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RESEARCH ARTICLE

Modelling and Outdoor Performance Characterization of Monocrystalline and Polycrystalline Silicon Photovoltaic Modules

Adriano Pamain[1*], P.V. Kanaka Rao[1]

[1]University of Dodoma, Tanzania

*Corresponding author: Adriano Pamain: adrianopamain85@gmail.com

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Abstract:

This paper presents the modeling and outdoor performance of monocrystalline silicon (m-Si) and polycrystalline silicon (p-Si) Photovoltaic (PV) modules. The I – V and P – V characteristics curves obtained by simulation and from outdoor experiments, were used to extract electrical parameters such as open-circuit voltage, short circuit current, maximum current, and maximum voltage. Parameters acquired were further used to compute maximum power output, fill factor, and conversion efficiency of PV modules. The simulation results obtained were in agreement with the manufacturer's datasheet value while experimental results showed a slight deviation from Standard Test Condition (STC) values. The effects of solar irradiance, module temperature, ideality factor, and series resistance on the performance of PV modules were considered. It was observed that as solar irradiance increased the performance of PV modules improved, whereas the increase of other parameters such as module temperature, series resistance, and diode ideality factor declined the performance of PV modules.

Keywords: Photovoltaic (PV), Modelling, m-Si, p-Si, I – V & P – V Curves

Introduction

The application of photovoltaic (PV) technology has become an important source of energy in many countries during the past decades (Parida et al., 2011; Kidegho et al., 2021). The potential use of renewable energy to replace conventional energy sources is a driving force for increased research on PV technology (Meflah et al., 2017; Charfi et al., 2018; Mesquita et al., 2019). Its market demand has significantly increased, with global power generation expected to rise by 50% by

2050 (Creutzig et al., 2017). PV cells are the fundamental units of a PV system, and when connected electrically in series and/or parallel circuits, they form PV modules. A group of PV modules finally forms a PV array (Gul et al., 2016). Many PV modules exist on the market, but m-Si and p-Si PV modules are still the most widely used due to their high efficiency compared to other PV technologies (Mulcué-Nieto et al., 2020).

The output characteristics and performance of PV modules strongly depend on internal factors (i.e., ideality factor and series resistance) and external factors (environmental parameters), which include solar irradiance, ambient temperature, relative humidity, and wind speed. Amongst these environmental parameters, solar irradiance and temperature are the most influential parameters on the PV module's performance (Matchanov et al., 2017; Wessel, 2016; Mussard & Amara, 2018; Tabish & Ashraf, 2018).

Two approaches are necessary to understand the influence of these characteristics on PV module performance: theoretical (modeling) and experimental (outdoor testing) to provide correct PV module performance in the ambient conditions prevailing on site (Kvols & Johra, 2018). Several studies have conducted outdoor performance testing of PV modules in order to better understand the impact of these parameters on the characteristics of PV modules in real-world conditions (Sharma et al., 2013; Mussard, M., & Amara, M. 2018). On the other hand, other researchers have considered modelling approaches using several simulation tools, including MATLAB-Simulink, Spice, and SABER transient, to understand the non-linear I-V/P-V characteristics of the PV module (Xiao et al., 2012; Batzelis et al., 2015; Apostolou et al., 2016). The combination of both theoretical and experimental approaches suggests the best way to describe PV module behaviour, which, however, is seldom mentioned in most previous work (Sheikholeslami et al 2021). Modeling precisely predicts the power output anticipated to be produced under real operating conditions, whereas outdoor testing presents the actual power output generated in a real environment. Single-diode and double-diode are the two widely used analytical models in the simulation of PV characteristics (Groenewolt et al., 2016; Louzazni et al., 2018). The single-diode model is the easiest way to figure out how PV works, and it does so fairly and accurately (Bellia et al., 2014).

In this paper, both experimental and modeling approaches are employed in order to understand the characteristic behavior of the PV nodule under testing. A single diode model is implemented with simplified and user-friendly blocks in MATLAB/Simulink and used to comprehensively investigate the I-V and P-V characteristics. The simulated results and experimentally obtained values were compared with the manufacturer's datasheet to observe its deviation from the Standard Test Condition.

Modelling a PV module

A PV module is modeled using a generalized equivalent circuit model as shown in figure 1, which comprises a current source (Photocurrent, I_{ph}), connected in parallel with the diode, a shunt resistor (R_{sh}), which expresses a leakage current (I_{sh}), and a series resistor (R_s), which describes an internal current loss. The equivalent circuit of the PV cell is shown in Figure 1.

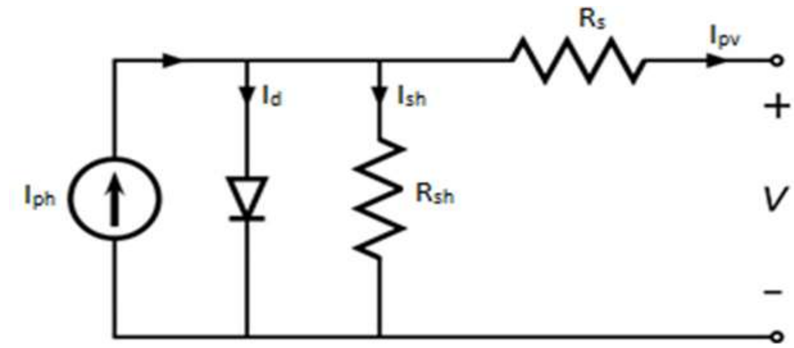

Figure 1. Solar cell equivalent circuit

From the equivalent circuit in Figure 1, applying Kirchhoff's current law (KCL), The PV output current, I_{pv} is given by

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

and the PV Photocurrent current, I_{ph} is expressed by

$$I_{ph} = \frac{[I_{sc} + \alpha(T - T_r)]G}{G_r} \tag{2}$$

Where: α is the temperature coefficient of a cell, T is the ambient/operating temperature, T_r is the reference temperature at STC, G is solar irradiance (W/m^2) and G_r is the reference solar irradiance (W/m^2) at STC.

The PV current through the intrinsic diode, I_d is expressed as

$$I_d = I_s \left(\frac{T}{T_r}\right)^{n/3} exp\left[\frac{qE_g\left(\frac{1}{T_r} - \frac{1}{T}\right)}{nk}\right] \tag{3}$$

Where: n is an ideality factor dependent on technology, k is the Boltzmann's constant (k=1.38×10^{-23} J/°K), E_g is the bandgap energy and q is the electronic charge (1.602×10^{-19} C).

The PV reverse saturation current, I_s is expressed

$$I_s = I_r / \left[exp\left(\frac{qV_r}{nkT_r}\right) - 1\right] \tag{4}$$

Where: V_r is the reference voltage and I_r is the reference current.

The PV current delivered by parallel/shunt resistance, I_{sh} is

$$I_{sh} = \frac{V + IR_S}{R_{sh}} \tag{5}$$

From equations (1 – 5), we can deduce the expression of the current delivered by a photovoltaic cell as

$$I_{pv} = I_{ph} - I_s\left(exp\left(\frac{q(V + IR_S)}{nkT} - 1\right)\right) - \frac{(V - IR_S)}{R_{sh}} \tag{6}$$

The Simulink model developed based on the final equations (6) using MATLAB-SIMULINK is shown in figure 2. The current, voltage, and power output of the PV module vary as a function of solar irradiance and module temperature. Using MATLAB script as well as Simulink, the resulting current, voltage, and power values were exported to the MATLAB workspace in the form of arrays using the "To workspace" Simulink blocks, and finally, the I–V and P–V characteristics curves were generated for further analysis for each PV module under experimentation.

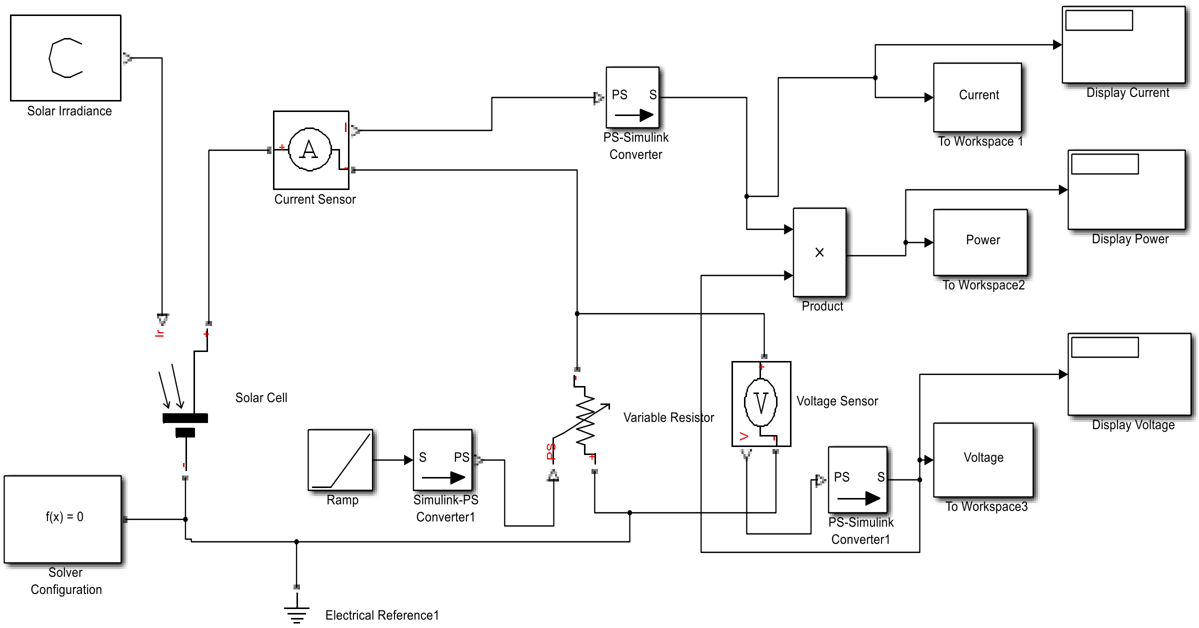

Figure 2: Simulink Model for generalized PV

Outdoor experimental set up

The experimental setup for outdoor measurement of m-Si and p-Si PV modules is shown in figure 3. It consists of two variable load resistances, two digital multimeters, a solar power meter, and m–Si and p–Si PV modules. The specifications of PV modules at STC are indicated in Table 1. The current and voltage of PV modules were recorded using a Mastech MAS830L Digital Multimeter while solar irradiance placed in the same orientation as the PV module was measured using a TES 132 solar power meter. Initially, the variable load resistance was set at its minimum value to give approximately a short-circuit current. Then the variable resistance was adjusted from the minimum to the maximum resistance position within a few seconds while taking readings with the camera simultaneously. Corresponding results of current and voltage obtained were tabulated for further analysis.

The experiments were done at noon for three days on a clear day with an average solar irradiance of 1000.23 W/m^2.

Figure 3: Outdoor PV modules testing

Table 1: Module specifications and characteristic parameters

PV module Technologies	m- Si	p- Si
Maximum Power (P_m)	50 W	50 W
Open-Circuit Voltage (V_{oc})	22.7 V	22.4 V
Short-Circuit Current (I_{sc})	2.84 A	2.95 A
Optimum Operating Voltage (V_m)	18.5 V	17.8 V
Optimum Operating Current (I_m)	2.70 A	2.84 A
Temp Coefficient of P_m	-0.23%C	-0.44%C
Temp Coefficient of V_{oc}	-0.33%C	0.30%C
Temp Coefficient of I_{sc}	-0.05%C	-0.04%C
Dimensions (in mm)	630×541×30	680×550×30

Results and discussion

The MATLAB-Simulink model, together with experimental results, was used to generate solar cell I–V and P–V characteristic curves, which are useful in evaluating the performance of PV modules. Table 2 shows the results of both experiments and simulations based on these characteristic curves.

Figures 4 and 5 show experimental and simulated I–V and P–V characteristic curves for m–Si and p–Si, respectively. It is observed from figures 4 and 5 as well as in table 2, that the simulated values of most parameters, notably efficiency and fill factor, were found to match the datasheet (manufacturer) values for both PV modules. The experimental values obtained under outdoor conditions at an irradiance of 1000.23W/m^2 are found to deviate from those of the datasheet value and simulated results. The decrease in the performance of PV modules can be attributed to environmental parameters such as ambient temperature, which greatly influence the performance of PV modules.

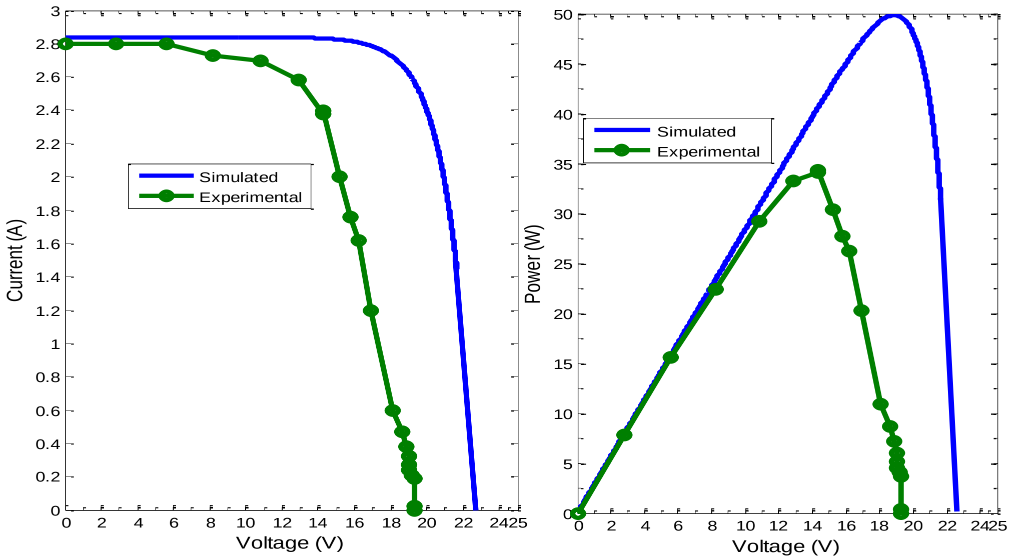

Figure 4: Simulated and Experimental (a) I – V and (b) P – V Characteristic Curves of m – Si PV module

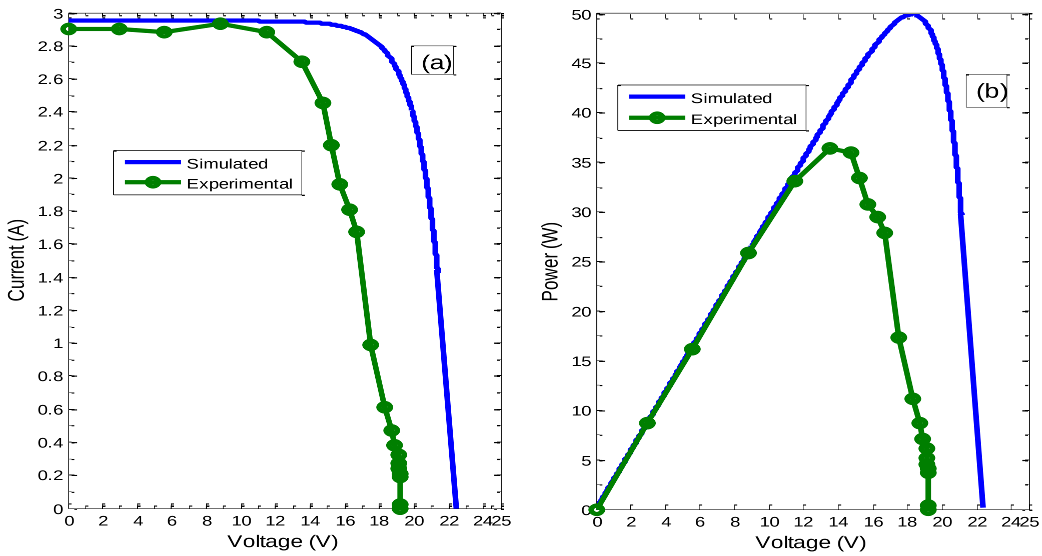

Figure 5: Simulated and Experimental (a) I – V and (b) P – V Characteristic Curves of p – Si PV module

Table 2: Summary of the test results of PV Modules

	Data sheet Results		Simulated results		Experimental Results	
Parameters	**p-Si**	**m-Si**	**p-Si**	**m-Si**	**p-Si**	**m-Si**
Open-Circuit Voltage (V)	22.4	22.7	22.5	22.4	19.2	19.3
Short-Circuit Current (Isc)	2.95	2.84	2.95	2.84	3	2.8
Optimum Operating Voltage (Vm)	17.8	18.5	18.5	19	13.5	14.3
Optimum Operating Current (Im)	2.84	2.7	2.75	2.64	2.7	2.38
Maximum Power (Pm)	50	50	50.88	50.16	36.45	34.08
Efficiency (%)	17	18	17	18	12.4	12.2
Fill Factor	76	78	76	78	63	68

To understand the effect of internal and external factors on the performance of PV modules, a single cell with an open-circuit voltage of 0.63V and 0.62V for m-Si and p–Si, respectively, was considered. The I–V and P–V characteristics curves for m-Si and p-Si PV modules with irradiances ranging from 100W/m2 to 1000W/m2 at 25 °C are shown in Figures 6 and 7

. Both current and power output significantly increase with increased irradiance intensities, whereas the voltage remains fairly constant at different irradiances. The voltage is less affected by irradiance, such that at a very low irradiance (i.e., 100W/m^2) the voltage is practically at the maximum voltage level, whereas the increase in solar irradiance strongly increases the short-circuit current.

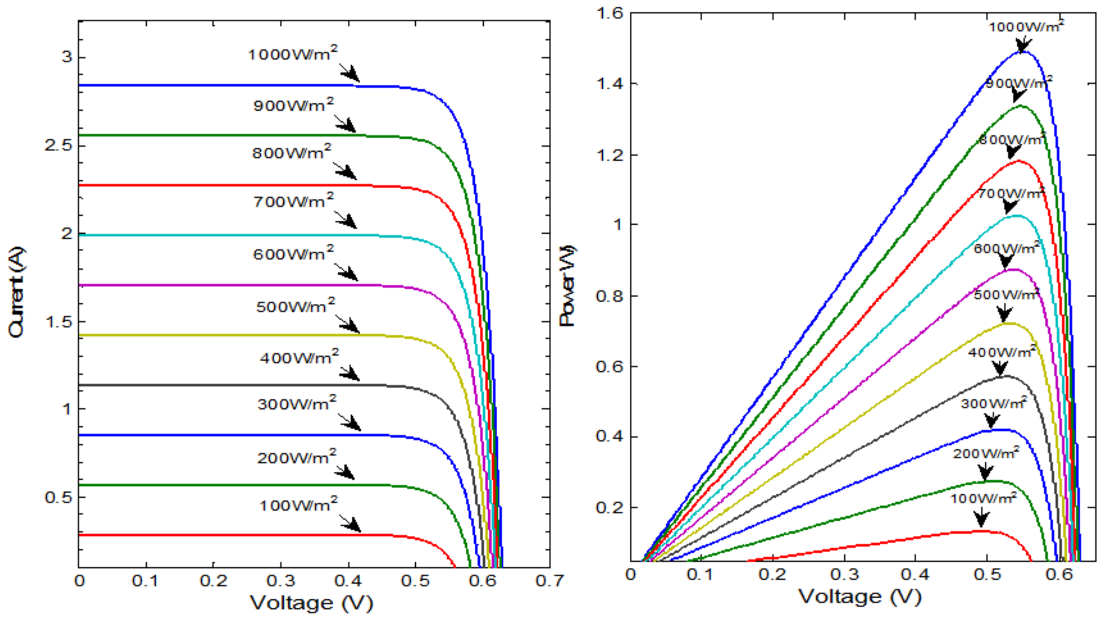

Figure 6: Simulated (a) I – V, and (b) P – V Characteristic Curves for m-Si PV modules with varying irradiance

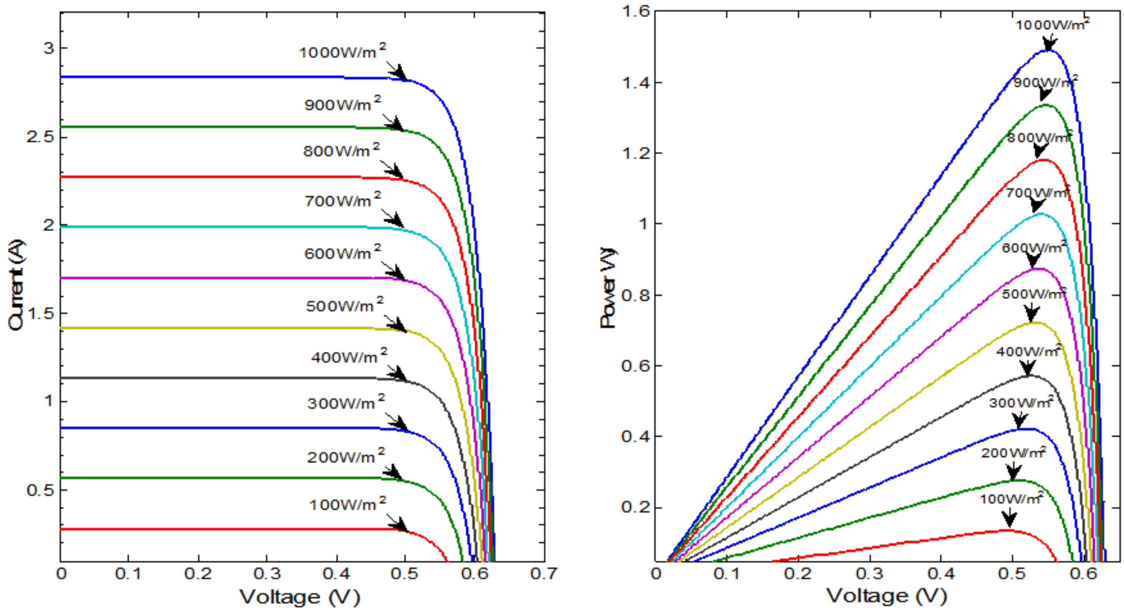

Figure 7: Simulated (a) I – V, and (b) P – V Characteristic Curves for p-Si Modules with varying irradiance

The effect of module temperature on the performance of m-Si and p-Si PV modules is shown in figures 8 and 9, respectively. The module temperature was varied from 0°C to 75°C at constant irradiance (i.e., 1000W/m^2). The results show a decrease in voltage as the operating temperature increases and a decrease in power output. On the other hand, an increase in operating temperature only slightly affects the current. In short, an increase in solar irradiance causes an increase in short-circuit current, whereas an increase in module temperature decreases the open-circuit voltage. This trend was also observed in studies done by Bonkaney et al., 2017 and Subhash Chandra et al., 2020. The power output is highly dependent on voltage, such that any increase in voltage results in an increase in power output.

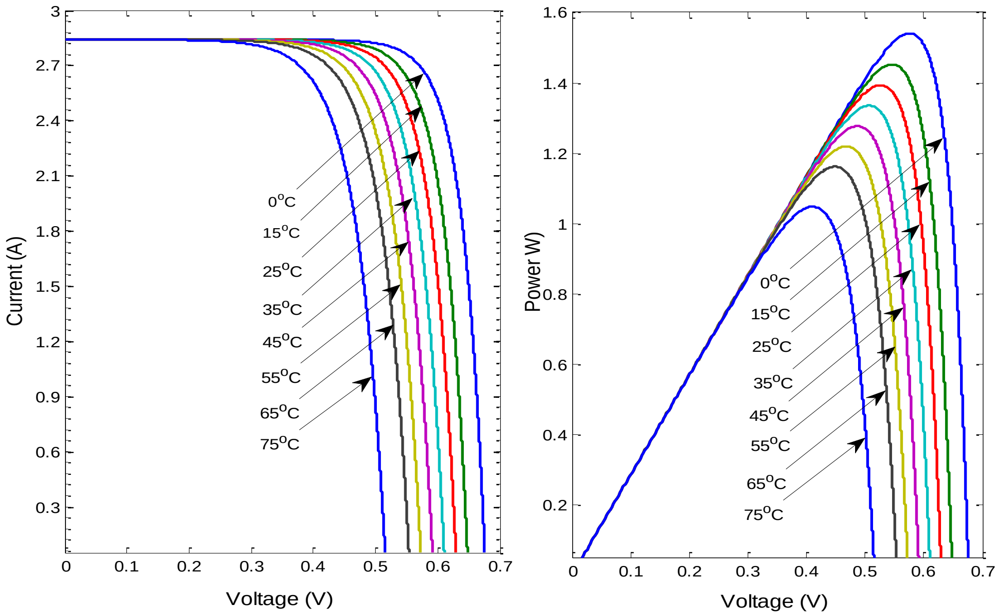

Figure 8: Simulated (a) I – V, and (b) P – V Characteristic Curves for m-Si Modules with varying Module Temperature at constant irradiance

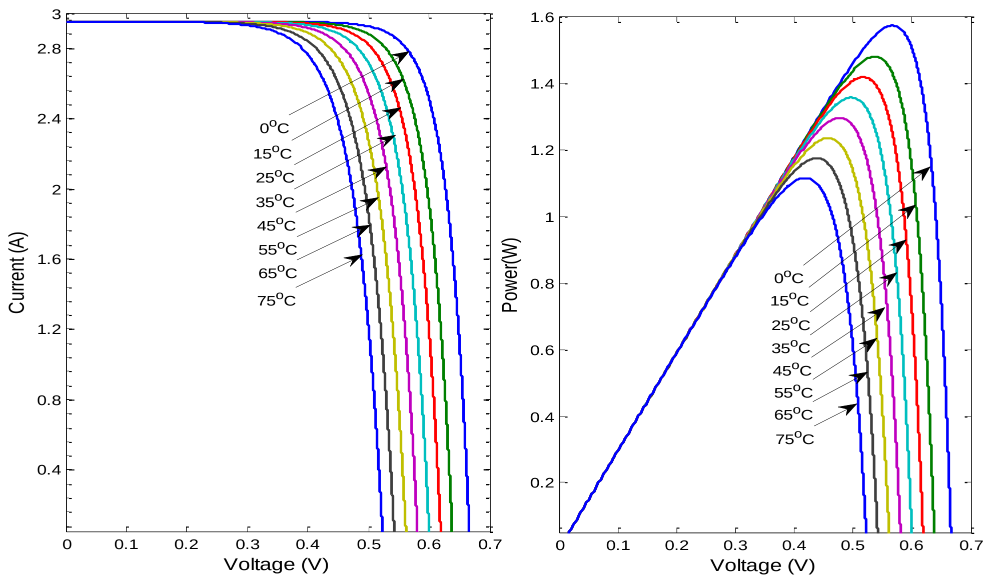

Figure 9: Simulated (a) I – V, and (b) P – V Characteristic Curves for p-Si Modules with varying Module Temperature at constant irradiance

Figures 10 and 11 show how the I–V and P–V characteristic curves change as the ideality factor of PV modules changes. The ideality factor was varied from 1 to 2. The power output decreases with an increase in the ideality factor. The best performance was registered when the ideality factor was set to 1. As revealed from the plots, the ideality factor doesn't affect short-circuit and open-circuit voltage and they remain unchanged despite the increase in ideality factor from 1 to 2. The same trend was observed for the I – V and P – V characteristics curves with the variation of series resistance as indicated in figures 12 and 13. The short circuit current and open-circuit voltage remained almost constant despite the series resistance being varied from 0 to 0.2Ω. However, the power output decreased as series resistance varied from 0 to 0.2Ω.

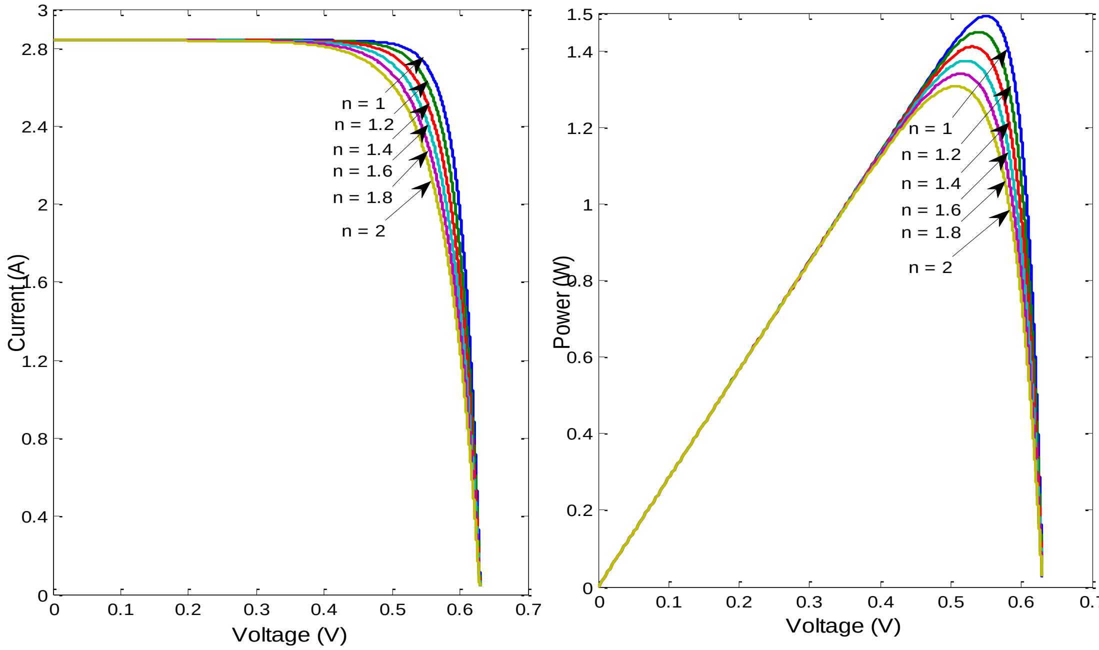

Figure 10: Simulated (a) I – V, and (b) P – V Characteristic Curves for m-Si Modules with varying quality factor at constant irradiance and module temperature

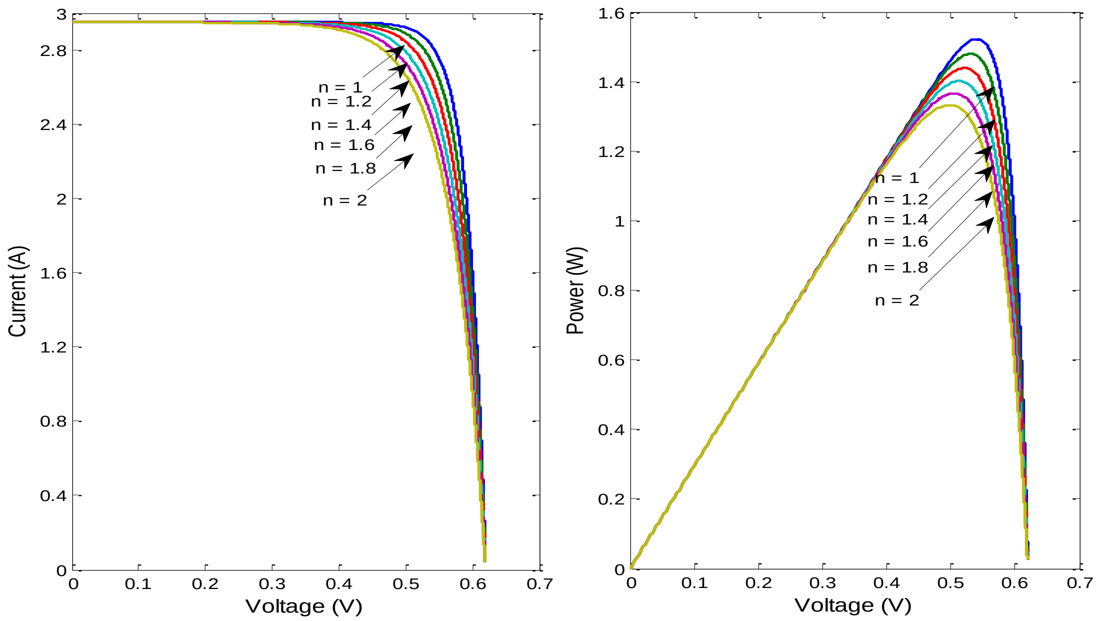

Figure 11: Simulated (a) I – V, and (b) P – V Characteristic Curves for p-Si Modules with varying quality factor at constant irradiance and module temperature

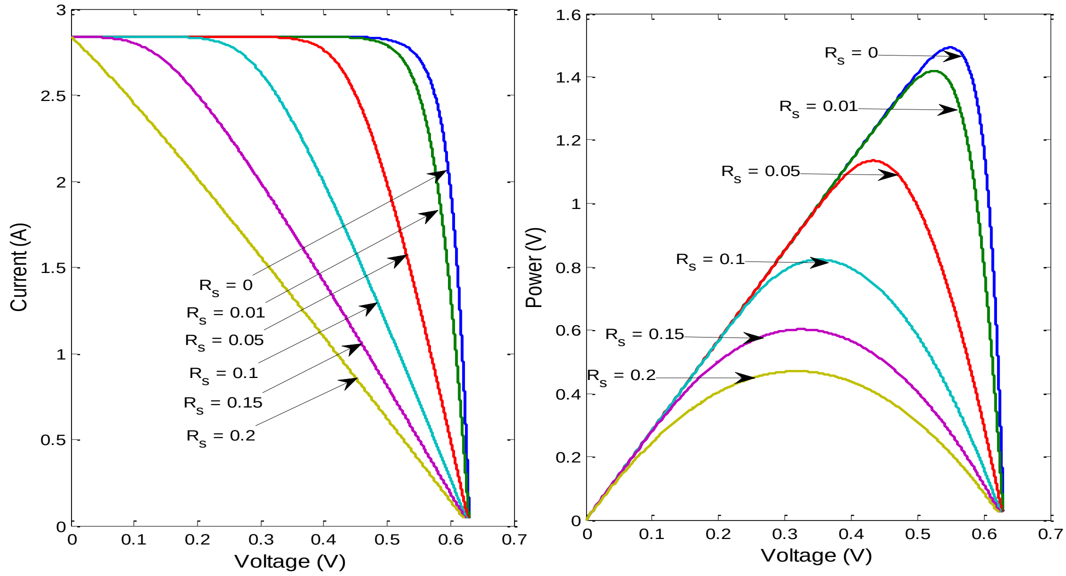

Figure 12: Simulated (a) I – V, and (b) P – V Characteristic Curves for m-Si Modules with varying Series resistance at constant irradiance and module temperature

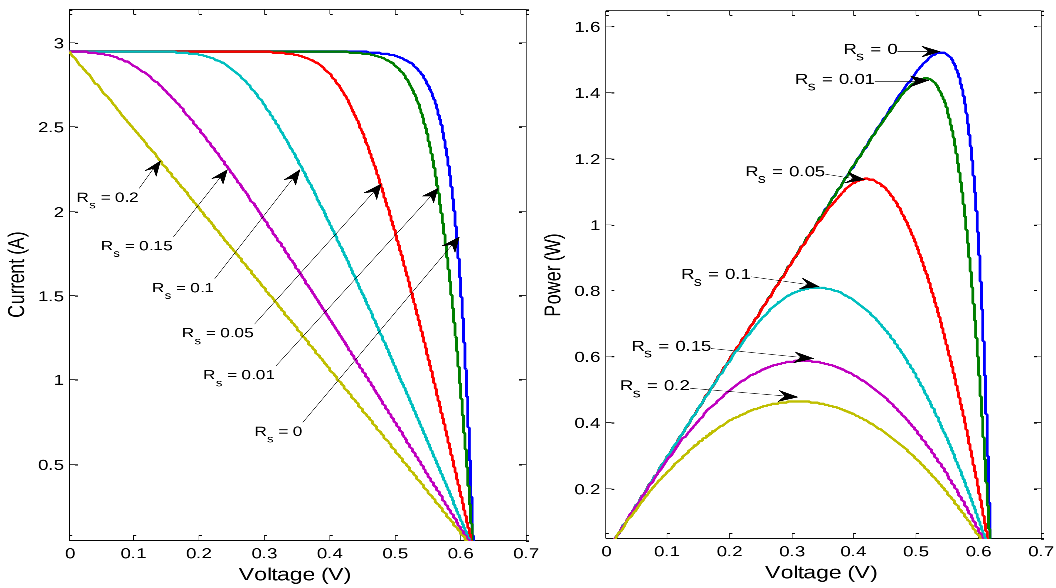

Figure 13: Simulated (a) I – V, and (b) P – V Characteristic Curves for p-Si Modules with varying Series resistance at constant irradiance and module temperature

Conclusion

In summary, this study discussed the detailed simulation and outdoor performance of monocrystalline and polycrystalline silicon PV modules. The effects of both internal factors (i.e., series resistance and ideality factor) and external factors (i.e., solar irradiance and temperature) in its wide range are discussed. Furthermore, the comparison between experimental value and that of simulated and STC results has been made. The results of simulated parameters were found to match with the datasheet (manufacturer) values for both PV modules, whereas the experimental values obtained under the outdoor conditions at an irradiance closer to STC (i.e., 1000.23W/m^2) were found to deviate from the datasheet values and simulated results. These results justify the need for testing PV modules beyond STC to understand the behavior and characteristics of PV modules when subjected to real environmental conditions.

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