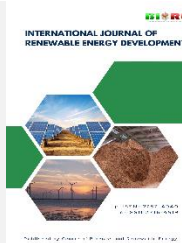




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Research Article

Performance analysis of a photovoltaic component integrated into a hybrid power plant in Southeast Mauritania

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Abstract. This study investigated the performance of photovoltaic components of the 1.3MW KIFFA hybrid power plant in Mauritania. Data from the plant's monitoring system (January-December 2021) was used to assess various performance metrics. The analysis revealed a high daily reference yield (5.60 h/d), indicating good solar resource availability. However, final and array yields (4.78 h/d and 4.86 h/d, respectively) suggested potential for improvement. System component efficiencies were within acceptable ranges, with particularly high inverter efficiency (98.31%). Array capture losses were moderate (0.74 h/d), and system losses were minimal (0.08 h/d). The annual performance ratio (86.33%) and capacity factor (19.91%) indicated good overall plant performance. These findings were then compared with data from similar installations in various climate zones to understand the impact of climatic variations on photovoltaic performance. Compared to installations in temperate zones with lower irradiation levels, the KIFFA plant's reference yield was significantly higher. However, the final and array yields were closer due to potentially higher operating temperatures in Mauritania affecting module efficiency. Interestingly, comparisons with installations in other desert regions with similarly high irradiation levels revealed lower performance, particularly in terms of final yield, (4.71 h/d) in Algérie (Adrar) and (4.10 h/d) in Oman (Muscat). This suggests that climatic factors beyond just sunlight availability, such as dust accumulation, may have played a significant role in their performance compared to the KIFFA plant.

Keywords: Climate impacts, KIFFA hybrid power plant, Module yields, Performances factors, PV plant performances, PV system losses.



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1. Introduction

The escalating demand for clean and sustainable energy sources has positioned renewable energies as a pivotal solution for the current and future energy landscape. Unlike traditional fossil fuels, RE sources like solar and wind are abundant, environmentally friendly, and contribute significantly to reducing greenhouse gas emissions. Their widespread adoption offers the potential for energy independence, reduced reliance on volatile fossil fuel markets, and long-term cost savings for both consumers and utilities (Kerboua, Boukli-Hacene, & Mourad, 2020).

These factors clearly demonstrate that renewable energies are a cornerstone of the Mauritanian development program. However, the large-scale implementation of these clean energy resources faces significant challenges related to infrastructure development and securing investment funds (IRENA, 2015).

In line with this global shift towards renewables, the electricity sector in Mauritania has experienced steady growth in all its segments: generation, transmission and distribution. The government is currently conducting an ambitious program, based on a series of sound reforms and major investments. The

action plan aims to ensure a universal access to sustainable energy at a lower cost and make reliable and secure electricity available for economic operators. This program attaches great importance to the reduction of energy costs by strengthening national energy resources, including lower-emission fossil fuels like natural gas and renewable energies especially solar and wind energies (IRENA, 2015).

The Poverty Reduction Strategy Paper (PRSP) has set in Mauritania, the goal of increasing the share of renewable energies in the national energy mix to 41% by 2030 (IRENA, 2015). This focus on renewables is crucial for isolated areas facing economic and logistical burdens associated with fuel delivery and grid expansion (Ramdhane, *et al.*, 2017); (Ba, *et al.*, 2019)). Additionally, incorporating photovoltaic generators in hybrid systems can further reduce dependence on diesel generators in the electrical system (Biyik, *et al.*, 2017); (Zhou, Lou, Li, Lu, & Yang, 2010)). These factors demonstrate that renewable energies are a central pillar of the Mauritanian development program. However, the transition to large-scale deployment of these clean energy resources faces significant challenges related to infrastructure development and securing investment funds (IRENA, 2015).

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With electricity infrastructure composed of micro-grids and hybrid systems, Mauritania is well-positioned to integrate renewable energy solutions like the one presented in this study. Performance analysis of hybrid power plants, particularly those incorporating photovoltaic components, has been a key area of research globally. Several notable studies have been conducted, providing valuable insights into the performance characteristics and optimization strategies for such systems like in European region (Huld, T; Gottschalg, R; Beyer, H G; Topič, M, 2010), Greece (Kymakis, E; Kalykakis, S; Papazoglou, T M, 2009), Spain (Fuster-Palop, Vargas-Salgado, Ferri-Revert, & Payá, 2022), Ireland (Ayompe, Duffy, McCormack, & Conlon, 2011), Morocco (Attari, Elyaakoubi, & Asselman, 2016); (Bouaichi, El Amrani, Ouhadou, Lfakir, & Messaoudi, 2020)), India((Kumar & Sudhakar, 2015); (Sundaram & Babu, 2015); (Sharma & Chandel, 2013)), Algeria ((Aoun, N, 2020); (Maouedj, Mammeri, Draou, & Benyoucef, 2015); (Dabou, *et al.*, 2016); (Dahbi, Aoun, & Sellam, 2021)), Oman (Al-Badi, 2018), Ghana (Quansah, Adaramola, Appiah, & Edwin, 2017), USA (Veerendra Kumar, *et al.*, 2022), Lesotho (Mpholo, Nchaba, & Monese, 2015), and Mauritania((Sidi, *et al.*, 2016); (Heyine, *et al.*, 2022)).

Understanding the performance characteristics of photovoltaic modules is crucial for optimizing the design and operation of hybrid power plants. In this regard, a method was developed to quantify the energy yield of PV modules based on the climatic conditions of a European region (Huld, T; Gottschalg, R; Beyer, H G; Topič, M, 2010). Among the CdTe modules studied, the highest efficiency was achieved under moderate illumination levels, around 400 W/m². In contrast, for crystalline silicon modules, the authors concluded that high temporal resolution data is necessary for an accurate performance analysis. A performance analysis of a 171kW grid-connected photovoltaic power plant located in Crete, Greece, was conducted by (Kymakis, E; Kalykakis, S; Papazoglou, T M, 2009) over a one-year period. The analysis revealed that the final yield varied between 1.96 and 5.07 kWh/day, with a performance ratio of 67.36% and a capacity factor of 15.26%.

A performance evaluation of a hybrid system consisting of photovoltaic panels and a diesel generator with a storage system was carried out by (Stoyanov, L; Notton, G; Lazarov, V D, 2007). To analyze the energy flow within the hybrid system, the authors propose a technical-economic optimization focused on enhancing the reliability of its components. Their evaluation revealed that the relative contribution of different energy sources depends more on the size of the PV array than the battery capacity. Large storage capacity has minimal impact on the hybrid system's performance, as shown in this study.

To estimate the daily performance ratio, particularly for days with low sunshine, the authors in (Fuster-Palop, Vargas-Salgado, Ferri-Revert, & Payá, 2022) employed two different modeling approaches. They found that a random forest model achieved the highest accuracy using only solar irradiation and ambient temperature as predictor variables. This model resulted in a root mean squared error (RMSE) of 1% for both the energy produced and the performance ratio.

Studies lead by (Kumar & Sudhakar, 2015); (Sundaram & Babu, 2015) and (Sharma & Chandel, 2013) evaluated the performance of 10 MWp, 5 MWp, and 190 kWp grid-connected photovoltaic plants in India, respectively. The final yield varied across the plants, ranging from 4.36 kWh/day for the largest plant (Kumar & Sudhakar, 2015) to 4.81 kWh/day for the mid-sized plant ((Sundaram & Babu, 2015)) and 2.23 kWh/day for the smallest plant ((Sharma & Chandel, 2013)). Similarly, the annual performance ratio exhibited variation, with (Kumar & Sudhakar, 2015) achieving 86.12%, (Sundaram & Babu, 2015) reaching 88.20%, and (Sharma & Chandel, 2013) at 74%. The annual capacity factor was 17.68% for the 10 MWp plant

(Kumar & Sudhakar, 2015) and ranged from 16.17% to 22.90% for the 5 MWp plant (Sundaram & Babu, 2015).

The study in Muscat, Oman (Al-Badi, 2018) evaluated the performance of a 1.4 kWp grid-connected photovoltaic power plant and found a 10% reduction in energy production from uncleaned PV modules compared to cleaned ones. This finding highlighted the significant impact that cleaning PV modules has on their productivity.

The study in Adrar, Algeria (Dahbi, Aoun, & Sellam, 2021) investigated the performance of a 6 MW grid-connected photovoltaic power plant. The analysis revealed a final yield of 5.15 kWh/day, a performance ratio of 73.7%, and a capacity factor of 21%. In addition, factors such as ambient temperature, wind, rain, and dust can affect the solar radiation received by photovoltaic modules, which can in turn influence the performance ratio.

Studies in (Olawejaju, Ogunjuyigbe, Ayodele, & Yusuff, August 2020) and (Attari, Elyaakoubi, & Asselman, 2016) found that PV modules generally produce more energy during hot seasons compared to cold seasons. These studies also revealed that the best performance ratios and efficiencies occur under conditions of moderate ambient temperatures and average irradiation levels. However, (Aoun, N, 2020) reported contrasting findings, suggesting higher energy output from photovoltaic modules in hot weather, but with better efficiency and performance ratios observed in cold weather.

Building upon the knowledge of PV module performance, research in arid/semi-arid regions offers valuable insights for optimizing hybrid power plants in these environments. Study like (Quansah, Adaramola, Appiah, & Edwin, 2017) in Ghana evaluated the performance of five photovoltaic systems using different technologies: monocrystalline silicon (m-Si), polycrystalline silicon (p-Si), amorphous silicon (a-Si), copper indium selenide (CIS), and heterojunction with intrinsic thin layer (HIT). The results showed that crystalline technologies (m-Si and p-Si) were the most commonly adopted for similar climates, followed by a-Si, HIT, and CIS. Notably, the HIT-based system emerged as the most suitable option for situations with limited space.

Several research works in Mauritania have shed light on PV performance within the country. For instance, (Soukeyna, *et al.*, 2018) and (Abdi, *et al.*, 2018) conducted a feasibility study in Nouakchott, assessing the performance of both photovoltaic and wind turbine generators under various weather conditions. This study provided valuable insights into the combined potential of these renewable energy sources in Mauritania's arid climate. Additionally, the authors of (Sidi, *et al.*, 2016) presented a performance evaluation of the Sheikh Zayed power plant, Mauritania's first large-scale photovoltaic plant. Their analysis examined various performance metrics, including factors that can significantly impact energy production. Building upon these efforts, paper (Heyine, *et al.*, 2022) conducted a performance evaluation of a 50 MWp solar plant using measurement data from Nouakchott's Saharan environment. These studies have provided a strong foundation for understanding PV performance in Mauritania.

This study distinguished itself by pioneering the exploration of photovoltaic power plant performance in the unique climate of southeastern Mauritania. It delved deeper into analyzing the performance of the photovoltaic component of the Kiffa hybrid power plant, surpassing previous studies conducted in other regions of Mauritania. The study adhered to the IEC 61724 standard, which outlines performance requirements and testing methodologies for photovoltaic system monitoring and data exchange. It employed real-world parameters of the power plant's photovoltaic panels and inverters. The power plant's

evaluation was anchored in a multitude of performance parameters, encompassing reference yield, final yield, field yield, field efficiency, system efficiency, inverter efficiency, performance ratio, capacity factor, and breakdowns of various losses.

2. Methodology

The commune of Kiffa, where the power plant under study is located, is situated in southeast-ern Mauritania, approximately 600 kilometers from the capital, Nouakchott. Its geographic coordinates are: latitude 16.621060°, longitude - 11.403360°, and altitude 125 meters.

Kiffa holds a strategic position as both the administrative center of the moughataa (sub-prefecture) of the same name and the regional capital of Assaba. It ranks among the most populous cities in Mauritania, second only to Nouakchott. This commune exhibits a dual char-acter: an urban area concentrated around the city of Kiffa, encompassing 18 neighborhoods, and a surrounding rural area comprising 25 villages and encampments. As projected by the National Statistics Office (ONS) in 2019, the total population of the commune amounts to 69,535 inhabitants, of whom 36,939 are women and 32,596 are men (ONS, 2017); (PNIDDLE, 2020)).

Kiffa serves as a crucial transportation hub, situated along the Nouakchott-Néma highway, also known as the "Route de l'Espoir" (Road of Hope). Its landscape, characterized by rocky plateaus and dune systems, significantly shapes its environment and local activities. The Assaba region, of which Kiffa is a part, is essentially rural and has an agro-pastoral vocation. The inhabitants mainly practice agriculture and livestock farming. It benefits from a thriving trade and intense exchanges with neighboring regions, its geographical position making it an important transit center (ONS, 2017); (PNIDDLE, 2020)).

2.1 Kiffa hybrid power plant overview

The Kiffa Hybrid Power Plant is a combined photovoltaic-thermal system with a total capacity of 6.3 MWp. It combines thermal power generation of 5 MW with photovoltaic solar power generation of 1.3 MWp. The Mauritanian Electricity Company (SOMELEC) was delegated by the contracting authority, the Ministry of Petroleum, Energy and Mines, for the construction and operation of the power plant. The latter was built as part of a project financed by the French Development Agency (AFD) and the European Union (EU). The companies



Fig 1. Aerial views of the Kiffa Hybrid Power Plant, © VERGNET © ABC CONTRACTING

Table 1
Kiffa plants description

Photovoltaic System	
Capacity	1.3 MW
Modules	4320 modules
Configuration	36 strings
Orientation	15° tilt angle facing south
Inverters	Two ABB PVS800-57-630 kW
Grid Connection	Tow transformers of 0.4/33kV- 315 kVA
Thermal Power Plant	
Capacity	5 MW
Engines	Four motors operating at 750 rpm: Two 1000 kW motors Two 1500 kW motors
Alternators	Four Alternators Generate 400 V, 50 Hz AC power
Grid Connection	
Six transformers of 0.4/33kV - 315 kVA	

ABC and VERGNET were responsible for construction, ABC handling the thermal part and VERGNET the solar part. The project's financing amounts to €23.8 million, divided between the power plant and the high-voltage/low-voltage (HV/LV) grid (AFD, ABC, SOMELEC, 2023, 2021).

2.1.1 Presentation of the Kiffa Hybrid Power Plant Site

The Kiffa hybrid power plant is situated approximately 13 kilometers from the city of Kiffa. Its coordinates are: latitude 16.6677°, longitude -11.5076°, and altitude 143 meters (16°40'03.0"N 11°30'27.4"W). This plant provides electricity to both Kiffa and Guerou, which is about 60 kilometers away. The aerial view of The Kiffa Hybrid Power Plant is shown in Figure 1 and cited in (AFD, ABC, SOMELEC, 2023, 2021).

2.1.2 Power Plant description

The Kiffa Hybrid Power Plant, commissioned in April 2018, has a rated capacity of 6.3 MW. The plant combines photovoltaic and thermal technologies to generate electricity. The description of each plant is given in Table 1. Leveraging both solar and thermal technologies, the Kiffa Hybrid Power Plant architecture is illustrated in Figure 2.

To evaluate the energy production potential and overall performance of the Kiffa Hybrid Power Plant's solar modules, understanding their specifications is crucial. Table 2 details

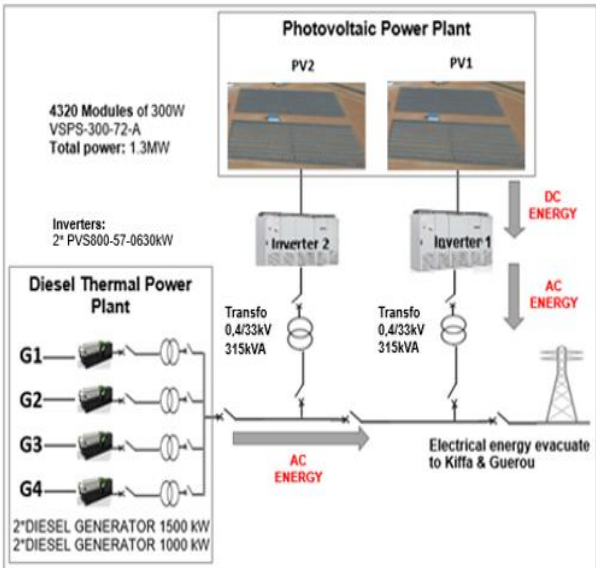


Fig 2. Architecture of the Kiffa Hybrid Power Plant

Table 2
PV modules and array characteristics

Parameters	Specification
Type of cells	Poly-crystalline
Solar module type	VSPS-300-72-A
Maximum power (P_{max})	303,08Wp
Power tolerance	0/+3%
Maximum power voltage (V_{mp})	36.34 V
Maximum power current (I_{mp})	8.33 A
Open circuit voltage (V_{oc})	44.72 V
Short current circuit (I_{sc})	8.77 A
Maximum wind/snow load	2400Pa /5400Pa
Electric safety	Class II
Maximum system voltage	1000 VDC
Maximum reserve current	15 A
Operating temperature	-40 °C to +85 °C
Dimensions and number of cells	156 x 156 mm / 72 cells
Dimension and Weight of the panel	1980x998x42 (±1mm)/26Kg
Temperature coefficients:	
- For power	-0.409%/°C
- For V_{oc}	-0.332%/°C
- For I_{sc}	0.052%/°C

these specifications, outlining key parameters such as cell type and module reference. Additionally, the table includes other information on power tolerance like maximum power, output voltage and current characteristics at maximum power point, open circuit voltage, and short circuit current under STC conditions.

Table 3 presents the technical specifications of the inverters used in the Kiffa Hybrid Power Plant. This table details the input and output characteristics of the inverters, including DC voltage range, maximum DC current, nominal and maximum AC power output, and efficiency. Understanding these specifications is crucial for evaluating the inverter's performance and its suitability for the solar system.

2.2 Performance evaluation's yield factors

Investing in precise performance evaluations for photovoltaic installations unlocks significant benefits. This data empowers informed decision-making on critical project aspects like return on investment, technology options, geographical suitability, and design methods, ultimately leading to cost-optimized solar power plants (Goss, et al., 2017); (Chimtavee & Ketjoy, 2012)).

The International Energy Agency's Photovoltaic Energy Systems Program establishes standards for photovoltaic plant energy output, which are then standardized by the International Electrotechnical Commission as international standards. Power plant production factors, a specific measure within these standards, determine the extent to which operational energy production offsets the energy used to build the plant (Chioncel, Kohake, Augustinov, Chioncel, & Tirian, 2010).

2.2.1 System yields

2.2.1.1 Array yield

The yield of a photovoltaic (PV) array refers to the ratio between the actual energy output of the modules over a specific period and their rated power (Attari, Elyaakoubi, & Asselman, 2016). This metric can be calculated using the following equation:

$$Y_a = \frac{E_{DC}}{P_{pv, rated}} \quad (1)$$

Table 3
Technical data of inverters

Type designation	PVS800-57-0630kW-B
Input (DC)	
DC voltage range	525 to 825 V
Maximum DC	1100 V
Maximum DC	1230 A
Output (AC)	
Nominal power	630 kW
Maximum output power	700 kW
Nominal AC current	1040 A
Nominal output voltage	350 V
Output frequency	50/60 Hz
Harmonic distortion, current	< 3%
Efficiency	
Maximum	98.6%
Power consumption	
Own consumption in operation	490 W
Standby operation consumption	65 W
External auxiliary voltage	230 V, 50 Hz
Dimensions and weight	
Weight	1800

To calculate the array yield, the chosen evaluation period needs to be considered. Daily, monthly, and annual yields can be determined as follows:

$$Y_{a,d} = \frac{E_{DC,d}}{P_{pv, rated}} \quad (2)$$

$$Y_{a,m} = \sum_{d=1}^{N_d} Y_{a,d} \quad (3)$$

$$Y_{a,y} = \sum_{m=1}^{12} Y_{a,m} \quad (4)$$

To calculate the various yield metrics for a photovoltaic plant, the following variables are used:

" $Y_{a,d}$ " is the daily array yield.

" $Y_{a,m}$ " is the monthly array yield.

" $Y_{a,y}$ " is the annual array yield.

" $P_{pv, rated}$ " is the rated power of the PV plant.

" $E_{DC,d}$ " is the daily DC energy output from the PV plant.

" N_d " is the number of days in a month.

2.2.1.2 Final Yield

The final yield of a photovoltaic system is calculated by dividing the total AC energy produced over a specific period by the system's rated power (Kymakis, E; Kalykakis, S; Papazoglou, T M, 2009). This metric reflects the plant's performance in terms of alternating current energy production, accounting for inverter efficiency losses. The chosen period can be a day (daily final yield), a month (monthly final yield), or a year (yearly final yield) as follows:

$$Y_{f,d} = \frac{E_{AC,d}}{P_{pv, rated}} \quad (5)$$

$$Y_{f,m} = \sum_{d=1}^{N_d} Y_{f,d} \quad (6)$$

$$Y_{f,y} = \sum_{m=1}^{12} Y_{f,m} \quad (7)$$

Where " $E_{AC,d}$ " represents the daily AC energy output from the PV plant delivered to the grid.

2.2.1.3 Reference Yield

The reference yield represents the ratio of global solar radiation at a location to the reference irradiance of a photovoltaic cell (Attari, Elyaakoubi, & Asselman, 2016). In essence, it characterizes the solar energy resource available for the photovoltaic plant. This factor depends on several key aspects: the orientation of the PV panels, the geographical location of the plant, and the variability of weather patterns at the site (Kumar & Sudhakar, 2015); (Chioncel, Kohake, Augustinov, Chioncel, & Tirian, 2010). These factors significantly influence how much sunlight the panels can capture and convert into electricity. The calculation method for reference yield is shown as follows:

$$Y_r = \frac{H_t}{H_R} \quad (8)$$

Where:

" H_t " : The total horizontal irradiance in (kW/m^2).

" H_R " : The global irradiance at STC (1kW/m^2).

" Y_r " : The equivalent of Peak Sun Hours.

2.2.2 Performance Ratio

The performance ratio is calculated by dividing the final yield by the reference yield. It allows the evaluation of the impact of total losses on the rated power of the photovoltaic plant. This parameter is used to assess the performance of a photovoltaic installation and identify potential quality problems (Aoun, N; Bouchouicha, K; Chenni, R, 2017).

$$PR = \frac{Y_f}{Y_r} \quad (9)$$

By utilizing equations (7) and (9), we can derive another important relationship for the performance ratio of a site. This relationship defines the performance ratio as the ratio of the actual annual energy yield of the system to the ideal energy output of the PV array. This approach provides a normalized basis for comparison, allowing us to compare the performance of different types and sizes of photovoltaic systems.

$$PR = \frac{E_{sys}}{E_{ideal}} \quad (10)$$

Where:

" E_{sys} " is the actual annual energy yield of the system.

" E_{ideal} " is the ideal energy output of the PV array under Standard Test Conditions (STC). It can be determined as follows:

$$E_{ideal} = P_{array} H_t \quad (11)$$

" P_{array} " represents the peak power output of the PV array under standard test conditions.

2.2.3 Capacity Factor

The capacity factor is an important key metric to assess a photovoltaic system's performance. It's the ratio of the system's actual AC energy output over a specific period by the theoretical maximum it could generate if running constantly at its rated power during that same period (Kumar, Gupta, Mathew, Jayakumar, & Singh, 2019); (Kazem, Khatib, Sopian, & Elmenreich, 2014); (Sharma & Goel, (2017)).

$$C_f = \frac{E_{AC}}{P_{PV, rated} * Ah} \quad (12)$$

Where:

"Ah" represents the total expected number of operating hours over the specific period, typically one year. It's common practice to use a value of 8760 hours to represent the annual number of hours.

" E_{AC} " represents the total annual energy generated by the photovoltaic system.

" $P_{PV, Rated}$ " represents the rated power of the PV system (Ayompe, Duffy, McCormack, & Conlon, 2011); (Kymakis, E; Kalykakis, S; Papazoglou, T M, 2009)).

2.2.4 Losses

2.2.4.1 Array capture losses

Array capture losses refer to the reduction in energy output of a photovoltaic system due to various factors within the PV array itself (Ayompe, Duffy, McCormack, & Conlon, 2011). These losses can be determined as follows:

$$L_c = Y_r - Y_a \quad (13)$$

2.2.4.2 System losses

System losses represent the energy losses that occur within the entire photovoltaic system, primarily due to inefficiencies in the inverter (Ayompe, Duffy, McCormack, & Conlon, 2011). This factor can be determined as follows:

$$L_s = Y_a - Y_f \quad (14)$$

2.2.5 System efficiencies

The effectiveness of a solar power system depends on three main factors: panel efficiency, system efficiency and inverter efficiency.

2.2.5.1 PV module efficiency

The module efficiency reflects how well the solar panels convert sunlight into usable electricity over a day. It's calculated by dividing the total DC electricity produced by the array by the total amount of solar energy received by the panels' surface area

((Wittkopf, Valliappan, Liu, Ang, & Cheng, 2012); (de Lima, de Araújo Ferreira, & de Lima Morais, 2017)). It is expressed as a percentage and calculated by the following equation:

$$\eta_{PV} = \frac{E_{DC}}{H_t \cdot M_a} * 100 \quad (15)$$

Where:

"H_t" : The total horizontal irradiance in (kW/m²).

"M_a" : The module area (m²).

2.2.5.2 System efficiency

System efficiency represents the proportion of incident solar energy converted into usable electricity at the grid level. It is expressed as a percentage and given as (de Lima, de Araújo Ferreira, & de Lima Morais, 2017); (Kumar, Gupta, Mathew, Jayakumar, & Singh, 2019); (Sharma & Goel, (2017)).

$$\eta_{PV} = \frac{E_{AC}}{H_t \cdot M_a} * 100 \quad (16)$$

2.2.5.3 Inverter efficiency

Inverter efficiency represents the proportion of DC power produced by PV modules converted into usable AC power. It is also expressed as a percentage and calculate as follows (de Lima, de Araújo Ferreira, & de Lima Morais, 2017); (Kumar, Gupta, Mathew, Jayakumar, & Singh, 2019); (Sharma & Goel, (2017)).

$$\eta_{inv} = \frac{E_{AC}}{E_{DC}} * 100 \quad (17)$$

3. Results and Discussions

This section delved into the results of a comprehensive performance analysis conducted on the photovoltaic component of the Kiffa Hybrid Power Plant. The analysis began by examining the meteorological factors that influenced the plant's performance, such as solar irradiation and ambient temperature. Next, it assessed a variety of performance parameters, including reference yield, final yield, and a breakdown of various efficiency metrics (array, system, and inverter). Additionally, the analysis investigated the performance ratio and capacity factor to gain a deeper understanding of the PV system's effectiveness. Finally, to broaden the context, the study compared these findings with results from similar studies conducted elsewhere, providing valuable insights into the Kiffa plant's performance within the regional context.

3.1 Meteorological factors

Mauritania is characterized by an arid and subtropical climate, dominated by high temperatures, intense sunshine, and dry, dusty air. The influence of the Atlantic Ocean is felt on the west coast but does not prevent aridity from prevailing throughout the country. The rainfall pattern is marked by a single, short and irregular rainy season, generally extending from July to October. The dry seasons, on the other hand, are subdivided into a short, cool period from November to February and a long, hot period from March to June (Naia & Brito, 2021).

The city of Kiffa, where the studied power plant is located, is distinguished by its contrasting climate marked by scorching summers and mild, windy winters. This climatic peculiarity is mainly due to its geographical position within the Sahel, characterized by an arid climate and significant seasonal variations. The monitoring equipment installed at the study site

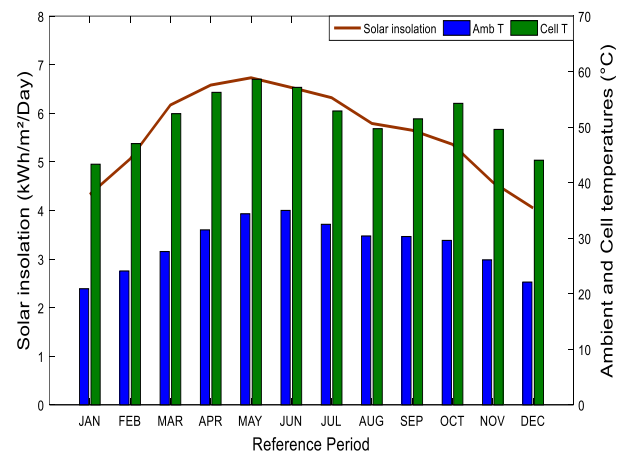


Fig 3. Monthly Distribution of Solar Insolation, Ambient and Photovoltaic Cell Temperatures

included a pyranometer and temperature sensors. This equipment allowed us to collect detailed meteorological data for one year (from January to December 2021), including solar irradiation and ambient and photovoltaic cell temperatures. To simplify calculations, we used the monthly average values for each parameter. Solar irradiance and ambient temperature are two of the main parameters for analyzing the performance of photovoltaic modules. Figure 3 illustrates the distribution of monthly average values of solar radiation, ambient temperatures, and cells at the Kiffa power plant site over the reference period.

Figure 3 shows that the average daily solar irradiation exhibits a slight seasonal variation throughout the year, ranging from a minimum of 4.05 kWh/m²/day in December (the least sunny month) to a maximum of 6.73 kWh/m²/day in May (the sunniest month). This seasonal variation in solar irradiation has a direct impact on the energy production of photovoltaic systems, which is higher during the sunniest months.

Similarly, ambient and photovoltaic cell temperatures also exhibit daily average seasonal fluctuations. The hottest month of the year in Kiffa is June, with an average maximum ambient temperature of 35°C and 54°C for photovoltaic cells. In contrast, the coldest month is January, with an average minimum ambient temperature of 20.9°C and 44.94°C for photovoltaic cells. These temperature variations also influence the performance of photovoltaic systems, as the conversion efficiency of the cells decreases with increasing temperature.

These seasonal trends highlight the interaction between solar irradiation, ambient temperature, and cell temperature, which influence the performance of photovoltaic systems as demonstrated in ((Sidi, *et al.*, 2016); (Heyine, *et al.*, 2022) and (Aoun, N; Bouchouicha, K; Chennai, R, 2017)). Understanding these relationships is essential for optimizing the design and operation of photovoltaic systems in Kiffa.

The electrical energy produced by the photovoltaic component of the power plant results from the conversion of solar radiation that strikes its surface. This energy varies depending on the amount of solar irradiation (sunshine) and the ambient temperature. Figures 4 and 5 illustrate the distribution of energy injected into the grid and energy produced by the photovoltaic modules at the Kiffa power plant site over the reference period, considering the climatic conditions.

As seen in Figures 4 and 5, during the winter months (December, January and February), photovoltaic field energy production is at its lowest, with an average monthly energy production of 161.17 MWh in December. This corresponds to low solar insolation (4.05 kWh/m²/day) and fair ambient

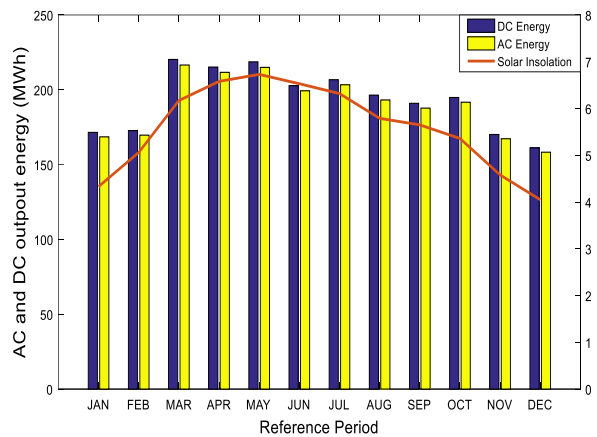


Fig 4. Monthly Distribution of AC&DC Energy as a Function of Solar Irradiation

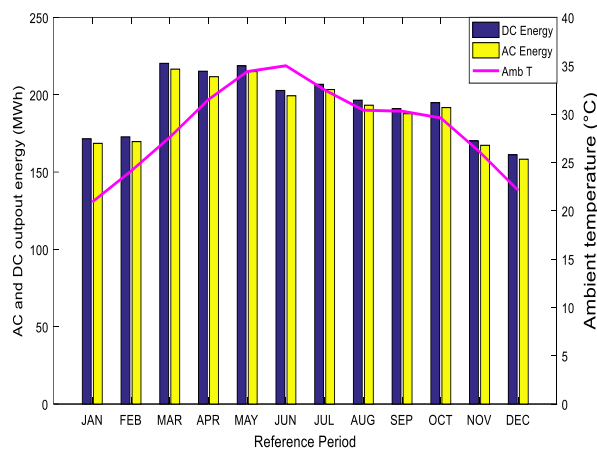


Fig 5. Monthly Distribution of AC&DC Energy as a Function of Ambient Temperature

temperature, a combination that hinders photovoltaic system production.

Conversely, the months of Spring, Summer, and Autumn (March, April, May, June, July, August, September, October and November) experience the highest solar irradiation and energy production, with an average monthly energy production of 220.29 MWh in March. This peak production aligns with high solar insolation (6.17 kWh/m²/day) and average ambient temperature, conditions favorable for photovoltaic system operation.

Therefore, the power plant's photovoltaic energy production varies considerably depending on the season, with peaks in summer and troughs in winter. This variability is primarily due to the influence of solar irradiation and ambient temperature. These results confirm the established link between temperature and irradiation, where high temperatures can decrease photovoltaic energy production even under favorable irradiation conditions. This trend was confirmed in study (Aoun, N; Bouchouicha, K; Chenni, R, 2017).

3.2 Performance parameter assessment

In this section, we take a closer look at the solar plant's performance throughout the reference period. Our focus is on the factors that influence how much power it generates, how efficiently it operates, and any energy losses that occur. Figure 6 presents the distribution of the Kiffa power plant's yields over the reference period. It compares the reference yields, the photovoltaic system yields, and the final yields. It is clear that

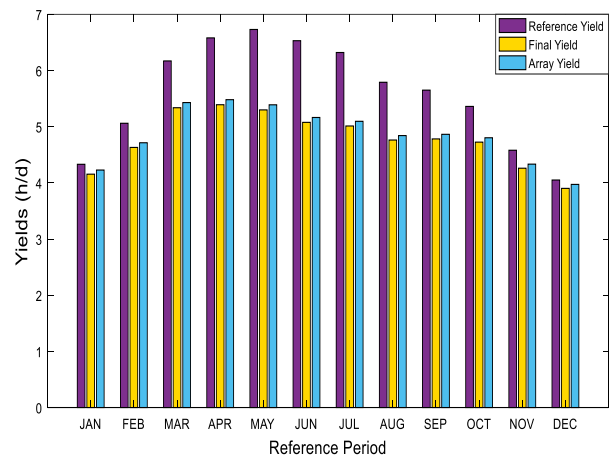


Fig 6. Monthly variation of PV yields

the final yield, which is the actual energy produced by the system, varies from a minimum of 3.9 hours per day in December (cool period) with an average energy generation of 5106.67 kWh/kWp/day, to a maximum of 5.39 h/day in April (hot period) with an average energy generation of 7056.08 kWh/kWp/day with average value of (4.78 h/d). This variation can be explained by the significant difference in monthly daily average solar insolation: low in December (4.05 kWh/m²/day) and high in April (6.58 kWh/m²/day). This value (4.78 h/d) is comparable to final yields reported in other studies, such (4.98 h/d) (Aoun, N, 2020) in Algéria (Adrar) and higher than those found in Morocco (4.45 h/day) (Attari, Elyaakoubi, & Asselman, 2016) and in Oman (Muscat) (4.10 h/d) (Al-Badi, 2018).

The reference yield, which is a theoretical value representing the maximum possible energy production based solely on solar insolation. It follows a similar seasonal pattern as final yield, ranging from 4.05 h/day in December to 6.73 h/day in May. The array yield, which represents the energy produced by the entire solar panel array before conversion to AC electricity. Figure 6 clearly shows that the trends of the final yield and the array yield closely follow that of the reference yield, exhibiting similar variations. The daily average array yield varies from a minimum of 3.97 h/day in December to a maximum of 5.48 h/day in April. The small difference between final and array yields (0.07 h/day to 0.09 h/day) indicates minimal energy loss during the DC/AC conversion process in the inverter, highlighting its efficiency. This affirms the results published in (Sundaram & Babu, 2015); (Sidi, et al., 2016) and (Heyne, et al., 2022)).

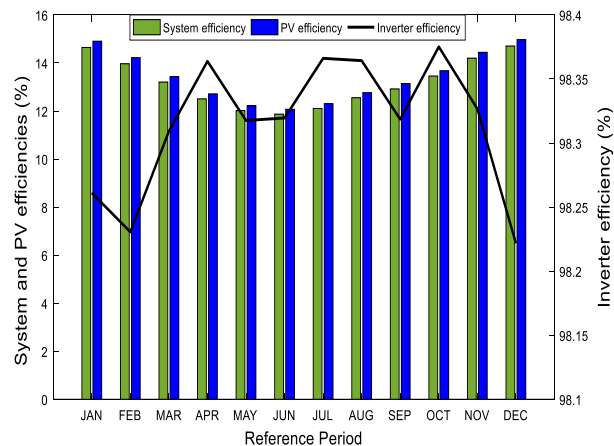


Fig 7. Monthly variation of efficiencies

Figure 7 presents the monthly variation in the average efficiency of the system, PV module, and inverter of the Kiffa power plant over the reference period. As shown in Figure 7, the monthly average efficiency of the system, PV module, and inverter varies respectively from a minimum of 11.87% in June to a maximum of 14.70% in December, 12.07% in June to 14.97% in December, and 98.22% in February to 98.38% in September. The average module efficiency is 13.41%, while the system efficiency is 13.18%. These results indicate that lower efficiencies for the system, PV module, and inverter are recorded during the summer and autumn months when solar insolation and energy generated by the system are high. The observed decrease in efficiency during summer and autumn months is likely due to the combined effect of high solar insolation and high temperatures. Affirmed by studies ((Sidi, *et al.*, 2016); (Heyine, *et al.*, 2022)).

On Figure 8, it is represented the monthly variation in the daily average of array capture losses and system losses over the reference period. As shown in Figure 8, the array capture losses range from a minimum of 0.08 hours per day (h/day) in December to a maximum of 1.37 h/day in June. System losses vary from a minimum of 0.07 h/day in December to a maximum of 0.09 h/day in June. These results indicate that higher capture and system losses occur during hot months. This is likely caused by a combination of factors, including dust accumulation on the panels and elevated ambient temperatures, both of which can reduce energy production. This affirms the results published in ((Aoun, N, 2020); (Heyine, *et al.*, 2022) and (Sidi, *et al.*, 2016).

As shown in Figures 9 and 10, the performance ratio ranges from a minimum of 77.74% in June to a maximum of 96.33% in December, with an annual average of 86.33%. The capacity factor, on the other hand, varies from a minimum of 16.25% in December to a maximum of 22.46% in April, with an annual average of 19.91%. Other PV plants have reported the following capacity factors and performance ratios: Algeria (Adrar): 20.76% and 71.71% (Aoun, N, 2020), Morocco (Tangier): 14.84% and 58-98% (Attari, Elyaakoubi, & Asselman, 2016), India (Ramagundam): 17.68% and 86.12% (Kumar & Sudhakar, 2015) , and Oman (Muscat): 21% and 84.6% (Al-Badi, 2018).

These results indicate that the plant's performance ratio is higher in December, January, and February due to lower ambient and cell temperatures. Conversely, the capacity factor is lower in winter compared to other months because the increased daylight hours have a greater impact on the total energy generated by the system. Consequently, PV systems tend to have a higher performance ratio and a lower capacity factor in winter compared to other seasons.

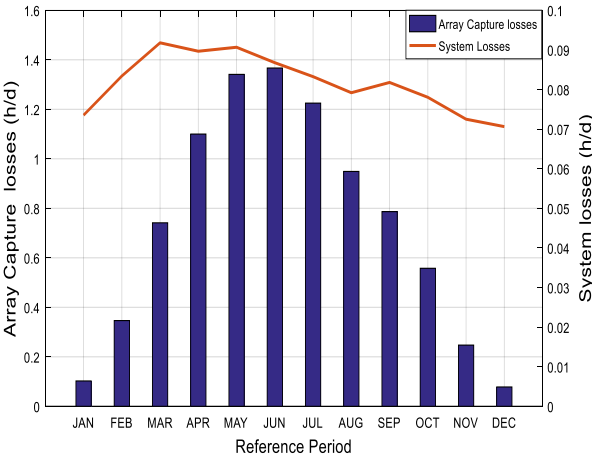


Fig 8. Distribution of the monthly variation of daily average of losses

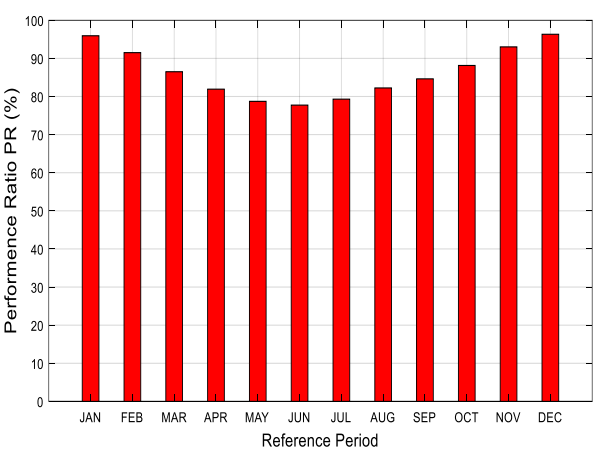


Fig 9. Monthly variation of the performance ratio

3.3 Comparison with Other Studies

The performance of the Kiffa photovoltaic power plant depends on three key factors: the specific environmental conditions of southeastern Mauritania, the photovoltaic module technologies employed, and the plant's system configuration.

In the context of the analysis and evaluation of photovoltaic system performance, we have selected the following parameters, considered to be the most influential: Final yield, performance factor, capacity factor, photovoltaic system efficiency, and inverter efficiency. In order to put the results obtained into perspective, we compared the performance of our plant with that of other studies carried out in different regions, based on the aforementioned parameters. Table 4 summarizes this comparison and highlights the performance of our plant compared to existing grid-connected photovoltaic plants described in the literature.

Based on the comparison of results presented in Table 4, this study achieved a high-performance factor. However, the final yield and capacity factor were comparable to those reported in other studies. These results highlight the dependence of photovoltaic system performance on the climatic conditions of the site and the type of photovoltaic technology used.

One standout aspect is Kiffa's performance ratio. Despite having a lower capacity factor compared to some other plants, Kiffa efficiently converts available solar radiation into usable electricity. This suggests good plant operation and maintenance

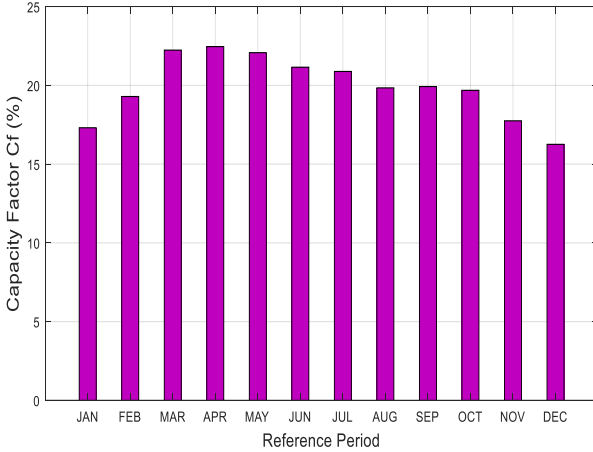


Fig 10. Monthly distribution of capacity factor

Table 4
Performance comparison of the studied plant with other grid-connected PV installations

Location	PV module technology	Installed Capacity (kWp)	Finale Yield kWh/kWp /day	PV efficiency (%)	Inverter efficiency (%)	PR%	Cf%	Monitoring period	Reference
India	p-Si	10MWp	1.96-5.07	13.3	97	86.12	17.68	One year	(Kumar & Sudhakar, 2015)
Errachidia-Morocco	m-Si	2.04	5.31	15.52	-	82.24	-	three years	(Bouaichi, El Amrani, Ouhadou, Lfakir, &
	p-Si	2.04	5.32	15.52	-	82.54	-	three years	Messaoudi, 2020)
	a-Si	1,86	5.28	10	-	81.63	-	three years	
Nouakchott-Mauritania	a-Si, μ a-Si	15MWp	2.95-4.94	-	98.6	63.59-73.56	11.74-20.54	One year	(Sidi, <i>et al.</i> , 2016)
Olmedilla de Alarcón-Spain	m-Si, p-Si	50MWp	4.28	-	-	79.24	19.77	One year	(Fuster-Palop, Vargas-Salgado, Ferri-Revert, & Payá, 2022)
Crete-Greece	p-Si	171.36	1.96-5.07	15	-	67.36	15.26	One year	(Kymakis, E; Kalykakis, S; Papazoglou, T M, 2009)
Nouakchott-Mauritania	p-Si	50MWp	5.28	13.78-14	65.84-79.75	64.1-78.9	-	One year	(Heyine, <i>et al.</i> , 2022)
Muscat-Oman	m-Si	1.4	6.36	17.2	91	84.6	21	One year	(Al-Badi, 2018)
Adrar-Algeria	p-Si	20MWp	4.39-5.56	15.1	-	71.71	20.76	One year	(Aoun, N, 2020)
Tangier-Marocco	p-Si	5	1.96-6.42	15.2	96	58-98	14.84	One year	(Attari, Elyaakoubi, & Asselman, 2016)
Adrar-Algeria	m-Si	1.75	2.12-4.71	10.88-11.84	94.65-97.79	76.5-80.2	-	One year	(Dabou, <i>et al.</i> , 2016)
Dublin- Ireland	m-Si	1.72	2.4	14.9	89.2	81.5	-	One year	(Ayompe, Duffy, McCormack, & Conlon, 2011)
Louisiana-USA	CIGC	20.28	3.81	9.5	-	79	16.08	One year	(Veerendra Kumar, <i>et al.</i> , 2022)
Lesotho	m-Si	281	4.17	10.93	87.75	67	17.2	8 months	(Mpholo, Nchaba, & Monese, 2015)
Adrar-Algeria	p-Si	6MWp	5.15	11.39	-	73.7	21.44	One year	(Dahbi, Aoun, & Sellam, 2021)
Kiffa-Mauritania	p-Si	1.3MWp	3.97-5.48	13.41	98.31	86.33	19.91	One year	This study

practices. Muscat stands out for its exceptionally high final yield, likely due to its geographical advantage and abundant sunshine. This highlights the significant impact of solar irradiation on plant performance. Louisiana's lower final yield, compared to most crystalline silicon plants, is likely due to its use of CIGS technology. While CIGS offers advantages, it generally has lower efficiencies than crystalline silicon. Despite a lower capacity factor, Kiffa's high performance ratio suggests efficient plant operation and potential advantages in design or maintenance practices compared to other locations.

3.4 Environmental and Technological Considerations

The Kiffa Hybrid Power Plant plays a crucial role in reducing environmental pollution by exploring solar energy sources instead of conventional fossil fuels. By producing nearly 2.3 GWh of clean electricity in 2021, it has saved over 550 tons of fossil fuels, significantly reducing greenhouse gas emissions and improving air quality, particularly in a region heavily impacted by climate change. Strategically located in a remote desert area, approximately 13 kilometers from the city of Kiffa, the power plant minimizes any potential impact on natural habitats or agricultural areas. Additionally, the plant's design and operations prioritize environmental sustainability, with a focus on water conservation. By using a waterless cleaning solution for the photovoltaic panels, the plant significantly reduces its water consumption, ensuring a minimal impact on local water resources.

The Kiffa hybrid power plant faced significant energy constraints due to its location in an arid, subtropical region. The photovoltaic component was particularly affected by seasonal variations in solar irradiation, resulting in fluctuating energy production throughout the year, as shown in Figures 4 and 5. Additionally, high temperatures and intense solar radiation, especially during summer months, reduced the efficiency of photovoltaic modules, while dust accumulation further decreased energy output, as illustrated in Figure 7.

However, the combination of solar and thermal energy enabled the plant to contribute significantly to grid stability. The thermal component provided a constant baseload, while the photovoltaic component offered a variable, intermittent source of power. This complementarity mitigated production fluctuations and provided a more stable and reliable electricity supply to the cities of Kiffa and Guerou. These results make the Kiffa plant a promising solution for meeting the growing demand for electricity in arid regions.

To optimize the efficiency and sustainability of the Kiffa hybrid power plant, while aligning with Mauritania's overall energy strategy and leveraging the potential of innovative gas projects such as the Grand Tortue Ahmeyim (GTA) project, approved for development in 2018, and aiming to become a major player in green hydrogen (BP, 2023), it is proposed to implement an ambitious technological strategy. This strategy, based on the latest technological advancements, foresees the integration of advanced monitoring systems, particularly within the photovoltaic component to significantly increase energy production by continuously adjusting solar panel orientation, the adoption of cleaner combustion technologies, the deployment of energy storage batteries, and the exploitation of green hydrogen. These innovative solutions, combined with the development of the GTA project, will enable the Kiffa power plant to become a model of flexibility and energy sustainability, thereby addressing the challenges of the energy transition.

4. Conclusion

Our analysis of the Kiffa Hybrid Power Plant's photovoltaic components in Mauritania utilized 2021 monitoring data to provide a detailed performance evaluation. The findings painted a nuanced picture, revealing both strengths and areas for potential improvement. Notably, the final yield, array yield, and performance ratio all peaked during winter months. This demonstrated the plant's capability for efficient energy

production under favorable temperature conditions. The analysis revealed that despite experiencing efficiency reductions in hot weather, the system, module, and inverter efficiencies remained within acceptable ranges. This indicated a well-designed overall system. However, higher ambient temperatures significantly impacted energy production, even with good solar radiation. The study further revealed significant seasonal fluctuations in yield and performance ratio due to temperature variations. The study also revealed that capture and system losses were highest during hot months, likely due to dust accumulation and high ambient temperatures. Despite these challenges, the Kiffa PV plant offered valuable insights for integrating renewable energy into Mauritania's national grid. The analysis demonstrated the plant's potential to significantly reduce reliance on fossil fuels and greenhouse gas emissions.

Our analysis not only highlighted areas for improvement at the plant level but also underscored the importance of supportive energy policies for large-scale renewable energy integration in Mauritania. This study demonstrated that policies incentivizing advanced cooling technologies, dust mitigation strategies, and energy storage solutions could have significantly enhanced the performance and economic viability of future photovoltaic projects. By implementing such policies, Mauritania could accelerate its transition to a cleaner and more sustainable energy future.

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Nomenclature

E_{AC} , E_{PV}	: Energy output from the inverter and PV array (kW/h)
H_t	: Horizontal irradiation in (kW/m ²).
H_R	: Global irradiation at STC (1kW/m ²).
H	: insolation (kWh/m ² /d)
I_{mp}	: nominal current (A)
I_{sc}	: short-circuit current (A)
L_c , L_s	: capture and system losses (h/d)
P_m	: maximum power output (W)
P_{nom}	: nominal power (W)
PR	: performance ratio (%)
Cf	: capacity factor (%)
T_{amb} , T_{cell}	: ambient and Cell temperatures (°C)
V_{mp}	: nominal voltage (V)
V_{oc}	: open circuit voltage (V)
Y_a	: array yield (kWh/d)
Y_r	: reference yield (h/d)
Y_s	: system yield (h/d)
η_{sys}	: system efficiency (%)
η_{pv}	: PV module efficiency (%)
η_{inv}	: inverter efficiency (%)
RMSE	: root mean squared error (%)

Acronyms

PV	: photovoltaic
WT	: wind turbine
SH	: hybrid systems
p-Si, m-Si	: mono and polycrystalline
a-Si, μ a-Si	: amorphous and micromorph silicon
CIGS	: copper indium gallium selenide
STC	: standard test conditions
IEA	: International Energy Agency
IEC	: International Electrotechnical Commission
PRSP	: Poverty Reduction Strategy Paper
GTA	: The Grand Tortue Ahmeyim
BP	: British Petroleum
ONS	: the National Statistics Office

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