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Original citation & hyperlink:
Abdullahi, N, Saha, C & Jinks, R 2017, 'Modelling and performance analysis of a silicon PV module' *Journal of Renewable and Sustainable Energy*, vol 9, no. 3, 033501
https://dx.doi.org/10.1088/1742-5468/aa5dc3

DOI 10.1063/1.4982744
ISSN 1941-7012

Publisher: AIP Publishing

Modelling and Performance Analysis of a Silicon PV Module

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Significant effect and progress have been made by manufacturers and researchers to understand the performance and modelling concept of the PV modules under various conditions such as wind, dust, snow etc., which are often harsh and may lead to degradation of the PV module. This paper presents a study on the performance of an 85 W monocrystalline photovoltaic module under different conditions, with measurements being taken under indoor and outdoor conditions. To obtain maximum irradiation under outdoor conditions, the module was inclined at an angle of 25^o facing the southern direction (UK). To investigate the I-V characteristic of the PV module a single diode electrical equivalent model has been developed using MATLAB-Simulink and the measured results are discussed together with the simulation results. The measured results have shown that the module is capable of generating 17.75 W/m^2 with an efficiency of 7% and 138 W/m^2 with an efficiency of 8% from indoor office building and outdoor conditions respectively in UK during summer time. This research work makes a significant contribution to photovoltaic researchers to identify the suitable applications such as embedded devices or body-worn sensor for use both in indoor and outdoor conditions.

I. INTRODUCTION

The renewable energy markets have increased significantly over the last 20 years and the applications of the photovoltaic (PV) system are becoming important in many countries globally particularly interest in the field of distributed electric power generation from solar energy. There are different types of solar PV cells available in the market and they range from monocrystalline, multi crystalline, thin film, and amorphous silicon cells.[1-5] The panels can be placed in fields or on the rooftops of buildings, connected to an inverter for the direct solar energy conversion to an alternating current. However, the performance of a photovoltaic cell is mostly influenced by both external and internal factors which include radiation, wind, electrical losses, structural features, pollution, visual losses, aging, temperature, and shading.[6-9] The theoretical modelling and computer simulation of PV systems are essential to understand the output characteristics, efficiency, performance and to analyse the system with the variation of solar insolation, temperature and the output voltage. Over the past decades a significant amount of research has already been done on the PV modelling and parameterizations using various simulation tools such as MATLAB-Simulink, Spice, SABER, electromagnetic transient etc. to understand the non-linear I-V/P-V characteristic of the PV module.[10-25]

However, the majority of the reported works discuss the theoretical background and performance of the I-V and P-V characteristics generated from the fundamental modelling equation of the module current and verified the modelling results using the data sheet information under standard test conditions (STC) without considering real test results under indoor and outdoor conditions. There have also been several attempts to verify the modelling results with the experimental values.[13-16] For example, Rahman et al. [13] who validated their power output of his proposed model against measured power output for a polycrystalline module provided by National Institute of Standards and Technology. Unlike Rahman et al. [13], Adamo et al. [14] developed the evaluation tools of a PV panel to monitor and estimate the modelling parameters based on Labview and MATLAB environment. They also tested a polycrystalline silicon panel IP10P by Istar Solar under outdoor condition during a summer sunny day and the measured results verified with the simulation results. Also Xiao et al.[15] presented a general approach to modelling and simulation of a PV system and their model is compared with the datasheet results provided by the product manufacturer. Furthermore, their proposed model is also evaluated by measured results of a 2.4 kW practical grid system. Rather than focusing on modelling, simulations and analysis of an 85 W monocrystalline photovoltaic module this paper has placed an emphasis on the details real indoor and outdoor test conditions performance. The structure of the paper is organised as follows: In section 2, the modelling of the PV module is based on the single diode electrical equivalent circuit where the current is expressed in voltage and other parameters are briefly described.

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The MATLAB-Simulink block diagram model is presented in section 3 and the model will be used to generate the I-V and P-V curves to assess module performance and efficiency under various conditions. The performance of the module at STC and real test conditions (RTC) will be discussed in section 4 and 5 respectively. Performance under standard test conditions will be discussed in the following section. Finally the measured results are compared and discussed with the modelling results.

II. SINGLE DIODE EQUIVALENT CIRCUIT MODEL

The equivalent circuit of a PV cell consists of a current source in parallel with a single diode and two resistances: shunt and series resistance as shown in figure 1. This is an accurate and simplified model which could define the entire I-V and P-V curve of a cell, module or array as a continuous function for a given set of operating conditions.[20-23] The photo-current of the module is given by;

$$I_{ph} = \frac{[I_{sc} + \alpha(T - 298)]E}{1000} \tag{1}$$

The reverse saturation current of the module can be defined by;

$$I_{rs} = \frac{I_{sc}}{[\exp(\frac{qV_{oc}}{N_s kAT}) - 1]} \tag{2}$$

The diode current is expressed by;

$$I_D = I_{rs}\left[\frac{T}{T_r}\right]^3 \exp[\frac{qE_g}{Ak}(\frac{1}{T_r} - \frac{1}{T})] \tag{3}$$

The PV module output current can be calculated using the equation;

$$I = N_p I_{ph} - N_p I_D[\exp(\frac{q(V_{pv} + IR_s}{N_s akT}) - 1] \tag{4}$$

Where the definitions of I_{sc}, α, E, T, q, V_{oc}, N_s, k, A, I_{rs}, q, E_g, a, T_r N_p, V_{pv}, N_s and I are described to appendix table.

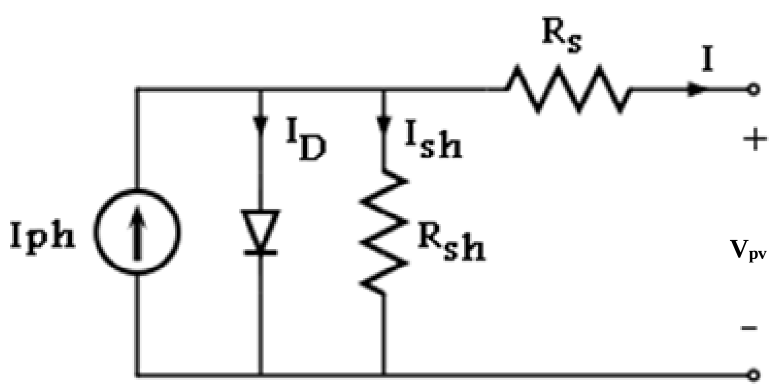

FIG. 1. Single diode equivalent circuit Model of the PV cell.

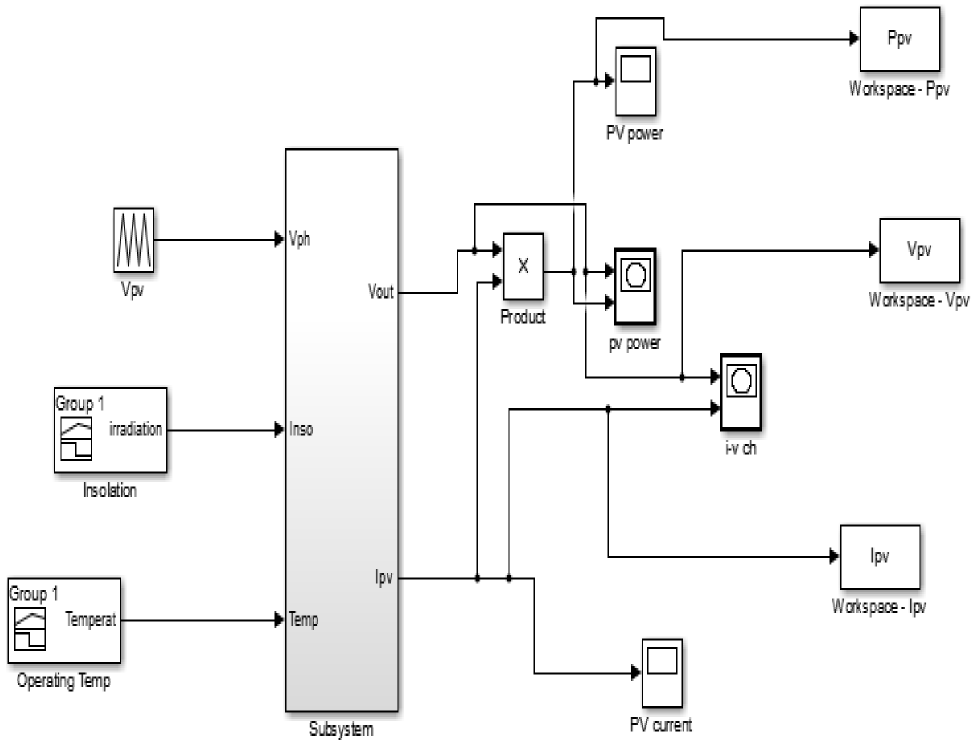

FIG. 2. Simulink model of an 85 W monocrystalline PV Module (SPR S85).

III. BLOCK DIAGRAM MODEL

The Simulink block diagram model has been developed using MATLAB-Simulink environment based on equation (4). The model is implemented as indicated in figure 2 above and it is made of six subsystems which are connected to form an individual subsystem. The output current, voltage and power vary as a function of temperature and irradiation. The step by step procedure for building the respective subsystems are found in many literatures.[18-21] From the diagram it can be seen that the input/output parameters are voltage, irradiation, operating temperature, the output current and output voltage. Ultimately this model will be used to generate the I-V and P-V characteristics of the tested PV module (PN SPR S85)[26] under standard test conditions (STC) and real test conditions (RTC) and evaluate the results.

IV. PERFORMANCE EVALUATION OF THE MODULE

The tested module[26] consists of 30 cells connected in series as shown in figure **3** and each module is capable of generating 18 V (open circuit) with each cell having **0.6** volts at **STC.** Table I shows the main parameters of the PV module.

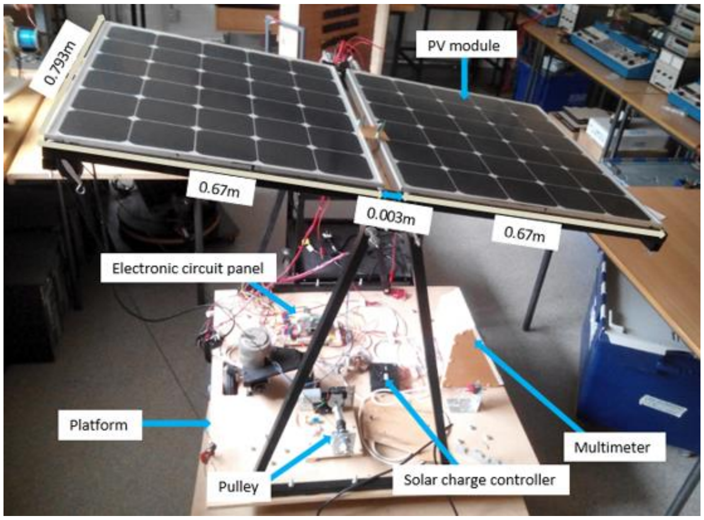

FIG. 3. Tested photovoltaic panel (SPR S85).

TABLE I. Electrical parameters of the reference PV module

Parameters	values
Maximum Power (P_{max})	85.00 W
Voltage at maximum power (V_{mp})	15.90 V
Current at Maximum power (I_{mp})	5.34 A
Open Circuit Voltage (V_{oc})	19.00 V
Short Circuit Current (I_{sc})	5.98 A
Total number of cells in series (N_s)	30.00
Cell Efficiency	19.60 %
Module Efficiency	16.00 %
Maximum Power Tolerance	±5.00 %
Nominal Operating Cell Temperature	46 ºC ±2
Maximum System Voltage	70.00 V

A. Standard test condition (STC)

The standard test condition of a photovoltaic module is a test performed at irradiation of 1000 W/m^2, a temperature of 25 ºC and an air mass of 1.5 (which is the equivalent for Europe) in order to have a uniform test condition of the PV modules thereby making it possible in conducting uniform comparison of PV modules made by different manufacturers.[27] The performance of the photovoltaic module under standard test conditions has been carried out using the specifications and parameters obtained from the manufacturer's data sheet.[26] Table II shows the comparative results between the model and data sheet values and the error from the modelling results is less than 10%.

TABLE II. Comparison of model output with datasheet value under STC condition.

Parameters	Datasheet values	Model value	Error (%)
Maximum Power, P_{max} (W)	85.00	79.00	7.00
Voltage at P_{max}, V_{mp} (V)	15.90	14.40	9.40
Current at P_{max}, I_{mp} (A)	5.34	5.57	4.30
Open Circuit Voltage, V_{oc} (V)	19.00	18.05	5.00
Short Circuit Current, I_{sc} (A)	5.98	5.97	0.10

Figure 4 shows the simulation results obtained from the performance of the PV module under standard test conditions. The values obtained from parameters measurements and the **I-V** and **P-V** behaviours of the module indicate a good correlation with the manufacturer's parameters. It can be seen from this graph that the maximum simulated power and the maximum voltage (OC) are 80 W and 18 V which is very close to data sheet values 85 W and 19 V respectively. However, the data sheet indicated 32 cells and +5 W to - 5 W tolerances but the real module consists of only 30 cells.

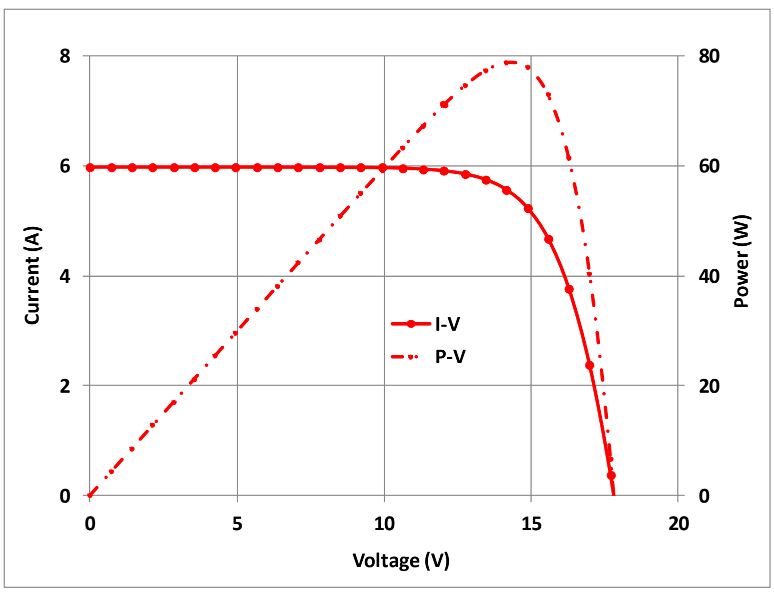

FIG 4. I-V and P-V characteristics of the module at STC (G =1000 W/m^2, T = 25 ^{o}C = 298 K).

B. Real test condition (RTC)

The real test performance of the module has been carried out with the variation of operating temperatures and irradiations under indoor and outdoor conditions. The indoor real test experiment was demonstrated using flood lights and without flood lights at the Mezzanine lab, ECB building, Coventry University. Indoor lighting usually consists of a mixture of sunlight entering the room and artificial light sources used during the experiment. Solar irradiance levels indoor measurement would be neglected since the lab is suited below the underground and the window is insulated double-glass.[28]

1. Indoor performance with floodlight

Two flood lights rated 400 W each were stationed at a distance of 0.61 meters over the PV panel with a cross sectional area of 1.08641 m^2. The irradiance produced by the flood lights for individual PV module is obtained as 753.3 W/m^2 at a temperature of 289 K. The measured maximum power is 63.12 W and the corresponding voltage and current at maximum power point are 15.98 V and 3.95 A respectively. Table III shows the comparative analysis of voltage, current and power between the experiment and simulation results. Figure 5 represents the simulations' readings obtained from the photovoltaic module when it was exposed to an irradiance of 753.3 W/m^2 obtained from the flood lights at a temperature of 289K (real test condition, RTC). The figure shows some slight variances of around 0.5 A current and 0.45 V voltage at maximum power point compare to measured values.

TABLE III. Comparison of indoor measured results with the model under floodlight (753.3 W/m^2, 289 K).

Parameters	Datasheet values	Model value	Error (%)
Maximum Power, P_{max} (W)	61.00	63.12	3.34
Voltage at P_{max}, V_{mp} (V)	15.90	15.98	6.50
Current at P_{max}, I_{mp} (A)	4.09	3.95	3.50
Open Circuit Voltage, V_{oc} (V)	18.05	18.47	2.28
Short Circuit Current, I_{sc} (A)	4.49	4.40	2.00

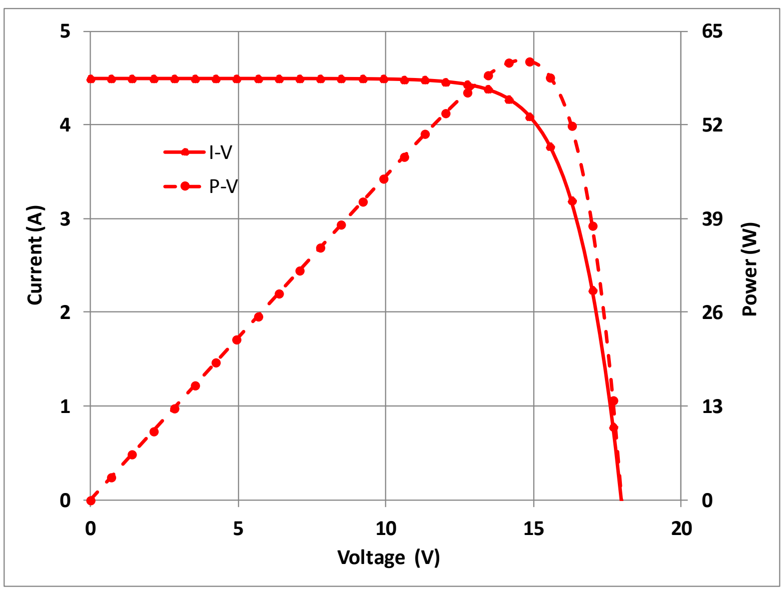

FIG 5. I-V and P-V characteristics of the module under floodlight (G =753.3 W/m^2, T = 16 ^oC = 289 K).

2. Indoor performance without floodlight

Further study was continued on the PV module performance indoors under real time conditions (RTC) without the flood lights. The irradiance levels indoors are significantly lower and it varies from 7.7 W/m^2 to 134.4 W/m^2. The panel was shifted at various positions and sides to obtain different lux values, because the readings differed from one side of the lab to the other, although the temperature remained the same. The irradiation and temperature readings were taken for several days but only three readings from the three days were chosen for simulation purposes. Due to lower temperature and irradiance values, the current and voltage values were very minimal; hence

3 of the values (each for a day) were selected for the simulation. Table IV shows the comparative analysis of voltage, current and power between the experiment and simulation results.

TABLE IV. Comparison of indoor measured results with the model without floodlight.

Parameters	Model value	Experimental value	Error (%)
(1) For G = 134.4 W/m^2, T = 294 K			
Maximum Power, P_{max} (W)	9.44	10.01	6.50
Voltage at P_{max}, V_{mp} (V)	12.74	13.51	5.60
Current at P_{max}, I_{mp} (A)	0.74	0.74	0.00
Open Circuit Voltage, V_{oc} (V)	15.92	15.93	0.06
Short Circuit Current, I_{sc} (A)	0.80	0.78	2.50
(2) For G = 91.09 W/m^2, T = 294 K			
Maximum Power, P_{max} (W)	6.48	6.34	2.21
Voltage at P_{max}, V_{mp} (V)	12.90	12.92	0.15
Current at P_{max}, I_{mp} (A)	0.50	0.49	8.00
Open Circuit Voltage, V_{oc} (V)	15.22	15.22	0.00
Short Circuit Current, I_{sc} (A)	0.54	0.50	8.00
(3) For G = 7.77 W/m^2, T = 294 K			
Maximum Power, P_{max} (W)	0.43	0.45	4.44
Voltage at P_{max}, V_{mp} (V)	9.91	10.46	5.25
Current at P_{max}, I_{mp} (A)	0.04	0.04	0.00
Open Circuit Voltage, V_{oc} (V)	12.80	12.86	0.47
Short Circuit Current, I_{sc} (A)	0.46	0.50	8.00

Figure **6** represents the simulation readings obtained from the module when exposed to different indoors irradiance and different temperatures under real test conditions (RTC). The results obtained indicate that an increase in temperature results in an increase in short circuit current (I_{sc}) and an increase in irradiance generates an increase in open circuit voltage (V_{oc}) and power output. However, the module performance under such conditions is inefficient in that a low output of all the measurements parameters are achieved with a low power output. This is due to the impact the irradiance has on the power output of a PV module thus a high irradiance even at a low temperature generates an increase in power output.

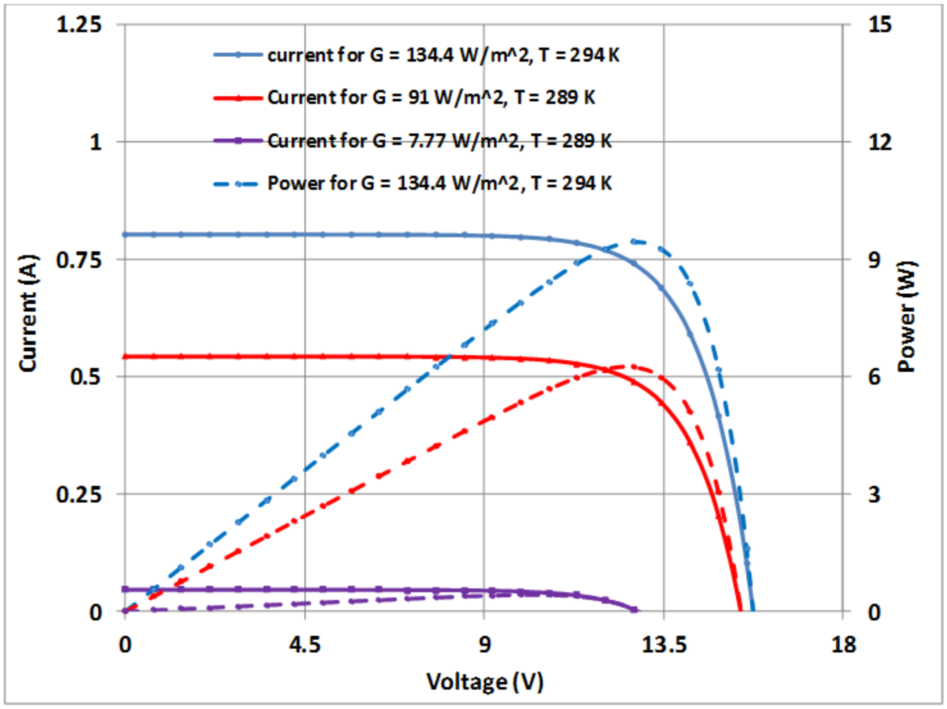

FIG. 6. Indoor I-V and P-V characteristics of the PV module with the variation of irradiation and temperature.

2. Outdoor performance of the PV module

Outdoor performance of the PV module was also carried out as a continuation of the real test performance of the PV module as shown in figure 7 below.

FIG. 7. PV module at outdoor measurement.

Only three readings from the three days were chosen for simulation purposes. The variation of temperature and irradiation with day timing for different days is indicated in figure 8 where day 1 represents a day with rain drops, day 2 represents a clear sunny day and day 3 represents a cloudy day.

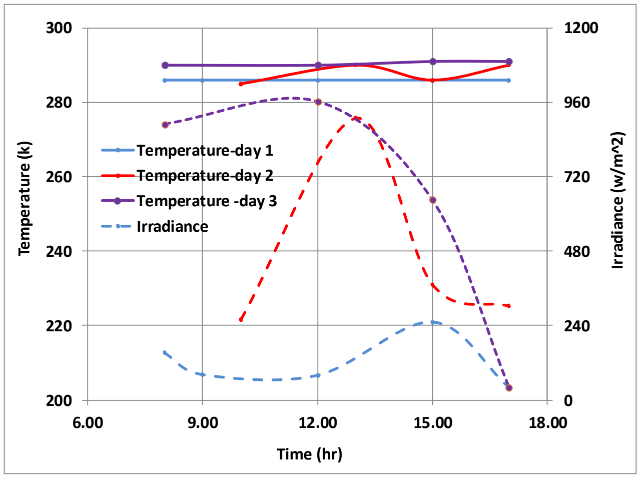

FIG. 8. Measured temperature and irradiation at outdoor for different days.

The module was placed outside and inclined at an angle of 25° facing the southern direction to obtain maximum irradiation. Since solar panels are supposed to be facing south in the northern hemisphere (as in UK) and to be tilted equivalent to the latitude minus 15° in summer and plus 15° in winter; which equals to 25.5° in summer and 63° in winter for latitude 50° which UK is ranged. Also, the optimum value from the PV panel is usually obtained when it is pointed in the direction where the sun is captured most. The figures clearly demonstrate the variations in temperature and irradiation with the times of the days.

Table V shows the comparative analysis of voltage, current and power between the experiment and modelling results. The irradiance levels outdoor varied from 79 W/m2 to 909 W/m2 and the simulation results are well agree with the measured results.

TABLE V. Comparison of outdoor measured results with the model.

Parameters	Model value	Experimental value	Error (%)
(1) For $G = 908.6$ W/m^2, $T = 290$ K			
Maximum Power, P_{max} (W)	73.79	75.07	1.70
Voltage at P_{max}, V_{mp} (V)	14.86	15.51	4.19
Current at P_{max}, I_{mp} (A)	4.96	4.80	3.33
Open Circuit Voltage, V_{oc} (V)	18.05	18.43	2.06
Short Circuit Current, I_{sc} (A)	5.42	5.42	0.00
(2) For $G = 91.09$ W/m^2, $T = 294$ K			
Maximum Power, P_{max} (W)	51.27	52.67	2.65
Voltage at P_{max}, V_{mp} (V)	14.16	15.40	8.05
Current at P_{max}, I_{mp} (A)	3.62	3.42	5.84
Open Circuit Voltage, V_{oc} (V)	17.98	17.88	0.56
Short Circuit Current, I_{sc} (A)	3.85	3.92	1.78
	5.57	5.80	3.96

(3) For G = 7.77 W/m^2, T = 294 K			
Maximum Power, P_{max} (W)			
Voltage at P_{max}, V_{mp} (V)	12.74	13.31	4.28
Current at P_{max}, I_{mp} (A)	0.44	0.44	0.00
Open Circuit Voltage, V_{oc} (V)	15.93	15.91	0.12
Short Circuit Current, I_{sc} (A)	0.47	0.43	9.30

Figure 9 represents the simulated graphs obtained from the module when exposed to different outdoors irradiance and different temperatures under real test conditions (RTC). It can be seen from the figure 9 that an increase in temperature results in an increase in short circuit current (I_{sc}), and an increase in irradiance generates an increase in open circuit voltage (V_{oc}) and power output. This is due to the impact of the irradiance which has on the power output of a PV module thus a high irradiance even at a low temperature generates an increase in power output

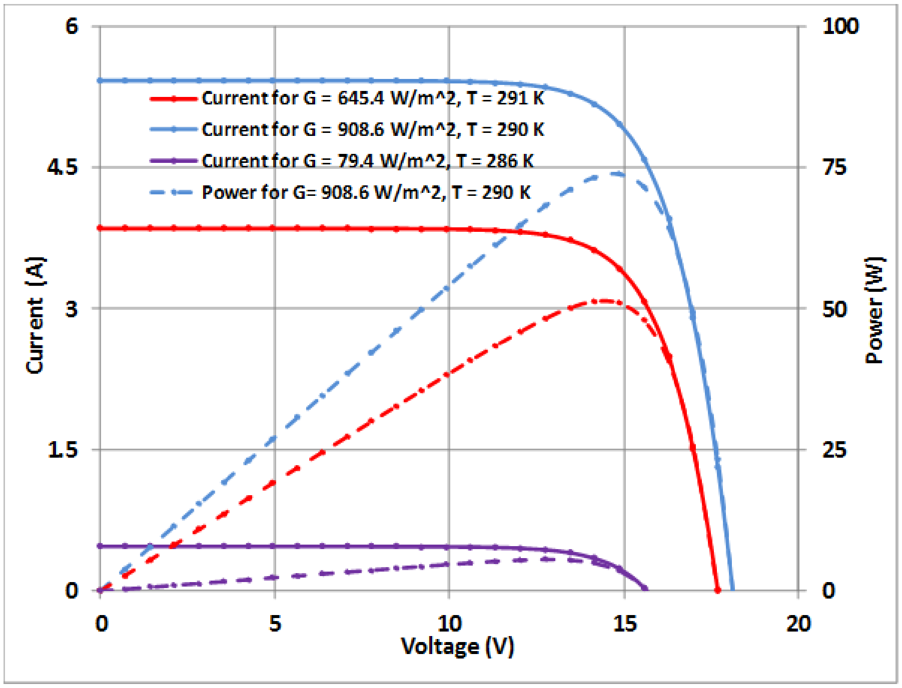

FIG. 9. Outdoor I-V and P-V characteristics of the PV module with the variation of irradiation and temperature

V. Conclusion

This paper discusses the generalised modelling approach and performance analysis of a 85W monocrystalline solar module. All the simulations results are thoroughly evaluated by comparing the experimental results and datasheet values provided by the manufacturer in terms of the PV module's maximum power (Pmax), open circuit voltage (Voc), and short circuit current (Isc). For both the indoors and outdoors measurements, the results analysed indicate that temperature, irradiation and resistance are the vital parameters that determine the electrical characteristics of the photovoltaic module. Hence, an increase in temperature results in an increase in the short circuit current (Isc) and series resistance (Rs); however it causes to a decrease in open circuit voltage (Voc). In contracts, the increase in irradiance results in an increase in the power output (Pmax), the open circuit voltage (Voc) and the voltage at maximum power (Vmp) of the module however it leads to a decrease in the Rs of the module. Even though temperature has a significant influence on the power output of a photovoltaic module, under real test conditions (RTC) solar irradiation has a high influence on the resultant power output of a PV module, because irradiation is proportional to current. High irradiation even at low temperatures, generates an increase in the PV module power. The measured results showed that the module is capable of generating 17.75 W/m2 with an efficiency of 7% and 138 W/m2 with an efficiency of 8% from indoor office building and outdoor conditions respectively in UK during summer time.

APPENDIX

I_{ph} is the photo current of a PV module (A)

I_{sc} is the PV short circuit current at STC.

α is the temperature coefficient on PV short circuit current (0.0017A/^{o}C).

T is the operating temperature of the module in Kelvin.

T_r is the reference temperature in Kelvin.

E is the insolation or solar irradiance (W/m^2).

q is the magnitude of electron charge (1.6 x 10^{-19} C).

V_{oc} is open circuit voltage (V).

K is Boltzman constant (1.3805 × 10^{-23} J/K).

A is diode ideality factor (1.6).

E_g is the bandgap for silicon (1.1 eV).

V_{pv} is the PV output voltage (V).

R_s is the series resistance of the PV module (Ω).

N_s is the number of cells connected in series.

N_p is the number of cells connected in parallel.

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