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Assessing the Efficiency of the Zagtouli Solar Plant: A Large-Scale Grid-Connected PV System in Burkina Faso

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ABSTRACT

This paper presents an evaluation and analysis of the energy performance of a 33.7 MWp solar photovoltaic plant. Monitoring data for 36 months (January 2019-December 2021) have been used to evaluate the performance of the power plant according to the IEC 61724 standard. Normalized parameters that are (i) performance ratio, (ii) reference yield, (iii) array yield, (iv) final yield, (v) array capture losses, (vi) system losses, (vii) system efficiency, and (viii) capacity factor were quantified. During the study period, monthly averages of the normalized yields Y_r, Y_a, and Y_f obtained are respectively 5.81 h/d, 4.59 h/d, and 4.52 h/d with average total losses (T_L) estimated at 1.29 h/d and an average performance ratio (PR) of 78%. In light of this study, more than 80% of array capture losses are related to miscellaneous capture losses. Thus, periods of low production due to a drop in performance are compounded by other external climatic factors. The performance ratio becomes increasingly sensitive to the effect of temperature over time. This study could constitute a decision support tool for solar power plant projects underway at the national level and in the Sudan-Sahelian zone.

Keywords: Performance analysis, Grid-connected, Normalized yields, Sudano-sahelian zone, Zagtouli.

1. Introduction

Energy is one of the main key factors in the development in reason of the socioeconomic and technological advancements that it permits (IEA, 2020). Nowadays, providing energy sufficient for homes, buildings, agriculture, transportation, services and industries in a sustainable manner while securing its availability for future generations is the ultimate challenge for the countries (Académie des Sciences, 2012). Because of the greenhouse gas emissions associated with the use of fossil fuels, their dwindling reserves and the resulting increase in their price, as well as their potential impact on climate change, many countries are reviewing their national energy policies with a view to moving towards renewable and low-carbon energy sources. Burkina Faso, like countries of the West African sub-region, is not on the sidelines of this context. Utilizing Burkina Faso's renewable resource potential would allow the country to reduce its heavy dependence on thermal power generation and energy imports. Among various forms of renewable energy such as wind power, bioenergy and others, photovoltaic (PV) energy occupies a prominent place due to many particularities (Amani et al., 2016; Kuik et al., 2019). Rapid technological developments make use of grid-connected photovoltaic systems simple, efficient and cost-effective. Associated with production cost reductions and economic incentives, photovoltaic energy is therefore playing an increasing occupying an increasing choice in renewable energy sources. As a result, the global cumulative capacity of installed PV systems has increased rapidly from about 72.04 GW in 2011 to 707.50 GW at the end of 2020 (Renewable & Agency, 2021). Between 2010 and 2018 corresponding to an eight-year period, the levelized cost of energy (LCOE) of photovoltaic solar would have decreased by 77% (Zhang et al., 2022). As a Sahelian country, Burkina Faso has advantageous solar radiation conditions. Its sunshine is estimated 5-6 kWh/m²/d for 3000 to 3500 hours per year(Sawadogo et al., 2020). Then, solar energy is expected to contribute substantially to increasing the part of the energy mix. According to data from operating solar photovoltaic projects, Burkina Faso's solar energy potential is estimated at about 95.9 GW with an installation density of 50 MW per square kilometre (IRENA, 2021). Also, according to the International Renewable Energy Agency (IRENA), Burkina PV capacity increased from 6 to 62 MWp between 2011 and 2020 (Renewable & Agency, 2021). The government of Burkina Faso is aiming for 30% of the country's electricity consumption to come from solar power by 2025. Eighteen (18) solar energy projects are currently underway, with the aim of adding more than 700 MWp of photovoltaic solar energy to the country's electricity production(PNDES-II, 2021). The ambition is to increase national available electrical power from 712.2 MW in 2020 to 1500 MW in 2025(PNDES-II, 2021). It's therefore important and imperative for the country to prepare and accumulate experience with grid-connected PV, the subject of the present study. This is the background to the present study. General objective of this is to determine the performance of a large-capacity PV plant connected to the grid in real operating conditions. Although the performance evaluation of a photovoltaic system can be realized using simulation (software) tools such as PV SYST, solar GIS-PVthat conducted in situ remains the best method (Bermudez-Garcia et al., 2021; Gunen, 2021).Usually, the performance of photovoltaic modules is evaluated according to Standard Test Conditions (STC), which are not always representative of their real operation (Zhang et al., 2022). Photovoltaic module technology, weather conditions (incident radiation), environmental conditions (ambient temperature, aerosols, cloud passages, and shading), tilt, inverter and control systems, sun-tracking system and cabling are all factors that influence the performance of a photovoltaic system(Marion et al., 2005).It’s therefore necessary to study the behavior of these solar installations according to their operating area. Thus, several studies have been conducted to present energy performance of large and small grid-connected solar PV systems in their operating areas (Aoun, 2020; Dahbi et al., 2021; Dahmoun et al., 2021; Elhadj Sidi et al., 2016), (Dabou et al., 2021; Daher et al., 2018; Med YAHYA et al., 2021; Purohit & Purohit, 2018; Quansah et al., 2017; Tahri et al., 2018). A recent study by Mouhcen El-Hadi Dahmoun et al. evaluated and analyzed the performance of a large-scale 23.92 MWp photovoltaic power plant connected to the Algerian electrical grid. Total annual energy production was 43,261.4 MWh. The final yield was around 5.46 kWh/kWp/d with an annual average of PR and CF of 82.02% and 20.64% respectively(Dahmoun et al., 2021). In Mauritania, the performance of a 15 MWp photovoltaic power plant was evaluated by Cheikh El Banany Elhadj Sidi et al. (Elhadj Sidi et al., 2016). It appears that the parameters that seem to be most influenced in the analysis of the performance of photovoltaic systems are performance ratio (PR), field yield (Y_a) and final yield (Y_f). They confirm that the performance of such a system doesn’t only depend on irradiation, but also on the environmental conditions of the region where the system is installed (Elhadj Sidi et al., 2016). Lutero Carmo de Lima et al analyzed the performance of a 2.2kWp PV installation in Brazil between June 2013 and May 2014. Reference yield, array yield and final yield are respectively in the order of 5.6 kWh/kW, 4.9 kWh/kWp and 4.6 kWh/kWp with a performance ratio of 82.9% and a capacity factor of 19.2%(Lima et al., 2017). However, very few studies present an evaluation and analysis of PV installation performance installed in the Sudano-Sahelian environment. On the other hand, most studies related to this issue are carried out on small installations and on an average duration of one year (Dabou et al., 2021; Quansah et al., 2017) (Daher et al., 2014; de Lima et al., 2017; Kymakis et al., 2009; Lima et al., 2017; Macêdo & Zilles, 2009; Med YAHYA et al., 2021; Milosavljević et al., 2015; Sahouane et al., 2019). This article, it presents the evaluation and analysis of energy performances of a strong solar plant of 33,7 MWp located in a zone of type Soudano-Sahelian precisely in Burkina Faso. Monitoring data for a period of 36 months (2019-2021) such as energy output, wind speed, solar irradiation, relative humidity, ambient and cell temperature were collected in order to characterize actual performance of the installation, such as reference yield, array yield, final yield, performance ratio, system losses, array capture losses, total losses, capacity factor, system efficiency. Following this introduction section, the paper is structured as follows: section 2 summarizes materials and method used in this study, the section 3 describes the results and discussion and the last section summarizes the main conclusion.

2. Methodological Approaches and Materials

2.1. Study Area Description

The studied solar plant is located at Zagtouli (12°18'33.3"N, 1°38'27.7"W) which is situated southwest of Ouagadougou, capital of Burkina Faso. This solar power plant covers an area of 60 hectares with a capacity of 33.7 MWp. Its production represents 4% of the annual electricity consumption in Burkina Faso. An aerial view of the Zagtouli solar plant is shown in Figure 1.

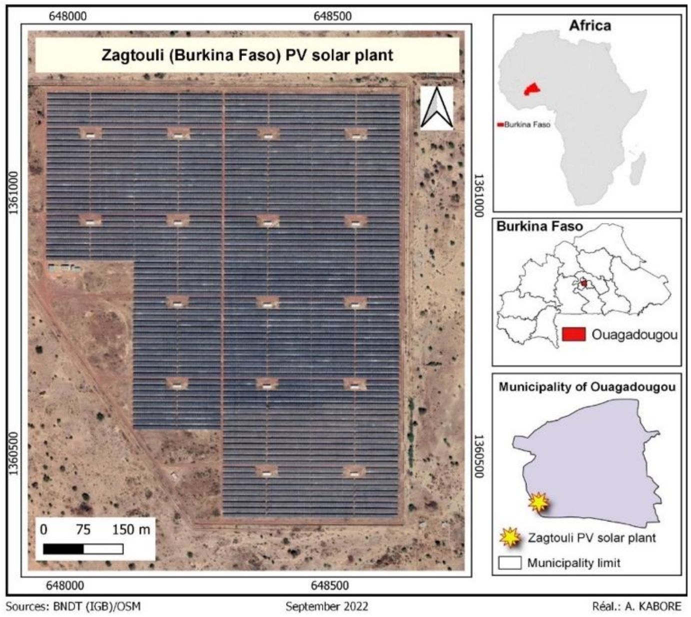

Figure 1: Aerial view of Zagtouli solar PV plant

In this PV solar plant, four (04) weather stations continuously measure the meteorological parameters. Three of these four weather stations are inclined along the plane of the solar modules and the fourth is on the horizontal plane. Each station includes a pyranometer, anemometer, and thermocouples for measuring solar irradiation, wind speed, air temperature and PV cell temperature. For the collection and recording of meteorological data, RS-485, Ethernet and fiber optic protocols are used. The meteorological data measurement devices are shown in Figure 2.

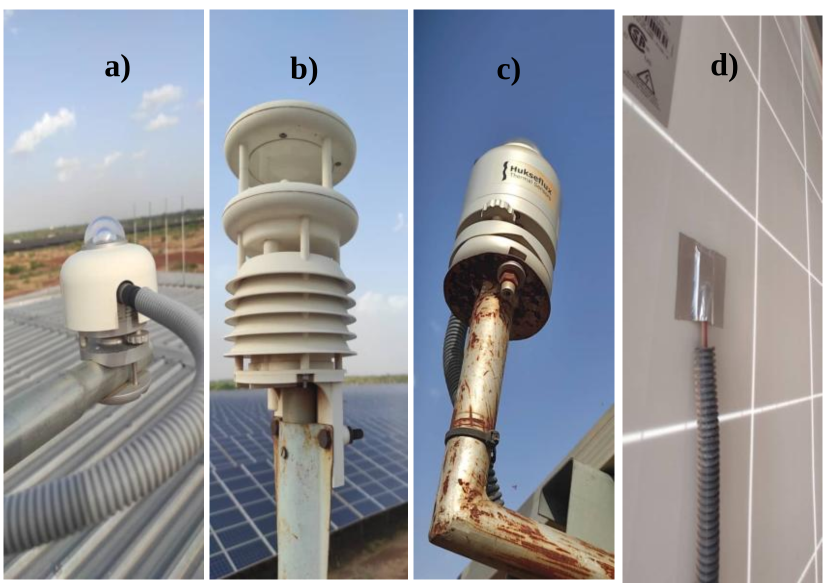

Figure 2: Meteoequipments: a) Pyranometer b) Anemometer c) Pyranometer d) Thermocouple

2.2. Description of Zagtouli Solar Power Plant

The solar array covers about 51 hectares. It consists of 129600 PV modules of 260 Wp in polycrystalline, 1800 structures of 72 modules in parallel, 5400 chains of 24 modules in series, 466 string combiner boxes and the produced energy is injected on a 33kV electrical grid. The PV modules are oriented toward the south and tilted at an angle of 15° and their technical characteristics under standard conditions (STC) are given in Table 1. The integrated PV centres are containers divided into three compartments: (i) an inverter compartment containing two central inverters of 1.1 MW of ingecon sun powermax brand, (ii) a LV/HV transformer with a rated power of 2330 kVA and (iii) a HV compartment made up of three 36 kV compact cells of Siemens brand. Tables 2 and 3 show inverters and transformers technical characteristics, respectively. Integrated photovoltaic center are grouped into three loops of six feeders which are grouped at solar substations as shown in Figure 3.

Table 1: Modules technical characteristics

Technical characteristics of PV modules		
Electrical characteristics	Power at maximum power point	260 Wc
	No-load voltage	37.6 V
	Voltage at maximum power point	30.8V
	Short circuit current	9.06 A
	Current at point of maximum power	8.54 A
	Module efficiency	15.51%
Thermal characteristics	NOCT (Normal Operating Cell Temperature)	46 °C
	Temperature coefficient of current	0.051%/°C
	Temperature coefficient of voltage	-0.31%/°C
	Temperature coefficient of power	-0.41%/°C

Table 2: Inverters Technical characteristics

	Brand	**INGECON SUN 1165TL B420**
Input	Recommended PV power range	1 178-1513,2 kWc
	MPP voltage range	610-820V
	Max voltage	1050 V
	Max current	2000A
	Number of inputs with fuse holder	5-15
	MPPT (Maximum Power Point Tracking)	1
	Power block	1
Output	Power 35 °C/50 °C	1163,9 kVA/1071 kVA
	Current 35 °C/50 °C	1600A/1472
	Nominal voltage	420 V
	Nominal frequency	50/60 Hz
	Maximum efficiency	98,9%
	Operating temperature	-20 °C à +65 °C

Table 3: Technical characteristics of the transformers

Technical characteristics	
Rated power	2 330 kVA
Rated no-load voltage	420 V/33000 V
Cooling current	3203 A/41 A
Insulation level	1,1 kV/36,0kV
Rated frequency	50 Hz
Daily ambient temperature limit	50 °C
Number of phases	3
Number of windings	2
Max. short circuit time	2 s

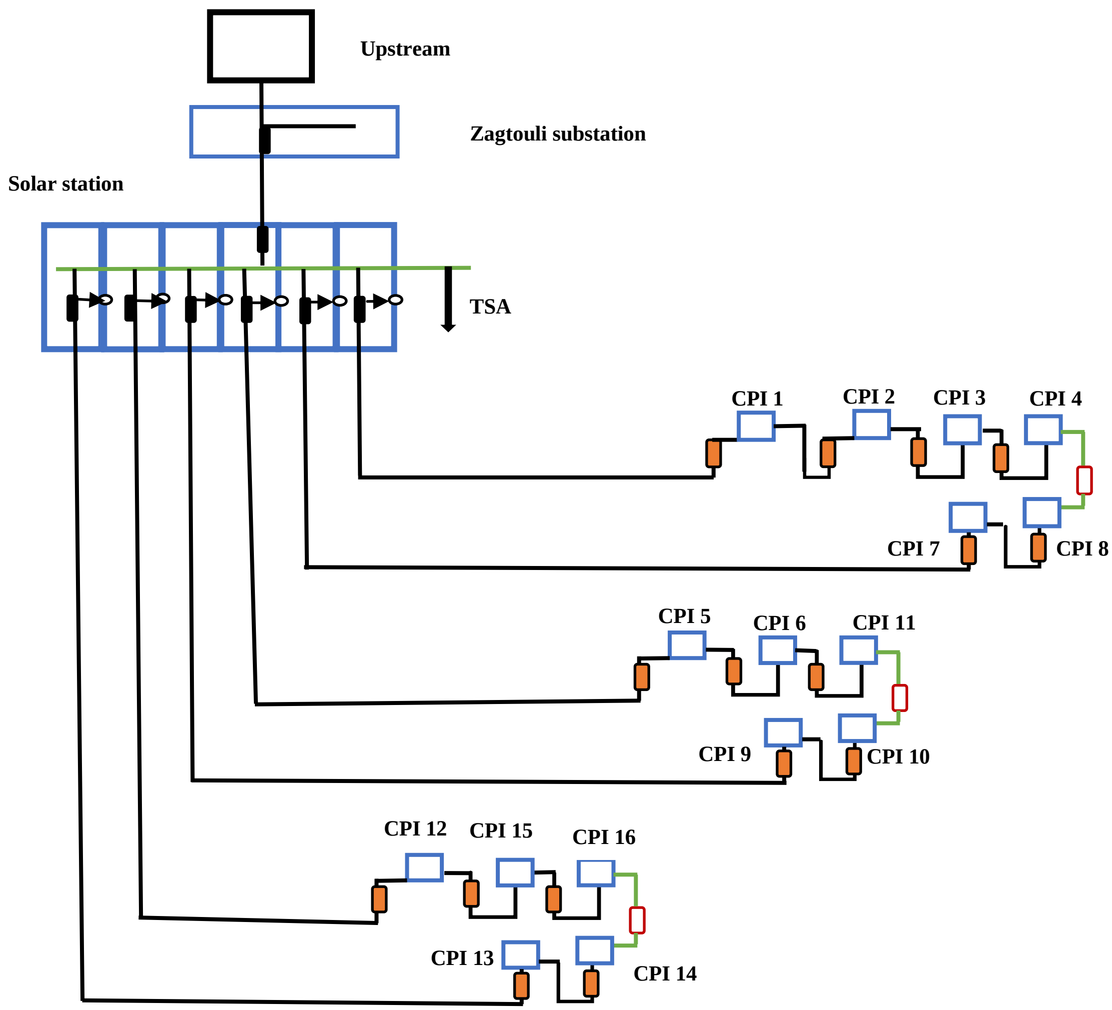

Figure 3: Distribution loop

2.3. Data Collection

RS-485, Ethernet and optic fiber devices were used to collect and record meteorological data. Daily production (DC and AC energy) and meteorological data such as solar irradiation, wind speed, air temperature, solar cell temperature and relative humidity covering the analysis period were collected via the plant's Supervisory Control And Data Acquisition (SCADA) system.

2.4. Data Processing and Analysis

The performance parameters are those that allow us to determine the performance of the overall PV system with respect to its energy production solar resources, and the overall effect of its losses(Daher et al., 2014). These parameters have been specified by the International Energy Agency (IEA) and are described in the International Electrotechnical Commission (IEC) 61724 standard for the evaluation of energy performance of a solar PV system(IEC61724, 1998). Daily production data (DC and AC energy), and weather data such as solar irradiation, wind speed, air temperature, module temperature, and relative humidity covering the period of analysis were collected in SCADA system. Reference yield, array yield, final yield, performance ratio, system losses, array capture losses, total losses, capacity factor, and system efficiency are performance parameters that have been quantified according to the equations presented in table 4.

Table 4: Normalized performance parameters

Parameter	Description	Formula	Unit	Ref.
Reference yield	Reference yield is the ratio of insolation arriving at the surface of Zagtouli PV solar panels (H_z) to the reference irradiance in STC conditions G_0(1kW/m2).	$Y_r = \frac{H_z}{G_0}$	h/d	(Ketjoy et al., 2013)
Corrected reference Yield	It's the reference yield corrected by the effect of the PV module operating temperature. γ: the temperature coefficient, T_c: PV cell temperature(°C), T_a: STC Temperature (25°C).	$Y_{cr} = Y_r\left(1 - \gamma(T_c - T_a)\right)$	h/d	(Elhadj Sidi et al., 2016)
Array yield	It's the ratio of total energy generated E_{DC} (kWh) by the PV arrays for a defined period of time (day, month, or year) to the rated power Pc (kWp) of the arrays under standard conditions (STC: irradiance: 1000 W/m^2, 25°C ambient temperature, and reference spectrum AM 1.5).	$Y_a = \frac{E_{DC}}{P_c}$	h/d	(de Lima et al., 2017; Elhadj Sidi et al., 2016)
Final PV system yield	It's the total energy produced by PV system, E_{AC} (kWh) relative to the installed nominal power Pc at STC(kWp).	$Y_f = \frac{E_{AC}}{P_c}$	h/d	(Elhadj Sidi et al., 2016)
Performance Ratio	PR values indicate how close a PV system is to ideal performance under actual operating conditions.	$PR = \frac{Y_f}{Y_r}$	%	(IEC61724, 1998)
System losses	Losses system are due to the conversion losses of the inverters	$L_S = Y_a - Y_f$	h/d	(Chouder &

Parameter	Description	Formula	Unit	Ref.
	(DC-AC)			Silvestre, 2010)
Array capture losses	They represent the sum of thermal capture losses, L_{ct}, and miscellaneous capture losses, L_{cm}. It's all the losses that occur during operation of the PV modules.	$L_c = Y_r - Y_a$	h/d	(IEC61724, 1998)
Miscellaneous capture losses	They represent losses associated with multiple causes such as the Joule effect in the wiring; diodes losses; shading effects; inhomogeneous or low irradiance; snow, contamination or dirt accumulation; mismatch and maximum power tracking error.	$L_{cm} = Y_{cr} - Y_a$	h/d	(B. S. Kumar & Sudhakar, 2015a)
Thermal capture losses	They represent losses caused by cell temperature higher than 25 °C	$L_{ct} = Y_r - Y_{cr}$	h/d	(B. S. Kumar & Sudhakar, 2015a)
Total losses	They are the sum of capture losses and system losses	$L_T = L_s + L_c$	h/d	(IEC61724, 1998)
System efficiency	It can be grouped into PV array efficiency, system efficiency and inverter efficiency.	$\eta_{sys} = \frac{E_{AC} x 100}{H_t x A_z}$	%	(Heyine et al., 2022)
PV array efficiency	PV generator efficiency η_{PV} represents the average energy conversion efficiency of the PV generator.	$\eta_{PV} = \frac{E_{DC} x 100}{H_t x A_z}$	%	(Al-aboosi & Al-aboosi, 2021)
Capacity factor	It's the ratio of the AC energy produced by the PV system over a given period of time (typically one year) to the energy production that would have been generated if the system had been operating at full capacity for the entire period.	$CF = \frac{E_{AC}}{(P_c x 24 x 365)}$	%	(Elhadj Sidi et al., 2016; Quansah et al., 2017)
Inverter efficiency	Inverter efficiency depends on its input voltage to (some inverters operate more efficiently in the upper area of the MPP voltage window, other manufacturers prefer the lower and even some choose the intermediate zone).	$\eta_{inv} = \frac{E_{AC} x 100}{E_{DC}}$	%	(Heyine et al., 2022)

3. Results and Discussions

3.1. Meteorological Data Analysis

Figure 4 shows the evolution in function of time of solar irradiation and air temperature on the plane of the modules and wind speed at Zagtouli PV solar plant site. As results:

1) The solar irradiation, daily average values per month vary between 4.63 and 6.77 kWh/m^2/d recorded respectively in August 2020 and April 2021. An average value of 5.81 kWh/m^2/d is obtained for the three years of monitoring. The sunniest period is going from February to May and a little less, the period going from September to December. The year 2021 was the sunniest with an average daily value per month of 5.94 kWh/m^2/d compared to 5.80 and 5.70 kWh/m^2/d in 2020 and 2019, respectively.
2) the air temperature, the lower and higher average values are 26.4 and 35.2°C measured in August 2020 and April 2021, respectively. The temperature peaks have been observed every April and November. The hottest periods are in agreement with those of the sunniest mentioned previously. For all three years of the study, the average temperature is 30.34°C.
3) The wind speed average values vary from a minimum of 1.74 m/s in October 2020 to a maximum of 2.67 m/s in June 2020. For the whole monitoring period, a wind speed average value of 2.28 m/s is obtained. This result confirms the relative low wind speed in Burkina Faso, especially in country center (Salami et al., 2022).

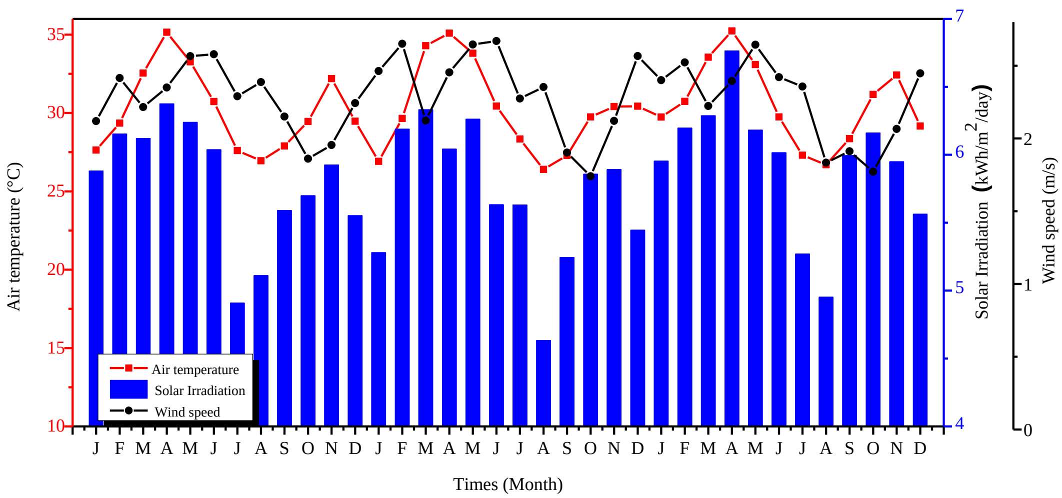

Figure 4: Evolution of daily average values per month of solar irradiation, air temperature and wind speed (The first J corresponds to January 2019 and the last D, December 2021).

3.2. Energy Production Analysis

Figure 5 shows the evolution in the function of time of the daily average of AC electrical energy production, the air temperature and the solar irradiation along the plane of the PV array modules. During the three years of monitoring, a daily average per month of 153 MWh/d of AC electrical energy production has been measured for it was noted that Zagtouli PV solar plant. August months record the lowest values of electrical production of approximately 121 MWh/d. This result can be related to the low daily solar radiation marked by a permanent and very important clouding characterizing the rainy season. Also, this month is characterized by high humidity, 81.39%, 83.26% and 83.19% in 2019, 2020 and 2021, respectively that can cause a decrease in incident irradiance as a result of possible reflections of photons by water vapour in the air due to increased relative humidity (Aoun, 2020)(Gunen, 2021). Despite a high irradiation in the months of April and May, the measured daily average values are lower. Indeed, these months are marked by strong solar radiation, which leads to an ambient temperature increase, which in turn affects photovoltaic cells' temperature, resulting in a decrease in production (Bermudez-Garcia et al., 2021). Also, this period is marked by a high level of aerosol pollution, particularly in the desert (harmattan), resulting in a drop in electricity production despite the advantageous amount of sunshine.

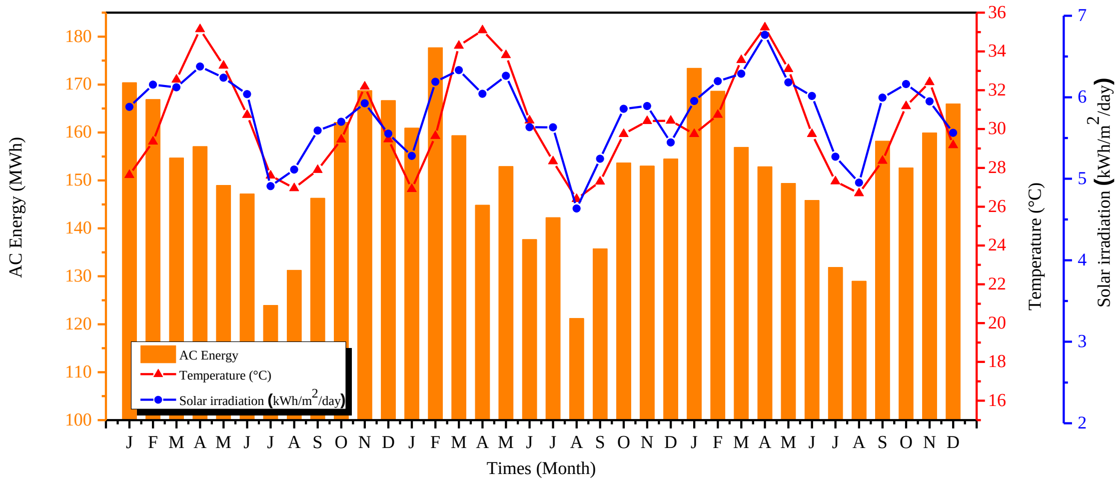

Figure 5: Evolution of daily average values per month of AC energy, temperature and solar irradiance

3.3. Analysis of the Performance Returns Y_r, Y_a and Y_f

Figure 6 shows the evolutions of the daily average values per month of reference (Y_r), array (Y_a) and final (Y_f) yields of Zagtouli PV solar plant. Over the three years of monitoring, the average reference yield of 5.81 h/d was obtained. The array yield (Y_a) varies between 3.65 and 5.35 h/d measured in August 2020 and February 2020, respectively with an average value of 4.59 h/d over the three years of monitoring. The final yield (Y_f) behaviour is similar to that of the array yield because system losses by DC-AC conversion are almost constant and insignificant. This shows that inverters are working under optimal conditions.

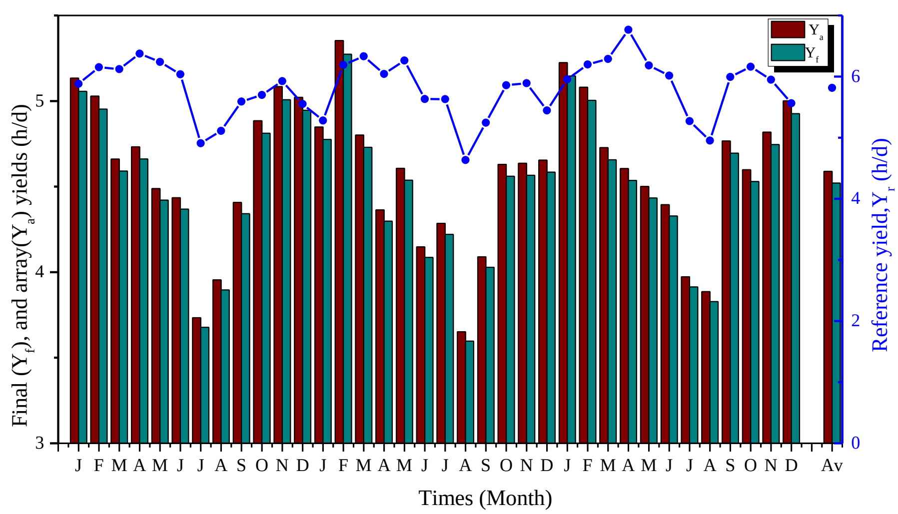

Figure 6: Evolution of daily average values per month of final, reference and array yields

3.4. Losses Analysis

Figure 7 shows the monthly average values of system conversion losses (L_s), array capture losses (L_c), and total losses (L_T) of the Zagtouli power plant. System losses (L_s) values are relatively low, between 0.06h/d and 0.08h/d and almost constant due respectively to the good working order of the inverters whose efficiency is around 98.9%. Array capture losses (L_c), which make up a large proportion of the PV solar plant total losses, vary periodically with minimum and maximum values recorded in January-December and April-May, respectively. The maximum value is 1.75 h/d, 1.68 h/d and 2.16h/d recorded in 2019, 2020 and 2021, respectively. Each year, there is an increase in losses between January and May. This phenomenon is thought to be due to a rise in ambient temperature profiles and a gradual accumulation of particles linked to harmattan dust storms, which play a major role in soiling solar modules. Between May and August, there is a reduction in various losses linked to the onset of the winter season, contributing to the gradual fall in temperature profiles and the leaching of solar modules. The resumption of the upward trend in array capture losses between September and November is explained by the onset of the dry season. The resumption of cleaning activities at the end of November led to a drop in losses in December.

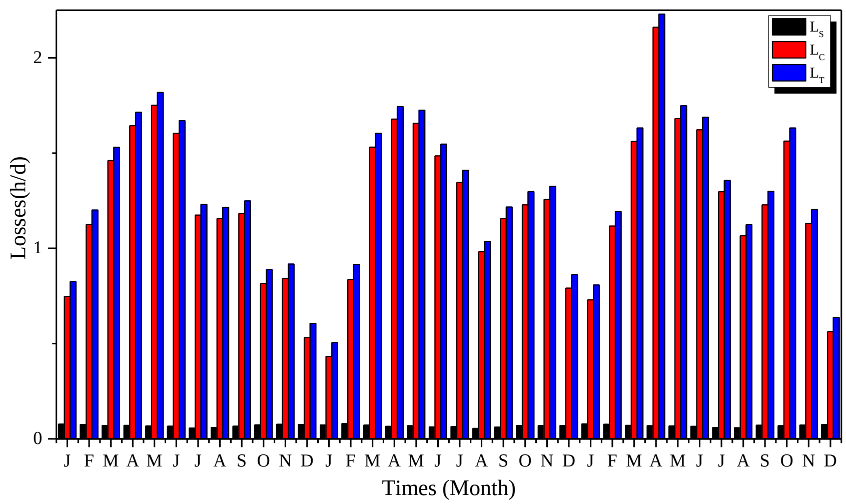

Figure 7: Evolution of monthly average loss values

Array capture losses are a combination of miscellaneous capture losses (L_{cm})(Chouder & Silvestre, 2010)(Med YAHYA et al., 2021)which are a good indicator of excessive losses and failures in the DC portion of PV systems and thermal capture losses (L_{ct})(Al-aboosi& Al-aboosi, 2021). As shown in Figure 8, the Zagtouli solar power plant is mainly and regularly subject to miscellaneous capture losses (L_{cm}), which make up a large proportion of array capture losses. The regularity of this loss could be explained by the fact that during the dry season (end of October-end of May), the PV field is subject to continuous soiling, which is also linked to the plant's proximity to national road number one, which carries a lot of traffic. During the winter season, the increase in relative humidity profiles also favours an increase in this type of loss.

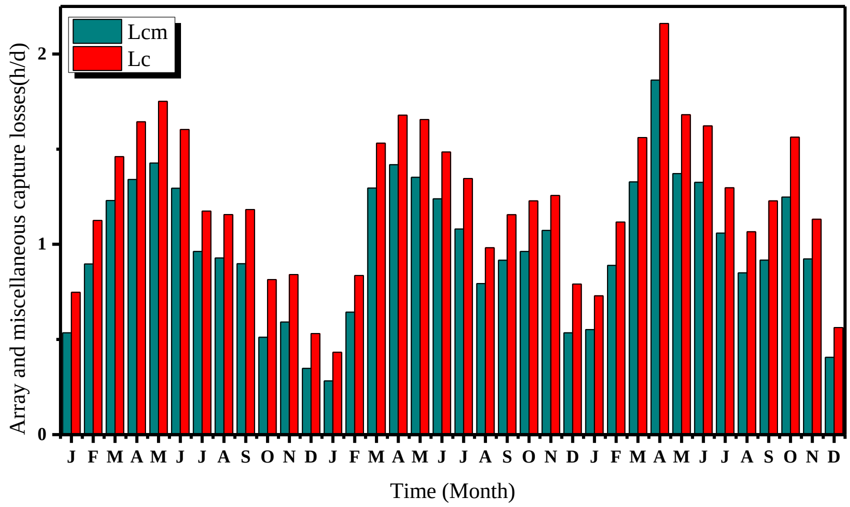

Figure 8: Evolution of array and miscellaneous capture losses per month

3.5. Performance Ratio (PR) and AC Energy Analysis (EAC)

Figure 9 shows the daily monthly average performance ratio (PR) and AC energy of the Zagtouli PV power plant variation. The results of the performance ratio indicate an almost periodic evolution during the study period with maxima and minima in January and April, respectively. A PR minimum value of 0.67 was obtained in April 2021 and can be related to the fact that the panel cleaning device was unavailable, so an excessive dust situation was observed at the Zagtouli site. A PR maximum value of 0.90 was obtained in January 2020. Except for April 2021, the PR value is higher than 0.71 for the other months of the study period. This indicates a good operation of the PV power plant because a PV system fails if its PR is less than 0.7 (Sampaio & González, 2017). The PR peaks observed in January months are related to low temperatures of 27.63°C, 26.91°C, and 29.74°C recorded in 2019, 2020, and 2021, respectively. These temperature values are close to the ambient temperature of the standard test conditions. In addition, during the January months, the PV panels are cleaned. Also, the December and January months are relatively well-vented and that contributes mainly to the cooling process of the solar modules. It can be noticed that the evolution of the performance ratio does not follow that of the AC energy production. The August months record low AC energy production of about 120 MWh/d. This could be explained by the low solar irradiation usually recorded during this month. However, the monthly average values of the performance ratio of about 78% are acceptable. In general, low energy production translates into a low-performance ratio. In the present case, due to climatic factors, low energy production in the August months has given rise to a good performance.

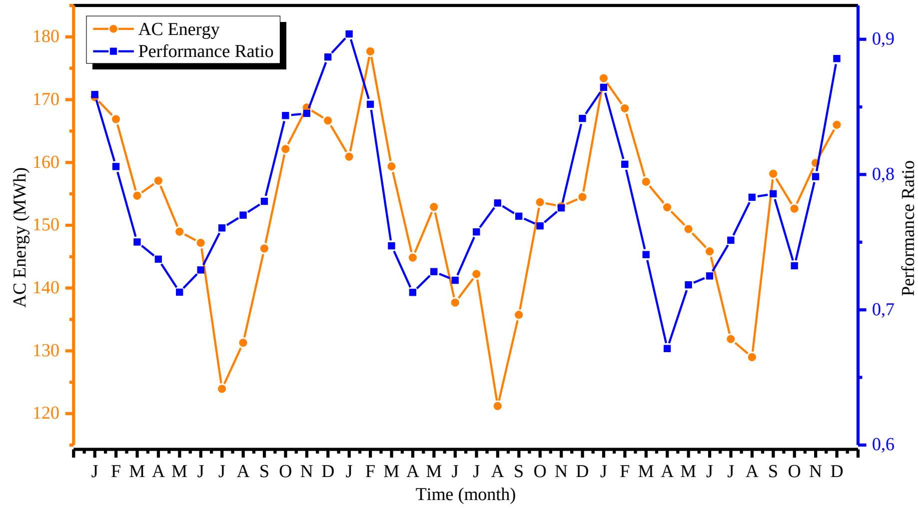

Figure 9: Variation of monthly averages performance ratio and AC energy

3.6. Capacity Factor and System Performance Analysis

The results of the capacity factor and the system efficiency are presented in Figure 10. The maximum and minimum values of the capacity factor are 20.28% and 13.84% obtained in February 2020 and August 2020, respectively. For the three years of plant operation, an average value of 17.43% is obtained. Concerning the system efficiency, its value varies from a minimum of 10.41% in April 2021 to a maximum of 14.02% in January 2020 with an average of 12.10% for the period study of three years. The best module efficiency under actual operating conditions at the Zagtouli site is 14.23% obtained in January 2020 with a monthly average of 12.28% over 36 months. However, standard test conditions rated the PV module efficiency at 15.51%.

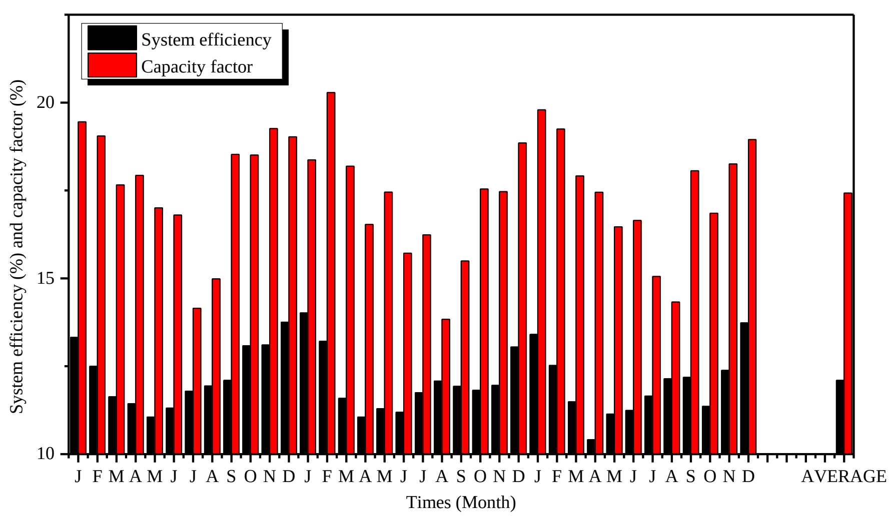

Figure 10: Evolution of monthly averages capacity factor and system efficiency

3.7. Influence of Temperature on Performance Ratio Analysis

Figure 11 presents the correlation relationship between the performance ratios and the temperatures registered on the solar cells in 2019, 2020 and 2021. As a result, the performance ratio undergoes a nearly negative linear regression with temperature. The correlation coefficient, R^2, of 34%, 54% and 65% is calculated in 2019, 2020 and 2021, respectively. These results show that the performance ratio becomes more and more sensitive to the temperature effect over time in agreement with Bertrand al. (2017) (Herteleer et al., 2017).

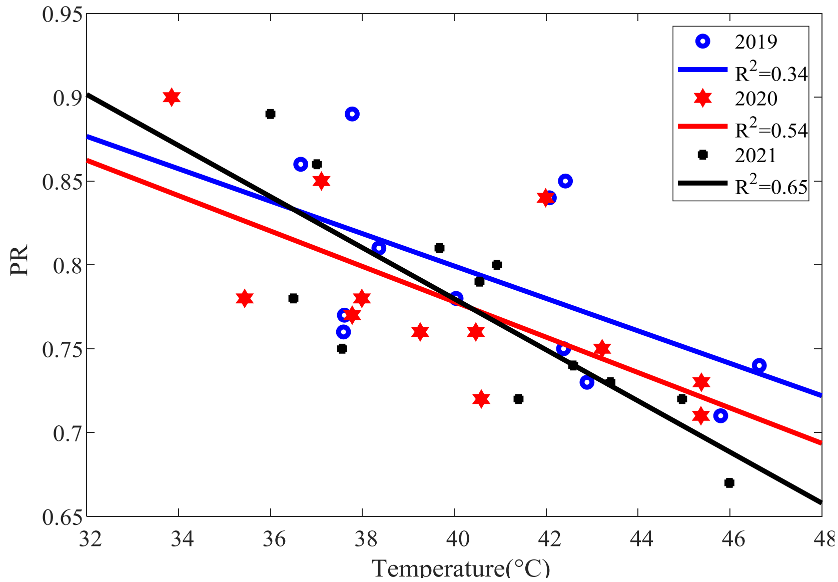

Figure 11: Correlation between monthly averages of performance ratio and solar cell temperature

3.8. Comparison of Present Results with Other Similar Studies

Table 5 presents the performance parameters obtained in the present work for the Zagtouli PV solar plant and those of other solar PV plants installed in tropical climates. Regardless of the PV system size, the main performance parameters that allow comparison are performance ratio, final yield, and capacity factor. As commented, the final yield of the Zagtouli solar plant is higher than others. This is probably due to the fact that on the one hand sunshine of the Zagtouli site is slightly higher than other sites, especially the Navrongo site and on the other hand, solar panels of the Zagtouli power plant have a slightly better performance under STC conditions. Ramagundam solar plant has higher values of performance ratio and capacity factor. This could be explained by the fact that it uses a modern seasonal technology for tilting the solar panels to exploit maximum solar radiation. In addition, it undergoes a regular cleaning plan insofar as all its panels are cleaned regularly twice a month.

Table 5: Comparison with large-scale solar power plants in tropical climates

Location, country	Climate type	PV module technology	Power (MWp)	PR (%)	Y_f (h/d)	CF (%)	Ref.
Zagtouli, Burkina Faso	Tropical	Polycrystalline	33.7	78	4.52	17.43	This study
Navrongo, Ghana	Tropical	Polycrystalline	2.5	70.6	3.89	16.2	(Mensah et al., 2019)
Ramagundam, Inde	Tropical	Polycrystalline	10	86.12	4.24	17.68	(B. S. Kumar & Sudhakar, 2015b)
Sama, Inde	Tropical	Polycrystalline	10	78	4.17	17.37	(M. Kumar et al., 2020)

3.9. Variation in the Main Performance Indicators

Table 6 shows the daily averages per year and standard deviations of energy production, PR, yields and losses over the study period. Excepted for L_c, no significant differences in the values from one year to the next.

Table 6: Means, standard deviation and extremes of some of the parameters studied

	2019		2020		2021			
Parmeters	mean±sd	Range	mean±sd	Range	mean±sd	Range	CV	P-value
EAC (MWh)	153.69±14.89	123.94-170.39	149.48±14.44	121.21-177.69	153.72±13.48	128.98-173.4	9.38	0.71
PR (%)	0.79±0.06	0.71-0.89	0.78±0.06	0.71-0.9	0.77±0.06	0,67-0.89	7.55	0.75
Y_a(h/d)	4.63±0.45	3.73-5.13	4.51±0.44	3.65-5.35	4.63±0.41	3.89-5.22	9.38	0.72
Y_r(h/d)	5.80±0.45	4.91-6.38	5.7±0.5	4.63-6.33	5.94±0.48	4,95-6.77	8.20	0.48
Y_f ((h/d)	4/56±0.44	3.68-5.06	4.44±0.43	3.6-5.27	4.56±0.4	3.83-5.15	9,38	0.72
L_c (h/d)	1.17±0.39	0.53-1.75	1.2±0.38	0.43-1.68	1.31±0.44	0.56-2.16	32.89	0.67
L_s(h/d)	0.07±0.01	0.06-0.08	0.07±0.01	0.05-0.08	0.07±0.01	0.06-0.08	9.38	0.72

4. Conclusion

In this paper, we evaluated and analyzed the performance of a 33.7 MWp large solar power plant in the Sudan-Sahelian environment, more precisely at Zagtouli, located about 15 km from the city of Ouagadougou in Burkina Faso. Few studies on the evaluation and analysis of PV systems performance have been conducted over a long period of time and very few have analyzed the performance of large-scale solar plants in this type of climate. Monitoring data for 36 months (2019-2021) such as energy output, wind speed, solar irradiance, relative humidity, and ambient and cell temperature were collected to characterize their impact on the operation PV plant. During the monitoring period, a maximum solar irradiation of 6.77 kWh/m^2/d and a minimum of 4.63 kWh/m^2/d were recorded in April 2021 and August 2020 respectively. February, March, April, May, June and November are the sunniest months. Air temperature varies from a minimum of 26.39 °C in August 2020 to a maximum of 35.24 °C in April 2021. Temperature peaks are observed every April and November, characterizing the hot period in the study area. At the Zagtouli site, October records the lowest wind speeds. February, May, June, and December are the windiest. The average wind speed during the monitoring period is 2.28 m/s. Zagtouli PV plant produces an average of 153 MWh/d. Low production periods with good performance of the plant are due to external climatic and environmental factors. Daily averages per month of the normalized yields Y_r, Y_a, and Y_f are 5.81 h/d, 4.59 h/d, and 4.52 h/d respectively. For the months of March, April, and May more than 80% of the various losses are related to capture losses. Thus, the origin of performance losses of the Zagtouli solar plant is strongly related to the losses of solar radiation capture due to the clogging of PV modules. The performance ratio has varied from a minimum of 67% obtained in April 2021 to a maximum of 90% reached in January 2020. Its three-year average is around 78%. The performance ratio is becoming increasingly sensitive to temperature effects over time. This study could constitute a reference for the panoply of solar power plant projects underway nationally and in the Sudano-Sahelian zone. In our future work, an analysis of the impact of aerosols on the performance of power plants will be done in order to contribute further to the productivity control of photovoltaic farms.

Conflicts of Interest: There are no conflicts to declare.

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