

Modeling and Analysis of Environmental Effects on Photovoltaic Cell Characteristics Using MATLAB

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ABSTRACT

This work analyzes the operational dynamics of a photovoltaic module under varying weather conditions. It specifically emphasizes the joint effects of ambient temperature, solar irradiance, and atmospheric turbidity on the overall electrical performance. Numerical simulations were performed to obtain the electrical behavior, specifically the I–V and P–V output curves, which were examined under diverse operating points, including temperatures from 0°C to 75°C and insolation levels from 400W/m² to 1000W/m². Furthermore, atmospheric turbidity was incorporated into the model to evaluate its attenuation influence on the incident spectral irradiance reaching the PV module. The results indicate that, when evaluated under the reference environment of standard test conditions (STC: 25°C, 1000W/m²), PV module achieves a maximum output power (P_{max} of approximately 105W). While the short-circuit current and maximum power generation are markedly amplified when solar irradiance scales from 400 W/m² to 1000 W/m², the open-circuit voltage remains relatively stable, showing only marginal fluctuations. In contrast, when the operating thermal conditions scale from 0°C up to 75°C, a noticeable degradation in performance occurs, reducing P_{max} to approximately 80W as a result of the decreased output voltage. Moreover, atmospheric turbidity was found to adversely affect the PV performance by attenuating the incident solar radiation, resulting in reduction in the maximum power output under identical irradiance conditions. Overall, the obtained results confirm that temperature mainly affects the voltage characteristics of the PV module, whereas atmospheric turbidity substantially decreases the generated current due to solar radiation attenuation. These outcomes provide useful guidance for the optimization and reliable deployment of photovoltaic systems in dusty and aerosol-rich environments.

نمذجة وتحليل التأثيرات البيئية على خصائص الخلايا الكهروضوئية باستخدام MATLAB

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المُخلص

تتناول هذه الدراسة أداء وحدة الخلايا الكهروضوئية في ظل ظروف بيئية مختلفة، مع التركيز على التأثيرات المشتركة للإشعاع الشمسي، وتغيرات درجة الحرارة، وعكارة الغلاف الجوي على الخصائص الكهربائية وقدرة خرج النظام الكهروضوئي. أُجريت محاكاة عددية للحصول على خصائص التيار-الجهد (I-V) والقدرة-الجهد (P-V) ضمن نطاق درجة حرارة من 0°C إلى 75°C ، ومستويات إشعاع شمسي تتراوح من 400 W/m^2 إلى 1000 W/m^2 . علاوة على ذلك، أُدرجت عكارة الغلاف الجوي في النموذج لتقييم تأثيرها في تخفيف الإشعاع الطيفي الساقط على وحدة الخلايا الكهروضوئية. تشير النتائج إلى أنه في ظل ظروف الاختبار القياسية (25°C)، (1000 W/m^2) ، تحقق وحدة الخلايا الكهروضوئية أقصى قدرة خرج (Pmax) تبلغ حوالي 105 W . وتؤدي زيادة الإشعاع الشمسي من 400 W/m^2 إلى 1000 W/m^2 إلى تحسين ملحوظ في تيار الدائرة القصيرة وأقصى قدرة خرج، بينما لا يُظهر جهد الدائرة المفتوحة سوى تغير طفيف. في المقابل، تؤدي زيادة درجة حرارة التشغيل من 0°C إلى 75°C إلى تدهور ملحوظ في الأداء، مما يقلل Pmax إلى حوالي 80 W نتيجة لانخفاض جهد الخرج. علاوة على ذلك، وُجد أن عكارة الغلاف الجوي تؤثر سلبًا على أداء الخلايا الكهروضوئية من خلال إضعاف الإشعاع الشمسي الساقط، مما يؤدي إلى انخفاض في أقصى قدرة خرج في ظل ظروف إشعاع متطابقة. بشكل عام، تؤكد النتائج التي تم الحصول عليها أن درجة الحرارة تؤثر بشكل رئيسي على خصائص جهد وحدة الخلايا الكهروضوئية، في حين أن عكارة الغلاف الجوي تقلل بشكل كبير من التيار المتولد نتيجة التوهين للإشعاع الشمسي. توفر هذه النتائج إرشادات مفيدة لتحسين ونشر أنظمة الخلايا الكهروضوئية بشكل موثوق في البيئات المترتبة والغنية بالهباء الجوي.

الكلمات المفتاحية: الخلايا الكهروضوئية، الإشعاع الشمسي، درجة الحرارة، عكارة الغلاف الجوي، برنامج MATLAB

1 Introduction

The growing global demand for clean and sustainable energy has increased interest in photovoltaic (PV) systems as a viable alternative to conventional

energy sources. However, performance of PV cells is highly influenced by ambient operational factors, which directly affect their electrical characteristics and energy output. Based on the single-diode model, this paper

utilizes MATLAB simulations to numerically analyze how key environmental factors affect photovoltaic cell behavior. The study focuses on the impacts of solar radiation, temperature of the cells, and atmospheric turbidity (including air quality and dust) on the voltage–current (V–I) and power–voltage (P–V) properties. The solar radiation incident at the peak of the atmosphere of Earth, referred to as the solar constant, is roughly 1361W/m^2 . Due to atmospheric attenuation caused by scattering and absorption processes, the solar radiation incident on the Earth's surface during clear sky conditions is about 1000W/m^2 at solar noon, while the global average over the Earth's surface is approximately 340W/m^2 [1]. This immense and continuous influx of solar energy results in approximately $1.5 \times 10^{22}\text{J}$ reaching the Earth within just one and a half days. This amount is comparable to the energy content of trillions of barrels of oil, whereas the total annual global energy consumption by humans is only on the order of $5 \times 10^{20}\text{J}$. These figures clearly demonstrate the vast and largely untapped ability of solar energy as a renewable energy resource [2] [3]. Moreover, the solar power incident on the Earth in approximately one hour is comparable to the yearly total energy consumption of humanity, highlighting its vast potential as a renewable energy resource [4]. As a pivotal component of the global energy transition, solar photovoltaic (PV) technology offers a scalable and viable trajectory toward achieving long-term energy sustainability and climate objectives [5] [6]. For several decades, photovoltaic (PV) conversion has emerged as the predominant modality for solar-to-electrical energy generation. However, optimizing the selection of PV technologies for specific geographic and climatic conditions necessitates a comprehensive understanding of the underlying physical mechanisms and operational characteristics inherent in diverse cell architectures [7] [8]. Solar photovoltaic (PV) technology is centered on the straightforward transduction of incident solar photon energy into

electrical power. Traditionally, silicon-based architectures have constituted the initial generation of solar panels; however, extensive research has emphasized the necessity of enhancing optical absorption and conversion efficiency. To address these limitations, subsequent advancements led to the development of second-generation technologies, specifically amorphous silicon (a-Si) and diverse thin-film frameworks, aimed at optimizing material utilization and improving performance under varied spectral conditions [9]. To overcome the intrinsic efficiency constraints of conventional photovoltaics, a next-generation architecture is developed by exploiting the broadband plasmonic resonance of novel hybrid nanostructures. This design implements plasmon-sensitized solar cells (PSSCs) utilizing a synergistic heterostructure of silver nanocubes (Ag NCs) and gold nanorods (Au NRs), which serve as integrated broadband optical sensitizers. These metallic configurations are precisely anchored onto a TiO_2 functionalized Indium Tin Oxide (ITO) substrate to amplify the light-harvesting cross-section and accelerate charge carrier kinetics through localized surface plasmon resonance (LSPR) effects. The synthesized photoactive layers are rigorously evaluated using multi-scale morphological, optical, and spectroscopic analyses. Furthermore, the correlation between photothermal induction and photoelectric conversion is systematically investigated to substantiate the plasmonic enhancement of the device's overall photovoltaic performance [10]. Metal halide perovskites have become a central focus in photovoltaic study, driven by their exceptional and tunable optoelectronic characteristics. Beyond their elevated power conversion efficiencies (PCEs), perovskite solar cells (PSCs) exhibit a remarkable power-to-weight ratio and intrinsic compatibility with flexible substrates—critical parameters for aerospace applications. Furthermore, their superior radiation hardness against high-energy

protons and electrons positions PSCs as a formidable candidate for next-generation space-borne photovoltaic systems, offering a lightweight and resilient alternative to traditional multi-junction celestial energy technologies [11]. On the other hand, operational capability and productivity of photovoltaic cells are strongly affected by ecological impact and intrinsic electrical parameters, which can significantly limit their practical energy conversion efficiency. This paper will analyze some elements that affect the effectiveness of solar cells to enhance their effectiveness using MATLAB. This study aims to examine combined impacts of solar radiation, temperature, and atmospheric turbidity on the electrical performance of a photovoltaic module. The importance of this work lies in improving the understanding of environmental factors that degrade PV efficiency and affect power generation under harsh climatic conditions. To achieve this objective, a MATLAB-based numerical simulation using the single-diode PV model is utilized to analyze the I-V and P-V properties under varying operating conditions and atmospheric attenuation effects.

2 Materials and Methods

Environmental Effects on PV performance

The efficiency of solar cells is directly influenced by weather factors, particularly solar irradiance and temperature [12]. The impact of reduced irradiance entails a decline in both solar cell output current and voltage, while the influence of elevated cell temperature leads to a modest rise in output current and a significant fall in output voltage, culminating in an overall reduction in output power [12]. Among these environmental factors:

1. Temperature (T)

A PV cell, similar to other semiconductor devices, is highly responsive to temperature changes. The performance and energy production of a PV cell

decreases as its temperature rises. This is primarily because higher carrier concentrations lead to increased internal recombination rates. The temperature of a PV module rises as solar radiation and air temperature increase, but it decreases when wind speed rises. In summer at noon, when the sunlight is intense, the temperatures of PV modules can climb to 60-65 °C [13] [14].

With rising temperature, the intrinsic semiconductor's band gap narrows, and the open circuit voltage (OCV) lowers in accordance with the temperature dependence of the p-n junction voltage exhibited in the diode factor q/kT . As a result, solar cells exhibit a negative temperature coefficient for open-circuit voltage (OCV) [13].

2. Solar Irradiance (G)

Irradiance refers to the energy that enters a particular horizontal area at a specific wavelength and time [15]. The energy produced by photovoltaic systems varies based on the intensity of irradiance. The solar irradiance alters the properties of the I-V and P-V curves. It rises the I_{sc} and the V_{oc} , in succession, the produced power rises. However, the dependency on module temperature is inversely proportional. The level of solar irradiance hitting the array influences the energy produced. Simultaneously, the surrounding temperature directly affects its reduction, while the energy produced is directly related to the intensity of the irradiance [16].

3. Atmospheric turbidity

Atmospheric turbidity refers to the reduction of solar radiation as it travels through the atmosphere because of scattering and absorption by suspended particles such as dust, aerosols, and water vapor. It is closely related to the concentration of atmospheric aerosols, which may originate from natural sources, including volcanic eruptions, dust storms, sea spray, and biomass burning, as well as from human activities in urban environments. An increase in aerosol concentration leads to higher turbidity levels, resulting

in reduced visibility and degradation of air quality. Moreover, aerosols have an important part in the absorption and scattering of solar radiation and influence cloud formation and precipitation processes. Therefore, atmospheric turbidity is an important parameter in air pollution monitoring, as well as in meteorology, climatology, and the design of solar energy systems [17]. In photovoltaic (PV) applications, increased turbidity results in a decrease in the solar irradiance hitting the cell surface, which in turn decreases the photogenerated current almost proportionally. This effect is mainly reflected in a reduction of current at short circuit (I_{sc}), while the voltage in an open circuit (V_{oc}) shows only a slight variation due to its logarithmic dependence on irradiance. Consequently, the current–voltage (I–V) characteristic curve shifts downward, accompanied by a decrease the peak power point (PPP) and fill ratio. These changes indicate a degradation in PV performance under high turbidity conditions and highlight the importance of atmospheric clarity for maximizing energy conversion efficiency [18].

The reduction in solar irradiance due to atmospheric turbidity can be expressed using the Beer–Lambert law as follows:

$$G = G_0 e^{-\tau m} \quad (1)$$

Where G is the solar energy received at the Earth's surface, G_0 is the alien solar radiation, and τ is the optical depth representing atmospheric attenuation due to absorption and scattering by aerosols and atmospheric particles

Since the photocurrent is directly proportional to the incident irradiance, it can be expressed as: [19]

$$I_{ph} = \frac{G}{G_{ref}} I_{sc-ref} \quad (2)$$

Where I_{ph} is the photocurrent generated under actual operating conditions, G is the incident solar irradiance, G_{ref} is the reference irradiance (typically 1000W/m² in typical testing conditions), and I_{sc-ref} is the photocurrent at reference conditions.

Single-Diode Model of the PV Cell

Mathematical Model of Photovoltaic Cell (Single-Diode Model) contains a photogenerated current source (IPV), a diode connected in parallel, and two resistors (R_P and R_S) connected in parallel and series, respectively As shown in **Fig. 1**, [20]. This model is defined using five essential factors: photogenerated current (IPV), reverse saturation current (I_0), diode ideality factor (n), parallel resistance (R_P), and series resistance (R_S) [21] [22]. To achieve more accurate descriptions of solar cell behavior, particularly nonlinear processes (e.g., recombination in depletion and bulk regions, surface recombination, recombination through deep energy traps, thermionic emission, etc.), the SDM model has been extended by adding extra diodes in parallel to the current one within the equivalent circuit. This modification forms the basis for the two-diode (DDM) and three-diode (TDM) models, each introducing two and four extra parameters, respectively, compared to the single-diode approach [23].

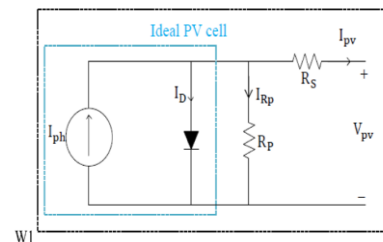


Fig. 1: The equivalent electrical model for a single-diode solar cell

The fundamental equation of semiconductor diode theory describes the behavior of an ideal PV cell in the following manner: [20] [24]

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_S)}{nkT}} - 1 \right) - \left(\frac{V+IR_S}{R_p} \right) \quad (3)$$

For simplicity, the effects of series resistance (R_S) and shunt resistance (R_p) were neglected in the present simulation. Therefore, the equation for photovoltaic current can be expressed in simpler terms as follows:

$$I = I_{ph} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \quad (4)$$

$$I_0 = I_{0-ref} * (T/T_{ref})^3 * e^{((qE_g/k)*(1/T_{ref}-1/T))} \quad (5)$$

Where the parameters used in the model are described as follows:-

I_{ph} : Photogenerated current or photocurrent (A)

I_0 : Reverse saturation current of the diode (A)

I_{0-ref} : Reverse saturation current at reference temperature (A)

V : Output voltage of the photovoltaic cell (V)

q : Electron charge ($1.6 \times 10^{-19} \text{C}$)

n : Diode ideality factor

k : Boltzmann constant ($1.38 \times 10^{-23} \text{ J/K}$)

T : Cell absolute temperature (K)

T_{ref} : Reference temperature (25°C or 298 K)

E_g : Bandgap energy of the semiconductor material (eV)

The electrical power (p) generated by a photovoltaic (PV) cell is defined as the product of its output voltage and current, expressed as [13]

$$p = I * V \quad (5)$$

3 Results and Discussion

Within this section, the performance of the PV cell is conducted by analyzing the primary environmental factors that influence its electrical characteristics. Specifically, the study investigates the impact of solar irradiance levels, operating temperature, and atmospheric turbidity on the cell's efficiency. Using the single-diode model as a baseline, the following results and discussions demonstrate how these factors influence the output power and I-V curves, as illustrated in the figures below. **Fig. 2(a)** illustrates the simulated current-voltage (I-V) characteristics of the photovoltaic (PV) module under constant environmental conditions using **Eq. (4)**. It can be noted that the output current remains nearly constant at approximately 6 A over a wide voltage range, indicating stable current generation under solar irradiation. As the terminal voltage access the open-circuit voltage region, the current decreases rapidly due to the nonlinear conduct of the p-n junction inside the

solar cell. The curve exhibits the typical exponential characteristic of photovoltaic devices, where the maximum operating region is located near the knee point of the curve. This behavior confirms the electrical performance expected from the single-diode photovoltaic model. **Fig. 2(b)** illustrates the Power-Voltage (P-V) characteristic curve of the photovoltaic cell. The curve demonstrates a non-linear relationship, where the output power initiates at zero and increases steadily with the operating voltage until it reaches the peak power point (PPP). At this peak, the cell delivers its maximum output of approximately 105 W at an optimal voltage of about 18 V. Beyond this point, a rapid decline in power is observed as the voltage nears the open-circuit voltage (V_{oc}) of nearly 22 V. This behavior highlights the critical role of MPPT algorithms in maintaining the operational voltage near the peak to maximize energy harvesting efficiency under varying conditions. The present findings show good agreement with previously reported results in the literature, such as those presented by [20] [13] [14] [25].

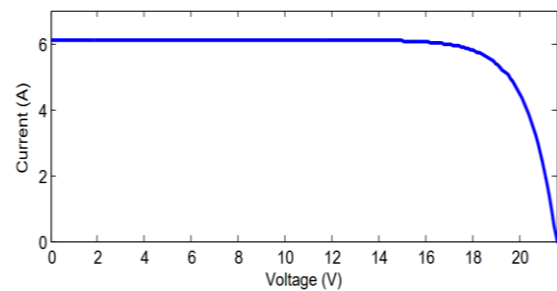


Fig. 2(a): Current-Voltage (I-V) properties of the solar cell.

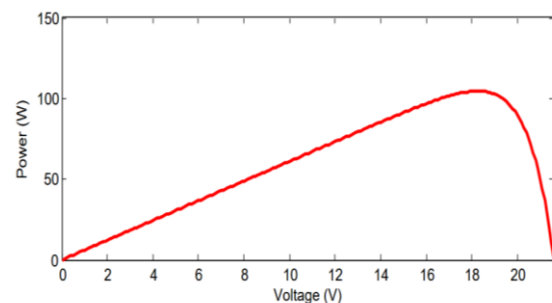


Fig. 2(b): P-V characteristics of the photovoltaic cell at 25 °C.

Fig. 3(a) displays the current–voltage (I–V) behavior of the solar cell at various operating temperatures: 0 °C, 25 °C, 50 °C, and 75 °C. As indicated by **Eq. (5)**, when the temperature rises, the output current little decreases for a given voltage, causing the I–V curves to shift downward. This behavior is mainly attributed to the increase in recombination losses and the reduction in carrier mobility at higher temperatures. At lower temperatures, the device exhibits higher current values, indicating improved electrical performance. The separation between the curves becomes more pronounced at higher voltages, highlighting the strong influence of temperature on the diode characteristics. Overall, the figure confirms that increasing temperature negatively affects the solar cell performance, particularly near the high-voltage operating region.

Fig. 3(b) illustrates the power–voltage (P–V) characteristics of the photovoltaic (PV) cell under the same temperature conditions while maintaining constant solar irradiance. The curves correspond to the four temperature levels mentioned. It is noted that raising the cell temperature causes a gradual reduction in the maximum output power (P_{max}). The PV cell achieves its highest power output at the lowest operating temperature (0°C). At 25°C, the power reaches approximately 118W; however, as the temperature rises to 75°C, the peak power decreases significantly to nearly 80W. This degradation is mainly attributed to the thermal effect on the electrical characteristics, particularly the substantial reduction in the open-circuit voltage (V_{oc}) with increasing temperature. Furthermore, the figure shows that the peak power point (PPP) shifts toward lower voltage values as temperature rises. At lower temperatures, the P–V curve extends to higher voltage levels, whereas at elevated temperatures, the curve contracts and terminates at lower voltages. This indicates that high operating temperatures negatively affect the conversion efficiency and overall performance of the photovoltaic cell. Generally, the figure

demonstrates the inverse relationship between temperature and photovoltaic performance. Although the output current is only slightly influenced by temperature variations, the voltage decreases considerably, resulting in a substantial reduction in the generated power. Therefore, thermal management and cooling techniques are essential for improving the efficiency and operational stability of photovoltaic systems. These findings show good agreement with previously reported results in the literature, such as those presented by [26] [27] [14] [25].

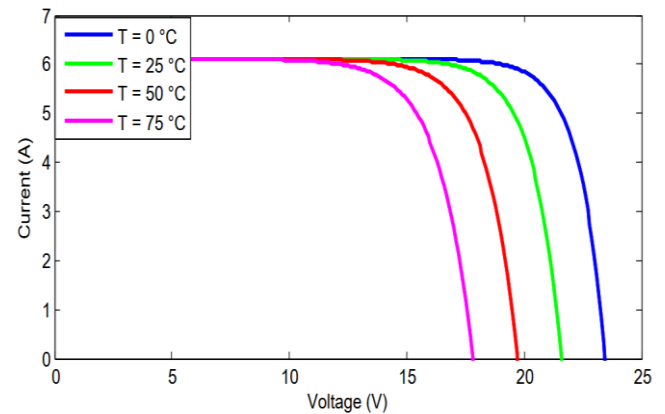


Fig. 3(a): shows the current–voltage (I–V) behavior of the photovoltaic cell under varying temperature conditions.

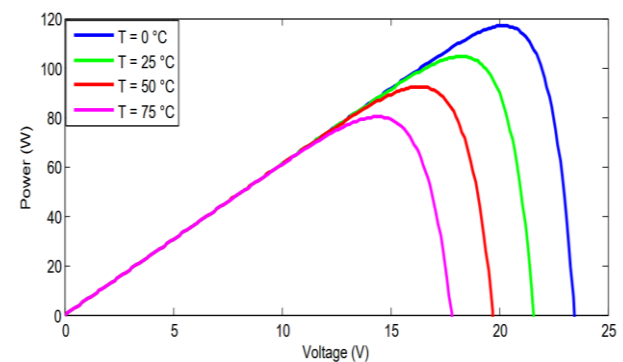


Fig. 3(b): depicts the corresponding power–voltage (P–V) characteristics, demonstrating how changes in temperature affect the power output of the solar cell.

Fig. 4(a) presents the current–voltage (I–V) characteristics of the solar cell under different levels of solar radiation ranging from 200 to 1000W/m². As indicated by **Eq. (1)**, as the irradiance grows, the output current increases significantly over the entire voltage range, reflecting the direct proportionality between photogenerated current and incident solar radiation. At low voltages, the current remains nearly constant for each irradiance level, indicating current-source behavior dominated by photogeneration. Near the open-circuit voltage region, a sharp drop in current is observed due to the increasing influence of the diode current. The results confirm that higher irradiance enhances the electrical output of the solar cell, while the open-circuit voltage shows only a slight variation compared to the current. **Fig. 4(b)** illustrates the P–V characteristics of the photovoltaic (PV) cell under varying solar irradiance levels ranging from 400W/m² to 1000W/m². The results clearly demonstrate that the output power of the PV cell is heavily dependent on the incident solar irradiance. As the irradiance increases, the generated power rises significantly over the entire operating voltage range. It may be observed that the peak power point (PPP) increases progressively with increasing irradiance. At an irradiance of 1000W/m², the PV cell achieves the highest maximum power, whereas lower irradiance levels produce proportionally lower power outputs. This behavior occurs because higher irradiance increases the number of incident photons striking the photovoltaic surface, leading to the generation of a greater photocurrent and consequently higher electrical power output.

The curves also indicate that the operating voltage corresponding to the maximum power point changes only slightly with irradiance, while the variation in output power is much more pronounced. Furthermore, after reaching the peak power point, the output power decreases sharply as the voltage near the open-circuit voltage region. This reduction is attributed to the rapid

decrease in output current near the open-circuit condition, which causes the generated power to diminish to zero.

Overall, the figure confirms that solar irradiance is a dominant environmental factor affecting photovoltaic performance, where higher irradiance levels enhance the power generation capability and improve the total energy conversion performance of the PV cell. These findings show good agreement with previously reported results in the literature, such as those presented by [14] [26] [27] [25].

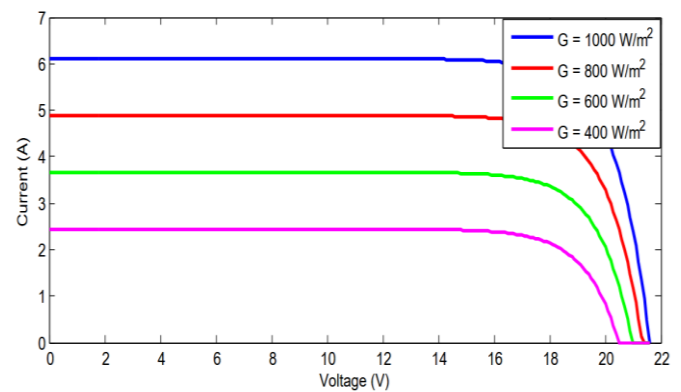


Fig. 4(a): Variation of the I–V characteristics of the photovoltaic cell with changing solar irradiance.

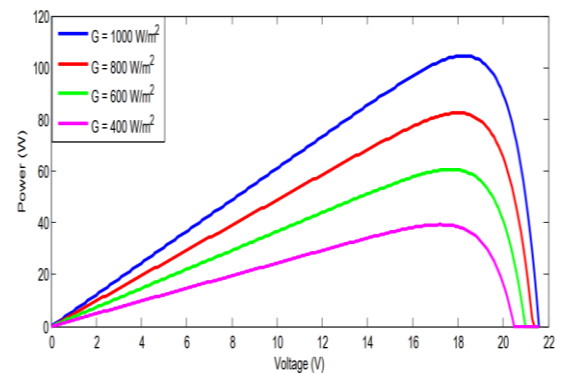


Fig. 4(b): Variation of the P–V characteristics of photovoltaic cell with changing solar irradiance.

4 Conclusions

This study presented a numerical investigation of the electrical performance of a photovoltaic (PV) cell using the single-diode model implemented in MATLAB. The current–voltage (I–V) and power–voltage (P–V) characteristics were analyzed in differing environmental conditions, including temperature, solar irradiance, and atmospheric turbidity. The results demonstrated that the performance of the PV cell is strongly influenced by environmental parameters, where increasing temperature negatively affects the output characteristics, while higher solar irradiance enhances the generated current and maximum power output. In regular testing conditions (25°C, 1000 W/m²), the PV module achieved a maximum power of approximately 105 W, whereas increasing the operating temperature to 75°C reduced the maximum power to nearly 80W due to the decline in output voltage. Moreover, increasing the irradiance level from 400W/m² to 1000W/m² significantly improved the short-circuit current and overall power generation. In addition, atmospheric turbidity was found to reduce the effective irradiance reaching the PV surface, resulting in a noticeable degradation in output power under identical operating conditions. The obtained characteristics confirmed the nonlinear behavior of photovoltaic devices and highlighted the importance of operating near the maximum power point to achieve efficient energy conversion. Overall, the simulation results showed good agreement with theoretical expectations and previously published studies, confirming the validity and effectiveness of the adopted mathematical model for photovoltaic performance analysis. Future work may include the incorporation of series and shunt resistance effects, partial shading conditions, and experimental validation to improve the accuracy of photovoltaic performance prediction.

Conflict of interest: The author declares that there are no conflicts of interest

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