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# Determination of the Performance Scores of a Photovoltaic Power Plant Connected to the Grid: The Zagtouli Photovoltaic Power Plant in Burkina-Faso

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## Abstract

Photovoltaic solar energy is still in its infancy in Burkina Faso, despite the country's high solar potential. The electricity grid is experiencing an increase in demand for energy, creating a shortfall in supply. The Zagtouli photovoltaic solar power plant in Burkina Faso is the first milestone in the development of renewable photovoltaic energy, with a rated output of 33.6 Megawatts peak, to strengthen the electricity grid by reducing hydrocarbon consumption. The aim of this work is to evaluate the performance of the plant by proposing a performance score for the Zagtouli plant, which should provide a basis for assessing the performance of a power plant. To meet the objectives, we collected data for three consecutive years of production, from 2019 to 2021. From this data, we used the method based on the calculation of the performance indicators specified by the International Energy Agency (IEA) and described in the standardised norms IEC (International Electrotechnical Commission) CEI61724, and we also carried out a performance classification using the K-Means method. It is clear that with the results obtained for the PR performance index (over 70%), the installation can be classified as one of the best-performing systems. It also emerges that various losses (temperatures on the panels, cabling, partial shading, spectral losses, dirt, and unexpected inverter failures) have a negative impact on the installation's energy production.

## Keywords

Solar Energy, Solar Power Plant, Climatic Parameters, Performance, Classification

## 1. Introduction

Burkina Faso is one of the central countries of the Sahel. Burkina Faso has an arid to semi-arid climate, with savannah, but it is also rich in energy resources [1]. It has no proven oil resources, but the sun and wood energy are the main renewable energy resources, with record levels of sunshine. The Zagtouli photovoltaic solar power plant is the first stage in a vast programme to develop photovoltaic energy in Burkina Faso. The plant's output supplies the entire Zagtouli load-shedding substation [2]. However, the coefficients of performance of the solar panels proposed by the IEC standards make it possible to calculate the performance of the power plant but do not say whether the system is efficient or not [3]. For these reasons, it is important to find a performance score on which we can base the state of performance of the plant by classifying the performance into three classes. To do this, after calculating the different performance coefficients, we will use the K-means method to divide these results into three clusters that will determine the performance of the plant. Cluster 0 identifies a less efficient system, cluster 1 a moderately efficient system, cluster 2 a more efficient system and cluster 2 a very efficient system.

## 2. Materials and Methods

This section describes the method used to assess the actual performance of the power plant, calculate the parameters required for the analysis, and then simulate the various performance indices in Python.

The performance analysis criteria used are those specified by the International Energy Agency (IEA) and described in the standardised norms (International Electrotechnical Commission) IEC617224. These parameters are field efficiency ($Y_a$), final efficiency ($Y_f$), reference efficiency ($Y_r$), performance ratio ($P_R$), system losses ($L_s$) and miscellaneous losses ($L_c$) [4]-[6]. Various performance indices are used to assess the performance of a solar photovoltaic power plant at actual operating sites. These indicators are physical quantities defined as follows:

✓The efficiency of the generator ($Y_A$) is defined as the ratio between the daily, monthly or annual direct current (DC) energy production of the photovoltaic array and the rated power of the array, $E_{DC}$ is the total DC energy production by the panels (kWh) and $P_{PV}$ the rated output power of the photovoltaic system (kW) [3].

$$Y_A = \frac{E_{DC}}{P_{PV}} \tag{1}$$

✓The final yield of the photovoltaic field ($Y_F$) defined as the quotient of the total AC energy ($E_{AC}$) during a given period over the nominal power of the photovoltaic field ($P_{PV}$) [4]. Here $P_{PV}$ is equal to 33.696 MWp.

$$Y_F = \frac{E_{AC}}{P_{PV}} \tag{2}$$

✓The reference yield ($Y_R$) is the ratio between the total solar radiation in the plane of the modules and the reference irradiance under standard test conditions (STC). This parameter represents the number of hours during which the irradiance is equal to the reference irradiance [5] [6]. Where $S_R$ is the total irradiance on the plane of the panels in kWh/m² and $H_R$ gives the STC reference irradiance *i.e.* 1 kW/m².

$$Y_R = \frac{S_R}{H_R} \tag{3}$$

✓The PR is the ratio between the final energy yield of the photovoltaic installation and the reference yield. It provides information on the overall losses incurred in converting direct current into alternating current. It therefore represents the percentage of energy actually available after deducting energy losses [7]-[10].

$$PR = \frac{Y_F}{Y_R} \tag{4}$$

✓The efficiency of the photovoltaic array ($\eta_{PV}$) is the ratio of the total energy generated by the PV rows ($E_{DC}$) to the product of the amount of irradiation on the plane of the panels and the overall surface area of the photovoltaic array ($A_{pv}$).

$$\eta_{PV} = \frac{E_{DC}}{S_R \times A_{PV}} \times 100 \tag{5}$$

✓The overall conversion efficiency of the photovoltaic system ($\eta_{sys}$) is defined as the energy output of a photovoltaic array divided by the total solar insolation in the plane of the panels.

$$\eta_{sys} = \frac{E_{AC}}{S_R \times A_{PV}} \times 100 \tag{6}$$

✓System losses $L_s$ are due to inverter conversion losses (DC-AC) and are defined by the difference between field efficiency ($Y_A$) and final efficiency ($Y_F$).

$$L_s = Y_A - Y_F \tag{7}$$

✓Miscellaneous losses ($L_c$) are defined by the difference between the reference yield and the yield of the PV array. They represent losses due to: Panel temperatures, cabling, partial shading, spectral losses, soiling, errors in finding the maximum power point, conversions (DC-AC), etc.

$$L_c = Y_R - Y_A \tag{8}$$

✓The efficiency of the installation can be assessed on the basis of the separate efficiencies of the PV array, the system and the inverter.

✓The k-means algorithm consists of grouping the parameters into k classes that are as homogeneous as possible [11]-[14].

## 3. Results

Meteorological stations installed within the power plant were used to measure meteorological parameters. Daily production data recorded every few minutes were used to analyse the PV plant. **Figure 1** shows the monthly yields $Y_a$, $Y_f$ and $Y_r$

for the PV plant from 2019 to 2021.

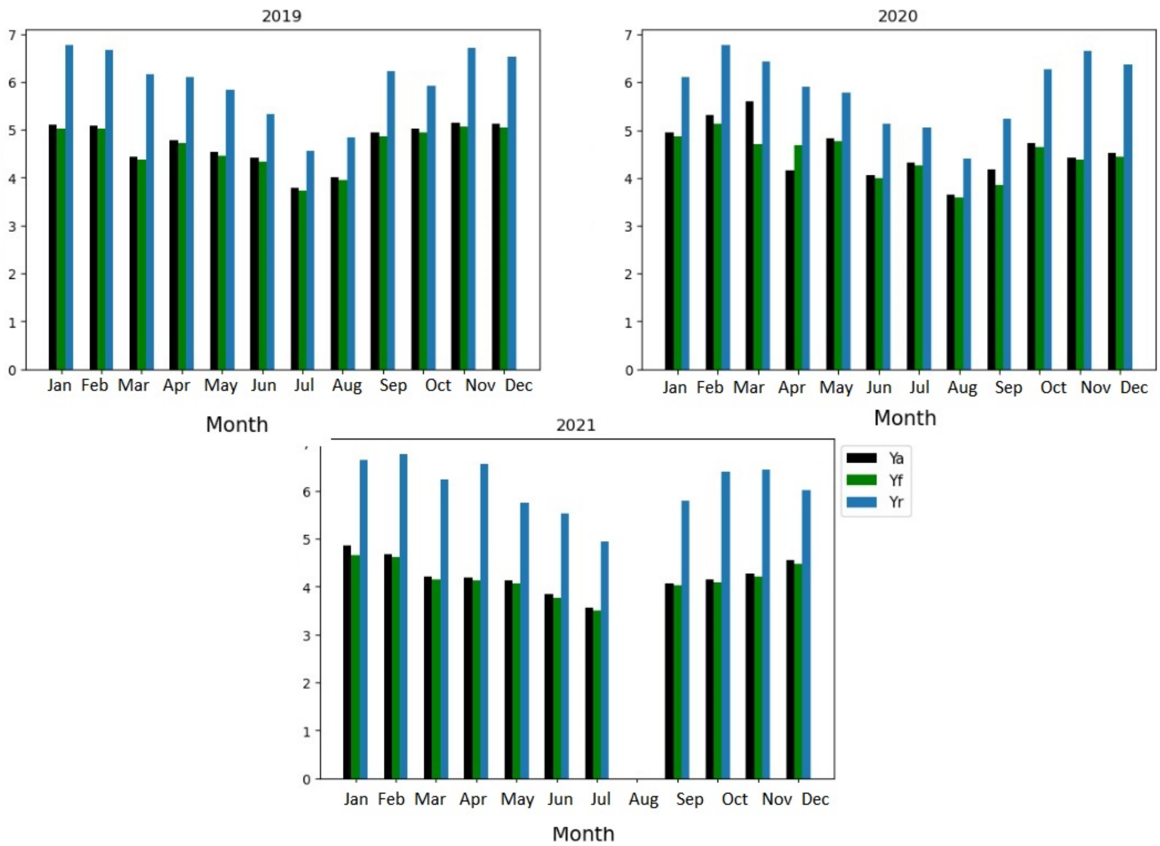



Figure 1. Monthly change in yield $Y_a$, $Y_f$, $Yr$ for the PV plant (2019 to 2021).

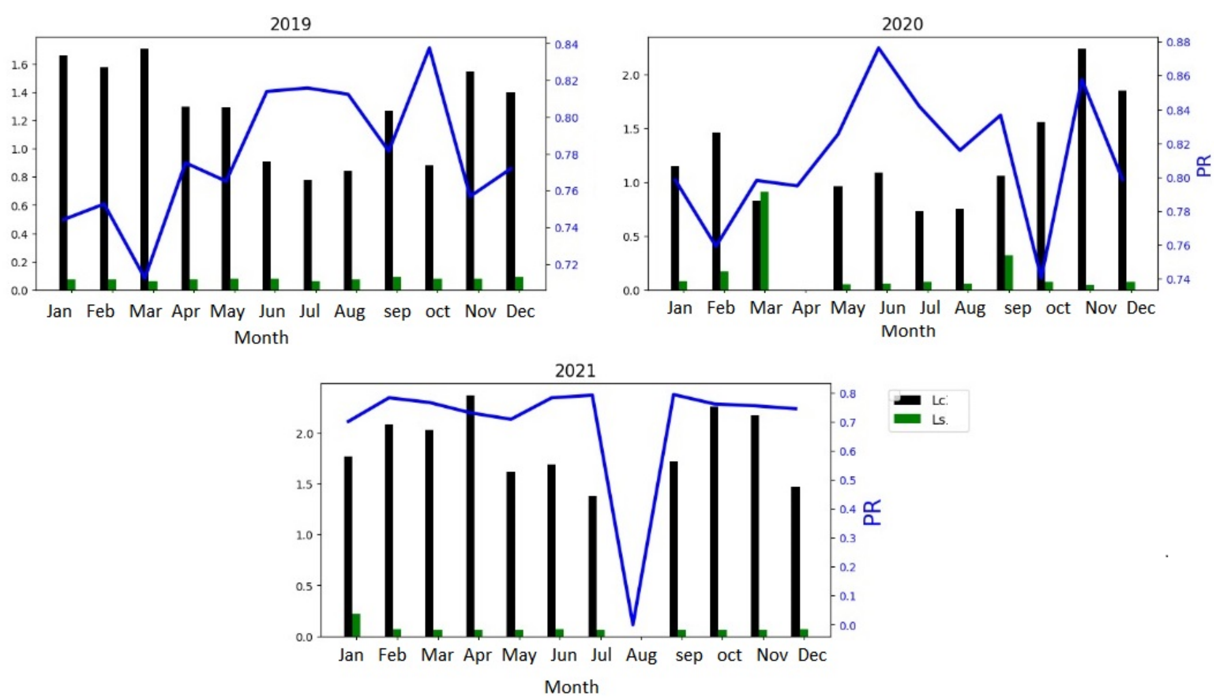
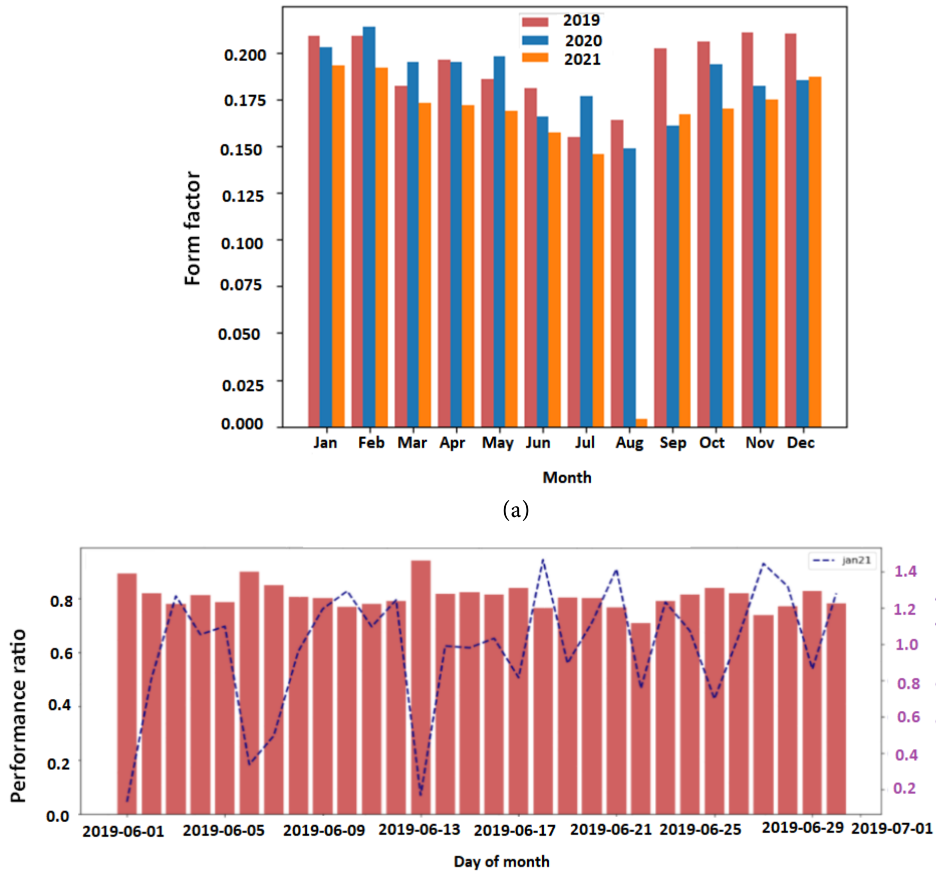



Figure 2. Monthly evolution of the PR and the various losses (Ls and Lc) of PV power plants from 2019 to 2021.

Figure 2 shows the monthly evolution of the PR and the various losses (Ls and Lc) of PV power plants from 2019 to 2021.




(a)

(b)

Figure 3. A histogram of shape factors from 2019 to 2021.

Figure 3 shows a histogram of shape factors from 2019 to 2021.

Figure 4 shows the variation in the daily performance ratio as a function of miscellaneous losses ($L_c$).

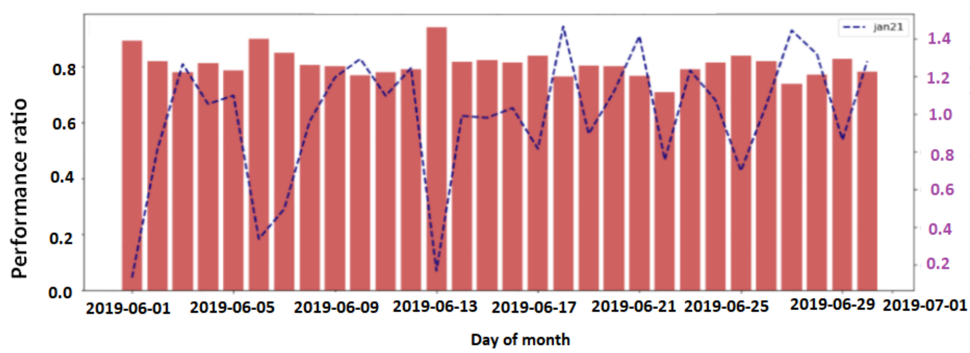



Figure 4. Form factor and other losses (2019).

Table 1 shows the performance score for our power plant for 2019 - 2021.

Table 1. Performance scores for the various parameters.

| Ya [h/j] | Yf [h/j] | Yr [h/j] | PR [%] | $E_{DC}$ [MWh] | $E_{AC}$ [MWh] | Ls [h/j] | Lc [h/j] | $R_{ond}$ [%] | FC [%] | Irr [KW/m²] | T-air [] | HR [kW/m²] | Labels |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5.10 | 5.03 | 6.76 | 0.744083 | 0.051 | 0.050 | 0.07 | 1.66 | 0.980 | 0.209 | 0.199378 | 28.535533 | 10.575598 | 0 |
| 5.09 | 5.02 | 6.67 | 0.752624 | 0.050 | 0.049 | 0.07 | 1.58 | 0.980 | 0.209 | 0.183669 | 30.186552 | 9.249461 | 0 |
| 4.44 | 4.38 | 6.15 | 0.712195 | 0.051 | 0.050 | 0.06 | 1.71 | 0.980 | 0.182 | 0.174488 | 33.439480 | 15.772166 | 0 |
| 4.79 | 4.72 | 6.09 | 0.775041 | 0.052 | 0.051 | 0.07 | 1.30 | 0.980 | 0.196 | 0.178578 | 35.653133 | 28.246810 | 0 |
| 4.54 | 4.46 | 5.83 | 0.765009 | 0.051 | 0.050 | 0.08 | 1.29 | 0.980 | 0.186 | 0.174555 | 33.740001 | 46.751950 | 0 |
| 4.41 | 4.33 | 5.32 | 0.813910 | 0.054 | 0.053 | 0.08 | 0.91 | 0.980 | 0.181 | 0.156456 | 31.366421 | 58.532379 | 2 |
| 3.78 | 3.72 | 4.56 | 0.815789 | 0.055 | 0.054 | 0.06 | 0.78 | 0.980 | 0.155 | 0.131102 | 28.479273 | 72.564594 | 2 |
| 4.01 | 3.94 | 4.85 | 0.812371 | 0.054 | 0.053 | 0.07 | 0.84 | 0.980 | 0.164 | 0.146360 | 27.668277 | 78.134820 | 2 |
| 4.95 | 4.86 | 6.22 | 0.781350 | 0.053 | 0.052 | 0.09 | 1.27 | 0.980 | 0.202 | 0.180646 | 29.668691 | 68.503321 | 0 |
| 5.03 | 4.95 | 5.91 | 0.837563 | 0.055 | 0.054 | 0.08 | 0.88 | 0.980 | 0.206 | 0.181012 | 30.159880 | 63.808980 | 0 |
| 5.15 | 5.07 | 6.70 | 0.756716 | 0.051 | 0.050 | 0.08 | 1.55 | 0.980 | 0.211 | 0.196511 | 32.699487 | 26.066612 | 0 |
| 5.13 | 5.04 | 6.53 | 0.771822 | 0.051 | 0.050 | 0.09 | 1.40 | 0.980 | 0.210 | 0.199834 | 30.099086 | 14.095395 | 0 |
| 4.95 | 4.87 | 6.10 | 0.798361 | 0.053 | 0.087 | 0.08 | 1.15 | 0.960 | 0.203 | 0.189679 | 27.832732 | 14.728955 | 0 |
| 5.31 | 5.14 | 6.77 | 0.759232 | 0.051 | 0.050 | 0.17 | 1.46 | 0.960 | 0.214 | 0.195613 | 30.722343 | 10.567386 | 0 |
| 5.61 | 4.70 | 6.44 | 0.798137 | 0.048 | 0.049 | 0.91 | 0.83 | 0.950 | 0.195 | 0.199342 | 35.223498 | 14.321951 | 0 |
| 4.82 | 4.77 | 5.78 | 0.825260 | 0.053 | 0.054 | 0.05 | 0.96 | 0.960 | 0.198 | 0.173592 | 34.095271 | 43.935813 | 0 |
| 4.05 | 3.99 | 5.14 | 0.876265 | 0.052 | 0.051 | 0.06 | 1.09 | 0.940 | 0.166 | 0.154888 | 31.381866 | 56.970551 | 2 |
| 4.33 | 4.26 | 5.06 | 0.841897 | 0.056 | 0.055 | 0.07 | 0.73 | 0.960 | 0.177 | 0.157868 | 29.304958 | 68.487597 | 2 |
| 3.65 | 3.59 | 4.40 | 0.815909 | 0.054 | 0.053 | 0.06 | 0.75 | 0.940 | 0.149 | 0.136796 | 27.362050 | 78.767796 | 2 |
| 4.18 | 3.86 | 5.24 | 0.836641 | 0.052 | 0.048 | 0.32 | 1.06 | 0.940 | 0.161 | 0.156674 | 28.304205 | 75.275771 | 2 |
| 4.72 | 4.65 | 6.28 | 0.740446 | 0.049 | 0.048 | 0.07 | 1.56 | 0.950 | 0.194 | 0.194994 | 30.260871 | 57.990716 | 0 |
| 4.42 | 4.38 | 6.66 | 0.857658 | 0.043 | 0.043 | 0.04 | 2.24 | 0.950 | 0.182 | 0.199739 | 31.259815 | 22.509313 | 1 |
| 4.52 | 4.45 | 6.37 | 0.798587 | 0.046 | 0.046 | 0.07 | 1.85 | 0.950 | 0.185 | 0.197416 | 28.720683 | 22.314937 | 1 |
| 4.87 | 4.65 | 6.64 | 0.700301 | 0.048 | 0.046 | 0.22 | 1.77 | 0.950 | 0.193 | 0.013789 | 31.921531 | 14.065008 | 0 |
| 4.68 | 4.61 | 6.76 | 0.781953 | 0.045 | 0.045 | 0.07 | 2.08 | 0.950 | 0.192 | 0.175241 | 31.634608 | 10.892815 | 1 |
| 4.22 | 4.16 | 6.25 | 0.765600 | 0.044 | 0.043 | 0.06 | 2.03 | 0.950 | 0.173 | 0.181655 | 34.339777 | 15.008603 | 1 |
| 4.20 | 4.14 | 6.57 | 0.730137 | 0.043 | 0.041 | 0.06 | 2.37 | 0.950 | 0.172 | 0.190142 | 35.837967 | 25.932864 | 1 |
| 4.13 | 4.07 | 5.75 | 0.707826 | 0.042 | 0.046 | 0.06 | 1.62 | 0.950 | 0.169 | 0.173004 | 33.540007 | 47.287519 | 1 |
| 3.84 | 3.77 | 5.53 | 0.781736 | 0.045 | 0.045 | 0.07 | 1.69 | 0.950 | 0.157 | 0.158886 | 30.467929 | 62.172921 | 1 |
| 3.57 | 3.51 | 4.95 | 0.790909 | 0.047 | 0.046 | 0.06 | 1.38 | 0.978 | 0.146 | 0.153480 | 27.939941 | 76.402448 | 2 |
| 4.08 | 4.02 | 5.80 | 0.793103 | 0.044 | 0.043 | 0.06 | 1.72 | 0.970 | 0.167 | 0.174153 | 29.342994 | 70.694695 | 1 |
| 4.15 | 4.09 | 6.41 | 0.760655 | 0.045 | 0.042 | 0.06 | 2.26 | 0.970 | 0.170 | 0.199132 | 32.047010 | 55.644902 | 1 |
| 4.28 | 4.22 | 6.45 | 0.754264 | 0.043 | 0.043 | 0.06 | 2.17 | 0.950 | 0.175 | 0.187972 | 33.114837 | 25.423042 | 1 |
| 4.55 | 4.48 | 6.02 | 0.744186 | 0.049 | 0.049 | 0.07 | 1.47 | 0.970 | 0.187 | 0.185644 | 30.046331 | 15.005391 | 0 |

## 4. Discussion

Simulations of the various performance analysis parameters are shown in Figures

1-4. Figure 1 shows the distribution of monthly field, final and reference yields. The monthly yield of the field ($Y_a$) varies from 3.57 h/d (July 2021) to 5.61 h/d (March 2020) with an average of 4.506 h/d. The final monthly yield ($Y_f$) varies from 3.51 h/d (July 2021) to 5.14 h/d (February 2020) and the reference yield ($Y_r$) varies between a minimum value of 4.4 h/d in August 2020 and a maximum value of 6.77 h/d in the same year. The number of hours of irradiation at the site close to the reference irradiation is approximately 5.9675 h. As for the different losses in Figure 2, the losses by conversion ($L_s$) are stable with an average of 0.075 h/d ranging from 0.06 h/d (March, July) to 0.09 h/d (September, November) during 2019. This shows the performance of the field's inverters in converting DC current into AC current. The same trend can be observed in 2020 (except for March and September, which could be due to a breakdown in some inverters) and in 2021 (except for August), and the various monthly losses ($L_c$) are highly remarkable, with a minimum of 0.78 h/d and a maximum of 1.71 h/d for 2019. However, the performance ratio fluctuates from month to month. In 2019, it is maintained at an average of 77.82%, varying from 71.21% (March) to 83.75% (October). In June, July, August, September and October 2019, the PR was around 81.22%, and miscellaneous losses $L_c$ were 0.936 h/d. These months appear to be favourable for the operation of the power plant because the temperature is falling, coinciding with the arrival of the rainy season. In the months of November, December, January, February, March, April, May and 2019, there was a considerable drop in PR (75.73% on average) due to huge $L_c$ losses (1.47 h/d). These months are characterised by the presence of hot winds (February, March) leading to dust deposits on the modules and high temperatures (April, May) and in 2020 - 2021 the range during these two years is from 70.03% (January 2021) to 87.62% (June 2020) with an average of 78.49%. Figure 3 also shows the plant's monthly form factor (FF), *i.e.*, its ability to operate at full power without interruption. In 2019 - 2020, the load factor varied between 14.9% in August 2020 and 21.4% in February 2020, with an average of 18.87% over the two years. The highest average value was reached in the first year (2019) with a FF of 19.25%. It was lower for the months of June, July and August and coincides with the rainy period, which could be explained by the diminution in the number of hours of sunshine. The lowest load factor values during the two production years are recorded for the months of July 2019 and August 2020, at 15.5% and 14.9%, respectively. In the following year, 2021, the load factor is between 4.0% (August) and 19.3% (January), with an average of 15.87%. The rainy months of June and July have values of 15.7% and 14.6% respectively. Figure 4 shows the variation in daily production as a function of the performance ratio in June 2019. We note that the normalised performance ratio is unstable. It varies between 70% (22/06/2019) and 94% (13/06/2019) with an average of 80%. For this month, PR values below 80% correspond to huge miscellaneous losses, with these energy losses generating an average of 0.985 MWh/d. Finally, Table 1 shows the performance scores for the various parameters studied. Visually, the parameters can be separated into three distinct Label groups:

- A first group (cluster 0): This is the group of parameters with an average ratio of 76.6% with various losses of around 1.365 h/month, considered here as less performing.
- A second group (cluster 1): This is the group of parameters with an average ratio of 77.4% with various losses of around 1.246 h/month, considered here as performing well.
- A third group (cluster 2): This is the group of parameters with an average ratio of 82.5% with various losses of around 0.942 h/month, considered here to be better performing.

## 5. Conclusions

It is important to know the performance of the Zagtouli photovoltaic plant after eight years of operation. To do this, we used the method specified by the International Electrotechnical Commission (IEC) and published in the international standard IEC 61724. The results show that the performance ratio is unstable and is more influenced by various losses while throughout the operating period due to environmental conditions (temperature, dust). However, the conversion losses are stable, which explains why the inverters perform satisfactorily. The performance score allowed you to have the following classes:

-Class 0 (less efficient), we have a PR around 76.6%, an average $L_C$ of 1.36 hours/month and $L_S$ around 0.08 hours/month.

-Class 1 (moderately efficient) with an average PR of 77.4%, an $Lc$ of 1.24 h/d and $L_s$ of 0.06 h/d.

-Class 2 (very efficient) with an average PR of 82.5%, an $L_c$ of 0.94 h/d and an $L_s$ of 0.05 h/d.

These results can constitute a basis for evaluating the performance of other PV plants.

We will then be able to compare these results with others obtained on different sites in order to improve the performance grid that we found.

To optimize our system, we can provide an air cooling system, and an automatic fault detection system linked to DC/AC conversion. For future performance analysis studies, software methods like PVUSA Improved and PVsyst could be used.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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