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# Comprehensive performance assessment of a 12-MW grid-connected photovoltaic power plant

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**ABSTRACT**

The increasing demand for electricity, driven by sustained population growth, has placed considerable pressure on Algeria's power generation infrastructure to expand its output. In parallel, the sharp decline in the cost of solar photovoltaic (PV) electricity and the rising tariffs on conventional energy sources have intensified interest in PV-based electricity generation. Accordingly, precise evaluation of the annual and monthly performance of solar PV plants has become essential for the optimal design and deployment of new facilities. This study presents a comprehensive performance assessment of a 12 MW grid-connected photovoltaic power plant located in Sidi Bel Abbès, Algeria. Real-time operational data were collected over a one-year period, from January 1st to December 31st, 2023. Key performance indicators analyzed include energy output, final yield (Yf), and performance ratio (PR), among others. The plant delivered a total of 20,780.67 MWh to the grid in 2023. The final yield ranged from 3.25 to 5.88 kWh/kWp, while the performance ratio varied between 79% and 89.71%. The annual capacity factor was calculated to be 19.44%. These empirical results are compared against simulation outputs obtained using PVsyst and the Solar GIS-PV Planner tools.



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**NOMENCLATURE**

| | | | |
|---|---|---|---|
| $P_0$ | : Peak power (kWp) | $E_{DC}$ | : Direct current energy |
| $H_T$ | : Daily irradiation (kWh/m$^2$) | $E_{AC}$ | : Alternating current energy |
| GlobHor | : Horizontal global irradiation (kWh/m$^2$) | T Amb | : Ambient temperature (°C) |
| GlobEff | : Effective global irradiance (kWh/m²) | GlobInc | : Global irradiation incident on the collector plane (kWh/m²) |

## 1. INTRODUCTION

Energy is a key component of socioeconomic development, and electricity in particular has become essential to industrial and social processes. The need for energy has increased dramatically over the last few decades; it is expected to reach 73,000 TWh by 2050 and rise at a 3.1% yearly pace [1], [2]. Historically, fossil fuels such as coal, oil, and natural gas have been the main sources of power. However, these fossil fuel reserves are limited [3], and generating power from them emits a significant amount of greenhouse gases (GHGs) [4], endangering ecosystems and the surrounding environment. The transition to cleaner and renewable energy sources is required for the sustainable production and consumption of energy.

To meet future energy demands and reduce environmental impacts, alternative and renewable energy sources such as solar, wind, and biomass are essential [5]. As a result, a number of nations are working hard to increase the share of renewable energy in their mix of power generation. In regard to renewable energy, solar photovoltaics (PVs) are leading the way due to their increased solar cell efficiency, lower production costs [6], [7], and easier installation compared to those of other renewables. Once placed, the PV panels begin producing electricity instantly. Furthermore, the globe receives approximately $3.8 \times 10^{14}$ kW of solar energy each second, indicating the free and plentiful availability of solar energy [8]. Because solar PV has a short payback period, it has proven to be a lucrative industry that has drastically lowered LCOE [9]. The International Renewable Energy Agency (IRENA) estimates that at the end of 2018, the installed capacity of solar PV worldwide reached 480.3 GW, and by 2025, it is expected to climb to 969 GW [10]. With 746.46 GW of installed capacity, Asia now has the highest share of PV installations.

Like the majority of developing nations, the Algerian government has developed the "National Program for Renewable Energies and Energy Efficiency" as a feasible first step in the direction of sustainability. By 2030, 40% of Algeria's electricity demand are expected to be supplied by renewable energy, according to the country's national program [11]. Due to its considerable sun exposure, which covers 90% of the nation across an area of 2,382 million km$^2$, China has committed to obtaining the bulk of its renewable energy supply from solar PVs [12]. According to [13], the expected amount of sunshine is 3000 hours per year, and the daily energy can reach up to 5 kWh/m$^2$.

Examining the effectiveness of PV systems in diverse settings while taking into account many influences has been a subject of research. For example, [14] used real performance metrics to track a PV system in Tangier over the course of a year. The PV system's efficient operation was shown by a capacity factor of 14.83% and a yearly performance ratio of 79%. In a similar vein, [15] examined the operation of a 50 MW PV project in southern India using SCADA data from April 2018 to March 2019. The capacity utilization factor and yearly average performance ratio yielded values of 24.65% and 79.94%, respectively. To evaluate the quality of substantial amounts of data for more precise research on PV system performance, the authors of [16] carried out the first performance analysis of time series databases of PV systems deployed in Europe. Comparative research between the simulated and measured approaches is therefore needed. [17] in Malaysia concentrated on utilizing a straightforward model and measurements to determine the desired performance. The dependability of the target-oriented model was proven by earlier investigations. After 12 years of operation, a grid-connected photovoltaic facility in central Spain was evaluated by [18] utilizing on-site data for 2020 and two additional modeling approaches, the physical model and the statistical model based on the random forest method. When metric parameters were included, the random forest algorithm technique produced good results when simple ambient temperature and sun radiation were used as inputs. Using both measured data and the PVGIS database, [19] assessed the performance of the Zagtouli grid-connected solar power station (ZGCSPS).

However, research evaluating large-scale PV systems in Algeria by comparing measured and simulated performances is limited. This study aimed to compare the measured performance values of the Sidi Bel-Abbes PV plant for the year 2023 with values simulated by both PVsyst and the solar GIS-PV planner. This comparison allows us to assess the reliability of the sizing software in the region for predicting production and performance parameters, facilitating the installation of other PV plants in Algeria. The comparison focuses on various performance indicators, such as the performance ratio, capacity factor, energy production, temperature, and irradiation.

## 2. DESCRIPTION OF THE SOLAR PV-GRID SYSTEM

### 2.1. Geographical location of the site

The Sidi Bel-Abbes photovoltaic power plant, located in Algeria, has a capacity of 12 MW (Figure 1). It is situated at a longitude of -0.6″ N and a latitude of 34.69″ E. Its altitude is 1,329 m [20].

### 2.2. Plant layout

The power plant covers 33.59 hectares and has a total power capacity of 12 megawatts. The facility divides this section into six skids. Each individual skid has a production capacity of approximately 2 MWp, as shown in Figure 2. Therefore, the total combined production capacity of all six skids is 12 MW. Each skid comprises around 7968 solar panels. We arrange the solar panels into 166 parallel-connected strings, each string consisting of 12 panels connected in series. A pair of sunny central 800-900 CP XT inverters links the strings.

### 2.3. Specification of the solar panel

The Dhaya solar power plant employs polycrystalline silicon photovoltaic modules, specifically the HSL60-PB-1-250 model. These are fixed-tilt panels, meaning they do not track the sun's movement. The panels exhibit an average conversion efficiency of 15%. The open-circuit voltage (Voc) is 37.7 V, while the short-circuit current (Isc) is 8.79 A. The panels are designed to operate reliably within a temperature range of -40 °C to +80 °C. To ensure optimal performance, a bi-monthly cleaning schedule is maintained.

Figure 1. Sidi Bel-Abbes photovoltaic power plant

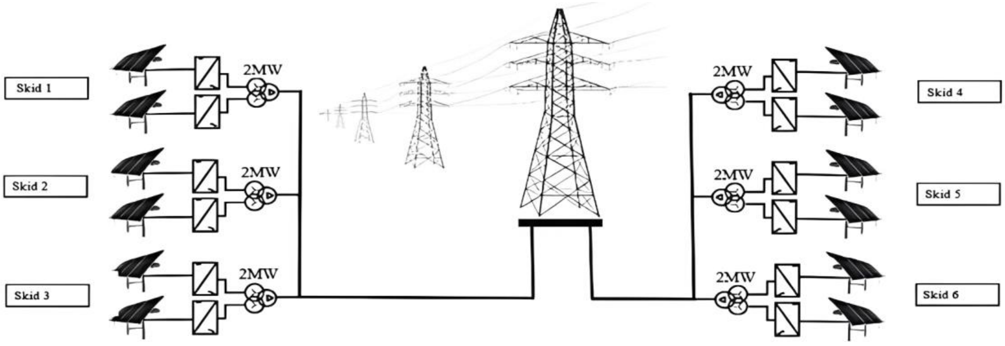


Figure 2. Schematic diagram of a skid

### 2.4. Power conditioning units

Inverters are used to convert the direct current (DC) produced by the photovoltaic modules into alternating current (AC), which is essential for grid integration and compatibility with most electrical loads [21]. This DC-to-AC conversion is particularly critical in systems where the power source, such as PV arrays, batteries, or rectifiers, delivers electricity in DC form [22]. The inverter installed at the facility has a rated output power of 880 kW. It operates with a DC input current of 1,270.9 A and an input voltage of 1,000 V. The AC output is delivered at a voltage of 360 V and a current of 1,411 A.

### 2.5. Data monitoring

Real-time information on wind, temperature, and sun radiation is available from a weather station close to the facility (Figure 3). In the control room, a specialized server with SCADA software records the voltage, current, and inverter power output minute by minute. The weather station's ambient temperature and sun irradiance are also recorded. This technology facilitates data flow across a bus and guarantees efficient monitoring and control. Through the assessment of electrical and environmental parameters, the SCADA software optimizes plant performance by simplifying retrieval and analysis [23].

Figure 3. Weather station and monitoring room

## 3. METHODOLOGY FOR ASSESSING THE PERFORMANCE OF THE PV SYSTEM

The subsequent stages comprise the performance assessment of solar PV power facilities that are connected to the grid:

- SCADA data collection: The SCADA system is employed to derive real power generation parameters (voltage, current, and power) in order to evaluate the system's actual performance.
- Simulation with PVsyst: PVsyst, a sizing software, is employed to simulate the theoretical system performance in order to estimate potential yields and losses.
- Validation with solar GIS: Solar GIS is employed to simulate performance by incorporating high-precision climatic data, thereby generating a second independent theoretical estimate.
- Results comparison: The accuracy of the sizing tools and the potential discrepancies are evaluated by comparing the real data collected via SCADA with the simulated results from PVsyst and solar GIS.

## 4. SYSTEM PARAMETERS

The performance of a PV solar farm is assessed using the metrics listed below, in accordance with IEC 61724 [24] and additional literature [25].

Array efficiency: $\eta_A = E_{DC}/H_T$ (1)

Inverter efficiency: $\eta_{inv} = P_{AC}/P_{DC}$ (2)

System efficiency: $\eta_{sys}T = \eta P_{VT}/\eta_{int}T$ (3)

Array yield: $Y_A = E_{DC}/P_0$ (4)

Reference yield: $Y_R = H_T/G_0$ (5)

Final yield: $Y_F = E_{AC}/P_0$ (6)

Performance ratio: $P_R = Y_F/Y_R$ (7)

Capacity factor: $C_F = E_{AC}/(P_0 \times 24 \times 365)$ (8)

## 5. SIMULATIONS USING PV SYST AND SOLAR GIS-PV

One of the simulation programs designed to gauge a solar power plant's efficiency is called PVsyst. Weather data may be imported from several sources. Using a defined module selection approach, this program may assess the performance of pumping, off-grid, and grid-connected systems. The program computes the system yields using comprehensive hourly simulation data, and it does so with accuracy [26]. According to [27], a solar GIS is a geographic information system designed specifically to meet the needs of the solar energy industry. This platform combines meteorological and solar resource data into a web-based application system, providing all-encompassing assistance for the design, development, and administration of solar energy systems.

## 6. RESULTS AND DISCUSSION

### 6.1. Peak power output

Solar panels transform the solar radiation they collect into usable power. Power production is dependent on both the ambient temperature and sun insolation. Figure 4 shows the average results for the Dhaya power plant for the longest and shortest days of the year, which helps to illustrate how irradiance and ambient temperature affect the power production of the system.

Figure 4 shows that electricity production is greater in June and more concentrated around noon, following the solar irradiation curve. A higher temperature during the day appears to have a secondary effect on production. In December, production is lower and correlated with lower and more variable irradiation, as observed at 11 a.m. when irradiation decreased due to cloudy winter weather, leading to a decrease in production. A lower and more stable temperature seems to have a less pronounced impact. These observations highlight the major influence of solar irradiation on PV energy production and confirm the intermittent nature of this energy source, which is more productive in summer than in winter.

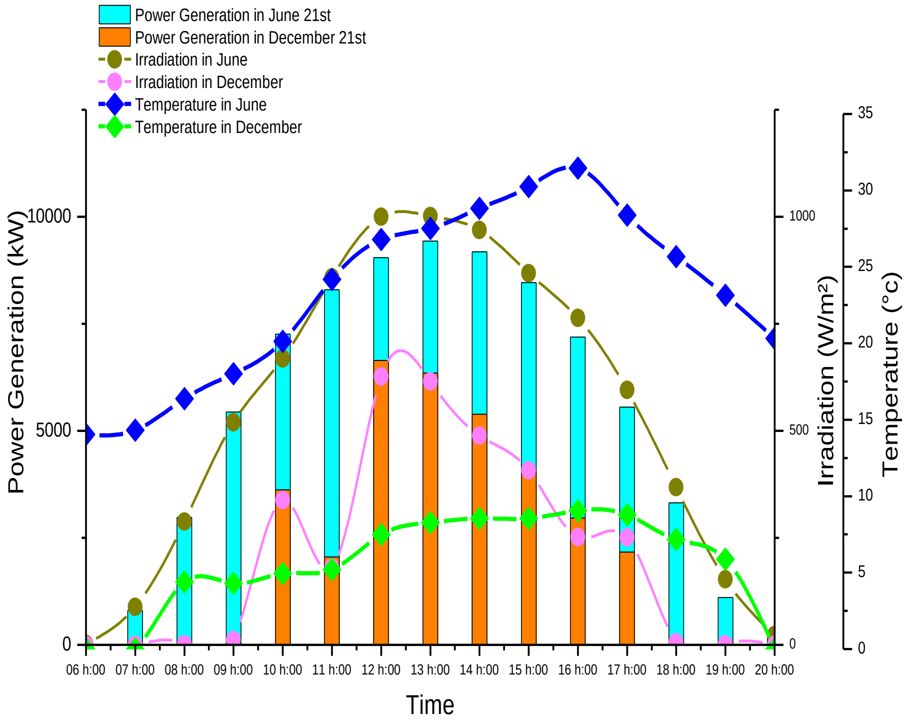


Figure 4. Difference in power generation between June and December

### 6.2. Performance ratio (PR)

The performance ratio (PR) is almost 85% on a yearly average. The PR for the month of August was 79.1%, while the PR for the month of December was the highest at 89.71%. Lower PR levels indicate problems such as improper system functioning and inverter faults. The PR values work as indications of system malfunction (Figure 5).

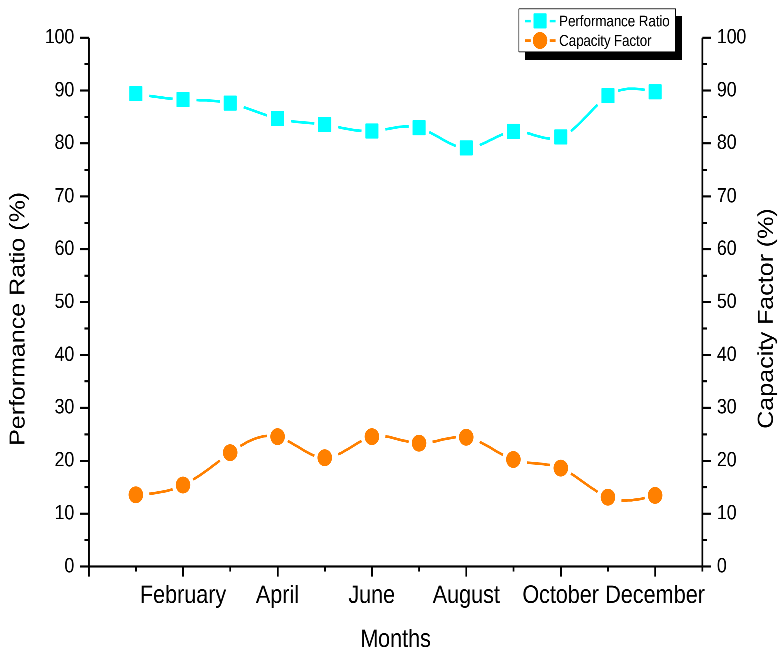


Figure 5. Monthly performance ratio and capacity utilization factor

### 6.3. Capacity utilization factor

The capacity utilization factor (CUF) ranges from 13.1% to 24.5%, with an average of 19.44% each year. Comparatively, throughout the course of a year of operation, Algerian PV plants usually display CUF values ranging from 12.29% to 18.8%. The fluctuations in CUF are ascribed to losses in the system that are impacted by regional weather patterns. It is noteworthy that this plant's average CUF of 19.44% closely matches the values published for comparable solar PV facilities in Algeria [28]. Lower energy-generating costs are implied by a greater CUF (Figure 5).

### 6.4. Energy generation

The data were gathered manually through SCADA software. Table 1 offers insights into the monthly and yearly production of PV energy, measured in megawatt hours (MWh). There is notable variation in production levels across different months, peaking during the summer and dipping in the winter. In particular, August emerges as the most productive month, recording a monthly total of 2,181.5 MWh. Conversely, December has the lowest production, with a monthly total of 1,193.27 MWh. The overall annual output was 20,780.67 MWh.

Table 1. Average energy production per month

| Months | Average daily energy generation (MWh) | Monthly energy (MWh) |
|---|---|---|
| January | 38.980 | 1,208.4 |
| February | 44.325 | 1,241.1 |
| March | 63.348 | 1,963.8 |
| April | 70.576 | 2,117.3 |
| May | 59.18 | 1,834.6 |
| June | 70.626 | 2,118.8 |
| July | 67.203 | 2,083.3 |
| August | 70.370 | 2,181.5 |
| September | 58.243 | 1,747.3 |
| October | 53.461 | 1,657.3 |
| November | 37.8 | 1,434 |
| December | 38.492 | 1,193.27 |

## 7. SIMULATION USING THE PV SYSTEM

The highest energy generation occurs in April, reaching 2,002 MWh, while December records the lowest at 1,604 MWh. Over the year, a total of 21,774 MWh is injected into the grid. Figure 6 highlights the seasonal fluctuation in energy production.

### 7.1. Balances and main results

The worldwide incident energy on the collector plane reaches 2,260.9 kWh/m$^2$ annually. In comparison, the global horizontal irradiation is recorded at 1,959.9 kWh/year. According to Table 2, the PV array produces a total energy output of 22,164 MWh.

### 7.2. Normalized productions

The LC value, which is estimated at 1.07 kWh/kWp/day, represents the climate-related losses. In the same way, the LS value, which is calculated at 0.09 kWh/kWp/day, represents the losses resulting from system issues. Additionally, the yield factor, or YF value, is calculated at 5.04 kWh/kWp/day, as illustrated in Figure 6.

### 7.3. Performance ratio

The yearly average performance ratio is 81.3%. There are minimal variations between the performance ratio obtained from PVsyst simulations and the actual performance ratio measured using the SCADA system. This demonstrates the reliability of the PVsyst model for performance evaluation.

### 7.4. Energy conservation step

The unit of measurement for global horizontal irradiance is 1959 kWh/m. On the collection plane, the effective irradiation rate is 2,247 kWh/m. Electrical energy is produced by solar panels using incident solar energy. The nominal array energy reaches 26,633 MWh after the PV conversion. The efficiency of the PV array, measured under standard test conditions (STC), is 15.48%. A total of 22,988 MWh of virtual energy was collected from the array. The available energy received at the inverter output is 21,774 MWh after accounting for the inverter losses (Table 3).

Table 2. Balances and main results

| Month | GlobHor kWh/m² | T_Amb °C | GlobInc kWh/m² | Energy into array kWh | Energy into grid kWh | PR |
|---|---|---|---|---|---|---|
| January | 94.6 | 7.17 | 152.3 | 1,636,304 | 1,604,752 | 89 |
| February | 108.9 | 8.73 | 155.6 | 1,657,284 | 1,627,079 | 88.3 |
| March | 161.3 | 12.99 | 197.1 | 2,020,962 | 1,985,493 | 85.1 |
| April | 194.5 | 16.44 | 204.9 | 2,036,264 | 2,002,165 | 82.5 |
| May | 213 | 21.11 | 202.2 | 1,976,264 | 1,939,913 | 81 |
| June | 231.9 | 26.38 | 207.7 | 1,939,514 | 1,908,226 | 77.6 |
| July | 233.7 | 31.11 | 215.6 | 1,867,584 | 1,835,810 | 71.9 |
| August | 215.8 | 29.7 | 219.5 | 1,903,322 | 1,871,415 | 72 |
| September | 172.1 | 23.97 | 199.8 | 1,852,613 | 1,821,567 | 77 |
| October | 141.4 | 19.09 | 192.6 | 1,917,382 | 1,884,608 | 82.6 |
| November | 103.7 | 11.43 | 162.6 | 1,720,421 | 1,689,518 | 87.7 |
| December | 88.5 | 7.90 | 151 | 1,636,270 | 1,604,114 | 89.7 |
| Total | 1,959.5 | 18.06 | 2,260.9 | 22,164,183 | 21,774,659 | 81.3 |

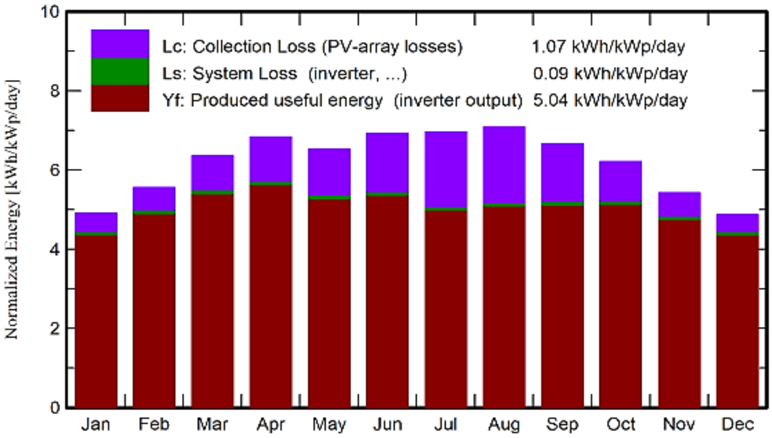


Figure 6. Normalized energy per month

Table 3. Loss chart for the whole year

| Energy conservation step | Energy (MWh) | Energy loss (MWh) | Energy loss (%) |
|---|---|---|---|
| Array nominal energy | 26,633 | 4,145 | 15.57 |
| Array virtual energy at MPP | 22,988 | 3,645 | 13.69 |
| Available energy at inverter output | 21,774 | 1,214 | 5.28 |

## 8. SIMULATION USING A SOLAR GIS-PV PLANNER

### 8.1. Direct normal and diffuse horizontal irradiation

The highest direct normal irradiation at the plant was recorded in June, reaching 201.6 kWh/m², while the lowest was observed in November at 136.7 kWh/m². For diffuse horizontal irradiation, July registered the highest value at 84.3 kWh/m², and December recorded the lowest at 27.4 kWh/m². These variations reflect seasonal shifts in solar energy availability (Figure 7).

### 8.2. PV electricity production

The electricity generation at the plant peaked in July at 1957 MWh, resulting in a higher daily sum of the specific electricity produced. Conversely, December had the lowest generation at 1408 MWh. March and April showed comparable energy generation, both reaching 1843 MWh (Tables 4 and 5).

### 8.3. Performance ratio

The performance ratio on a yearly average is 80.7%. Tables 4 and 5 demonstrate that there are few discrepancies between the performance ratio obtained from the Solar GIS-PV Planner and the real performance ratio recorded by the SCADA system. The conversion of solar energy through various stages involves a series of losses and adaptations that gradually diminish its initial potential, as shown in Table 5. Initially, the global solar irradiation at the incidence plane is assessed at 2,153 kWh/kWp, representing the energy captured by the solar panels over a year. However, this value is reduced to 2,077.6 kWh/kWp due to terrain shading, resulting in a loss of 3.5%. Furthermore, global irradiation is further reduced to 2,030.6 kWh/kWp due to reflectivity, which corresponds to an additional loss of 2.3% due to light reflection on solar panels. The remaining solar energy is then converted into direct current (DC) in the modules, with a conversion efficiency of 1,891.8 kWh/kWp, resulting in a loss of 6.8%. After this conversion, there are further losses in direct current, evaluated at 1,823.8 kWh/kWp, representing a loss of 3.6% due to connections and cables. Next, the step of converting direct current to alternating current (AC) by inverters incurs an additional loss of 2.9%, reducing the available energy to 1,770.5 kWh/kWp. These losses continue with reduced availability at 1,745.7 kWh/kWp, where 1.4% is lost due to outages and maintenance. Finally, the transformers and AC wiring losses add an additional loss of 0.5%, bringing the final available solar energy to 1,737 kWh/kWp. Thus, through these different conversion stages, solar energy undergoes adjustments and losses that diminish its initial yield.

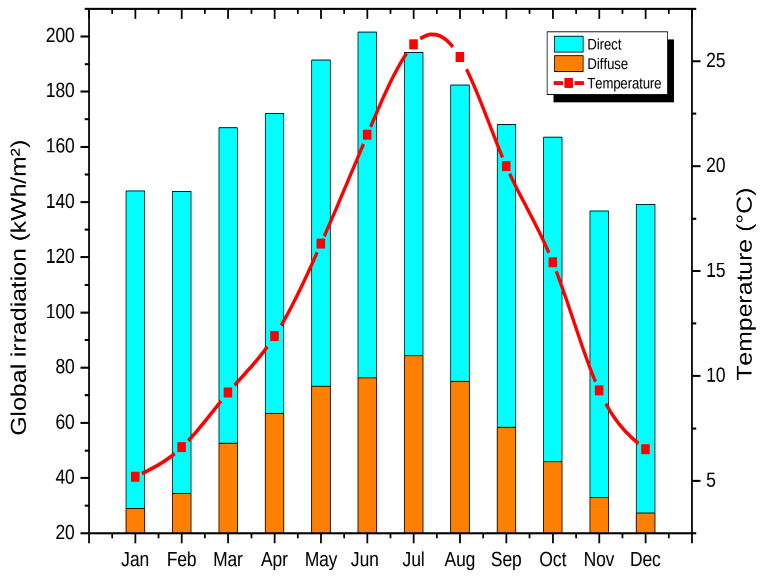


Figure 7. Monthly global solar irradiation in both horizontal and tilted (in-plane) orientations over a one-year period

Table 4. Monthly total energy production of the photovoltaic plant

| Month | Energy specific monthly sum kWh/kWp | Energy specific daily sum Wh/kWp | Energy total monthly sum MWh | Energy total share | PR ratio (%) |
|---|---|---|---|---|---|
| January | 123.7 | 3,991.2 | 1,485 | 7.1 | 85.9 |
| February | 127.6 | 4,555.8 | 1,531 | 7.35 | 84.8 |
| March | 153.6 | 4,954.4 | 1,843 | 8.84 | 82.8 |
| April | 153.6 | 5,118.7 | 1,843 | 8.84 | 81.1 |
| May | 159.8 | 5,154.0 | 1,917 | 9.2 | 79.3 |
| June | 158.6 | 5,287.3 | 1,903 | 9.13 | 77.4 |
| July | 163.1 | 5,260.2 | 1,957 | 9.39 | 75.8 |
| August | 159.6 | 5,149 | 1,915 | 9.19 | 76.3 |
| September | 151.8 | 5,058.6 | 1,821 | 8.74 | 79 |
| October | 147.2 | 4,748.3 | 1,766 | 8.47 | 81.6 |
| November | 121.2 | 4,040.8 | 1,455 | 6.98 | 84.6 |
| December | 117.3 | 3,784.6 | 1,408 | 6.75 | 85.4 |
| Total | 1,737 | 4,758.6 | 20,844 | 100 | 80.7 |

Table 5. Total losses in the plant system

| No | Energy conservation step | Energy output (kW h/kW p) | Energy loss (kW h/kW p) | Energy loss (%) | PR (%) |
|---|---|---|---|---|---|
| 1 | Global in-plane irradiation (input) | 2,153 | | | 100 |
| 2 | Global irradiation reduced by terrain shading | 2,077.6 | 75.4 | -3.5 | 96.5 |
| 3 | Global irradiation reduced by reflectivity | 2,030.6 | 47 | -2.3 | 94.3 |
| 4 | Conversion to DC in the modules | 1,891.8 | 138.8 | -6.8 | 87.9 |
| 5 | Other DC losses | 1,823.8 | 63 | -3.6 | 84.7 |
| 6 | Inverters (DC/AC conversion) | 1,770.5 | 53.3 | -2.9 | 82.2 |
| 7 | Transformer and AC cabling losses | 1,745.7 | 24.8 | -1.4 | 81.1 |
| 8 | Reduced availability | 1,737 | 8.7 | -0.5 | 80.7 |
| | Total system performance | 1,737 | 411 | 21 | 80.7 |

## 9. PERFORMANCE COMPARISON

The outcomes of the SCADA data system monitoring are contrasted with those of PVsyst software and the solar GIS PV planner simulations. The results, as illustrated in Figure 8, indicate a near-perfect match between the real performance and the simulated performance forecast by PVSYST and solar GIS for the whole year. Figure 8 shows that the actual energy production closely aligns with the estimations from the PVsyst and solar GIS simulations, although it tends to be slightly lower, especially during winter, and slightly greater in summer. This seasonal variation is attributed to the correlation between energy production and sunlight, which is more abundant in summer, as well as temperature, which is lower in winter. However, the monitoring performance ratio is higher than the performance ratio of the two simulations. These results lead to interpretations suggesting that simulations tend to slightly overestimate PV energy production, perhaps due to slightly inaccurate meteorological data.

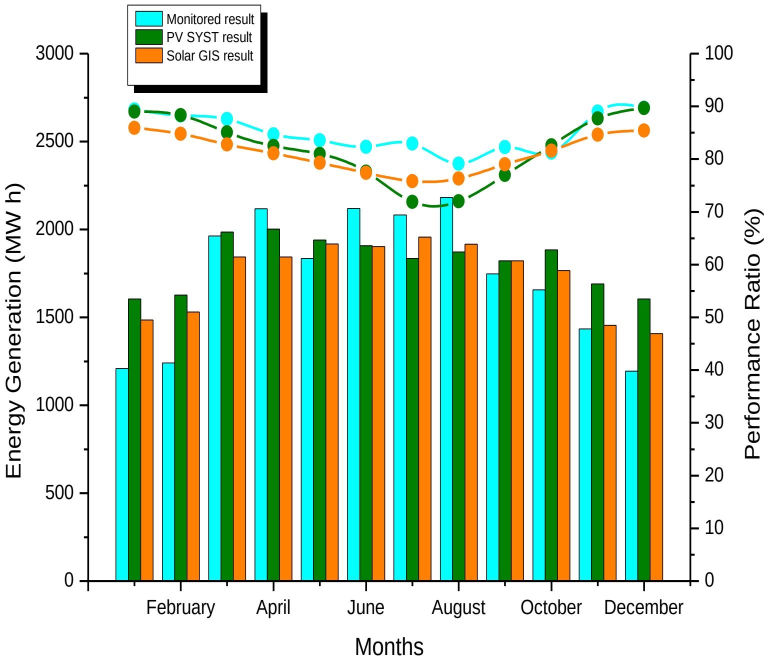


Figure 8. Comparison of the energy generation among the three results

## 10. CONCLUSION

An annual performance evaluation was carried out on a grid-connected 12 MW peak power solar PV plant situated in Sidi Bel Abbes, Dhaya area. This study led to numerous important conclusions. The plant demonstrated a maximum peak power of 10,249.86 KW and a low power of 47.102 KW during the course of the operating year. A total of 20,780.67 MWh of power was sent to the grid throughout the year, with August recording the highest total energy output of 2,181.5 MWh and December the lowest at 1,193.27 MWh. The facility achieved a capacity factor of 14.83% and an annual average performance ratio of 79%. The actual energy generation and predicted energy generation from the models showed strong alignment, as verified through simulation results from PVsyst and solar GIS-PV systems. Consequently, the 12 MW solar power plant demonstrated excellent capacity utilization, energy efficiency, and operational effectiveness with an approximately 99% availability rate. Future research will aim to perform an advanced evaluation of the plant's performance parameters over a six-year period to better understand its long-term operational sustainability.

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**AUTHOR CONTRIBUTIONS STATEMENT**

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

**CONFLICT OF INTEREST STATEMENT**

Authors state no conflict of interest.

**DATA AVAILABILITY**

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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