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Investigating the Impact of Internal and External Factors on Solar Cell Performance to Enhance Energy Conversion Efficiency

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ABSTRACT

Solar energy has become a promising renewable energy source due to rising worldwide energy demand and environmental concerns in recent decades. This study examines temperature, solar irradiance, and series resistance (Rs) as internal and external elements affecting solar panel efficiency to optimise photovoltaic (PV) performance. Sunlight increases current and voltage outputs, but incidence angle, air dust, and pollution can reduce efficiency. Therefore, solar panels should be orientated and cleaned often. Open-circuit voltage (VOC), maximum power output (Pmpp), and fill factor (FF) decrease performance at high temperatures. Water cooling or cooling plates can save PV cells from overheating. Finally, Power dissipation across resistance lowers voltage and current output as Rs increases. Preventive maintenance, material selection, and production techniques can lower Rs and maximise efficiency. This research emphasizes the importance of addressing environmental and material factors in solar panel installation and maintenance to achieve optimal efficiency and reliable energy generation in PV systems.

1. Introduction

Due to the rapid increase in demand for electrical energy in recent decades as a result of population growth, which has led to the exacerbation of the phenomenon of global warming [1,2,3], and the fact that current fuel sources have become expensive and are starting to run out, the search for alternative sources of energy has become necessary, and among these energies is solar energy[4],[5]. From here, the idea of how to convert this energy into electrical energy began, and from here the idea of the solar cells industry began.[6,7,8]

Solar energy is perpetually radiating from the sun and is poised to emerge as a primary energy source on which mankind will increasingly rely [9].

Solar cells are photovoltaic devices that convert electromagnetic radiation coming from the sun into usable electrical energy in a process called the photoelectric effect. In the dark, it works as a rectifier diode and generates a photovoltaic voltage when illuminated by sunlight, so curves (I-V) appear. When the energy of the photon falling from the sun to the absorbing layer in the solar cell is sufficient to separate the electrons from the gaps, it is possible that the energy of the photon is as much as it enables it to transfer electrons in the valence region to the conduction region in the n-type segment, and the gaps move to the conduction region in the P-type, to result in the potential difference between P-N, and after connecting the two surfaces with an electrical connector, it is possible to obtain an electric current, as electrons move from n-type to p-type through the electrical circuit, and thus the light energy is transformed into electrical energy[10].

The photovoltaic cell is the simplest kind of PV device. A panel consists of a series of interconnected cells. To achieve high output voltages, panels typically consist of cells connected in series. To create panels with high output currents, it is necessary to either increase the surface area of the cells or link the cells in parallel, A photovoltaic array may be a single panel or many panels wired in series or parallel to produce a large PV system [11]. As shown in figure 1:

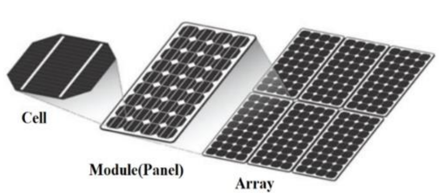


Figure 1. Photovoltaic Cell, Module & Array Arrangement

The efficiency of solar panels is affected by a wide range of parameters, including both internal and exterior components. The quality of materials and the internal design of the solar panel are crucial factors in solar cell manufacture. Externally, the performance of the panel is affected by solar radiation and lighting conditions[12], while ambient temperatures influence its effectiveness [13,14,15,16]. Solving this issue is crucial to the expansion of the solar panel industry. To predict the efficiency of solar power plants, it is necessary to diagnose and regulate the electrical properties of solar photovoltaic converter components, which are found in solar modules and panels. The light V-I characteristic of a solar cell is the determining factor in the efficiency of photovoltaic conversion. The form is based on several characteristics. This means that these factors must be carefully managed and optimized throughout solar cell manufacturing [17,18,19].

The presence of Rs in solar panels has a substantial influence on their performance and η. Rs refers to the total resistance that an electrical current encounters as it passes through the individual cells of a solar panel. Rs can arise from different causes, such as the resistance of the materials used in solar cells or connectors. The existence of Rs leads to negligible power dissipation as the electric current traverses the solar panel, Solar panel Rs can increase for many reasons including material impurities, and cell degradation.

This study aims to study the factors affecting the efficiency of solar panels in an attempt to reduce their impact by choosing appropriate methods to avoid them and reduce their negative impact in a way that contributes to enhancing the efficiency of solar panels. Many studies have been conducted to study the factors affecting the effectiveness and performance of solar panels, some of which will be mentioned:

Maan J B Buni et.al. [20] Systematically recorded data using digital tools to explore the relationship between solar radiation, current, voltage and efficiency of solar panels. Analyzes were performed to examine the relationships between solar radiation, current, voltage, and efficiency. The results reveal a direct correlation between solar radiation and the resulting current, as well as efficiency. This indicates that increased solar radiation corresponds to an increase in output current, thus enhancing the efficiency or performance of the solar panel. However, it is noted that an increase in solar radiation is accompanied by an increase in the temperature of the photovoltaic cells, which negatively affects all the parameters studied.

Dhass. A.D. & Natarajan E. [13] examine how Rp affects solar PV cell performance. It studies the P-V characteristic curve of a typical solar cell for various parallel resistances Rp and concludes that PV cell performance loss may cause hot spots. An algorithm for selecting and employing solar cells based on Rp is presented in the study, along with its effects on FF, output power, and η. It also examines how Rp affects solar cells I-V and FF. The conclusion draws from the primary findings of PV performance loss in I-V plots with variable Rp and lists resources for further reading.

Abir Chatterjee et.al. [12]used manufacturer data sheets to determine single-cell, string, and array PV model parameters. It also tackles PV module and array modelling and Gauss-Seidel method initialization and estimate of unknown parameters using sequential under-relaxation. In addition, examined how to estimate PV model parameters from PV module data and how temperature and irradiance affect parameters. The researchers concluded that accurate modelling of PV power generation sources is crucial for their integration into power grids.

Rashmi Singh et.al. [21] examined series resistance's effects on HIT technology across a wide range of irradiance and temperature conditions per IEC 61853-1. Long-term outdoor performance data was used to quantify how series resistance affects HIT technology's electrical performance parameters. The study found that series resistance decreases fill factor, power, and Isc after one year of outside exposure to HIT technology.

M. H. El-Ahmar et.al. [22] analyze single and double-diode Photovoltaic (PV) modules, focusing on Shockley diode models. These electrical models input sunlight and temperature. Multiple models were compared using many parameters. Multiple variables affect single and double-diode models. The simulation compares Voc and Isc values from I-V and P-V characteristics to the KC200GT-200W module datasheet.

A study was done by [23] about solar panel cleaning methods to improve electricity efficiency and panel durability. The study discussed electrostatic cleaning, super hyperbolic coating, mechanical, microcontroller-based automatic cleaning, self-cleaning nanodomes, and dust particle characteristics. The methods were mechanical, electrical, or both. Electrostatic cleaning was the best option in this study's analysis and comparison.

PV cell cooling methods including phase change materials (PCMs), nanoparticles, and jet impingement are reviewed by Mays N. Shaeli et.al [24]to reduce PV cell temperature rise and increase electrical efficiency. Jet impingement, phase change material, and nanoparticle cooling technologies have been used to increase solar photovoltaic thermal cell performance. The PCM core's latent heat absorption during the melting process may raise the PCM's apparent heat capacity and improve the convective heat transfer efficiency even further. As compared to a straightforward PV system, the performance of PV cells that use the jet impingement cooling approach will be better for energy generation.

Photovoltaic cells in Iraq were tested by [25] from April to October in three conditions: without cooling, air cooling, and phase-changing material cooling. Comparing the performance of PV panels in three cases revealed a decrease in average monthly temperature from 55.12 to 40.08 degrees Celsius, with an 11.04 degrees Celsius seasonal temperature difference. In air-cooled tests, solar panel efficiency increased from 12.1% to 12.75 per cent. The optimum module efficiency at 25°C is 13.95 percent. This PCM improves maximum electrical output power and efficiency by 0.2 per cent and 10 Watts, respectively.

2. Mathematical Modeling of PV Array

PV models have been published to demonstrate PV cell performance under different atmospheric conditions [21]PV cells directly convert light energy into electricity. Poly-crystalline and mono-crystalline semi-conducting materials are utilized to design PV cells during production. Temperature and solar insolation changes are used to evaluate PV model performance. A strong PV model is needed for MPP operation under dynamic environmental circumstances. PV cell performance parameters (I-V and P-V) are non-linear and output voltage and power depend on incoming solar insolation. PV cells typically produce 1.5–2 W. This work uses a single-diode model PV cell for MATLAB simulations because of its accuracy and simplicity [26]. Most researchers utilize two diodes. Figure (2) shows the realistic equivalent circuit of a PV cell with a photon current source parallel to a diode and series and parallel resistances.

The relationship between the current and voltage produced by a PV cell is given by equation 1

$$I = N_P I_{Ph} - N_P I_S \left[\exp\left(\frac{q(\frac{V}{N_S}+IR_S)/N_P}{KT_C A}\right) - 1\right] - \frac{(N_P\frac{V}{N_S}+IR_{S})}{R_p} \quad (1)$$

Where:
Iph is a light-generated current or photocurrent.
Is is the cell saturation of dark current.
q is an electron charge (1.6 x 10^{-19} C).
K is Boltzmann's constant (1.38 x 10^{-23} J/K).
Tc is the cell's working temperature.
A is an ideal factor.
Rp is parallel resistance.
Rs is series resistance.

The photocurrent mainly depends on the solar insolation and the cell's working temperature, which is described in Equation (2)

$$I_{PH} = [I_{SC} + K_I(T_C - T_{ref})]G \quad (2)$$

Where:
Isc is the cell's short-circuit current at a 25°C and 1000W/m^2
K_I is the cell's short-circuit current coefficient.
T_{ref} is the cell's reference temperature.
G is the solar insolation in KW/m2.
On the other hand, the cell's saturation current varies with the cell temperature, which is described in Equation (3)

$$I_S = I_{RS}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{qE_g\left(\frac{1}{T_{ref}}-\frac{1}{T_c}\right)}{KA}\right] \quad (3)$$

Where:
IRS is the cell's reverse saturation current at a reference temperature and solar radiation.
EG is the band-gap energy of the semiconductor used in the cell.

3. Solar cell parameter

Important parameters describing solar cell performance include maximum power (Pm), FF, ISC, and VO.C. These parameters are determined depending on the characteristics of the I-V curve, as shown in Figure (3). From these parameters, the efficiency(η) of the solar cell can be determined [11].

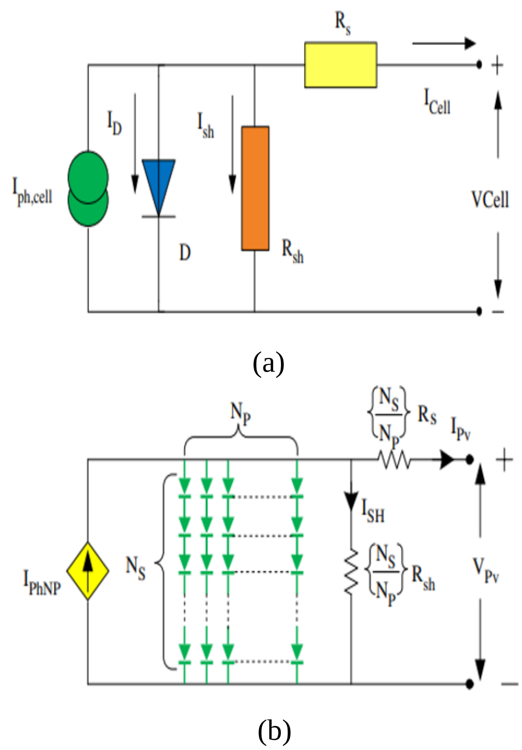


Figure 2. (a) PV cell equivalent circuit, (b) PV array equivalent circuit

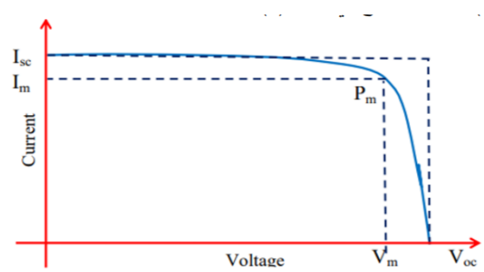


Figure 3. I-V Characteristics of solar cell

Short Circuit Current (I_{SC}): It is the maximum current produced by the solar cell when its terminals are in contact with each other.

maximum voltage that the solar cell can provide, and it represents the voltage at which current does not flow through the external circuit when the terminals of the cell are not connected.

Fill Factor (FF): A solar panel's capacity to convert available sunlight into electrical power is indicated by its FF. It is the ratio between the maximum power of the cell (the maximum voltage and current density that the solar cell can generate) divided by VOC and ISC, the value of FF between 0 and 1, with 1 denoting optimal solar energy utilization and maximum efficiency of the solar panel[27].

$$FF = \frac{V_{mpp} I_{mpp}}{V_{OC} I_{SC}} = \frac{P_{max}}{V_{OC} I_{SC}} \quad (4)$$

Multiple aspects affect the fill factor: the solar panel's inclination angle, lighting, weather, and overall quality. Determining the solar panel's efficiency in converting solar radiation into electrical energy can be done by using the fill factor.

Efficiency of Solar Cell (η): The ratio of electrical energy generated by a solar panel to solar energy incident on it is known as solar panel efficiency. It is typically stated as a percentage and is computed using the assist of the equation below.

$$Efficiency(\eta) = \frac{P_{max}}{P_{in}} = \frac{V_{OC} I_{SC}\, FF}{P_{in}} * 100\% \quad (5)$$

4. Results and discussion

The modelling of solar PV module single diode models is presented and examined in this paper. These models are created by using formulas in the MATLAB scripting environment, which are derived from the corresponding circuits that were previously covered. Table 1 displays Electrical Performance under Standard Test Conditions, while Figure (4) represents the mathematical representation of a photovoltaic cell using MATLAB/ Simulink.

Table 1. Electrical Performance of 1Solteach 1STH-215-P under Standard Test Conditions (STC)

Parameter	Value
Maximum power (W)	213.15
Voltage at Pmax Vmpp(V)	29
current at Pmax Impp (A)	7.35
Short circuit current Isc (A)	7.84
Open circuit voltage Voc (V)	36.3
Series Resistance Rs (Ω)	0.39383
Shunt Resistance Rsh (Ω)	313.3991
Number of series Cell	60
Temperature coefficient of Isc	0.102 mA/°C
Temperature coefficient of Voc	-0.36099 mV/°C
Dimensions	1626.0 X 964.0

5. The Effect of Temperature on The Dependent Solar Cell Parameters

The effect of temperature change on the solar cell parameters represented by VO.C, IS.C, Vmpp, Impp, Pmpp, FF, and η was studied, and the temperature was changed from 25-65 degrees Celsius with a change of 10 degrees Celsius at each measurement while fixing the rest of the parameters of the solar cell.

Figure. (a) shows the effect of temperature on the VO.C, IS.C, Vmpp, Impp. VO.C and Vmpp are inversely proportional to the temperature increase, As the temperature rises, both the VO.C and Vmpp tend to drop. This decrease could be explained by a decrease in minority charge carrier concentration, which would raise the reverse saturation current and widen the energy gap. More specifically, VO.C was measured to be 37 volts at 25 oC, but at 65 oC, it dropped to 22 volts. In a similar vein, at 25oC, Vmpp was 30 volts, but at 25 oC, it dropped to 16 volts. As for the effect of temperature on IS.C and Impp, it is shown in Figure 5(b), where it is noted that there is a slight decrease in IS.C with the increase in temperature. While Impp is more negatively affected as the temperature rises. Increasing the temperature of solar cells has a negative effect on Pmpp, η and FF, as shown in Figure 5 (b), this is due to increased energy loss and reduced conversion efficiency. Figure (6) shows the P-V and I-V curves of the solar panel when the temperature changes between (25-65)°.[14]

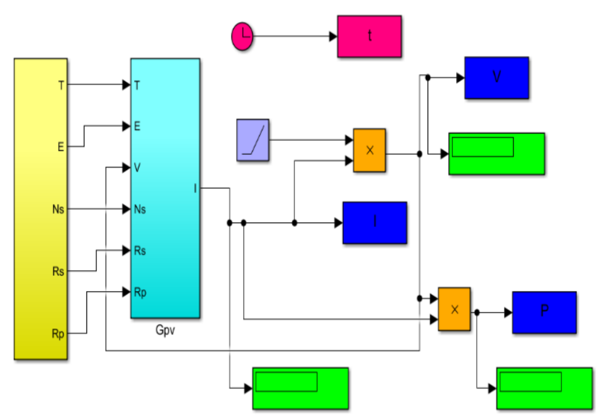
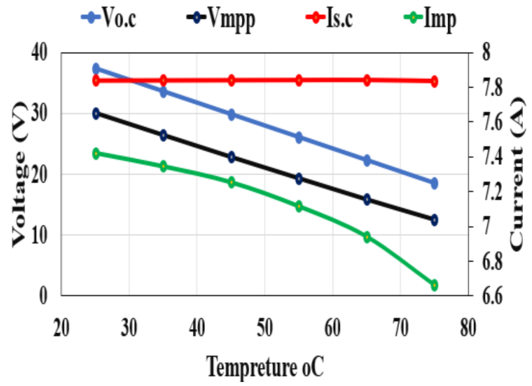


Figure 4. Simulink Model of PV cell



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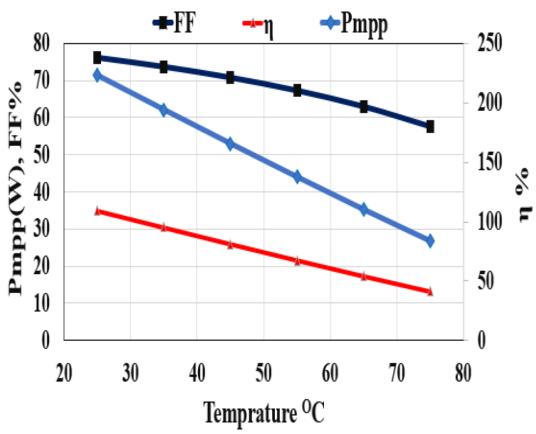
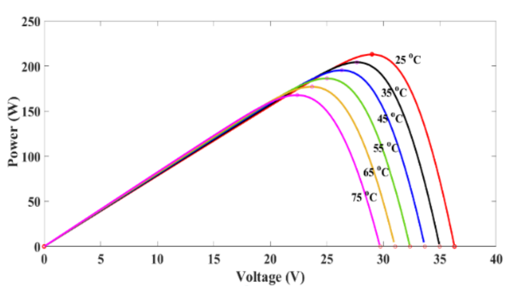


(b)

Figure 5. Effect of temperature change on (a) VO.C, Vmpp, Is.c, Impp (b)Pmpp, FF, η [28]



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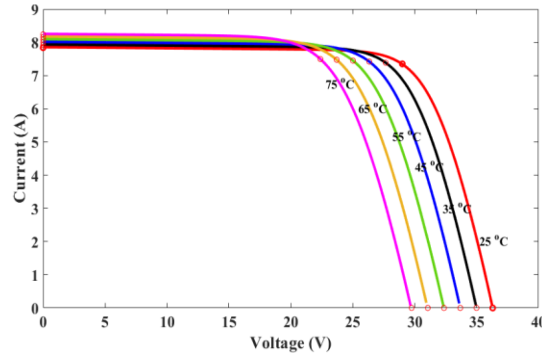


(b)

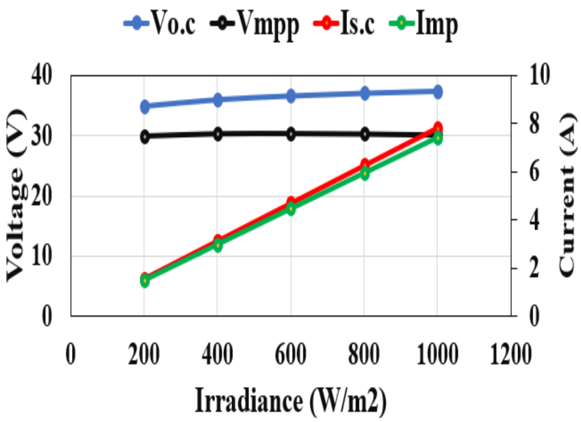
Figure 6. PV Module Characteristics for Different Temperatures (a) P-V Characteristics and (b) I-V Characteristics [11,14,28]

6. The Effect of Solar Irradiance on The Dependent Solar Cell Parameters

The effect of solar radiation changes on the solar cell parameters represented by VO.C, IS.C, Vmpp, Impp, Pmpp, FF and η was studied, and solar irradiance was changed from 200-1000 /m2 with a change of 200 W/m2 at each measurement while fixing the rest of the parameters of the solar cell. Solar radiation plays a crucial role in the performance of a solar panel, as the conversion of solar energy into electricity depends on the quantity and quality of solar radiation. Figure 7 (a) shows the effect of solar radiation on the VO.C, IS.C, Vmpp, Impp. The values of VO.C and Vmpp are positively impacted by rising solar radiation, and the inverse is true when falling solar radiation. Solar radiation has a particularly strong effect on the values of Impp and IS.C. This is explained by the fact that an increase in photon flow, which leads to an overall increase in current generation, directly correlates with an increase in solar radiation.

Solar radiation significantly impacts η of photovoltaic cells, predominantly influencing factors FF and Pmpp as depicted in Figure 7(b).

Figure (8) shows the P-V and I-V curve of the solar panel when the solar radiation changes between (200-1000) W/m2.



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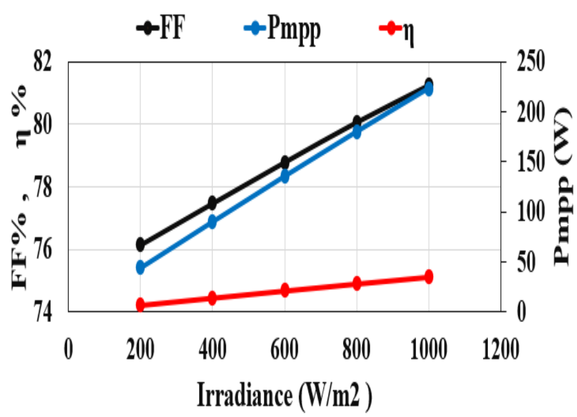
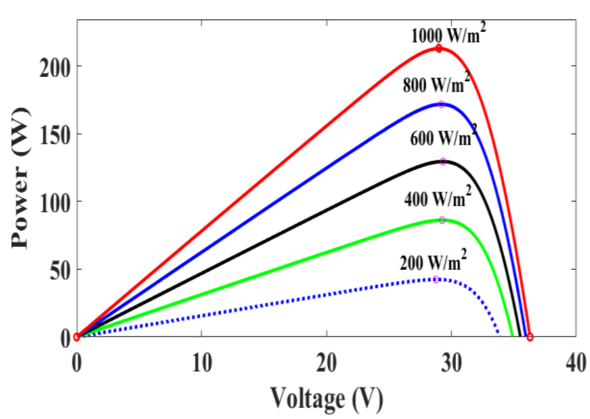


(b)

Figure 7. Effect of Solar Irradiance change on(a) VO.C, Vmpp, Is.c, Impp (b)Pmpp, FF, η[14]



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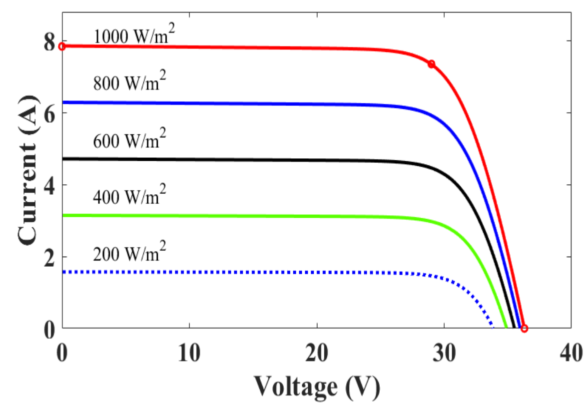


(b)

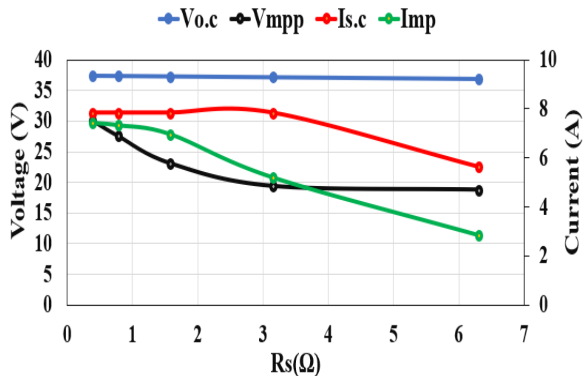
Figure 8. PV Module Characteristics for Different Solar Irradiance (a) P-V Characteristics and (b) I-V Characteristics [7,11,14,28]

7. Effect Of Series Resistance RS On Electrical And Optical Properties Of Solar Cells.

Series resistance (Rs) refers to the resistance that occurs within the solar cell itself, resulting from factors such as the choice of materials and manufacturing techniques. When multiple sun cells are combined to create a bigger solar module (such as a solar panel or submodule), they collectively exhibit internal resistance. The resistance mentioned here is of utmost importance in determining the efficiency of the solar module and its capacity to convert solar energy into electricity [29]. The effect of Rs on VO.C, IS.C, Vmpp, Impp, Pmpp, FF and η has been studied. Rs value was changed to take the following values (0.3938,0. 7877, 1.5753, 3.1506, 6.3013) Ω. cm^2 while fixing the rest of the parameters of the solar cell.

The influence VO.C is a slight impact, while the Vmpp is to be negatively affected and it is a greater negative impact at the small values to resist the consequences confined between (0.3938-3.1506) Ω.cm2, As for IS.C and Impp, it decreases with increasing Rs, because the conductivity of the charge carriers will decrease because as the Rs increases, the electric current will decrease. This is illustrated in the figure 9(a).

Figure 9(b) shows the relationship between Pmpp, FF and η by increasing the RS value. It also turns out that the three quantities mentioned are negatively affected by the increase in the value of the RS. This is because increasing the resistance increases the loss in voltage and current, which reduces Pmpp, FF and η. To reduce the effect of series resistance, the module design must improve and less resistive materials are used. Advances in solar technology aim to improve efficiency and performance in the face of challenges associated with the internal resistance of cells and panels.



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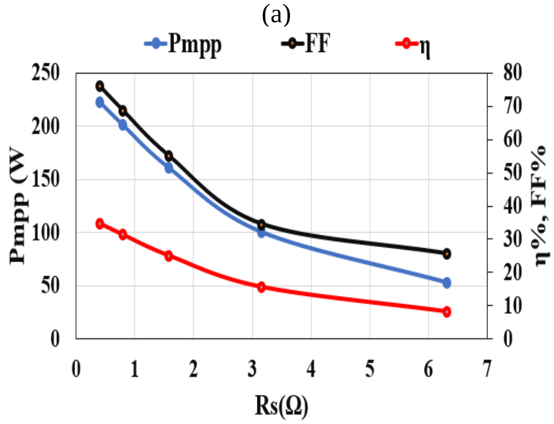
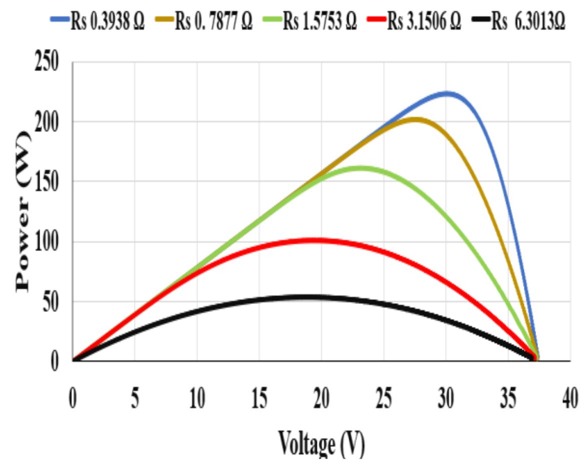


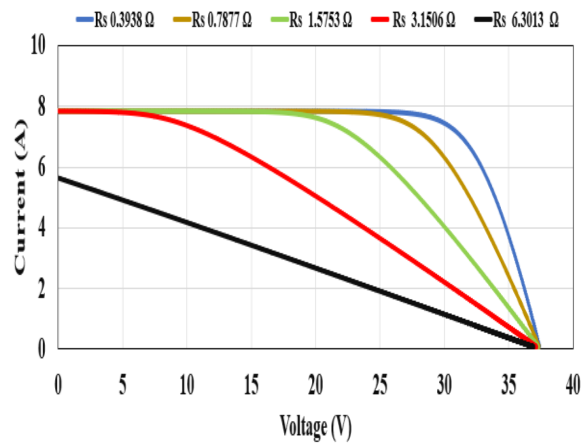
(b)

Figure 9. Effect of Rs change on(a) VO.C, Vmpp, Is.c, Impp (b)Pmpp, FF, η [14]

Figure (10) shows the P-V and I-V curves of the solar panel when at various values of RS. It is noted that increased RS causes a larger curvature in the P-V curve as in Figure10 (A), increasing RS leads to a decrease in voltage at MPP, which reduces the maximum electrical power that the PV panel can generate. As for the I-V curve, as in Figure 10(b), the increase in RS increases the effect on the current, as the current decreases at ISC due to the high resistance. This can result from an increase in the loss of voltage and current in a certain amount.



(a)



(b)

Figure 10. PV Module Characteristics for Different Rs on(a) P-V Characteristics and (b) I-V Characteristics [14]

8. Conclusions

Numerous internal and external elements impact solar panel's performance. External influences include the surrounding environment, such as temperature and sun radiation, while internal factors include Rs. Analysis was done to determine how the solar panel's performance was affected by temperature, solar radiation and Rs. This involves examining how these variables affect (VO.C, IS.C, Vmpp, Impp, Pmpp, FF, and η). The results drawn from this research are summarized as follows:

1- The performance of solar cells is positively affected by the solar radiation falling on them, but some factors have a negative impact, including the angle of incidence (solar angle), geographical location, and weather conditions, as dust and particles suspended in the air reduce the amount of solar radiation that reaches the solar panels, Atmospheric pollution causes the scattering and absorption of solar rays before they reach the ground, so it is recommended to choose the appropriate solar angle while installing the solar panel, as well as continuous periodic cleaning of the solar panels to increase their effectiveness and efficiency.

2- Temperature reduces the efficiency and performance of the solar cell, to improve cell performance and overcome overheating, cooling techniques can be applied to reduce the cell temperature, reducing efficiency loss resulting from overheating. Water cooling systems or special cooling plates can be used.

3- Series resistance (RS) reduces the effectiveness of the cell, as the performance of the cell decreases as the value of this resistance increases. So, careful material selection, enhanced manufacturing processes, cell design, and limiting exposure to environmental contaminants that could harm the panel are all necessary for reducing series resistance, to achieve maximum performance and lower series resistance, maintenance and inspection are crucial.

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