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Performance analysis of a photovoltaic system under real conditions using modeling and simulation

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ABSTRACT

The main objective of this study is to evaluate the performance of a photovoltaic (PV) system under real-world conditions by analyzing three key climatic variables on a monthly scale: insolation, average daily temperature, and photovoltaic power output. Insolation, defined as the average daily sunshine duration, is a critical parameter for estimating the solar energy potential in the Ghardaïa region, which is characterized by a desert climate. Average daily temperature directly influences the efficiency of PV panels, as elevated temperatures tend to reduce their performance. Photovoltaic power output, expressed in kWh/m²/day, is calculated based on solar radiation, providing a measure of actual energy generation under prevailing climate conditions. The analysis of these three climatic parameters offers valuable insights into seasonal variations and their impact on solar energy production in the Ghardaïa region. To optimize PV system performance, the study emphasizes the importance of accurate system design supported by advanced numerical methods. We extend the modeling from individual solar cells to complete PV modules and arrays, accurately reproducing their electrical characteristics. Simulations are performed in MATLAB/Simulink to validate the proposed model, which is based on an enhanced two-diode representation that reflects realistic operating conditions.

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1. INTRODUCTION

Since the beginning of the 21st century, global energy consumption has grown steadily across most regions of the world [1]. This trend is expected to continue, driven by ongoing economic growth and increasing per capita electricity demand. Currently, the majority of electrical energy is generated from conventional sources such as oil, natural gas, coal, and nuclear power. Although these sources are widely utilized, they pose two major drawbacks: they are non-renewable and contribute significantly to environmental pollution, thereby threatening both human health and ecological balance [2]. Despite its numerous advantages, photovoltaic (PV) energy has historically faced criticism due to its intermittency (day/night cycles, seasonal variation), perceived low reliability, and an initially unfavorable energy return on investment (i.e., high manufacturing energy costs compared to energy output). However, recent technological advancements in photovoltaic cell design and energy management systems have effectively addressed many of these concerns [3], [4].

This study focuses on the electrical and mathematical modeling of photovoltaic cells using both one-diode and two-diode models. Simulations of current-voltage (I–V) and power-voltage (P–V) characteristics are carried out on a photovoltaic module, accompanied by a comparative performance analysis. To demonstrate the practical applicability of these techniques, the study is conducted using real data from the Ghardaïa region, which is characterized by a Saharan climate. This area experiences high solar potential, with an average annual solar energy input of 5.8 kWh/m²/day. The annual global solar irradiance on a horizontal surface exceeds 6,000 Wh/m², and the region benefits from over 3,000 hours of sunshine per year.

Furthermore, the study evaluates the performance of a photovoltaic system under real-world conditions by analyzing three key climatic variables on a monthly basis: insolation, average daily temperature, and photovoltaic power output. This analysis offers critical insights into seasonal climate variations and their impact on solar energy production in the Ghardaïa region. Ultimately, the objective is to deepen the understanding of both the challenges and opportunities associated with deploying photovoltaic systems in desert environments, and to develop optimized strategies for meeting local energy needs more effectively.

2. PV TWO-DIODE MODEL

The two-diode model provides a more accurate representation of solar cell behavior, particularly under low irradiance conditions. It includes a photocurrent source, two diodes (Figure 1) accounting for recombination mechanisms [5], and series and shunt resistances modeling ohmic and leakage losses, respectively. Although more complex than the single-diode model, it significantly improves the accuracy of current–voltage characteristics [6], [7].

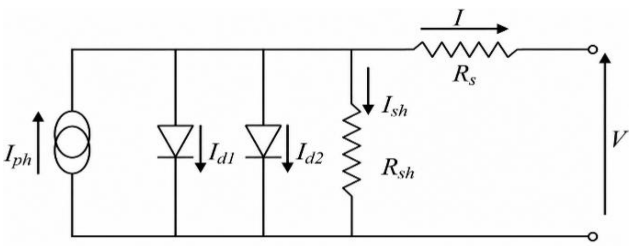


Figure 1. Two-diode model of the photovoltaic cell [5]

By applying Kirchhoff's laws to the equivalent circuit of the photovoltaic cell, the following current equation [7], [8] is obtained:

$$\mathrm{I} = \mathrm{I_{ph}} - \mathrm{I_{d1}} - \mathrm{I_{d2}} - \mathrm{I_{sh}} \tag{1}$$

Where:
I: is the output current of the cell.
I_{ph}: is the photo-generated current.
I_{d1} and I_{d2}: are the currents flowing through diodes D1 and D2, respectively.
I_{sh}: is the leakage current through the shunt resistance R_{sh}.
The currents through the two diodes are given by the following expressions [8]:

$$\mathrm{I_{d1}} = \mathrm{I_{s1}}\left[\exp\left(\frac{\mathrm{V+R_s*I}}{\mathrm{A_1*N_s*V_t}}\right) - 1\right] \tag{2}$$

$$\mathrm{I_{d2}} = \mathrm{I_{s2}}\left[\exp\left(\frac{\mathrm{V+R_s*I}}{\mathrm{A_2*N_s*V_t}}\right) - 1\right] \tag{3}$$

$$I_{s1} = I_{0_{ref1}}\left(\frac{T_c}{T_{c_{ref}}}\right)^3 * exp\left(\left(\frac{q*E_{gap}}{A*K}\right) * \left(\frac{1}{T_{c_{ref}}} - \frac{1}{T_c}\right)\right) \tag{4}$$

$$I_{s2} = I_{0_{ref2}} \left(\frac{T_c}{T_{c_{ref}}}\right)^3 * exp\left(\left(\frac{q*E_{gap}}{A*K}\right) * \left(\frac{1}{T_{c_{ref}}} - \frac{1}{T_c}\right)\right) \tag{5}$$

and the shunt current is as (6).

$$\mathrm{I_{sh}} = \frac{\mathrm{V+R_s*I}}{\mathrm{R_{sh}}} \tag{6}$$

By combining all these expressions, the complete current equation is obtained as (7).

$$\mathrm{I = I_{ph} - I_{s1}\left[exp\left(\frac{q(V+R_s*I)}{A_1*N_s*K*T}\right) - 1\right] - I_{s2}\left[exp\left(\frac{q(V+R_s*I)}{A_2*N_s*K*T}\right) - 1\right] - \frac{V+R_s*I}{R_{sh}}} \tag{7}$$

A_1: is the ideality factor of the first diode, related to diffusion current densities.
A_2: is the ideality factor of the second diode, related to recombination current density.

3. PARAMETER ESTIMATION

The accuracy of the two-diode PV model relies on the proper estimation of its seven parameters: I_{ph}, I_{s1}, I_{s2}, R_s, R_p, A_1, and A_2. While some parameters can be derived analytically, R_s and R_p are typically determined using analytical, numerical, or optimization-based methods because of their significant influence on the I–V and P–V characteristics, particularly around the maximum power point (MPP) [9], [10].

3.1. Photo-generated current Iph

The photo-generated current varies with the irradiance G and the cell temperature T_c. It can be estimated from its reference value Iph_ref, provided under standard test conditions (STC), using the following relation [11], [12]:

$$\mathrm{I_{ph}} = \frac{\mathrm{G}}{\mathrm{G_{ref}}}\left(\mathrm{I_{ph_{ref}}} + \mu_{sc}\Delta\mathrm{T}\right) \tag{8}$$

- Iph: Photo-generated current under STC.
- G: Irradiance (W/m²).
- Gref: Irradiance at STC = 1000 W/m².
- ΔT = Tc – Tc_ref
- Tc_ref: Cell temperature at STC = 25 °C + 273 = 298 K.
- µsc: Temperature coefficient of the short-circuit current (A/K), provided by the manufacturer.

3.2. Saturation currents I_{s1} and I_{s2}

The reverse saturation currents of the diodes, Is1 and Is2, represent the leakage current in the p-n junctions in the absence of light [12], [13]. They are strongly influenced by the operating temperature and can be expressed using Shockley's exponential law as follows:

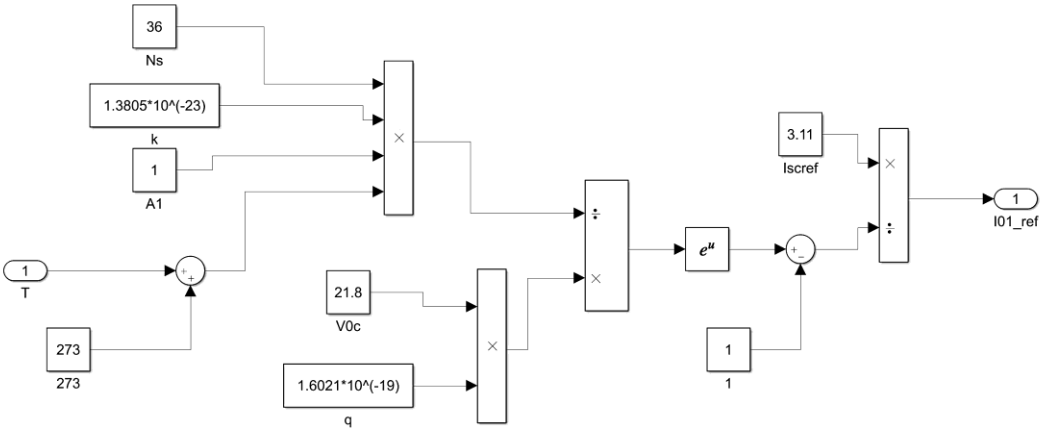
$$I_{s1} = I_{01} = I_{0_{ref1}} \left(\frac{T_c}{T_{c_{ref}}}\right)^3 * exp\left(\left(\frac{q*E_{gap}}{A*K}\right) * \left(\frac{1}{T_{c_{ref}}} - \frac{1}{T_c}\right)\right)$$

$$I_{s2} = I_{02} = I_{0_{ref2}} \left(\frac{T_c}{T_{c_{ref}}}\right)^3 * exp\left(\left(\frac{q*E_{gap}}{A*K}\right) * \left(\frac{1}{T_{c_{ref}}} - \frac{1}{T_c}\right)\right) \tag{9}$$

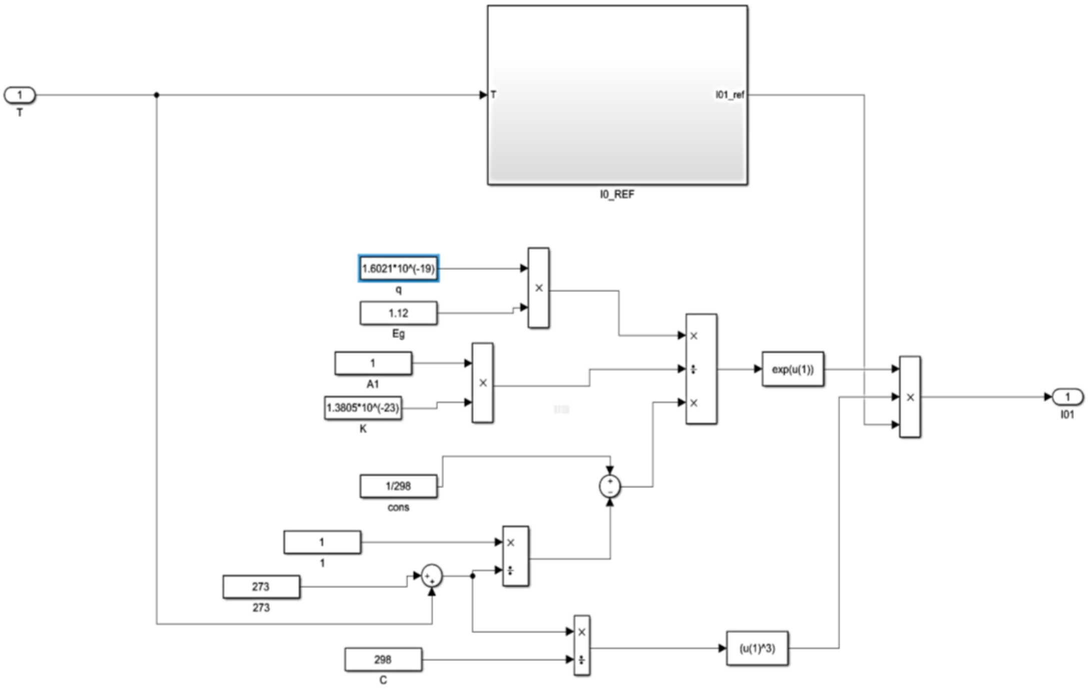
E_{gap}: Bandgap energy of the cell, and

$$I_{0_{ref1}} = \frac{I_{scref}}{\left[exp\left(\frac{V_{oc}*q}{A1*N_s*K*T}\right)-1\right]}, \; I_{0_{ref2}} = \frac{I_{scref}}{\left[exp\left(\frac{V_{oc}*q}{A2*N_s*K*T}\right)-1\right]} \tag{10}$$

Figure 2 shows the detailed implementation of the currents I_{0ref} and I_s in MATLAB.



(a)



(b)

Figure 2. Simulink implementation of the PV model parameters: (a) detailed implementation of $I_{01\text{ref}}$ and (b) detailed implementation of I_s

4. SIMULATION OF THE PV MODULE

The photovoltaic module model was implemented in MATLAB/Simulink, based on the previously derived analytical equations. The PWX 500 module was used as reference. Its electrical characteristics under STC are reported in Table 1, distinguishing between the single- and two-diode model parameters [6].

Figure 3 shows the implementation of the two-diode model in Simulink for validating the dynamic behavior of the photovoltaic module. Figure 4(a) shows the current–voltage (I–V) characteristics of a photovoltaic cell simulated using the single-diode and two-diode models. At low voltage, the current remains close to the short-circuit current Isc, then decreases to zero at the open-circuit voltage Voc. The two-diode model predicts a slightly lower Voc due to its improved representation of internal recombination effects, resulting in a more realistic description of the cell behavior. Figure 4(b) presents the power–voltage (P–V) characteristic. The output power increases with voltage, reaches a maximum at the MPP, and then drops to zero at Voc. The two-diode model provides a more accurate estimation of the MPP, which is important for the optimal control and efficiency of photovoltaic systems.

Table 1. Electrical characteristics of the PWX 500 module [14]

Parameter	Adjusted parameters for the single-diode model	Adjusted parameters for the two-diode model
$P_{\max}$	49 W	49 W
$I_{\max}$	2.88 A	2.88 A
$V_{\max}$	17 V	17 V
I_{sc}	3.11 A	3.11 A
V_{oc}	21.8 V	21.8 V
R_s	0.55 Ω	0.3 Ω
R_{sh}	1000 Ω	200 Ω
A_1	1.3	1
A_2	-	1.2
I_{s1}	$4.116*10^{-8}$ A	$1.782*10^{-10}$ A
I_{s2}	-	$9.075*10^{-9}$ A
N_{OCT}	45 °C	45 °C
μ_{sc}	$1.3*10^{-3}$ (/°K)	$1.3*10^{-3}$ (/°K)
E_{gap}	1.12	1.12
N_s	36	36

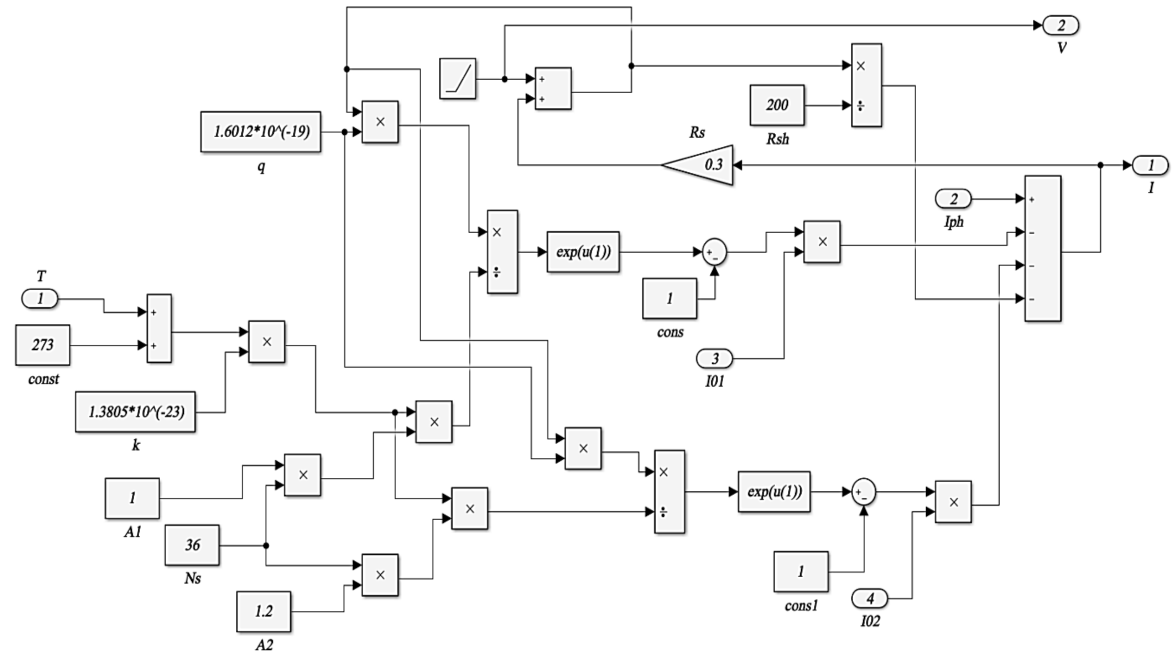
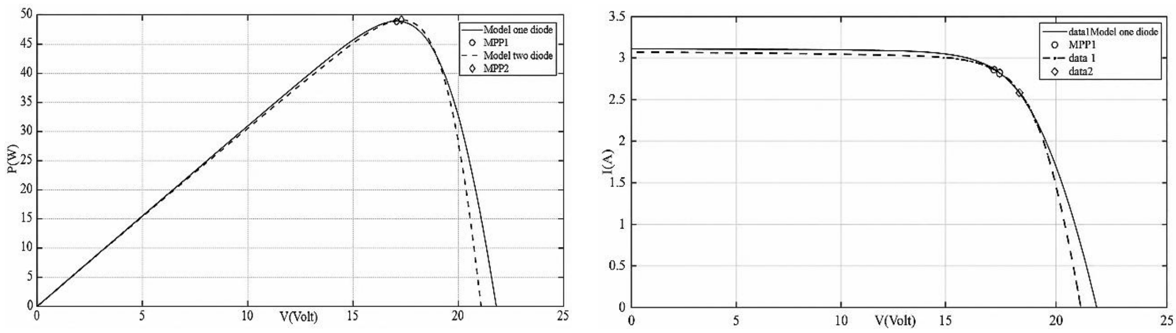


Figure 3. Detailed two-diode PV module model in MATLAB/Simulink



(a) (b)

Figure 4. PV cell characteristics for the single-diode and two-diode models: (a) P–V characteristics and (b) I–V characteristics

5. SERIES–PARALLEL TWO-DIODE PV MODEL

The output power of a single photovoltaic cell is relatively low (typically less than 2 W at approximately 0.5 V). To obtain practical voltage and power levels, cells are interconnected in series and parallel to form a photovoltaic module [8], as shown in Figure 5 [15]. Series connections increase the total output voltage, whereas parallel connections increase the current. Multiple modules can then be combined in series and/or parallel to form a PV array capable of delivering the voltage and current required by the photovoltaic system [11], [14], [16].

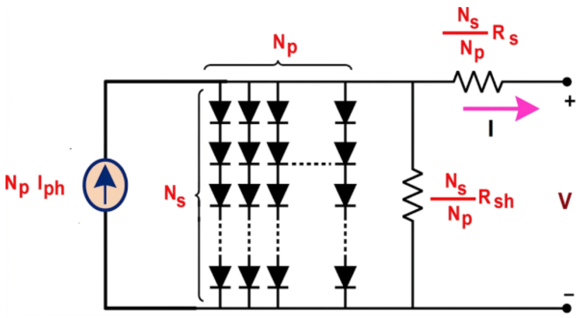


Figure 5. Series–parallel (Ns and Np) two-diode solar modules [15]

Regardless of the number of modules connected in series and parallel, the current generated by this model is given by (11).

$$I' = I'_{ph} - I'_{d1} - I'_{d2} - I'_{sh} \tag{11}$$

With:

$$I'_{ph} = N_p I_{ph},\ I'_d = N_p I_d \tag{12}$$

$$I'_{sh} = \frac{V' + R'_s * I'}{R'_{sh}} \text{ And } R'_s = \frac{N_s}{N_p} R_s,\ R'_{sh} = \frac{N_s}{N_p} R_{sh} \tag{13}$$

The final equation is therefore [17], [18]:

$$I' = N_p I_{ph} - N_p I_{s1}\left[e^{\left(\frac{q\left(V' + \frac{N_s}{N_p} R_s * I'\right)}{A_1 * N_s * K * T}\right)} - 1\right] - N_p I_{s2}\left[e^{\left(\frac{q\left(V' + \frac{N_s}{N_p} R_s * I'\right)}{A_2 * N_s * K * T}\right)} - 1\right] - \frac{V'\frac{N_p}{N_s} + R_s * I'}{R_{sh}}$$

Figure 6 shows the implementation of the two-diode PV array model in MATLAB/Simulink, used to simulate the electrical behavior of the photovoltaic generator.

Figure 7 illustrates that the short-circuit current increases proportionally with the number of parallel-connected cells, while the open-circuit voltage increases with the number of series-connected cells, leading to an enhancement of the overall power output of the photovoltaic generator. This study also evaluates the impact of partial shading on the PV array performance [19], [20] under different partial shading scenarios.
- Case 1: No shaded PV module (full irradiation on solar PV array): 1000 W/m^2.
- Case 2: One shaded module (receives irradiation of 800 W/m^2), others receive full irradiation of 1000 W/m^2.
- Case 3: Two shaded modules (receive irradiation of 800 and 600 W/m^2), others receive full irradiation of 1000 W/m^2.
- Case 4: Three shaded modules (receive irradiation of 800, 600 and 200 W/m^2), with the others receive irradiation of 1000 W/m^2.

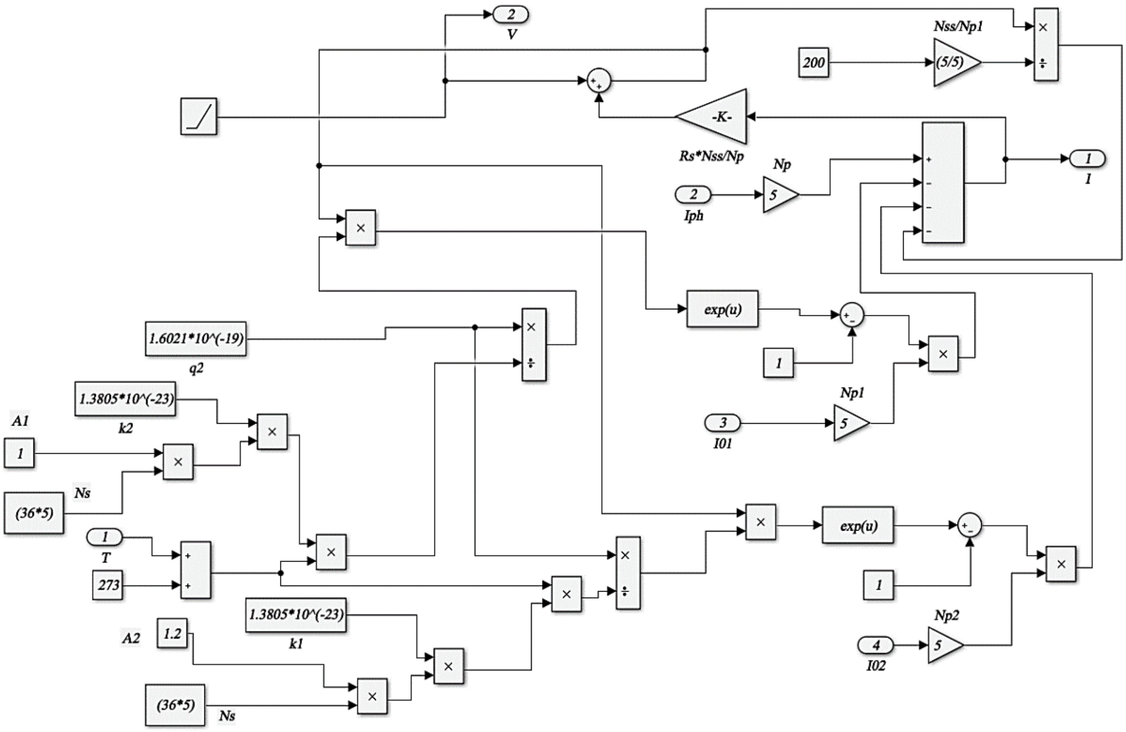
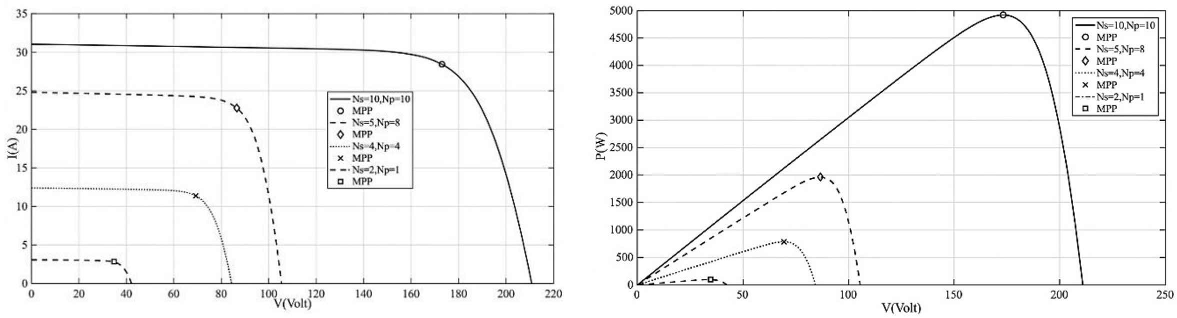


Figure 6. Two-diode PV model in series–parallel configuration (MATLAB/Simulink)



(a) (b)

Figure 7. Characteristics of the two-diode model for different N_s and N_p configurations: (a) I–V characteristics and (b) P–V characteristics

Figure 8 shows the MATLAB/Simulink model of the solar PV array under partial shading conditions. The model is used to simulate the effect of non-uniform solar irradiance on the electrical behavior and power generation of the PV array. Under partial shading, multiple local maximum power points may appear, making the PV system more challenging to operate at its global maximum power point.

The MPP is one of the most critical parameters of a photovoltaic panel, as it represents the operating point at which maximum efficiency is achieved. However, since the current–voltage (I–V) characteristic depends on solar irradiance and temperature, the MPP varies accordingly. Therefore, a MPPT system is an essential component of any PV installation [21]. These challenges become more significant under partial shading conditions. In large PV arrays, it is difficult to ensure uniform irradiance across all panels [22]. In practice, modules may experience different levels of irradiance due to dust, clouds, trees, or surrounding obstacles. This phenomenon, known as partial shading, leads to complex I–V and power–voltage (P–V) characteristics, often characterized by multiple power peaks [23]. As shown in Figure 9, local maximum power points may appear in addition to the global maximum power point. Consequently, MPPT algorithms must be capable of distinguishing between local and global maxima to ensure optimal system performance [24]. Investigating partial shading effects is essential in the design of PV systems. Accurate analysis under varying irradiance and temperature conditions requires a reliable electrical model of the PV cell [25], [26].

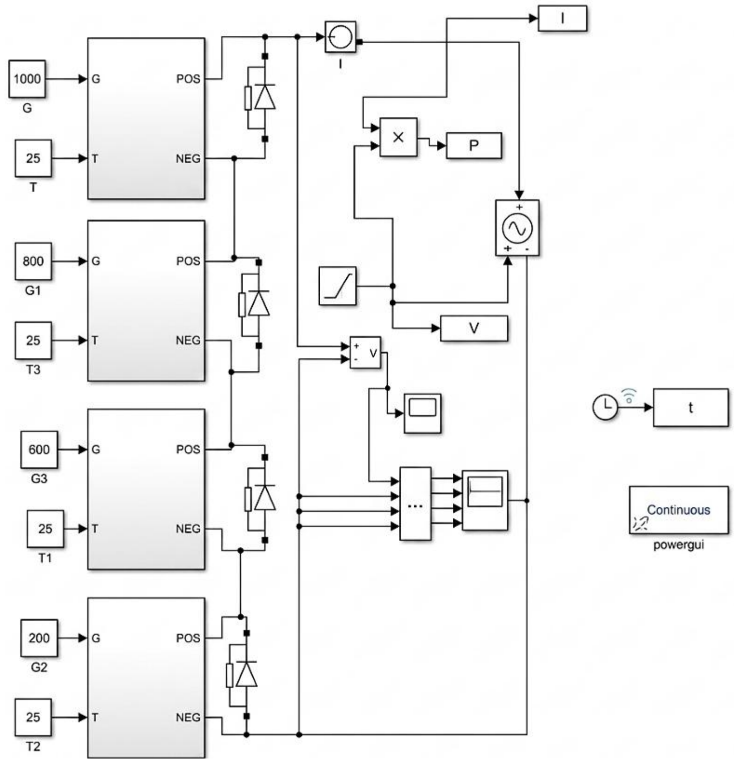


Figure 8. Simulation model of solar PV array under partial shading

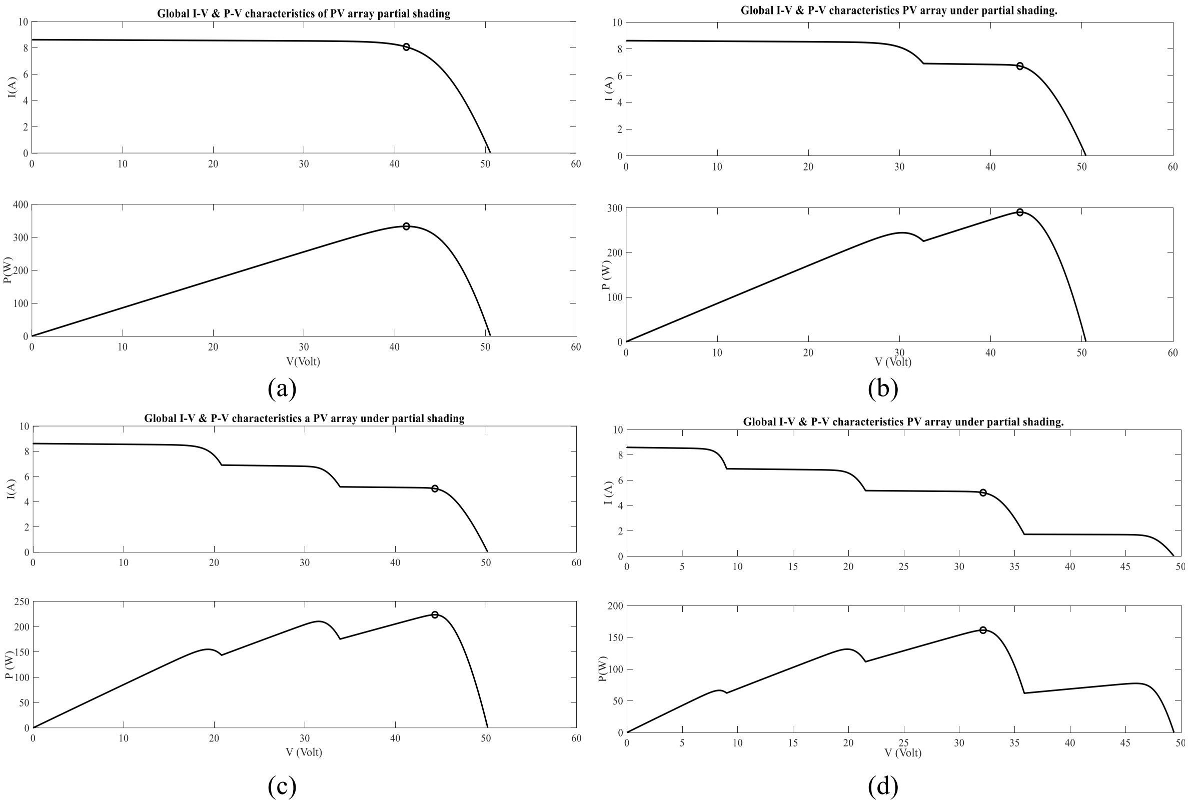


Figure 9. I–V and P–V characteristics of a PV array under different partial shading conditions: (a) uniform irradiance, (b) light partial shading, (c) moderate partial shading, and (d) severe partial shading

6. PV SYSTEM PERFORMANCE UNDER REAL CONDITIONS

The proposed methodologies were applied to the Ghardaïa region as a case study. This Saharan area has a high solar potential of approximately 5.8 kWh/m²/day, with annual global irradiation exceeding 6000 Wh/m² and more than 3000 sunshine hours per year.

6.1. Climatology of Ghardaïa

The Ghardaïa region is characterized by a typical Saharan climate, distinguished by significant thermal amplitude between day and night, as well as between summer and winter. The area experiences extremely low precipitation and high evaporation rates, which lead to the disappearance of vegetative cover. These conditions enhance the mechanical impact of even light winds, making aeolian processes particularly influential. The climatic variables analyzed in this study include precipitation, temperature, wind speed, relative humidity, solar radiation (insolation), and evapotranspiration over the period from 2003 to 2013, based on data from the National Office of Meteorology – Ghardaïa (O.N.M., 2013).

6.2. Numerical evaluation

The estimation of reference evapotranspiration (ETo) for the study area was conducted using meteorological data from the Ghardaïa station, provided by the National Office of Meteorology (O.N.M. Ghardaïa, 2013). This station was selected due to the availability and reliability of long-term climatic records, simplifying the modeling process. The Ghardaïa region is located at an altitude of 464 meters, with a latitude of 32°23′ N and a longitude of 3°46′ E. The monthly climatic parameters and the corresponding computed values of ETo are summarized in Table 2.

Table 2. Monthly climatic data and reference evapotranspiration (ETo) for the Ghardaïa region (2003–2012 average)

Month	Min temp (°C)	Max temp (°C)	Humidity (%)	Wind (m/s)	Sunshine (h/day)	Solar radiation (MJ/m²/day)	ETo (mm/day)
January	6.1	17.4	56	3.9	8.1	13.0	2.92
February	7.4	18.9	45	3.8	8.9	16.2	3.84
March	10.9	24.4	38	3.1	9.0	19.4	5.0
April	14.9	28.6	34	4.1	9.9	23.2	7.17
May	18.6	33.1	29	3.7	10.7	25.7	8.4
June	24.3	38.3	25	3.2	11.2	26.8	9.28
July	27.3	42.1	21	2.4	10.9	26.0	8.85
August	27.5	41.1	26	2.2	10.4	24.2	8.09
September	22.6	35.8	37	2.4	9.0	20.1	6.62
October	17.9	28.4	44	2.4	8.2	16.2	4.72
November	11.4	22.9	48	2.6	8.3	13.6	3.49
December	7.1	17.9	55	2.2	7.5	11.6	2.29
Average	16.3	29.1	38	3.0	9.3	19.7	5.89

The Pearson correlation coefficient between solar radiation and reference evapotranspiration is $r = 0.988$. A Pearson correlation analysis was performed to quantify the relationship between climatic parameters and reference evapotranspiration. The results indicate a very strong positive correlation between monthly solar radiation and reference evapotranspiration, with a correlation coefficient of $r = 0.988$, highlighting the dominant role of solar energy in evapotranspiration processes under the arid climatic conditions of the Ghardaïa region.

6.3. Analysis and interpretation of the curves

6.3.1. Sunshine duration analysis

Figure 10 shows the daily solar irradiance profiles for January, March, and June. All curves follow a typical bell-shaped pattern, with increasing peak irradiance and daylight duration from winter to summer. June provides the highest irradiance and longest sunshine duration, offering optimal PV production conditions. However, January irradiance remains sufficient for effective year-round photovoltaic operation. Understanding seasonal variations in sunshine duration is essential for designing efficient photovoltaic systems, predicting their performance, and planning hybrid configurations, particularly in regions such as Ghardaïa, where solar resources are abundant but vary seasonally.

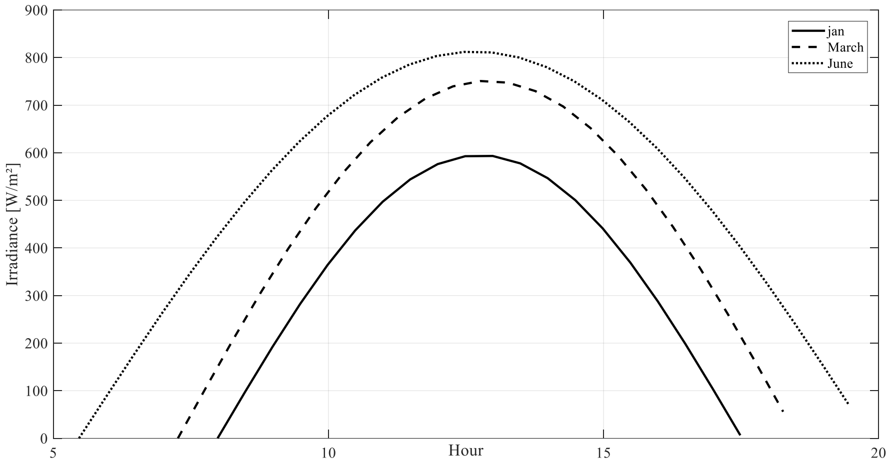


Figure 10. Daily variation of irradiance for the Ghardaïa region

6.3.2. Daily temperature analysis

Figure 11 illustrates the diurnal variation in ambient temperature for the months of January, March, and June. A clear seasonal trend is observed:

- January: temperatures remain relatively low, with a peak of around 17-18 °C occurring in the early afternoon.
- March: a moderate increase is observed, with temperatures reaching approximately 24 °C.
- June: the temperature rises sharply, peaking near 38 °C, reflecting typical summer conditions in arid regions.

In all cases, the temperature follows a parabolic trend: it rises steadily from morning, peaks around midday to early afternoon, and then declines towards the evening. These variations in temperature have a direct impact on the electrical performance of photovoltaic modules. Higher temperatures typically lead to a reduction in output voltage, which can significantly decrease the overall energy conversion efficiency of PV systems.

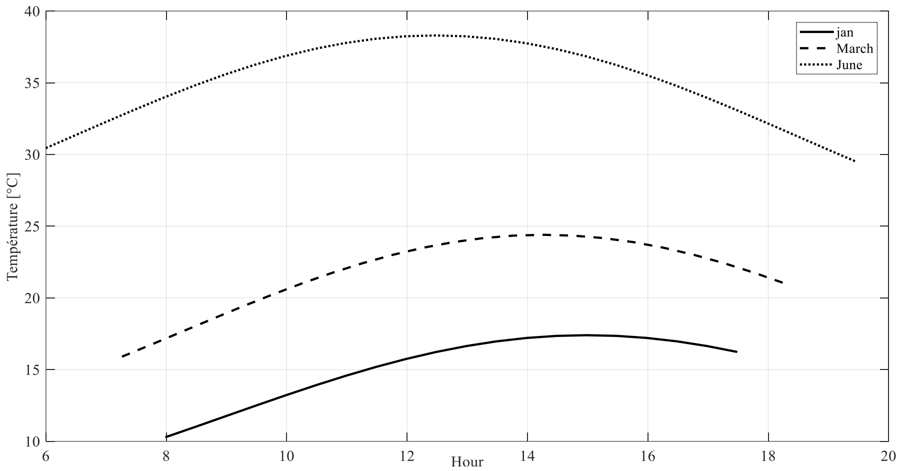


Figure 11. Daily variation of temperature in the Ghardaïa region under MATLAB

6.3.3. Photovoltaic power generation curve

Figure 12 shows the hourly PV output for January, March, and June. Power peaks increase from 25 W in January to 42 W in June, following the solar path. Minor deviations from the irradiance pattern are due to temperature effects, but overall output is dominated by solar radiation. This curve is essential for the sizing of photovoltaic or hybrid solar systems. It also helps in estimating energy storage requirements or the need for supplementary energy sources during low-production periods.

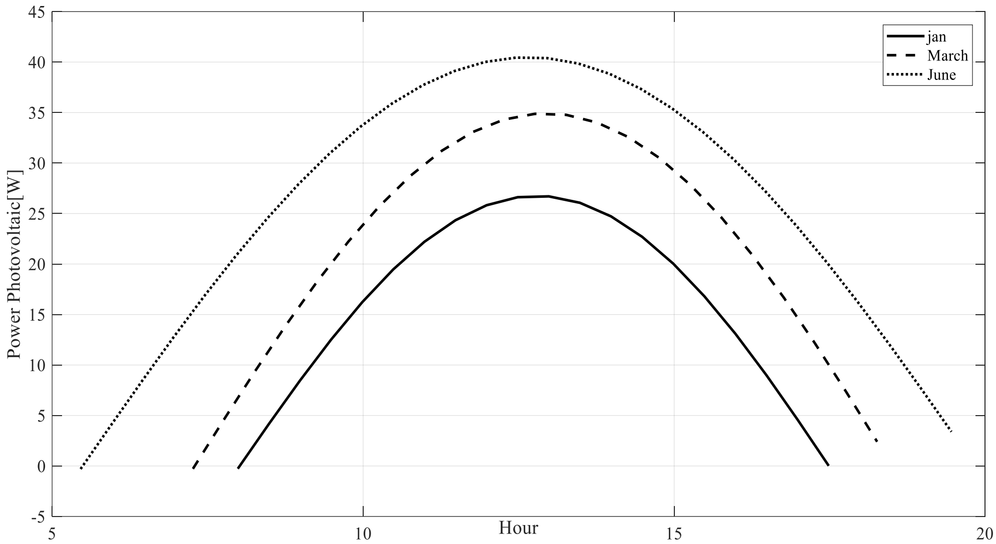


Figure 12. Daily variation of photovoltaic output power in the Ghardaïa region under MATLAB

7. CONCLUSION

Photovoltaic solar energy involves the direct conversion of solar radiation into electrical energy through the photovoltaic effect—a physical phenomenon exploited by solar cells. In this study, the electrical behavior of photovoltaic modules was modeled using the two-diode model, which offers improved accuracy, particularly around the maximum power point. This modeling approach enables more precise system sizing and enhanced control of photovoltaic systems. Our results confirm that the performance of photovoltaic modules is highly sensitive to environmental conditions, particularly solar irradiance and temperature. The efficiency of PV modules is also affected by partial shading, which was investigated through simulations using the developed photovoltaic network and available PV modules. Climatic curve analysis for the Ghardaïa region revealed several key insights into PV system performance. Summer months, marked by high irradiance and strong solar radiation, are the most favorable for optimal solar energy production. However, even during winter, when sunlight and irradiance levels are lower, the energy yield remains significant—demonstrating that solar energy can be a viable and continuous source of power throughout the year. While elevated temperatures tend to decrease panel efficiency, this effect can be mitigated through proper system design tailored to local environmental conditions. To ensure optimal performance, photovoltaic systems should be dimensioned based on seasonal variability in solar resources. Additionally, incorporating energy storage systems is recommended to compensate for low-production periods—especially during winter—thereby maintaining a stable and reliable solar energy supply year-round.

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C : **C**onceptualization
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E : Writing - Review & **E**diting
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Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] J. M. A. Myrzik and M. Calais, "String and module integrated inverters for single-phase grid connected photovoltaic systems - a review," in *2003 IEEE Bologna Power Tech Conference Proceedings,* 2023, vol. 2, pp. 430–437, doi: 10.1109/PTC.2003.1304589.

[2] J. J. Campayo *et al.*, "Two photovoltaic cell simulation models in MATLAB/Simulink," *International Journal on "Technical and Physical Problems of Engineering" (I JTPE)*, vol. 4, no. 10, pp. 45–51, 2012.

[3] M. M. Casaro and D. C. Martins, "Grid-connected PV system: Introduction to behavior matching," in *2008 IEEE Power Electronics Specialists Conference*, Jun. 2008, pp. 951–956, doi: 10.1109/PESC.2008.4592052.

[4] S. B. Kjaer, J. K. Pedersen, and F. Blaabjerg, "A review of single-phase grid-connected inverters for photovoltaic modules," *IEEE Transactions on Industry Applications*, vol. 41, no. 5, pp. 1292–1306, Sep. 2005, doi: 10.1109/TIA.2005.853371.

[5] A. Dolara, S. Leva, and G. Manzolini, "Comparison of different physical models for PV power output prediction," *Solar Energy*, vol. 119, pp. 83–99, Sep. 2015, doi: 10.1016/j.solener.2015.06.017.

[6] H. Bellia, R. Youcef, and M. Fatima, "A detailed modeling of photovoltaic module using MATLAB," *NRIAG Journal of Astronomy and Geophysics*, vol. 3, no. 1, pp. 53–61, Jun. 2014, doi: 10.1016/j.nrjag.2014.04.001.

[7] A. A. Teyabeen and A. E. Jwaid, "Modelling, validation, and simulation of solar photovoltaic modules," *ELECTRICA*, vol. 23, no. 1, pp. 48–60, Jan. 2023, doi: 10.5152/electrica.2022.21164.

[8] M. A. Islam, A. Merabet, R. Beguenane, and H. Ibrahim, "Modeling solar photovoltaic cell and simulated performance analysis of a 250W PV module," in *2013 IEEE Electrical Power & Energy Conference*, Aug. 2013, pp. 1–6, doi: 10.1109/EPEC.2013.6802959.

[9] S. Bana and R. P. Saini, "A mathematical modeling framework to evaluate the performance of single diode and double diode based SPV systems," *Energy Reports*, vol. 2, pp. 171–187, 2016, doi: 10.1016/j.egyr.2016.06.004.

[10] Z. Meng, Y. Zhao, S. Tang, and Y. Sun, "An efficient datasheet-based parameters extraction method for two-diode photovoltaic cell and cells model," *Renewable Energy*, vol. 153, pp. 1174–1182, 2020, doi: 10.1016/j.renene.2020.02.084.

[11] X. H. Nguyen and M. P. Nguyen, "Mathematical modeling of photovoltaic cell/module/arrays with tags in MATLAB/Simulink," *Environmental Systems Research*, vol. 4, no. 1, p. 24, Dec. 2015, doi: 10.1186/s40068-015-0047-9.

[12] M. Nfaoui *et al.*, "Comprehensive modeling and simulation of photovoltaic system performance by using MATLAB/Simulink: integrating dynamic meteorological parameters for enhanced accuracy," *Journal of Umm Al-Qura University for Applied Sciences*, vol. 11, no. 3, pp. 633–656, Sep. 2025, doi: 10.1007/s43994-024-00175-5.

[13] R. Blange, "Study of PV module for characterizations using MATLAB Simulink and tracking of maximum of PV power," *Journal of Electrical Systems*, vol. 20, no. 11s, pp. 2104–2113, 2024, doi: 10.52783/jes.7709.

[14] H. B. Assia and M. B. Fatima, "Detailed modeling of two diode photovoltaic module using MATLAB Simulink," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 10, no. 3, p. 1603, Sep. 2019, doi: 10.11591/ijpeds.v10.i3.pp1603-1612.

[15] N. Anani, M. Shahid, O. Al-kharji, and J. Ponciano, "A CAD package for modeling and simulation of PV arrays under partial shading conditions," *Energy Procedia*, vol. 42, pp. 397–405, 2013, doi: 10.1016/j.egypro.2013.11.040.

[16] W. De Soto, S. A. Klein, and W. A. Beckman, "Improvement and validation of a model for photovoltaic array performance," *Solar Energy*, vol. 80, no. 1, pp. 78–88, Jan. 2006, doi: 10.1016/j.solener.2005.06.010.

[17] I. H. Altas and A. M. Sharaf, "A photovoltaic array simulation model for MATLAB-Simulink GUI environment," in *2007 International Conference on Clean Electrical Power*, May 2007, pp. 341–345. doi: 10.1109/ICCEP.2007.384234.

[18] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Transactions on Power Electronics*, vol. 24, no. 5, pp. 1198–1208, May 2009, doi: 10.1109/TPEL.2009.2013862.

[19] N. Ismail *et al.*, "Modeling and analysis of simplified PV module with various temperature and irradiance inputs using MATLAB Simulink algorithm," *ELEKTRIKA- Journal of Electrical Engineering*, vol. 21, no. 3, pp. 28–39, Dec. 2022, doi: 10.11113/elektrika.v21n3.365.

[20] Sé. Daher, Jü. Schmid, and F. L. M. Antunes, “Multilevel inverter topologies for stand-alone PV systems,” *IEEE Transactions on Industrial Electronics*, vol. 55, no. 7, pp. 2703–2712, Jul. 2008, doi: 10.1109/TIE.2008.922601.
[21] J. A. Gow and C. D. Manning, “Development of a photovoltaic array model for use in power-electronics simulation studies,” *IEE Proceedings - Electric Power Applications*, vol. 146, no. 2, pp. 193–200, Mar. 1999, doi: 10.1049/ip-epa:19990116.
[22] H. M. Namaa, “Design and simulation of photovoltaic modules performance improvement under the effect of partial shading using MATLAB/Simulink,” vol. 12, no. 21s, pp. 4251–4259, 2024.
[23] A. Al Humairi, Z. A. Al Hemyari, H. El Asri, and P. Jung, “Modelling the performance of photovoltaic systems and studying the soiling effects: insights based on field data of environmental factors of solar panel systems,” *Applied System Innovation*, vol. 8, no. 1, p. 25, Feb. 2025, doi: 10.3390/asi8010025.
[24] A. F. Amiri, A. Chouder, H. Oudira, S. Silvestre, and S. Kichou, “Improving photovoltaic power prediction: insights through computational modeling and feature selection,” *Energies*, vol. 17, no. 13, p. 3078, Jun. 2024, doi: 10.3390/en17133078.
[25] M. F. Saltuk, “Comparative evaluation of solar photovoltaic cell technologies across Türkiye’s climatic regions: a PVsyst simulation-based analysis,” *Energy Storage and Conversion*, vol. 3, no. 4, Dec. 2025, doi: 10.59400/esc3850.
[26] S. Said, A. Massoud, M. Benammar, and S. Ahmed, “A MATLAB/Simulink-based photovoltaic array model employing simpowersystems toolbox,” *Journal of Energy and Power Engineering*, vol. 6, pp. 1965–1975, 2012.

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