International Journal of Computational and Experimental Science and ENgineering (IJCESEN)

Vol. 12-No.3 (2026) pp. 150-158
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Meteorological Impact on Solar Energy Yield of a Utility-Scale PV Plant in the Algerian Sahara.

Mohammed Bouzidi[1,*], Omar Ouledali[2], Abdelfatah Nasri[3]

[1]Department of Sciences and Technology, Faculty of Sciences and Technology, University of Tamanrasset, Sersouf P.O. Box 10034, Tamanghasset 11001, Algeria
* **Corresponding Author Email:** m.bouzidi@univ-tam.dz - **ORCID:** 0009-0007-0357-8202

[2]Department of Energy Technology, DDI Laboratory, Ahmed Draia University, 01000 Adrar, Algeria
Email: ouleomar@univ-adrar.edu.dz - **ORCID:** 0000-0003-3734-5398

[3]laboratory Smart Grid and Renewable Energy SGRE University Tahri Mohamed Bechar, BP 417 road kenadza Béchar 08000 Algeria
Email: nasri.abdelfatah@univ-bechar.dz - **ORCID:** 0000-0002-8279-6086

Article Info:

DOI: 10.22399/ijcesen.5361
Received : 01 February 2026
Revised : 10 June 2026
Accepted : 12 June 2026

Keywords

Photovoltaic
Solar radiation
Temperature
Renewable Energy
Tamanrasset

Abstract:

This study evaluates the performance of a photovoltaic (PV) solar power plant located in Tamanrasset, southern Algeria, under the harsh climatic condition's characteristic of the Sahara Desert. Tamanrasset occupies a strategic geographical position within the Sahara, benefiting from daily solar irradiation levels reaching up to 7.5 kWh/m², making it one of the world's richest regions in solar energy potential. The studied PV plant comprises more than 53,000 polycrystalline solar panels with a total installed capacity of 13 MW, distributed across 13 sub-fields of 1 MW each. The study relies on real-time measurement data collected from the plant over the period from December 2022 to December 2023, encompassing key parameters such as output power, ambient temperature, solar irradiance, wind speed, and relative humidity. Results revealed that peak energy production was recorded in March, reaching 1,929,340 kW, while the lowest production occurred in February. Monthly average solar irradiance ranged between 141.67 and 242.59 kW/m², peaking in May and June. The highest ambient temperatures were recorded in July and August, while relative humidity remained very low, averaging 23.98%, a condition that significantly enhances panel efficiency. Wind speeds were moderate, averaging between 5 and 12 m/s, contributing to a natural cooling effect on the panels. The researchers employed PV*SOL and PVGIS-SARAH2 simulation tools to validate experimental findings and compare them against modelled values, enabling a comprehensive assessment of the system's performance. The study concludes that Tamanrasset's desert climate constitutes a highly favorable environment for solar power generation, with elevated irradiance, low humidity, and moderate winds collectively improving PV efficiency and overall productivity.

1. Introduction

Owing to the consistent rise in energy demand and the escalating instances of fossil fuel depletion, there has been a surge in interest in harnessing renewable energy sources, particularly solar power [1], [2]. Renewable energy sources are a form of energy production that is both environmentally friendly and sustainable. Photovoltaic cell technologies are currently the predominant method for generating clean, sustainable, and cost-effective electricity among solar energy systems.[3], [4]

Recently, the utilization of photovoltaic systems for energy production has facilitated the reorganization of detrimental emissions of environmental gases. Furthermore, these systems exhibit a comparatively extended operational lifespan [5], [5]. The efficiency of photovoltaic systems plays a crucial role in their energy generation, although it is still relatively low when compared to conventional power generation systems [6], [7].
Owing to technological advancements, nations are swiftly embracing renewable energies, particularly

solar power, which offers costless and boundless electricity derived from sunlight [8], [9].

Due to its geographical location, Algeria possesses one of the largest solar fields globally. The daily solar irradiation in the south can reach a maximum of 6.6kWh/m^2, while in the north it can reach up to 5.1kWh/m^2. The Sahara Desert in Algeria, which spans 87% of the country's territory, is a vast reservoir of renewable solar energy that has the potential to provide global power [10]. In certain regions, the Sahara experiences high temperatures and receives solar radiation of up to 7.5 kWh/m^2 per day. The southeastern and central Sahara possess enormous solar energy potential, estimated at 11,641 TWh/year and 23,398 TWh/year, respectively, making them capable of satisfying regional and even global energy demands [11], [12]. Several studies have investigated photovoltaic performance under different climatic conditions. B. Bylykbashi et al. [13] compared models for predicting the daily energy output of photovoltaic systems in Kosovo. In Algeria, Benrahmoune et al. [14] and Naji et al. [15] evaluated the performance of solar power systems using artificial neural networks and adaptive neuro-fuzzy inference systems in MATLAB. The influence of atmospheric conditions and panel orientation on power generation was also analyzed [16]. Furthermore, Y. Kherbi et al. [17] assessed the feasibility of solar energy exploitation in M'Sila, while K. Gairaa et al. [18] investigated the solar potential of Ghardaïa based on one year of solar radiation measurements. N. Bailek et al. [19] proposed models for estimating global solar radiation in southwestern Algeria by comparing different statistical approaches [20], [21].

The primary objective of this study is to evaluate the influence of desert climatic conditions on the performance of a photovoltaic system in Tamanrasset, southern Algeria. Particular attention is given to the effects of key meteorological parameters, including solar irradiation, ambient temperature, humidity, and wind speed. By analyzing the long-term behavior of the photovoltaic system under harsh desert conditions, this study provides valuable insights into the relationship between climate variability and energy production. The findings contribute to a better understanding of photovoltaic system performance in desert environments and support the development of reliable and efficient solar energy systems.

2. Site Description and Meteorological Data

The Algerian desert covers nearly 90% of the country's territory and constitutes about 20% of the African Sahara Desert [22]. Owing to its arid climate, high solar irradiance (5.1–6.6 kWh/m²/day), and low cloud cover, this region offers exceptional potential for solar energy exploitation, making concentrated solar power economically viable [17], [23].

The Algerian desert, characterized by its vast area and high solar potential, represents a strategic source of renewable energy. Tamanrasset, located in southern Algeria, is one of the country's largest desert provinces, covering approximately 557,906 km². Situated about 2000 km from the capital, it is bordered by Ghardaïa and Ouargla to the north, Illizi to the east, Adrar to the west, and Niger and Mali to the south [24], [25].

Tamanghasset experiences a primarily temperate climate as a result of its mountainous topography. The provincial capital is situated at an elevation of 1400 meters above sea level. The Hoggar Mountains range encompasses Algeria's tallest summit, Tahat Mountain, reaching an elevation of 3303 meters [26], [27].

Algeria possesses a significant solar potential, thanks to its geographical position. It is estimated to have an annual solar energy capacity of 05 billion GWH. The Sahara and High Plateau regions experience an impressive sunshine duration of up to 3000 hours per year, as confirmed by experts. Tamanghasset experiences an annual sunshine duration of 3000 hours.

The photovoltaic solar power plant in Tamanghasset, with a capacity of 13 MW, is an integral component of the country's programme aimed at promoting renewable energy and enhancing energy efficiency. Figure 1.

Figure 1. *Photovoltaic Power Plant in Tamanrasset, Southern Algeria*

The Tamanghasset solar power plant is situated in the southern region of Algeria, specifically in the town of Tamanghasset, at the precise geographical coordinates of 22°50' N and 5°27' E. The solar power plant covers an expanse of 26 hectares and has a maximum power output of 13,000 kW. It feeds the electricity it generates into the national power grid at a voltage of 30 kV. The Algerian company Kahraba WA Taket Moutadjadi (SKTM) is the project owner, while the contractor consortium is composed of Yingli and CNTIC. The construction started on December 6, 2014, and is scheduled to last for a period of 8 months [19], [23]. The Tamanrasset solar plant includes 53,504 PV panels arranged in 13 sub-fields of 1 MW each. Table 1 summarizes the specifications of the photovoltaic modules used in the plant. [28], [29].

Table 1. *Photovoltaic Module Specifications.*

Module type	YL245P-29b
Application class	A
Measured power	245.0 W (0/+5 W)
Measured voltage	29.6V
Measured current	8.28A
Max series fuse	15.A
Open Circuit Voltage	37.5 V
Voltage System max	1000.V

The solar power plant in Tamanghasset comprises 13 sub-fields, with each sub-field having a generation capacity of 1 MW. The facility employs polycrystalline solar panels with a 15% efficiency rating, resulting in a power output of 245W per module. Each sub-field consists of 4,092 solar modules that are connected to 186 strings, with each string containing 22 modules. The plant consists of 13 sub-fields, each comprising more than 4,000 panels. In total, there are over 53,000 polycrystalline solar modules, which collectively have a generation capacity of 13 MW. The Tamanghasset plant utilizes a substantial quantity of high-efficiency solar panels organized into various sub-fields to optimize power generation from the ample solar resources present at its desert site. The system's energy performance will be analysed based on measurements taken over a one-year period. The system will undergo analysis through both analytical methods and software tools to present its energy analysis. Figure 2 depicts a schematic of the components and interconnections within the photovoltaic (PV) system

The schematic of the Tamanghasset solar plant illustrates the arrangement of the string connections that supply power to an inverter responsible for converting direct current (DC) into alternating current (AC) energy, which is then used to meet the energy demands of the factory. Energy measurements are obtained using a transformer before being connected to the grid. The system analysis will employ the PVGIS-SARAH2 software, which is based on actual one-year monitoring data. The study involved gathering data and information on energy, radiation, wind speed, humidity, and temperature from a solar power plant situated in the Tamanghasset region of the Algerian Sahara Desert. This region is known for its moderate climate. The measurement data was collected on a single working day each month (January, March, May, July, September, and December) from 6 a.m. to 8 p.m. During the nighttime,

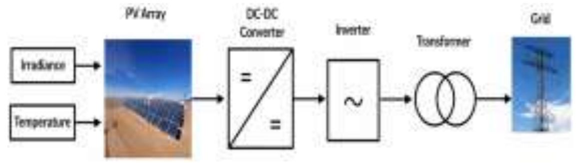

Figure 2. *Tamanghasset Solar Plant Schematic Diagram*

The solar power plant in Tamanghasset takes advantage of the abundant solar radiation levels. Figure 3 displays the daily solar irradiation over a period of six months. The values fluctuated within the range of approximately 250 W/m^2 and 350 W/m^2. Figure 4 illustrates that the mean solar irradiation over a period of 6 months was approximately 638.7 W/m^2.

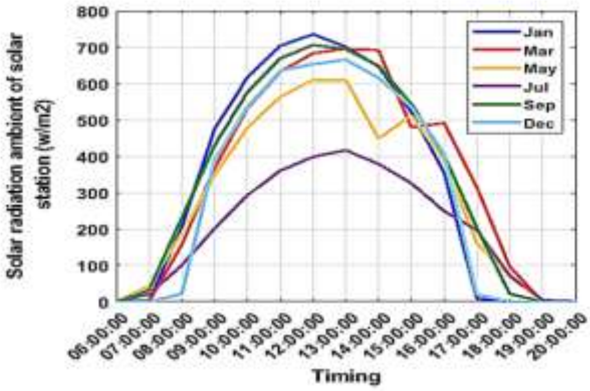

Figure 3. *Ambient Radiation at the studied solar station*

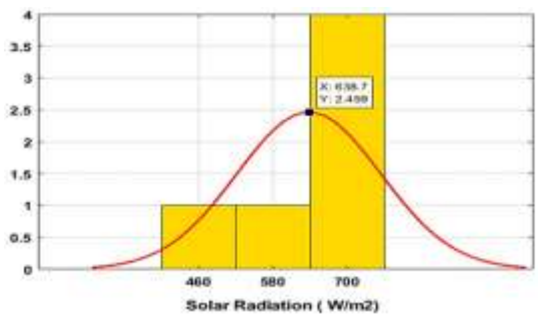

Figure 4. *Average Radiation for 6 months at the studied solar plant*

This is attributed to Tamanghasset geographical position within the Sahara Desert and its consistently clear and sunny weather conditions. Figure 5 displays the plant's daily power production over a period of 6 months. The range varied from around 5000 kW to 10,000 kW.

According to Figure 6, the average power output over a period of 6 months was approximately 7616 kW.

In addition, Tamanghasset experiences high temperatures, with an average of around 28.28°C. (Figures 7 and 8) These elevated temperatures contribute to the increased efficiency of solar panels. Nevertheless, the region encounters relatively moderate wind velocities, with an average range of 5 m/s to 12 m/s (as depicted in Figures 9 and 10). Increased wind velocities can enhance the cooling effect on the solar panels, thereby enhancing their efficiency.

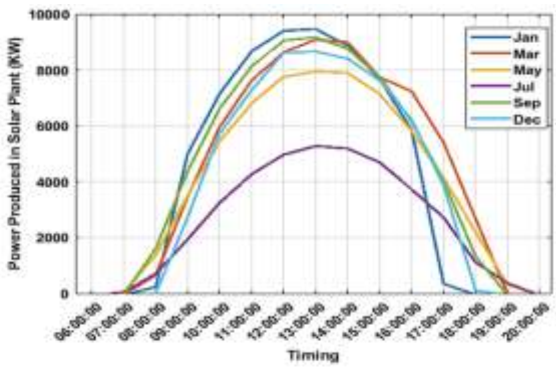

Figure 5. *Power Generation at the Tamanrasset Solar Plant*

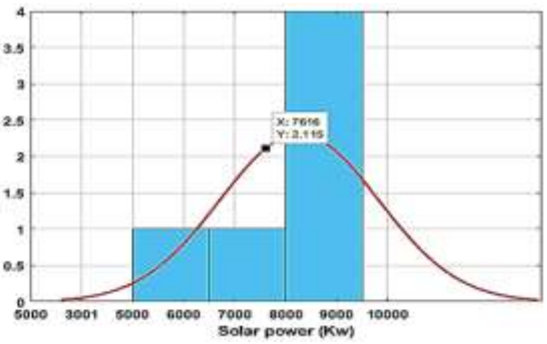

Figure 6. *Average Six-Month Power Output of the Solar Plant*

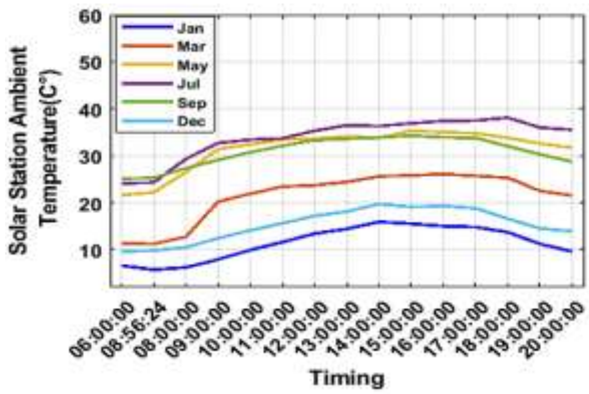

Figure 7. *Ambient Temperature at the studied solar station*

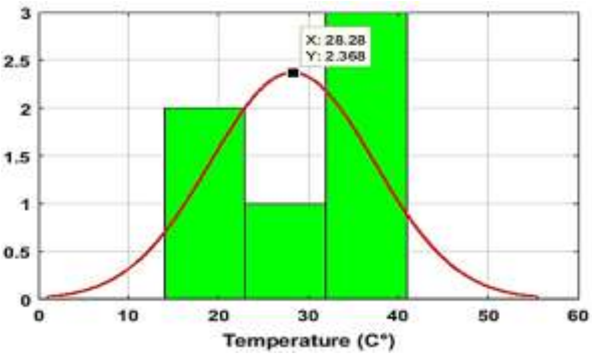

Figure 8. *Average Temperature Over Six Months*

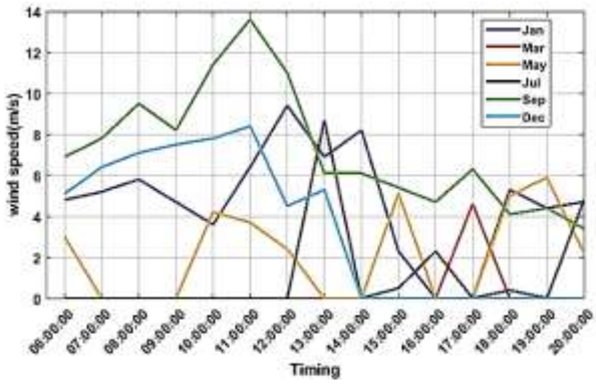

Figure 9. *Wind Speed at Tamanghasset Solar Power Plant*

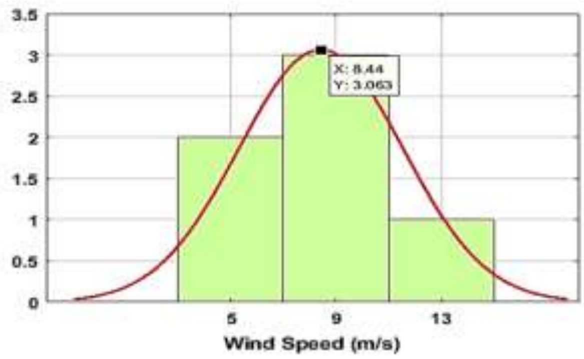

Figure 10. *Average Humidity for 6 months at the studied solar plant*

The relatively low levels of humidity, with an average ranging from 10% to 30% (as shown in Figure 11), have a positive impact on the efficiency of solar panels, as they perform better in dry conditions. Additionally, the average humidity over a period of 6 months was approximately 23.98%. Figure 12. Overall, the charts indicate that Tamanghasset possesses a favourable climate for the generation of solar power. The region benefits from ample solar resources and weather conditions characterised by elevated temperatures and reduced humidity, which effectively enhance the productivity of solar plants. The charts demonstrate that the climatic conditions in Tamanghasset are highly conducive to the generation of solar power.

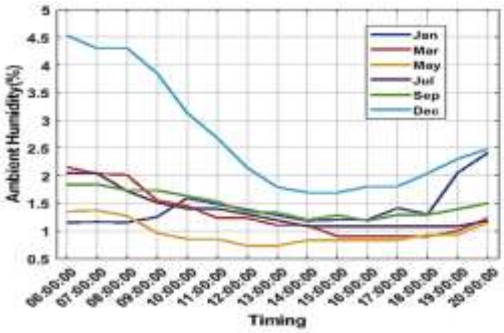

Figure 11. *Variation of Relative Humidity at the Tamanrasset Solar Plant Site*

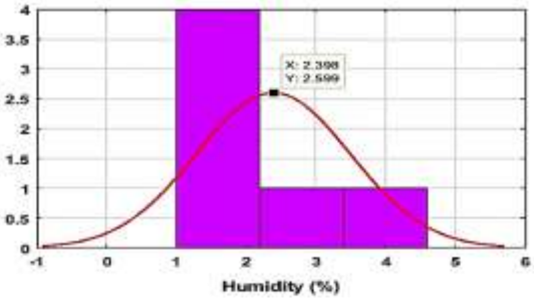

Figure 12. *Average Relative Humidity Over Six Months*

The charts demonstrate that the climatic conditions in Tamanghasset are highly conducive to the generation of solar power. Overall, the charts demonstrate that Tamanghasset possesses a favourable climate for the generation of solar power. This is due to its abundant solar irradiation, elevated temperatures, and minimal humidity levels, all of which contribute to the enhanced efficiency and productivity of the solar plant. The moderate wind speeds facilitate the cooling of the solar panels.

Once the location and climate conditions of the solar power plant being studied were established, the climate conditions that impact the plant's performance at that specific location were measured and presented. Figure 13 displays the values for global horizontal irradiance, direct normal irradiance, and the optimal angle for global irradiation. Figure 14 depicts the monthly mean ratio of diffuse to global radiation, while Figure 15 displays the monthly average temperature.

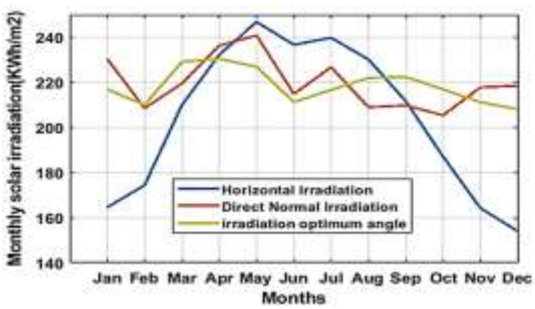

Figure 13. *Global Horizontal, Direct Normal, and Optimum-Tilt Irradiatio*

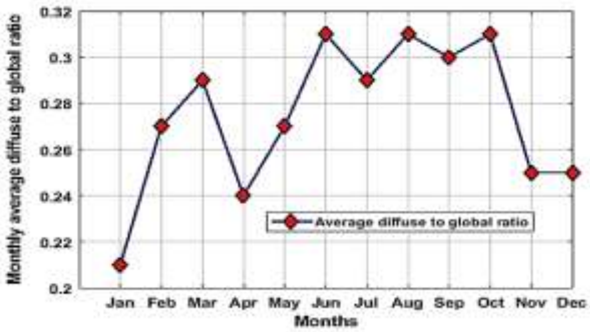

Figure 14. *Monthly average diffuse to global ratio*

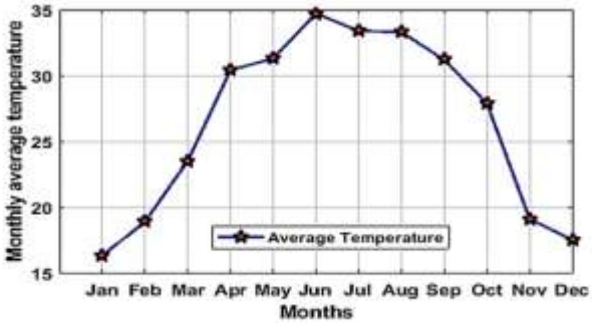

Figure 15 *Monthly average temperature*

Based on Figures 13, 14, and 15, the following observations can be made: April has the highest irradiation potential, measuring 346.5kWh/m^2, while December has the lowest irradiation, measuring 88.8kWh/m^2. During the summer, there is a greater potential for irradiation compared to the winter months. June exhibits the highest potential for horizontal irradiation, reaching 290.8 W/m^2. Based on the preceding diagram, it is evident that during the summer season, there is a greater likelihood of diffuse irradiation. The June diffuse irradiation reached its peak for the year, surpassing other months with a value of 185.4 kWh/m^2/day. Based on the preceding diagram, it is evident that during the summer season, the potential for diffuse irradiation is greater.

3. Methodology of PV Plant Modelling

In order to evaluate the efficiency of a solar cell, it is necessary to conduct tests under specific conditions. These conditions include a module temperature of 25 °C and an incident solar irradiation on the module of 1000 W/m2. At its zenith, the sun is at its highest point in the sky, resulting in the shortest distance for sunlight to travel through space to reach the solar module, approximately 150 million km [30].

In order to provide the most precise depiction of a PV system's performance, a comprehensive analysis is conducted, taking into account all factors that influence its operation, such as solar radiation, ambient temperature, and wind speed.

These parameters are essential for the optimal operation of the PV system. Under actual operating circumstances, the manufacturer's specified power output might not be possible to achieve [28-29]. Due to differences in irradiance, the power and energy produced by a photovoltaic solar station by a solar cell will differ from the maximum power [29-30]. The theoretical output of a solar cell is directly proportional to the intensity of the incident light it receives [13].

$$P_{th} = P_{peak} * \frac{G}{1000} \tag{1}$$

where: P_{th} is the theoretical power provided by the module [W], Ppeak is the peak power of the solar modules [W], and G is the solar irradiance [W/m^2].
The relationship between temperature and the electrical performance of a photovoltaic (PV) cell or module can be quantified using the following fundamental equation [30]:

$$\mathrm{P_M = V_M * I_M = I_{SC} * V_{OC} * (FF)} \tag{2}$$

where: (FF) is the fill factor, Vcc is the open circuit voltage, Isc is the short circuit current, $\mathrm{I_M}$ (A) is the maximum current of the solar station, $\mathrm{V_M}$ (v) is the maximum voltage of the solar station, and $\mathrm{P_M}$ (W) is the maximum power point in the modules.
The efficacy of the conversion process, which is the main criterion for assessing the efficiency of converting solar energy into electrical energy, can be quantified using the subsequent equation:

$$\eta = \frac{\mathrm{I_{SC}*V_{OC}*(FF)}}{\mathrm{P_{input}}} \tag{3}$$

Where: $\mathrm{P_{input}}$ is the input power [KW] and η: is the efficiency (%)

4. Results and discussion

The results presented in this study are based on real-time measurements from the Tamanghasset solar power plant, combined with simulation outputs generated using PV*SOL software. The dataset includes key parameters such as output power, ambient temperature, solar irradiance, wind speed, and relative humidity recorded from December 2022 to December 2023. This dataset enables a reliable assessment of the plant’s operating conditions under seasonal variations. The study also integrates numerical modelling results to complement the experimental data, allowing a comparison between simulated and real performance. Overall, this work analyzes the behavior of the PV system under real environmental conditions and evaluates its performance through measurement and modelling approaches. Figure 16 displays the mean daily solar radiation for each month of the year. The months of May and June exhibited the highest average solar radiation, with values of 240.49 and 242.59 kW/m^2, respectively. In December and January, the average radiation reached its lowest point, with values of 141.67 and 157.47 kW/m^2, respectively.
And displays the mean daily temperature for each month of the year The highest average temperature was observed in July and August, with recorded values of 34.7 and 34.2 °C, respectively. The months of January and February had the lowest average temperature, with values of 15.5°C for both months.
Figures 17, 18, 19 and 20 display the yearly values for various data points of the solar power plant, categorised by month. Based on these data, we observe:
In March, power production reached its peak at 1,929,340 kW. In February, the production reached its nadir, registering a value of 1,548,550 kW. Figure 17
In terms of solar radiation, May had the highest average value of 240.49kW/m^2; December had the lowest average radiation, measured at 141.67kW/m^2, as shown in Figure 18
Figure 19 displays the fluctuations in mean temperature and wind velocity throughout the months of the year. In July, the average temperature reached its peak at 34.4 °C, whereas in both January and February, it dropped to an average of 15.5 °C. In terms of wind speed, April recorded the highest mean velocity at 10.77 m/s, while December.
Exhibited the lowest average at 6.60 m/s. In general, it can be noted that the peak values were documented in the summer season, whereas the lowest values were observed in the winter season.
In July, the average humidity reached its peak at 4.49%. In January, the average reached its lowest point, measuring 2.88%. Figure 20.
Examining this empirically collected data yields a more comprehensive comprehension of the solar facility's efficacy and conduct in genuine operational circumstances. Additionally, it aids in validating the precision of the PV*SOL simulation outcomes and aligning them with the actual measurements. I appreciate your continued contribution of this invaluable data. An examination of this authentic data yields a more comprehensive comprehension of the performance and conduct of solar plants in real-world operational circumstances. Additionally, it aids in validating the precision of the simulation's outcomes (PV * SOL) and their adherence to actual values.

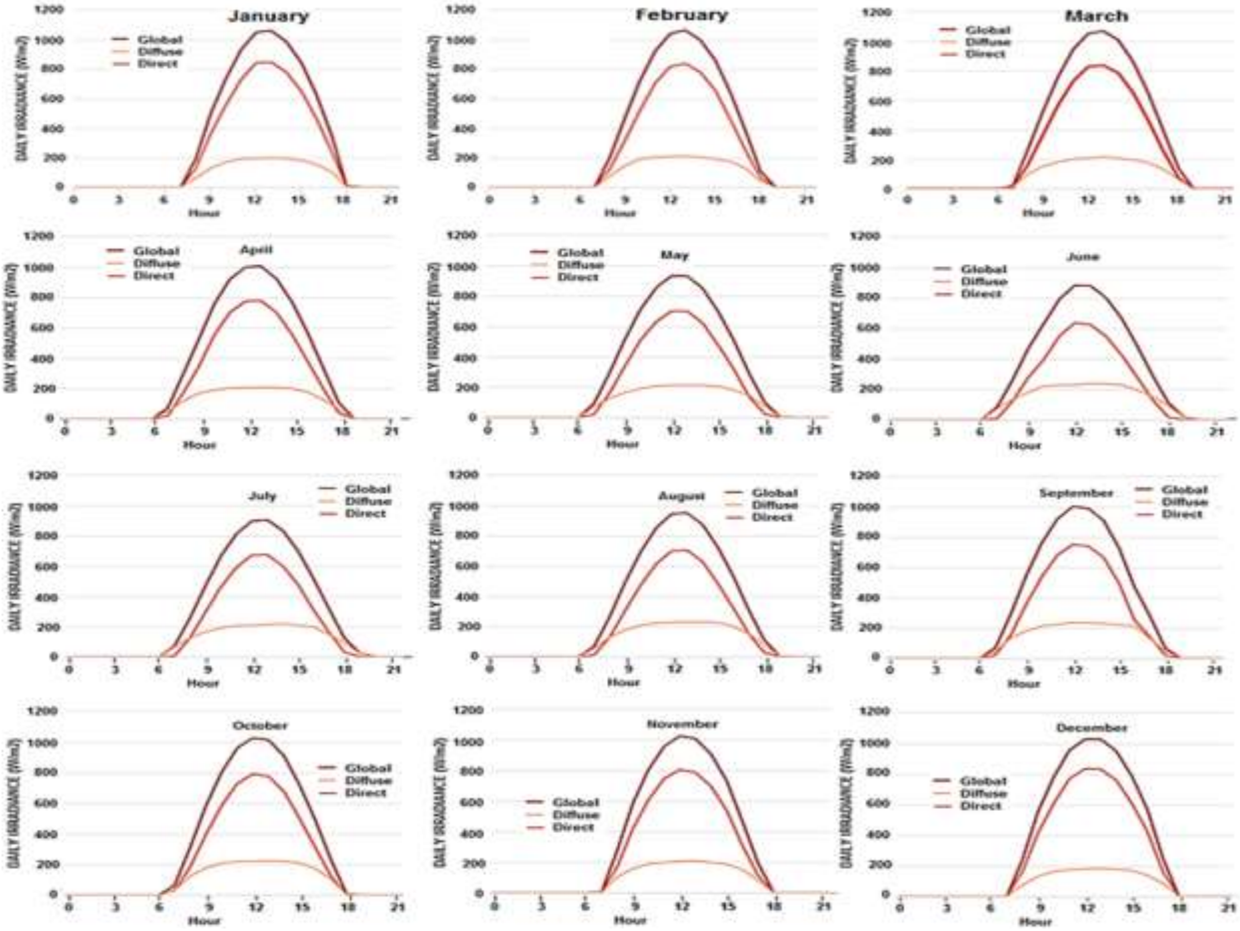

Figure 16. *Average daily radiation per month of the year*

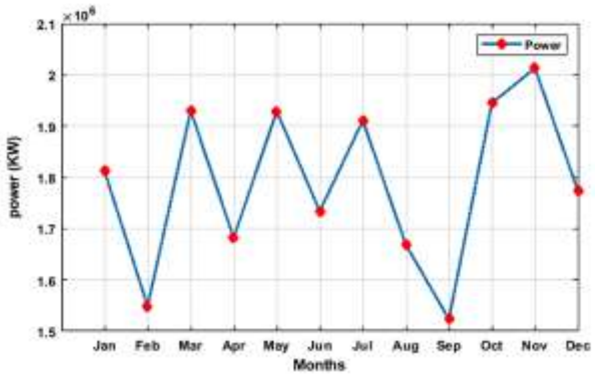

Figure 17 *Average power generation per month for the solar power plant*

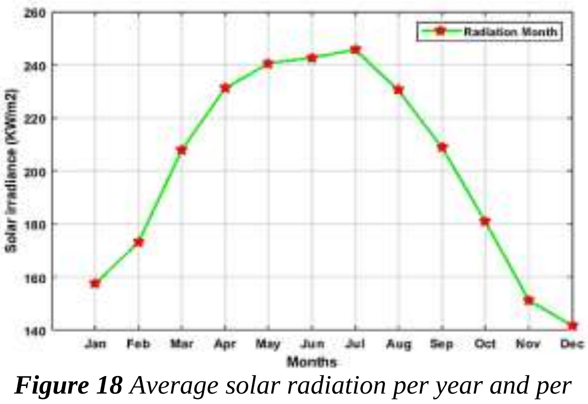

Figure 18 *Average solar radiation per year and per month*

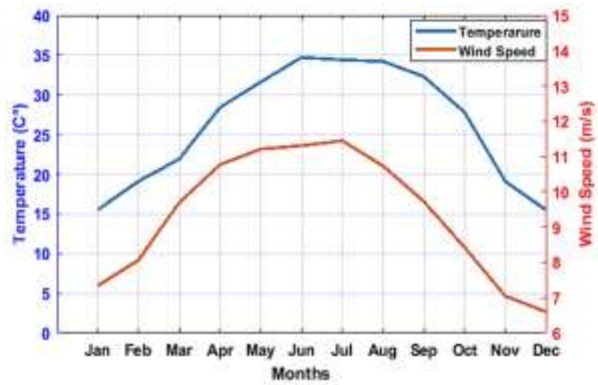

Figure 19 *Average temperature and wind speed during each month*

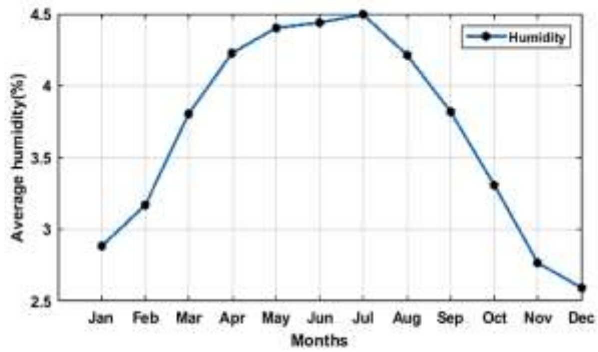

Figure 20 *Average humidity during each month of the year*

5. Conclusion

This study demonstrates that Tamanrasset, southern Algeria, possesses exceptional conditions for photovoltaic power generation, characterized by high solar irradiance reaching 242 kW/m², low relative humidity averaging below 24%, and moderate wind speeds that contribute to panel cooling and enhanced efficiency. The comparative analysis between real measured data and simulation outputs from PV*SOL and PVGIS-SARAH2 revealed strong agreement, confirming the accuracy and reliability of the models in representing the system's actual performance. Although elevated summer temperatures may theoretically reduce panel efficiency, the abundant solar irradiance effectively compensates for this effect, maintaining high production levels throughout the year. These findings highlight Algeria's immense untapped solar energy potential embedded within its vast Saharan territory, which, if strategically harnessed, can drive national energy self-sufficiency, significantly reduce dependence on fossil fuels, and contribute meaningfully to regional and global carbon emission reduction targets, positioning Algeria as a key player in the renewable energy transition.

Author Statements:

- **Ethical approval:** This study excludes any human or animal involvement.
- **Conflict of interest:** The authors declare no financial or personal conflicts of interest affecting this work.

- **Acknowledgement:** The authors have no individuals or organizations to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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