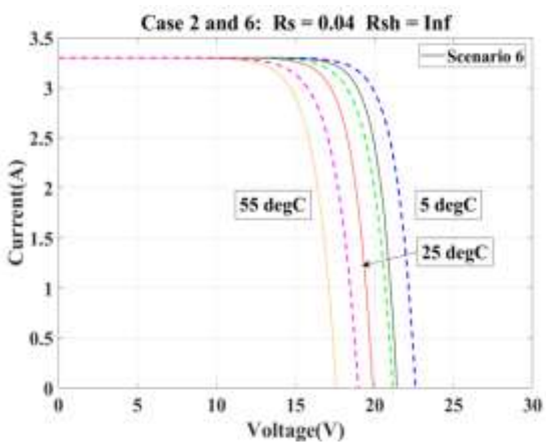


(a)



(b)

Fig. 13. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) structure (a) I-V and (b) P-V plots.



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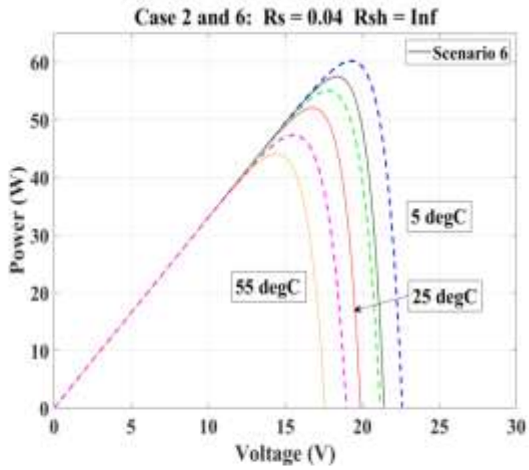


(b)

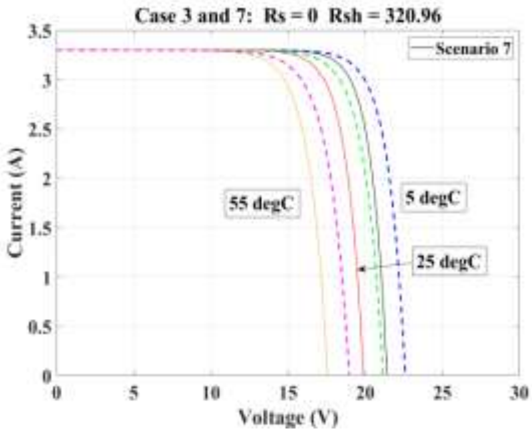
Fig. 14. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) structure (a) I-V and (b) P-V plots.

Under scenario 6, three different temperature values of 5^0C, 25^0C, and 55^0C with constant irradiation level 1000W/m^2 is studied for 1 and 2-diode model respectively. It is shown in Fig. 10. For 5^0C, we recognize that the maximum voltage for the 1-diode model is 18.33V and for the 2-diode model, it is 19.19V which indicates that the 2-diode model is 4.48% better than the 1-diode model. Maximum power for 1 and 2-diode models is 57.71W and 60.50W respectively which clearly shows that the 2-diode model is 4.61% higher than the 1-diode model.

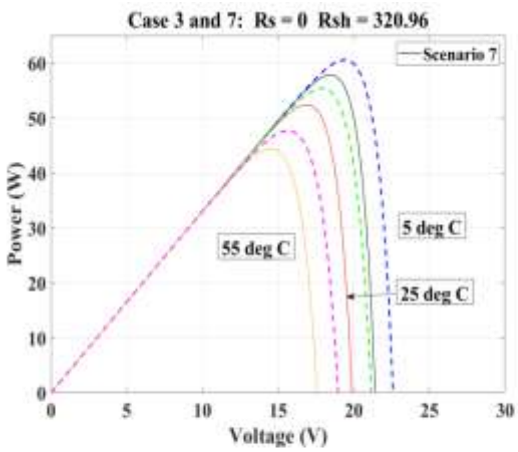
For 500W/m^2, the maximum voltage attained for the 1 and 2-diode models is 17.02V and 17.8V which demarcates that the 2-diode model is 4.38% better than the 1-diode model. Maximum power attained is 52W and 55.29W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 5.95% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for 1 and 2-diode models is 14.49V and 15.58V which denotes that the 2-diode model is 6.9% better than the 1-diode model. Maximum power attained is 44.29W and 47.50W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 6.75% over the 1-diode model.

Under scenario 7, three different temperature values of 5^0C, 25^0C, and 55^0C with constant irradiation level 1000W/m^2 for 1 and 2-diode models, respectively as shown in Fig.15 are taken into consideration. For 5^0C, we recognize that the maximum voltage for the 1-diode model is 18.3V and for the 2-diode model, it is 19.39V which indicates that the 2-diode model is 5.62% better with respect to the 1-diode model. Maximum power for the 1 and 2-diode models is 57.52W and 60.10W, respectively which clearly shows that the 2-diode model is 4.29% higher than the 1-diode model.



(a)



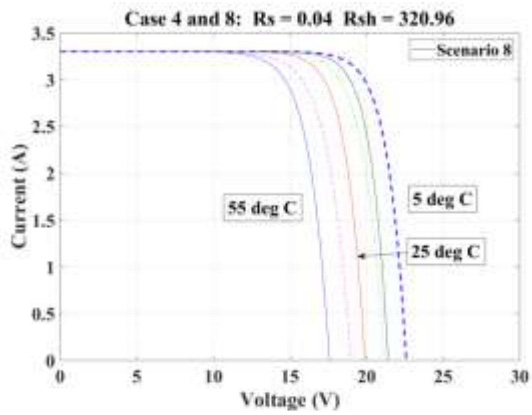
(b)

Fig. 15. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) structure (a) I-V and (b) P-V plots.

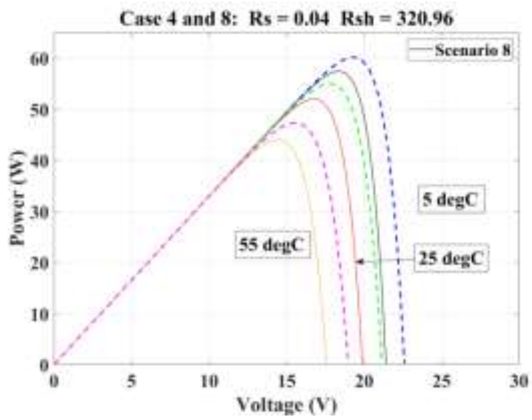
For 500W/m^2, the maximum voltage attained for the 1 and 2-diode models is 16.71V and 17.71V which demarcates that the 2-diode model is 5.64% better than the 1-diode model. Maximum power attained is 52.09W and 55.20W respectively for 1 and 2-diode models which account for the 2-diode's betterment of 5.63% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for 1 and 2-diode models is 14.10V and 15.06V which denotes that the 2-diode model is 6.37% better than 1 diode model. Maximum power attained is 44.19W and 47.42W, respectively for 1 and 2-diode models which account for the 2-diode's betterment of 6.81% over the 1-diode model.

Under scenario 8, three different temperature values of 5^{0}C, 25^{0}C, and 55^{0}C with constant irradiation levels of 1000W/m^2 for 1 and 2-diode models are considered. It is shown in Fig. 16. For 5^{0}C, we recognize that the maximum voltage for the 1-diode model is 18.01V and for the 2-diode model, it is 19.33V which indicates that the 2-diode model is 6.82% better than respect to the 1-diode model. Maximum power for 1 and 2-diode models is 57.42W and 60.15W, respectively which clearly shows that the 2-diode model is 4.53% higher than the 1-diode model.



(a)

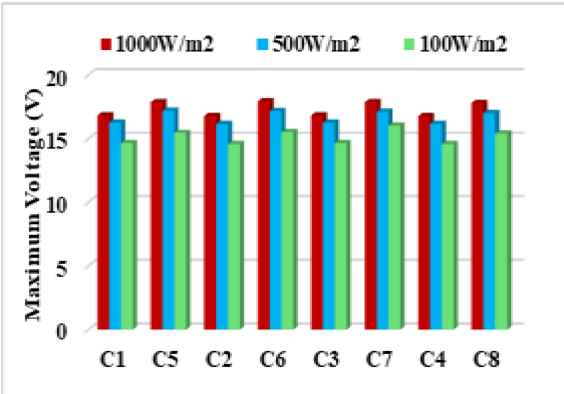


(b)

Fig. 16. Output performance characteristics of PV module for 1 (bold-line) and 2-diodes (dotted-line) structure (a) I-V and (b) P-V plots.

For 500W/m^2, the maximum voltage attained for 1 and 2-diode solar models is 17V and 17.8V which denotes that the 2-diode model is 4.49% better than the 1-diode model. Maximum power attained is 52.02W and 54.98W, respectively for 1 and 2-diode models. It shows that the 2-diode model is much better up to 5.38% over the 1-diode model.

For 100W/m^2, the maximum voltage attained for the 1 and 2-diode solar models is 14.01V and 15V which denotes that the 2-diode model is 6.6% better than the 1-diode model. Maximum power attained is 44.01W and 47.31W, respectively for 1 and 2-diode models which account for 2- the diode's betterment of 6.97% over the 1-diode model.



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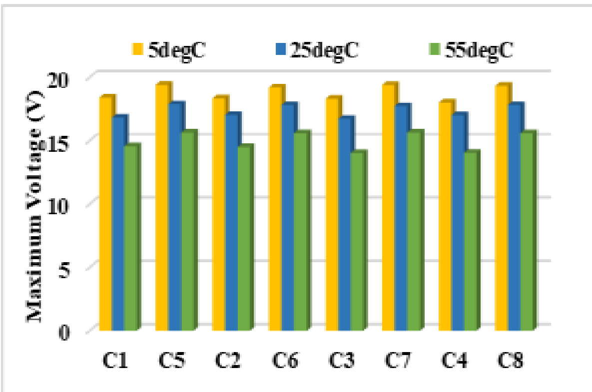
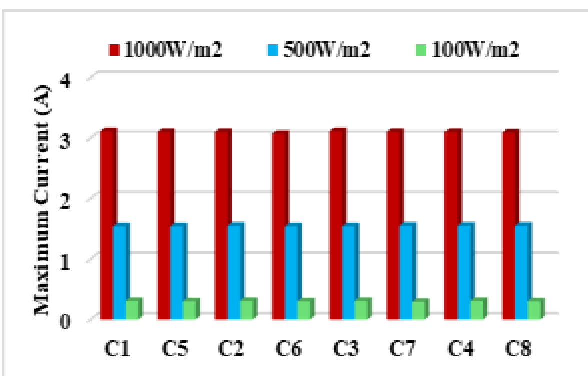


(b)

Fig. 17. Maximum Voltage (a) At dissimilar irradiation levels and 25^{0}C (b) At dissimilar temperature values and 1000W/m^2.

The maximum Voltage of the PV module at dissimilar irradiation levels with 25^{0}C and at dissimilar temperature values with a 1000W/m^2 is depicted in Fig. 17. It can be observed that as the irradiation level increases, maximum voltage increases and as temperature values increase, its value decreases.



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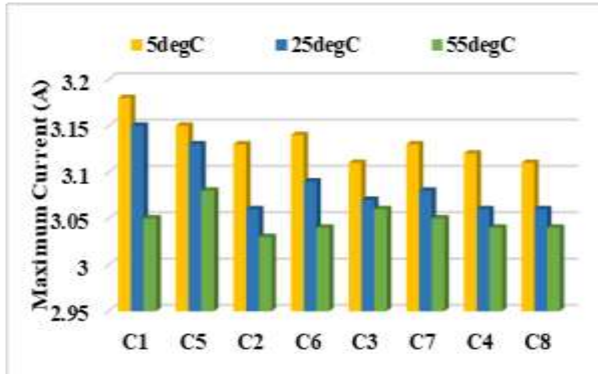
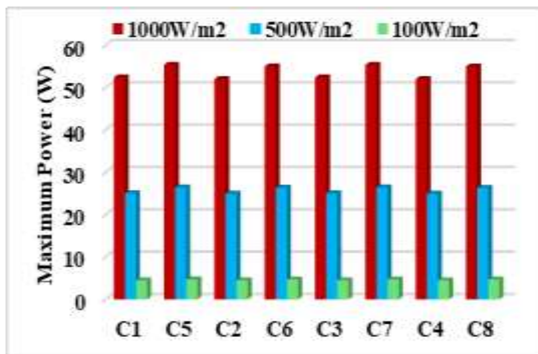


(b)

Fig. 18. Maximum Current (a) At dissimilar irradiation levels and 25^{0}C (b) At dissimilar temperature values with 1000W/m^2.

The maximum current of the solar module under varying irradiations with 25^{0}C and at varying temperature values with 1000W/m^2 is shown in Fig. 18 for both the 1 and 2-diode models. It shows that with the increase in solar level, the value of maximum current increases and with an increase in temperature at a constant irradiation level, the maximum current value decreases.



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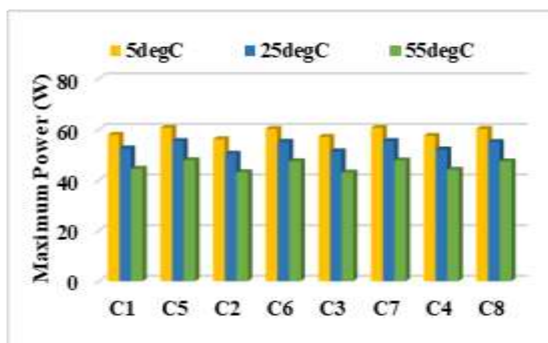
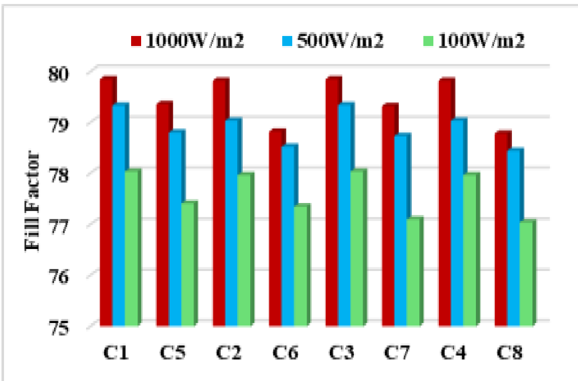


(b)

Fig. 19. Maximum power (a) At dissimilar irradiation levels and 25^{0}C (b) At dissimilar temperature values and 1000W/m^2.

The 2-diode model exhibits larger power of 4.29% as compared to the 1-diode model at each instance of non-uniform irradiation level and temperature as observed in Fig. 19.

As the irradiance level decreases, accuracy is lost, and the 2-diode solar model is more precise than the 1-diode solar model as observed in Fig.20 (a). In contrast, to a change in open circuit voltage and short circuit current, the fill-factor value decreases as shown in Fig. 20(b).



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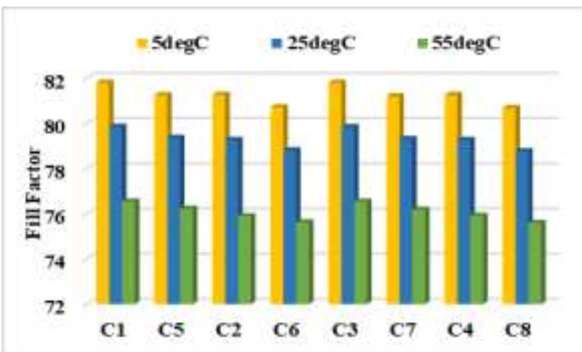
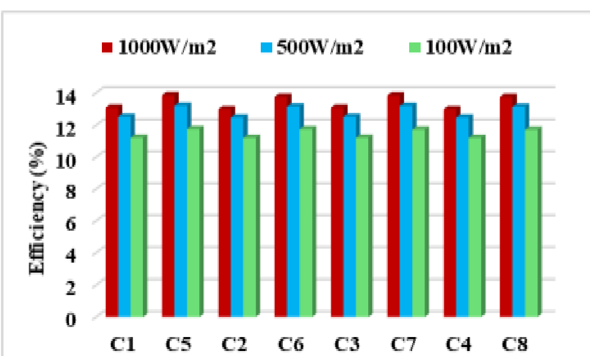


(b)

Fig. 20. Fill Factor (a) At dissimilar irradiation levels and 25^0C (b) At dissimilar temperature values and 1000W/m^2.



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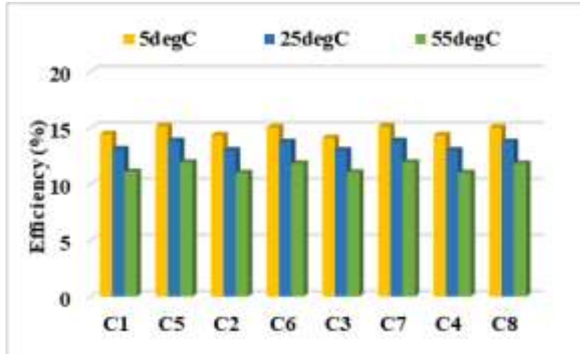
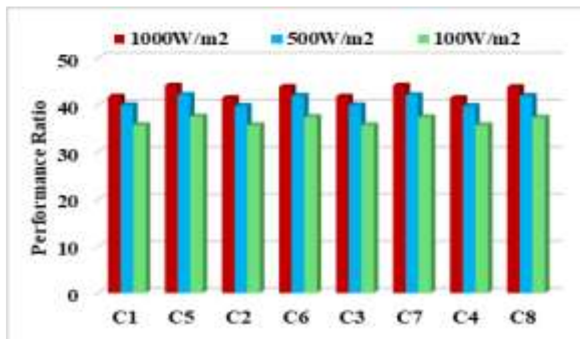


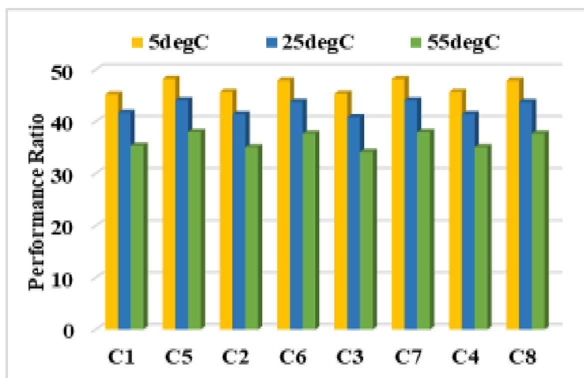
(b)

Fig. 21. Efficiency (a) At dissimilar irradiation levels and 25^0C (b) At dissimilar temperature values and 1000W/m^2.

A decrease in solar radiation reduces the solar module's efficiency whereas for temperature it is observed that there exists an inverse relationship between temperature and panel efficiency i.e., panel efficiency decreases as the ambient temperature increases as shown in Fig. 21.



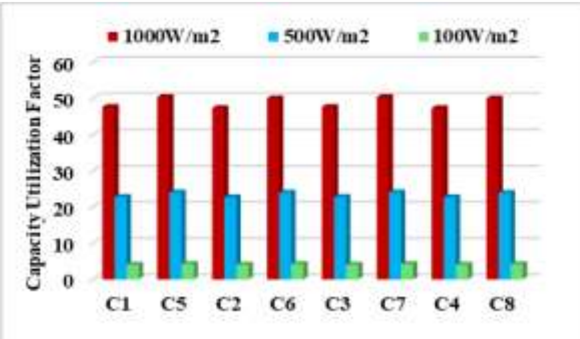
(a)



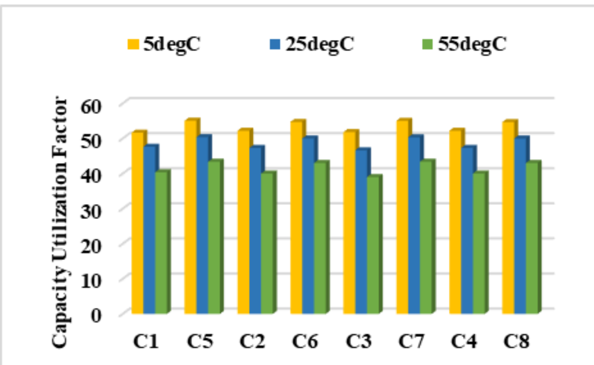
(b)

Fig. 22. Performance Ratio (a) At dissimilar irradiation levels and 25^0C (b) At dissimilar temperature values and 1000W/m^2.

The performance ratio of a solar cell at dissimilar irradiations with 25^0C and at dissimilar temperature values with 1000W/m^2 is depicted in Fig. 22. So, for a given solar structure under STC, the PR value is approximately 41.73%. This means that 58.27% of the sun's energy remained useless due to wear and tear of the solar photovoltaic module or some kind of shading due to dust, the shadow of trees, buildings, etc.



(a)



(b)

Fig. 23. Capacity Utilization Factor (a) At dissimilar irradiation levels and 25^{0}C (b) At dissimilar temperature values and 1000W/m^2.

As observed from Fig. 23, a decrease in solar radiation reduces the solar module's capacity utilization factor whereas for temperature it is observed that there exists an inverse relationship between temperature and the panel's capacity utilization factor i.e., capacity utilization factor decreases as the ambient temperature increases.

4.3. End Result of Diode Ideality Factor (n)

The value of the diode's ideal factor for the 1-diode solar model is 1.15 and for the 2-diode model is n_1 = 1.25 and n_2 = 1.3. Output voltage and maximum power get affected when there is variation in their corresponding values. It is observed that for a 2-diode model, with a change in the diode's ideality factor, there is a change in the output power.

4.4. End Result of Resistance Connected in Series (R_S)

The value of series resistance used in the proposed novel study is 0.04 Ω. Regarding shunt resistance, the series resistance value is kept too small and its effects are observed as shown in Fig. 21-23.

4.3 End result of Resistance Connected in Parallel (R_{SH})

PV cell efficiency as well as maximum power is increased with the increased value of shunt resistance as shown in Fig. 19 and Fig. 21.

5. COMPARISON OF CIRCUIT MODELS

Table 2 focuses clearly on the distinct parameters that are investigated in this study. It is observed that the 2-diode model leads to enhanced efficiency and fill factor. It harvests maximum power under varying irradiations and temperature changes. Also, the performance of the 2-diode model is reported to be closer to the actual performance of the solar cell.

Table 2. Comparison of circuits with 1 and 2 diodes based on various parameters.

Parameter	Circuit with 1 and 2 diodes		Remarks
	Irradiation	Temperature	
Maximum Voltage	Fig. 17 (a)	Fig. 17 (b)	5.82 % more improved data of the 2-diode model specifies its worth to the 1-diode model giving the more reliable value of maximum voltage.
Maximum Current	Fig. 18 (a)	Fig. 18 (b)	The I-V curve of the 2-diode model is abruptly increased concerning the 1-diode model. Hence, the maximum current obtained for the 2-diode model is 0.32% more realistic than the 1-diode model.
Maximum Power	Fig. 19 (a)	Fig. 19 (b)	The 2-diode model exhibits 5.38% larger power as compared to the 1-diode model at each instance of varying irradiation level.
Fill Factor	Fig. 20 (a)	Fig. 20 (b)	As irradiance goes lower, accuracy is lost but still, the 2-diode model is 0.61% more precise than the 1-diode model.
Efficiency	Fig. 21 (a)	Fig. 21 (b)	The 2-diode model maximizes the η by

			5.41%. Thus, it leads to excellent accuracy at lower irradiation conditions and higher temperatures.
Performance Ratio	Fig. 22 (a)	Fig. 22 (b)	The performance of the 2-diode model is 5.38% superior as compared to other structures taken in this study both in terms of higher efficiency and execution of parameters at varying conditions.
Capacity Utilization Factor	Fig. 23 (a)	Fig. 23 (b)	The capacity utilization factor is 5.38% better for the 2-diode solar model than the 1-diode model.
Series Resistance	Fig.13 (a)-(b) - 16 (a)-(b)	Fig.13 (a)-(b)-16 (a)-(b)	No such significant problem is observed for a circuit consisting of the 2-diode solar model when subjected to temperature variation as regards to 1-diode model.
Shunt Resistance	Fig.13 (a)-(b) - 16 (a)-(b)	Fig.13 (a)-(b)-16 (a)-(b)	The effect of shunt resistance is observed particularly more at low irradiance since there will be less magnitude of current, and here the 2-diode model is much more accurate than the 1-diode model.
Ideality Factor	Fig.13 (a)-(b) - 16 (a)-(b)	Fig.13 (a)-(b)-16 (a)-(b)	The I-V curve calculated by the 2-diode model fits accurately higher than the 1-diode model at the changed values of the ideality factors.

6. CONCLUSION

The proposed mathematical modeling is elaborately studied under varying irradiation levels and temperature changes for 8 cases of 1-diode and 2-diode models of the solar cell, respectively. In this study, the fill factor for the 2-diode model is 0.61% better than the 1-diode model. The efficiency of the 2-diode model is 5.41% better than the 1-diode model under the considered cases. Even the minute variation in series and shunt resistance tends to drastically affect the value traced for maximum power. Hence, it is concluded from the study that the capacity utilization factor of the 2-diode solar model is improved by 5.38% as compared to the 1-diode model. The performance ratio is observed much more precise and accurate for the 2-diode model than for the 1-diode model which accounts for 5.39%. The outstanding outcomes of this study reveal the supremacy of the 2-diode model over the 1-diode model under varying irradiation levels and temperature values. The results of the 2-diode solar model are closer and more accurate to actual performance than the 1-diode solar model. In the future, this work can be experimentally validated to observe the authenticity of the proposed work. Also, it provides a one-shot solution to researchers, academicians, and keen learners working in the domain of solar energy to quickly start their work.

NOMENCLATURE

I_{ph}	Current of a photon (A)
I_D, I_{D1}, and I_{D2}	Diode currents (A)
n, n_1 and n_2	Diode's ideal factor
I_{cell}	Output current of PV cell (A)
V_{cell}	Output voltage of PV cell (V)
q	Electron charge (1.602 X 10^{-19} C)
k	Boltzmann constant (1.380 X 10^{-23}J/K)
T	Operating temperature (deg C)
I_0, I_{01}, I_{02}	Diode reverse saturation current (A)
I_{sc}	Short circuit current (A)
V_{oc}	Open circuit voltage (V)
R_S	Series resistance (Ω)
R_{SH}	Shunt resistance (Ω)
P	Power (W)
n_s	Number of cells connected in series
STC	Standard Test Conditions (1000W/m^2 and 25^0C)
D-1, 2, 3, 4	Correlate with a circuit having 1 diode
D-5, 6, 7, 8	Correlate with a circuit having 2 diodes

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