American Journal of Electrical Power and Energy Systems
2023; 12(1): 10-23
http://www.sciencepublishinggroup.com/j/epes
doi: 10.11648/j.epes.20231201.12
ISSN: 2326-912X (Print); ISSN: 2326-9200 (Online)

Performance Evaluation of an Installed On-Grid Photovoltaic System at Bamako

Bakamba dite Djeneba Sacko[1, *], Souleymane Sanogo[2], Abdramane Ba[1, 2]

[1]Hybrid Renewable Energy Laboratory, (HREL), Faculty of Sciences and Techniques (FST), University of Sciences, Techniques and Technologies of Bamako, Bamako, Mali

[2]Laboratory of Optics, Spectroscopy and Atmospheric Sciences (LOSSA), Faculty of Sciences and Technics (FST), University of Sciences Technics and Technologies of Bamako (USTTB), Bamako, Mali

Email address:

bdjeneba.sacko@usttb.edu.ml (Bakamba dite Djeneba Sacko)

[*]Corresponding author

To cite this article:

Bakamba dite Djeneba Sacko, Souleymane Sanogo, Abdramane Ba. Performance Evaluation of an Installed On-Grid Photovoltaic System at Bamako. *American Journal of Electrical Power and Energy Systems*. Vol. 12, No. 1, 2023, pp. 10-23. doi: 10.11648/j.epes.20231201.12

Received: March 30, 2023; **Accepted**: April 15, 2023; **Published**: April 27, 2023

Abstract: The primary goal of this paper is to analyze the performance of an installed on-grid photovoltaic 100 kW system installed on the roof of a building at the Institute of Applied Sciences, University of Sciences, Techniques and Technologies of Bamako. The system under consideration is part of a pilot project of a grid-connected system in Mali by the Renewable Energies Agency (AER). The PV system is located at 12.62°N latitude and -7.99°W longitude. It is composed of 313 monocrystalline modules of 320W for an installed power of approximately 101kWp and they are fixed on support inclined at 6 degrees orientated East-West. The system was monitored from March 2020 to February 2021. Within this period, the photovoltaic system supplied 114801.57 kWh to the grid with the final yield varying between 2.41 to 4.09 kWh/kWp/day. Additionally, the ratio of performance in this one year ranged from 53% to 89%. The annual capacity factor and efficiency are 13% and 10%, respectively. The main roots of this bad performance of the system are analyzed. The system performance is significantly affected by the soiling effects which are in other words attributed to meteorological and environmental parameters mainly dust accumulation and ambient temperature, as well as, factors like inclination (low tilt angle (6°)), the east and west orientation of the panels and finally lack of cleaning frequencies.

Keywords: On-Grid Photovoltaic System, Photovoltaic System Performance, Performance Ratio and Yields, Dust Accumulation, Soiling Effects

1. Introduction

One of the most influential factors for socioeconomic development and technological progress is surely energy in its various forms. Various forms of energy such as nuclear energy, fossil energy, natural gas, and renewable (forms like wind energy, solar energy, geothermal energy, and finally hydropower energy) are indeed used worldwide. However, the dominant sources of energy are the ones producing fossil fuels which are also the main ones responsible for a large chunk of global greenhouse gas emissions. Besides this drawback on our climate, we are facing a spectacular depletion of the sources of these energies; thus, making the price of these kinds of energies unaffordable for the benefit of many societies. Due to this concern in combination with the one on climate change, most countries around the world adopted mechanisms for replacing the part of fossil fuels with an alternative type of energy, especially renewable energy. One particular type of renewable energy which is head and shoulders above the other forms of renewable energy is photovoltaic (PV) energy due to its many advantages of it.

It is in this spirit that the government of Mali formulated several policies with the overall goal of diversifying energy resources and providing affordable, reliable, and sustainable energy. This National Energy Policy (PEN) adopted in 2006, in the energy sector is still not far from the drawing board of its implementation. The main purpose of these policies is to “contribute to the sustainable development of the country, through the provision of energy services accessible to the greatest number of the population at the lowest cost and thus promoting the promotion of socio-economic activities" [1]. These policies result in increasing photovoltaic installations in Bamako, the capital of Mali. According to reference, the power capacity of the total installed new sources of energy in Mali is estimated to be 720 MW in 2018 and the share of fuel thermal power stations accounts for approximately 72% of the country's total generation while the solar photovoltaic (PV) power had less than 1% of generation [2]. However, the management of installed PV systems faces many challenges, as several parameters can affect the performance and reliability of these systems.

In the field of PV installations, the verbatim report on the effects of meteorological and environmental parameters, as well as key factors such as tilt angle and orientation of the solar panels, of such modules is still not written down completely. Some of these are known to seriously worsen the photovoltaic system's performance and hence its reliability. For instance, the impact of these factors on the ratio of performance for PV-installed systems has been analyzed in references [3-11] and references therein. Conducting such analysis worldwide is imperative to improve the design of Photovoltaic systems. A report on renewable energy market forecasts by the International Energy Agency (IEA), indicates that renewable electric power capacity will increase by 1200 GW in 2024 due to cost reduction and PV systems will account for 60% of this increase [12]. There is also a great improvement in the PV cells' efficiency. More importantly, the use of the systems significantly leads to a considerable greenhouse gases reduction.

To benefit from this new form of energy, it can be connected to an available system resulting in the concept of a grid-connected PV system. Currently, grid-connected systems face many additional challenges affecting their performance due to several key factors. First of all the inverter used has to be selected properly and secondly the nature (poly or mono) crystalline of the panels are important as far as the ratio of performance or the efficiency of the Photovoltaic system is concerned. Especially, the array as well as systems energy losses which are defined from the reference yield, array yield, and final yield [13-16]. A historical review of the performance of PV systems has been done in [17]. The effects of meteorological (solar irradiation) conditions and the electrical components have been analyzed separately in [18]. What is more, it has been demonstrated that polycrystalline modules are more efficient than monocrystalline ones [19]. Current research activities hence focus on the reliability of the PV installations and the guarantee of lifetime performance through constant, solid, and traceable monitoring of photovoltaic installations [20]. The main challenge to ensure operational quality, in particular for photovoltaic systems connected to the grid, is to guarantee reliability and good performance by identifying and quantifying precisely the PV energy losses and the system failures [21]. It is well-known that for PV systems, about 70% of the investment costs are related to the PV modules, the inverter 12%, the installation 10%, and the other components (battery, connection cables, protection system, etc.) 8% [22]. Hence, analyzing the performance of PV systems is a complicated task due to many features [23-26].

Current methods for analyzing PV systems are either based on numerical simulation or focus on experimental investigation. One is generally comparing the actual values of the power, energy, voltage, or current produced by the system with the values it should produce under the meteorological conditions of the place of installation [27]. To do so, different parameters are used to evaluate the photovoltaic system performance and some are described in the standards references [28, 29].

The situation of our country is as follows. Mali benefits from an average solar irradiation potential of 5 to 7 $kWh/m^2/d$ comparatively to an estimated average of 4 to 5 $kWh/m^2/d$ worldwide. Importantly, the sunshine duration is 7 to 10 hours per day depending on the season [30, 31]. Light of all of these potentialities and the disposability of grants from public and non-governmental organizations (NGOs) have made PV systems gradually affordable in recent years. Consequently, we are thus witnessing an exponential implementation of PV systems. Few of them are grid-connected, though. Therefore, many efforts need to be done so that this type of energy becomes a dominant technology in energy production. In Mali, a great number of PV installations do not apply the standards of orientation (South for regions located in the northern hemisphere) and inclination (latitude of the location) of photovoltaic panels. This missing is reflected in the feasibility studies (energy performance, financial profitability, and environmental impact) before installing the PV systems, therein lies most of the problems. Additionally, few facilities are equipped with a monitoring system.

The primary objective of this study consists of evaluating the performance of a grid-connected PV system in Bamako. We investigate every possible source affecting the performance of this system. The remaining part of this manuscript is divided as follows. In the next section, we present our methodology which is followed by the section on results. The next section to these is devoted to the discussion surrounding the different results. We end up this article with the conclusion and perspectives for future directions.

2. Methodology and Data Acquisition

2.1. Methodology

2.1.1. Study Site Description

The study presented in this article is carried out on the grid-connected PV power plant installed on the roof of a two-floor building at the Institute of Applied Sciences, University of Sciences, Techniques and Technologies of Bamako. The University building is on the hill of Badalabougou in Bamako and is located at 12.62°N latitude and -7.99°W longitude. The PV plant has 313 monocrystalline modules of 320W for an installed power of approximately 101kWp and the characteristic of these modules are in Table 1. The modules are fixed on support inclined at 6 degrees and oriented east and west (see Figure 1) which contrasts standard orientation. This configuration hereafter will be referred as to study cases in contrast to the 12° tilting and south orientating referred to the standard case as indicated in the references above.

The 313 modules are connected to two SUN2000 (60 kW and 33 kW) inverters which have their characteristics presented in table 2. An array of 216 modules spread over 8 strings of 27 modules is connected to the 60 kW inverter. As for the 33kW inverter, it includes an array of 97 modules spread over 2 strings of 24 modules and one string of 23 modules. The system is equipped with a smart data logger for remote monitoring and data acquisition. The data are recorded each 15-minute intervals which are henceforth used to calculate the hourly, daily, and monthly energy produced by the systems.

Table 1. *Module characteristics.*

Crystalline Silicon Photovoltaic Modules	
Marque	JA SOLAR
Type	JAM60S09-320/PR
Peak power (Pmax)	320 W
Open circuit voltage (Voc)	40.78 V
Max power voltage (Vmp)	33.17 V
Short circuit current (Isc)	10.18 A
Max. power current (Imp)	9.65 A
Power Selection	5 W
PV module classification	Class II
Maximum system voltage	1000 V
Maximum overcurrent protection rating	20 A
Power production tolerance	3%
Open circuit voltage	2%
Short circuit current	4%
Standard test condition	AM (1.5), E (1000W/m^2), Tc (25°C)

Table 2. *The characteristics of the two inverters.*

SUN2000-60KTL-MO		**SUN2000-33KTL-A**	
d.c. Max. Input Voltage	1100 Vd.c.	d.c. Max. Input Voltage	1100 Vd.c.
d.c. Max. Input Current	22 A	d.c. Max. Input Current	22 A
d.c. Isc	30 A	d.c. Isc	30 A
d.c. MPP Range	200 – 1000 Vd.c.	d.c. MPP Range	200 – 1000 Vd.c.
a.c. Output Nominal Voltage	380/400 Va.c. 480 Va.c.	a.c. Output Nominal Voltage	400 Va.c.
a.c. Nominal Operating Frequency	50/60 Hz	a.c. Nominal Operating Frequency	50/60 Hz
a.c. Output Rated Power	60 KW	a.c. Output Rated Power	30 KW
a.c. Output Max. Apparent Power	66 KVA	a.c. Output Max. Apparent Power	33 KVA
a.c. Output Max. Current	100 A; 380 Va.c./ 95.3 A; 400 Va.c./ 79.4 A; 480 Va.c.	a.c. Output Max. Current	48 A
Power Factor	0.8	Power Factor	0.8
Operating Temp. Range	-20 - +60 °C	Operating Temp. Range	-20 - +60 °C

Figure 1. *Photo of installed PV panels.*

2.1.2. Performance Indicators

In evaluating the performance of our PV system, we adopt the IEC 61724 Standard prescription. In this respect, we will be considering energy output, reference yield, array yield, final yield, array and system energy losses, array efficiency, system efficiency and inverter efficiency, performance ratio, and capacity factor. The importance of these parameters and their basic definition is very standard and are given as follows:

(i). The Reference Yield

First of all, the reference yield, for instance, represents the ratio of the incident energy on the inclined modules H (kWh/m^2) to the reference radiation of the location (G = 1 kW/m^2) [32]. In this respect, it is known as the solar modules' conversion efficiency; hence, it stands for the number of hours during which the luminous flux incident on the modules is equal to that of reference for the location. It is in this sense very much influenced by the location, orientation, and tilt of the PV array and weather variability from month to month and year to year (33). The general formula quantifying this yield is given by the following equation:

$$Y_R = \frac{H}{G} \tag{1}$$

(ii). The Array Yield

The next parameter worth considering is the array yield.

This is different from the reference yield defined above. PV modules can produce an amount of energy above or below its nominal power at the STC. It has therefore been customary to define array yield as the ratio between the photovoltaic generator's energy production and its nominal power under STC [34]. Another way of cogitating this yield is to conceive it as the PV modules' array conversion efficiency having as units (kWh/kWp). The formula for this parameter is given as:

$$Y_A = \frac{E_{DC}}{P_{t,syst}} \quad (2)$$

(iii). The Final Yield

The third parameter we want to investigate on if the final yield Y_F. The PV modules produce total energy within a given period. However, the modules mostly operate in their nominal power.

The final yield measures the total energy produced in AC during a specific period divided by the installation nominal power. In other words, this quantity represents the number of hours during which the PV array operates at its nominal power [32]. It allows us to compute the efficiency of the system. The preferred unit for this yield is kWh/kW. In general, Y_F normalizes the energy produced relative to system size, therefore it is a good measure for comparing the energy produced by photovoltaic systems of different sizes (33). The final system yield is given by the following formula:

$$Y_F = \frac{E_{AC}}{P_{t,syst}} \quad (3)$$

The equations (1-3) are used to evaluate the yields of our PV system. They are also used in the evaluation of the ratio of performance for the photovoltaic system.

(iv). The System Efficiency

The next most important parameter used in quantifying the performance of a solar photovoltaic system is its efficiency. Efficiency is standardly defined as the percentage of solar radiation that a system can convert into electricity. Normally, the conversion rate into electricity for a generic panel lies between 8 and 20% of its incident solar radiation [35]. It is known that the panels begin to degrade and lose their efficiency in generating electricity every year. As a prelude, most manufacturers guarantee a maximum loss of 20% efficiency in the first 25 years of the panels [36]. Therefore, data efficiency measurement over time is an essential step in quantifying the performance of PV systems. To be beneficial for investors, a solar system must operate at the highest level of its efficiency. This is however challenged by the fact that the variation of the photovoltaic system's efficiency is indeed subjected to parameters like weather conditions, angle of inclination and orientation, shading, design of equipment, and dust dry deposition. These effects manifest themselves in three main places: modules, systems, and inverters. Therefore, to completely analyze photovoltaic system efficiency, one has to look into these three net-separated things: photovoltaic module efficiency, system efficiency and inverter efficiency. Depending on the available data and the level of desired resolution, these efficiencies can be instantaneously determined on an hourly, daily, monthly, or yearly basis. Module efficiency is calculated using the DC power output while system efficiency needs the AC power output in its formula [37]. Alternatively, system efficiency normally describes the ratio between the energy productions in a given period of the system to the total solar energy collected from the photovoltaic array H_t [38]. The efficiencies are given by:

$$\eta_{sys} = \frac{100 \times E_{AC}}{H_t \times A} \ (\%) \quad (4)$$

$$\eta_{PV} = \frac{100 \times E_{DC}}{H_t \times A} \ (\%) \quad (5)$$

$$\eta_{inv} = \frac{100 \times E_{AC}}{E_{DC}} \ (\%) \quad (6)$$

Where A is the total area of the modules, in m^2.

Having presented the above formulas, we now properly turn to the computation of the ratio of performance for the PV system.

(v). The Performance Ratio

Simply state, the performance ratio is the final yield divided by the reference yield. This key parameter allows one to obtain important information about the effect of global losses on the system [27]. For all kinds of PV systems, the performance ratio (PR) can be calculated. It simply relates the energy yield of ideal PV systems to the energy yield of actual PV systems operated at a certain location [39]. PR values are usually reported on a monthly or annual basis. Due to temperature losses of the PV module, PR values are higher in winter than in summer and are normally in the range of 0.6 to 0.8. Falling annual PR values may indicate permanent performance loss [33]. The performance ratio (PR) is estimated as follows:

$$PR = \frac{Y_F}{Y_R} \quad (7)$$

It is a proven fact that PR is highly dependent on ambient temperature. It has lower values during the hot periods of the year and higher ones throughout the colder seasons [40]. A recent study investigated the impact of dust accumulation on PR (41). Dust accumulation is an important newcomer into the field of PV systems even though it has always been part of the game.

An additional problem for grid-connected systems is the system losses LS and the miscellaneous losses LD. For instance, reference (41) in its table 1 presented a comparison of PV system soiling loss for different locations worldwide. Quantifying these two types of losses is an essential task.

(vi). System Losses by Conversion

The system losses are due to the inverters' conversion losses (direct current-alternating current) and are defined by the difference between the yield of the PV array (YC) and the final yield YF (32). It gives an idea of the energy quantity available for consumption.

$$LS = Y_C - Y_F \quad (8)$$

(vii). Miscellaneous Losses

The miscellaneous losses LD are defined by the difference between the reference yield and the PV array yield. They represent for instance losses due to: panel temperatures, wiring, partial shading, spectral losses, soiling and errors in finding the maximum power point of conversions (DC-AC) [32].

$$LD = Y_R - Y_C \quad (9)$$

(viii). The Capacity Factor

The last parameter we intend to characterize is the capacity factor (CF) which implies the ratio between the actual annual electrical energy and the electrical energy that could be generated if the solar photovoltaic system operated with its total rated power installed 24 hours a day over a period of one year [38]. CF depends on the PV system location and the more it is higher, the better the PV system performance [42]. It is expressed as follows:

$$FC = \frac{E_{AC}}{P_{t,syst} \times 8760} \quad (10)$$

2.2. Data Acquisition

2.2.1. Meteorological Data

In carrying out this study, meteorological variables from the meteonorm database on PVSyst are used. Data from the meteonorm are combined with the variables recorded from a weather station installed in the University. The meteorological variables used are air temperature and solar radiation. In the area under consideration, the monthly mean values of air temperature range between 23°C observed in January and 32°C recorded in April.

2.2.2. Environmental Data

Also, monthly mean values of dry dust deposition (Dustdd), aerosol optical depth (AOD), dust extinction of aerosol optical thickness (DustET), dust column mass density (DCMD), dust surface mass density (DustSMD), were retrieved from the webpage www.giovanni.gsfc.nasa.gov.

3. Results

3.1. Analysis of Surface Irradiance and Energy Output for the Two Cases of Configurations

3.1.1. Estimated Irradiance

In this manuscript, we first depicted the irradiation estimated for the PV modules. For this purpose, Figure 2 represents the monthly mean values of irradiance estimated on the 6° inclined plane oriented East and West as the installation under study and also the irradiance on the 12° inclined plane, oriented South (as in a Standard installation). It is visible that the maximum value of irradiation of 217 kWh/m^2 for all the planes of the module's surface is obtained in March compared to the standard value of 225 kWh/m^2. On the other hand, it is in August that the minimum value of 165 kWh/m^2 is obtained which is approximately equal to 161 kWh/m^2 for the standard condition. The minimum value of irradiation which is reached in August is mainly due to the period of the rainiest month of the year. It is quite interesting to notice that the irradiations on the standard plane (inclined 12° and oriented towards the South) are a little higher compared to the irradiations on the 6° inclined plane and oriented East or West for the whole year except for the months of May, June and July. The average annual irradiation is 6.41 $kWh/m^2/day$ for the standard condition which is higher compared to 6.02 $kWh/m^2/day$ for our PV system. To further push forwards the degree of comparison, we present in Figure 3 the average ambient temperature values over the year.

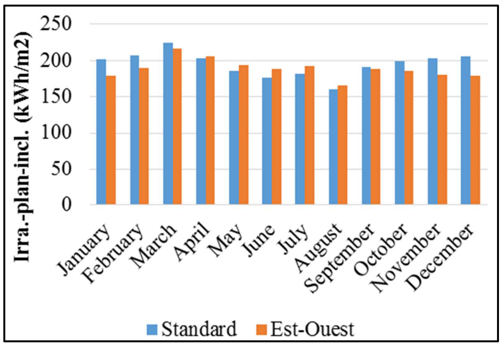

Figure 2. *The monthly average irradiation.*

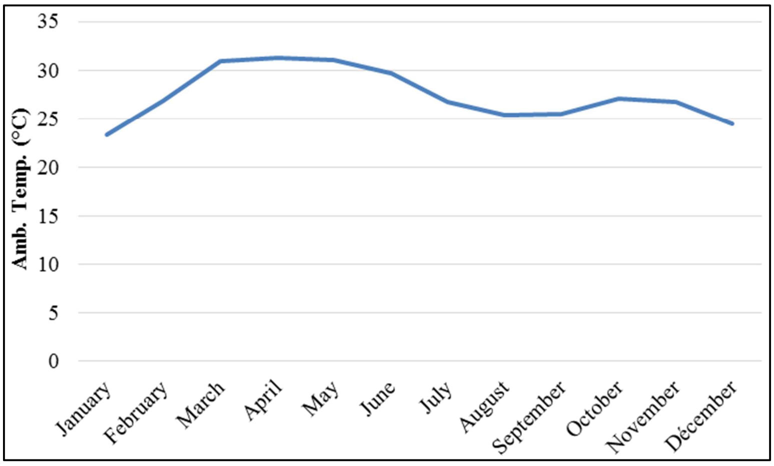

Figure 3. *The average monthly ambient temperature.*

The ambient temperature varies from its lowest value 23.38°C (January) to its highest point 31.23°C (May).

3.1.2. Energy Output

Since we are concerned with grid-connected PV systems, one particular aspect worth plotting is the energy produced by the system. The actual energy produced by the system from March 2020 to February 2021 is shown in Figure 4. In total, 114801.57 kWh were produced during this period with an average of 314.52 kWh/day. This production corresponds to 1136.65 kWh/kWp per year. The maximum energy (12815.84 kWh) was produced in March 2020 while the minimum, 6617.63 kWh is obtained in February 2021. There is a drop in production from November 2020 to February 2021 which can be explained by the effect of the accumulation of dust on the modules when the wintering stops, given that the system has not been cleaned during the dusty season.

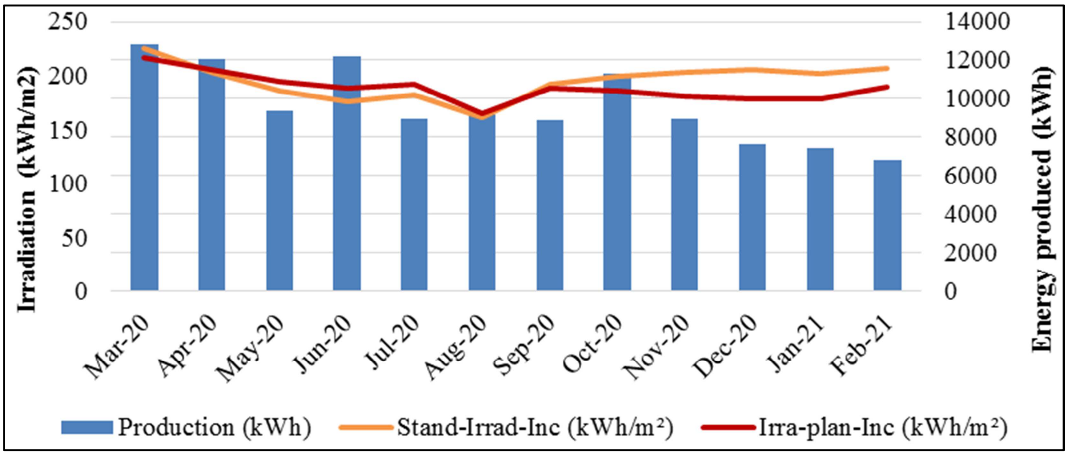

Figure 4. *Monthly energy production (blue) and monthly average irradiation on the standard plane (green) and the East-West oriented plane (red).*

3.2. Performance of the Installed PV Plant

3.2.1. Performance Ratio, Capacity Factor and System Efficiency

The monthly values of the performance ratio (PR), capacity factor and system efficiency are shown in Figure 5. The performance ratio varies from 53% in February 2021 to 89% in June 2020 (Figure 5).

It is noticeable that the performance ratio is mostly less than 70% in the one year under consideration. It is remarkable that the performance ratio exceeds 70% during March and April (in the dry and hot seasons) and from June to October (in the rainy seasons). The annual performance was found to be as 69% for our modules which is less than 83.03% of ref. [37].

As for the capacity factor and system efficiency, they vary from 10% in January to 17% in March and from 7% in February to 12% in June, respectively. To facilitate the analysis, we normalize the efficiencies by dividing them by their respective average. The plot of the three efficiencies is given in figure 6.

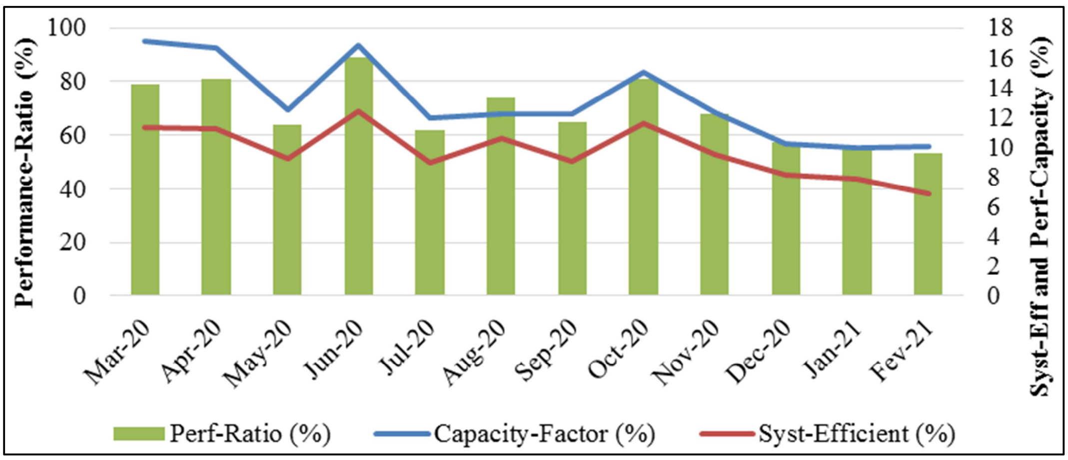

Figure 5. *Monthly variation of performance ratio, capacity factor and system efficiency.*

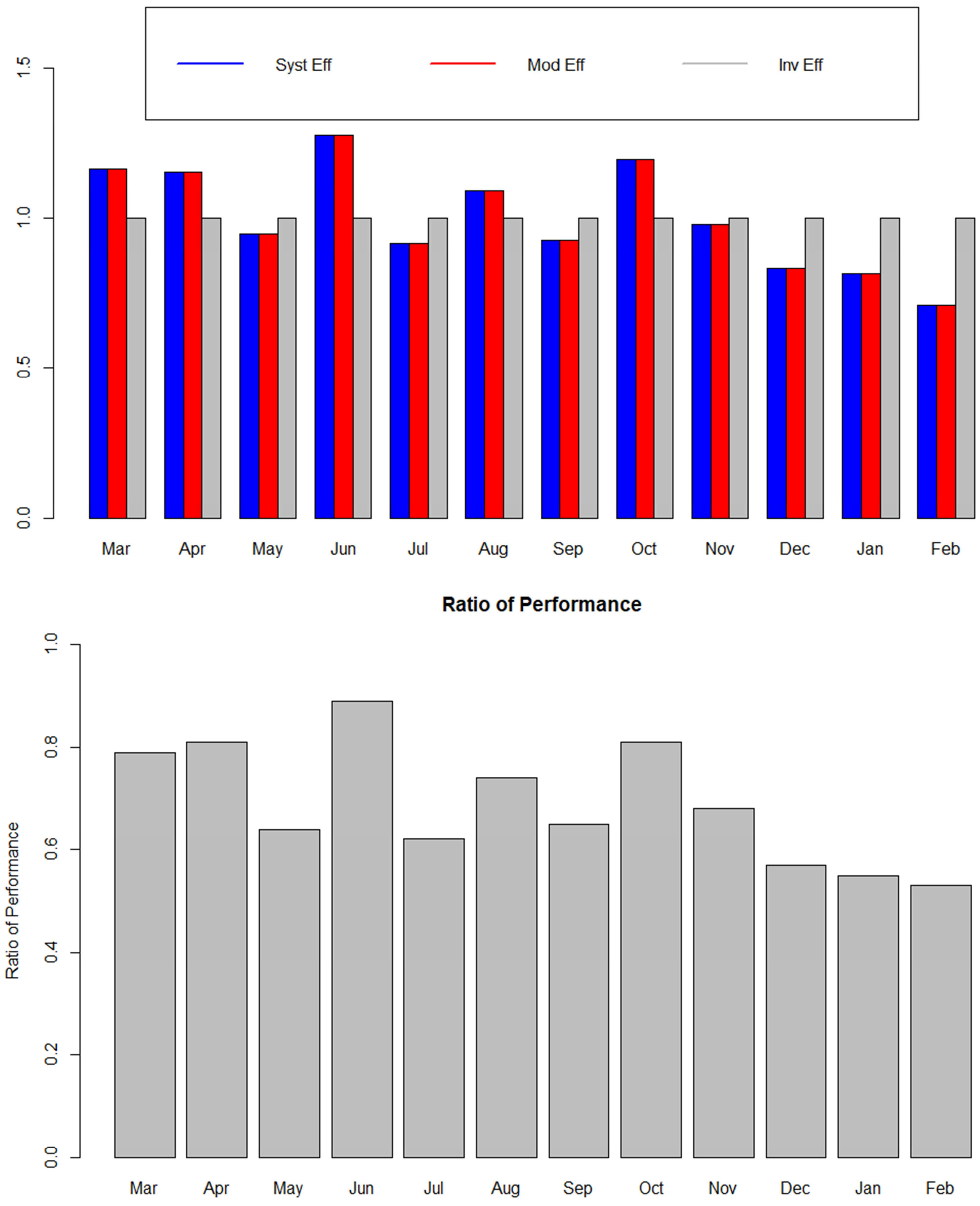

Figure 6. *System Efficiency, Module Efficiency, Inverter Efficiency, and Ratio of Performance.*

We notice that the system performs very perfectly in June compared to the other months.

3.2.2. Losses Analysis

Different factors can cause losses in a photovoltaic system such as incident solar radiation, cell temperature, module inclination angle. These losses can be from different sources such as module collection losses, temperature losses in cells, system losses, degradation losses, etc. In this study, we mainly focus on two types of losses, namely system losses and miscellaneous losses. The monthly values of these losses shown in Figures 7 and 8 reveal stronger variability in miscellaneous losses compared to the system losses. The highest system loss 2.59 kWh/kWp/month was recorded in March 2020 and the lowest was 1.38 kWh/kWp/month in February 2021. As far as the miscellaneous losses are concerned, they vary from 12.04 kWh/kWp/month in June 2020 to 58.63 kWh/kWp/month in February 2021 with an annual loss of 484.59 kWh/kWp. The results obtained show that the highest values of energy losses were recorded in December, January and February with respective loss values of 57.48 kWh/kWp/month, 59.45 kWh/kWp/month and 60.01 kWh/kWp/month. December-January-February corresponds to the very dusty period. The lowest values of energy losses are observed in June standing at 14.5 kWh/kWp. Then follow October and April having 26.65 kWh/kWp/month and 28.08 kWh/kWp/month, respectively.

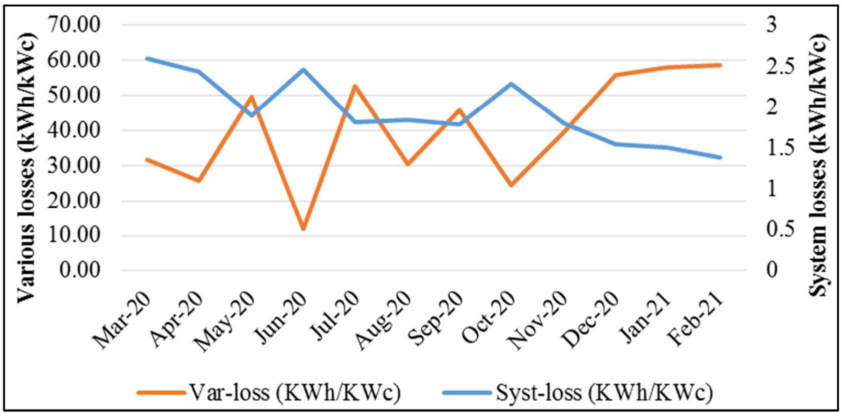

Figure 7. *Monthly variation of system losses in blue and miscellaneous losses in orange.*

One can represent the same figure in the bar graph format which easily makes comparison points visible. Such a representation is depicted in Figure 8 below.

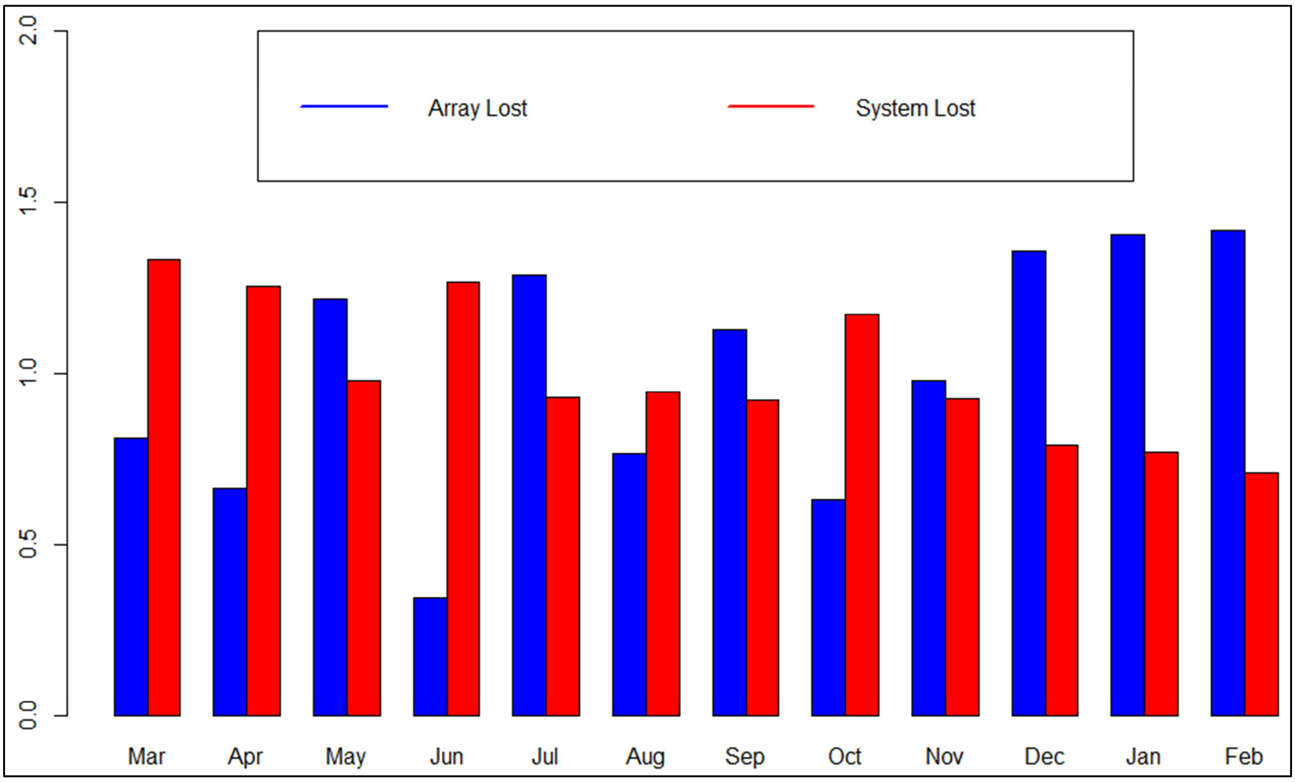

Figure 8. *The graphs of the two losses (array and system) normalize b their respective average.*

3.2.3. Yields Analysis

The normalized yields of a PV system in Figure 9 shows the daily monthly values of the reference yield YR, the array yield YC and the final yield YF. Firstly, the reference yield YR varies from 5.20 kWh/kWp/day in March 2020 to 3.96 kWh/kWp/day in August 2020, with an annual average of 4.59 kWh/kWp/day. A possible explanation for this outcome is that August is the rainiest month of the year; hence, in this month solar radiation is affected by high clouds covering the sky, unlike the other months. Secondly, the modules' conversion efficiency varies from 4.18 kWh/kWp/day in March 2020 to 2.42 kWh/kWp/day in January 2021. Finally, one observes that the final yield has a minimum value of 2.37 kWh/kWp/day in February 2021 and a maximum of 4.09 kWh/kWp/day in March 2020. We remark that this variation is similar to that of PV array yield if the inverter efficiency is taken into account. From our investigation, we discover that the annual average of the daily values of these two yields (YC and YF) is 3.24 kWh/kWp/day and 3.18 kWh/kWp/day, respectively. An additional remarkable feature of Figure 9 is that the minimum values of YC and YF are observed in December, January and February. Low solar irradiance and dust deposits on the modules are the main ones responsible for this observation.

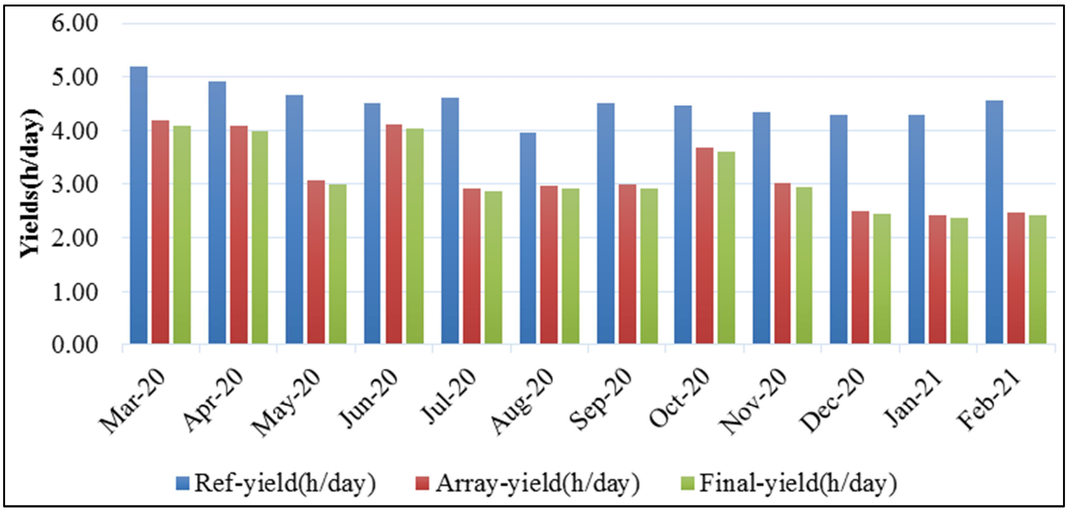

Figure 9. *The monthly variation of the reference yield, the array yield and the final yield.*

3.3. Environmental Parameters Affecting Performance Analysis

The roots of the low performance achieved by the installed PV system from December to February are mostly the soiling effects and a lack of cleaning frequency. Given the nature of the environment in which the PV system is located (eg: dusty), the parameter mostly likely affecting the system is dust accumulation during this period. It was demonstrated in [43] that the percentage efficiency reduction of PV monocrystalline modules is higher than that of PV polycrystalline modules. They concluded that (due to dust deposition on the cells) the percentage efficiency reduction after 11 weeks of environmental exposure for the monocrystalline is 3.55% compared to 3.01% for the polycrystalline module. A similar analysis for our PV module (monocrystalline) reveals that the percentage reduction in the 3 months is 18.58%. The reason for this high percentage reduction is the impact of the soiling effects. We therefore now turn to the impact (on the ratio of performance (RP) and the efficiency of the system (ES)) of environmental parameters like dry dust deposition (Dustdd), aerosol optical depth (AOD), dust extinction of aerosol optical thickness, total optical aerosol (DustET), dust column mass density (DustCMD), dust surface mass column (DustSMC), combined with, the air temperature. To do so, we perform a bivariate analysis between those parameters and the two most important PV performance parameters (the performance ratio and the efficiency of the system) using R software. Dust dry deposition (Dustdd) and the DustCMD are given in Figures 10 and 11 below. The results of these linear model regressions are in table 3.

Table 3. *The multiple regression results of the five environmental parameters and the temperature on the performance ratio and the system efficiency.*

Parameters	**Performance ratio**		**System Efficient**	
	Std. Error	**Pr (>|t|)**	**Std. Error**	**Pr (>|t|)**
Dustdd	1.02246	0.00877 **	0.107726	0.00235 **
AOD	0.09247	0.01175 *	0.009743	0.00225 **
DustET	0.76778	0.11245	0.080893	0.02806 *
DustCMD	0.60714	0.01689 *	0.063968	0.00357 **
DustSMC	1.14678	0.32073	0.120824	0.30005
TAmb	0.01417	0.00832 **	0.001493	0.00172 **
Signif. codes:	0 '***' 0.001 '**' 0.01 '*' 0.05 '.'		0 '***' 0.001 '**' 0.01 '*' 0.05 '.'	
R-Squared	0.9408		0.9688	
p-value	0.00615		0.001294	
Residual standard error	0.04213		0.004439	

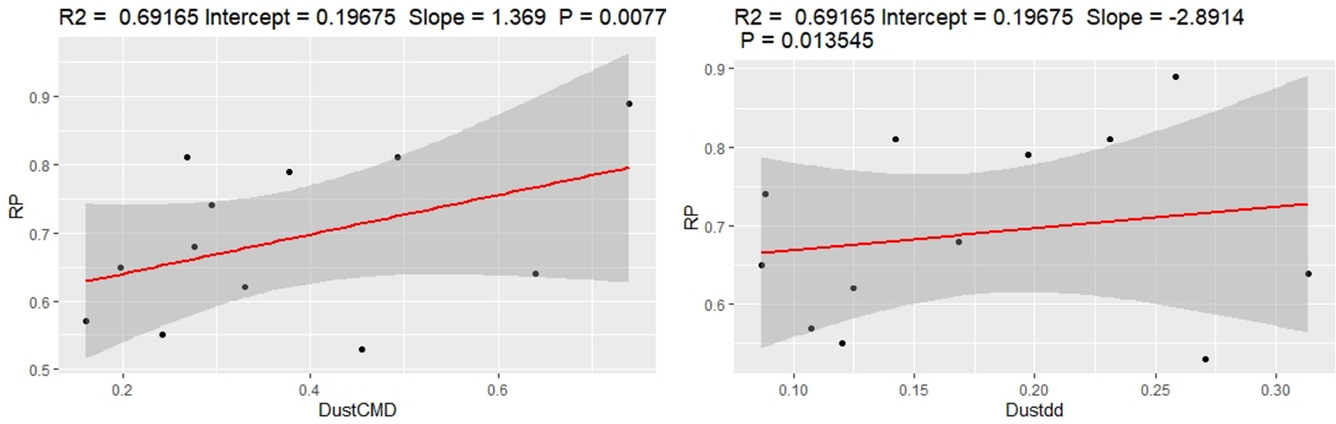

Figure 10. *Performance Ratio in terms of the soiling parameters.*

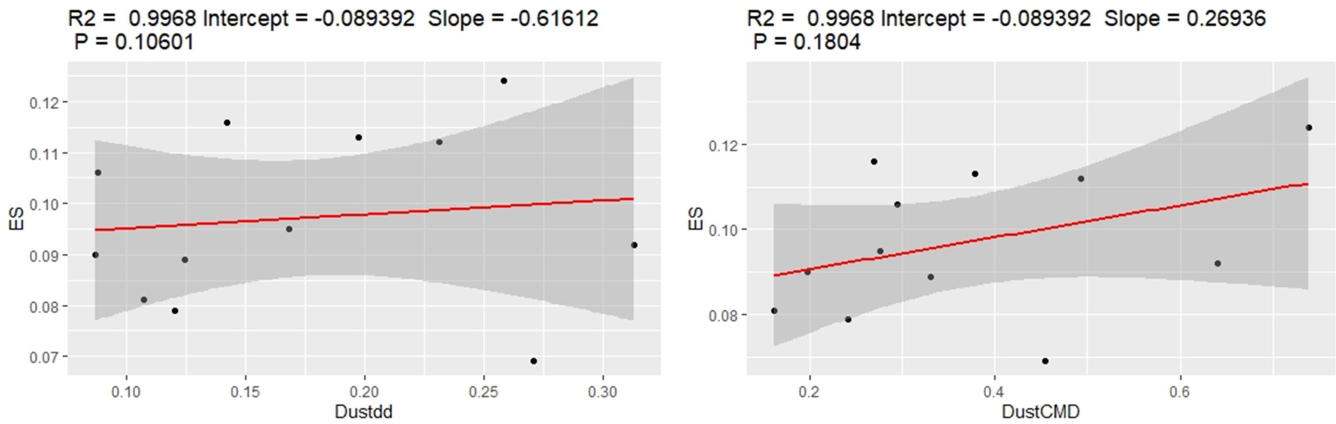

Figure 11. *System Efficiency in terms of the soiling parameters.*

We selected Dustdd and DustCMD because the modules is lacking a cleaning frequency mandatory for PV systems [41]. A proper cleaning frequency would have improved these two important parameters performance ratio and system efficiency. To demonstrate this affirmation, a multiple regression was carried out between the rest of the parameters used as explanatory variables namely dry dust deposition (Dustdd), aerosol optical depth (AOD), dust extinction of aerosol optical thickness (DustET), dust column mass density (DustCMD), dust surface mass column (DustSMC), and the temperature (T_Amb) and the performance ratio and the efficiency of the system taken as response variables (Table 3).

It is noticed that in this table 3, the dry dust deposition has the most significant effect on the system performance compared to the other parameters. This can be explained by the fact that our system is slightly inclined at only 6° and the modules non-cleaning during the dry period. To conclude this section on the results, let us also plot the monthly variation of the dust dry deposition and dust column mass density PM in figure 12.

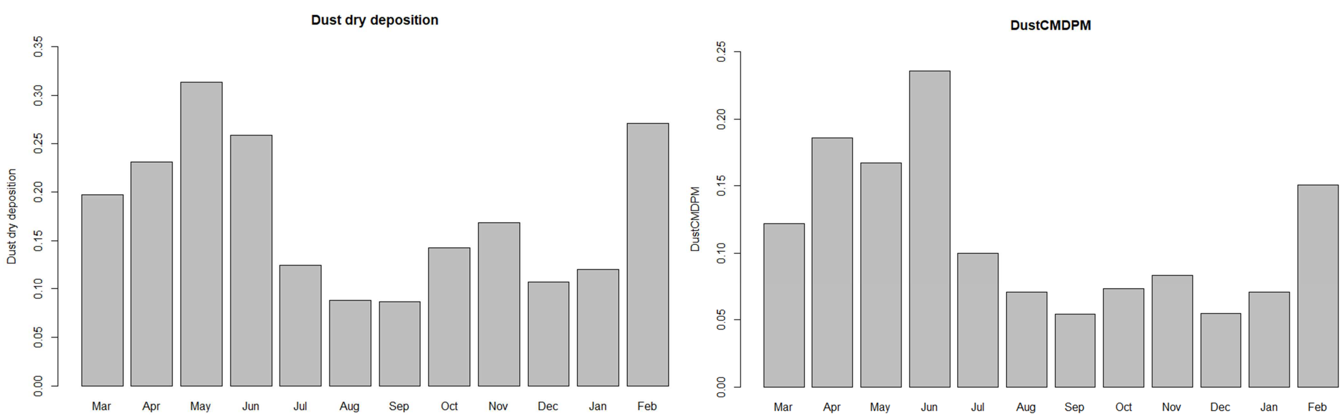

Figure 12. *Dust dry deposition and DustCMDPM monthly variation.*

4. Discussions

In this article, we address the issue of the performance of a grid-connected PV system. The results obtained show that the system efficiency still needs some care about dust accumulation. The drop in production from November 2020 to February 2021 is caused mainly by this parameter during this period. Hence, we arrive at a previous conclusion made by Kazem et al [44] which states that dust deposition is one of the important factors that reduce the PV system output current. Moreover, Zitouni et al [45] report that the energy loss due to the soiling effect reaches 0.61 kWh/day and 0.03 kWh/day during dry and rainy periods respectively. Our investigation agrees with this observation.

On the other hand, the annual value (69%) of the performance ratio is at the limit of the performance values of a PV system [46]. Currently, in the field of PV systems, PR greater than 80% should be interpreted as a system closer to ideal performance under STC conditions, whereas a system with RP less than 70% should be suspected of failure or malfunction of the system components (panels, inverters, etc.) or environmental factors (nearby shading, excessive dusting of panels, etc.). We witness this conclusion as far as the performance of our modules is concerned. More importantly, our RP is close to the 72% and 71% obtained by Aoun [47] and Cherfa et al [48], respectively on polycrystalline modules (southern Algeria) and monocrystalline (northern Algeria), which also used the guidelines of the IEA 61724 standard (International Energy Agency). However, the 78% performance ratio obtained in the desert climate of Nouakchott (Mauritania) by Yahya et al [26] is higher than the 69% of this manuscript. This is surely due to the lack of maintenance such as cleaning frequency on our system. Positively, our performance ratios are higher compared to the 40.75%-88.68% obtained by Adar et al in Morocco [49]. According to them, the low performance they obtained is due to high temperatures and the deposit of dust on the panels. The decreases in the performance ratio and system efficiency are related to three main reasons, namely dust, ambient temperature and solar radiation see for instance ref. [44] and ref. [47], which explains well the performance ratios obtained in this article. This observation is also confirmed by the multivariate regression in table 3.

What is more, the annual value (13%) for the capacity factor is below 14.83%, 19% and 20.77% obtained by Attari [50], Yahya [26] and Aoun [47], respectively. Nevertheless, the annual efficiency of the system (10%) is higher than the 9.49% of Yahya (26) but below the 11.6% - 16.8% and 12% obtained respectively by Al Badi [51]. and Attari [50]. Hence, based on results from table 3, we notice that the parameter significantly affecting the efficiency of our system is dry dust deposition. Indeed, the efficiency of the system decreased by 4.7% between October (the end of the rainy season) and February (the middle of the dry and dust season). The authors [52], have already pointed out that the soiling losses have their greatest impact during long dry summers which saw a drop in efficiency from 7.2% to 5.6% in 108 days. The dust accumulation on the PV modules' surface and in the ambient air dust surrounding the PV system adversely affects the PV modules' efficiency, because the dust particles normally absorb or scatter a considerable part of solar radiation [53, 54].

As far as the system losses are concerned, we observed that the system maximum losses are observed during the dusty period (December, January and February). Losses such as losses due to cell temperature, soiling and degradation losses are known to strongly affect the performance of the PV system [55]. In reference [49] it was shown that polycrystalline heats up more rapidly than monocrystalline. This could explain why our system does not have a large loss due to temperature.

The minimum yields in this study are also obtained during the dry season for array and final yields. On the other hand, the minimum reference yield was obtained in August (a month of heavy rain), a possible explanation is that this yield depends on solar radiation. The maximum yields (YR, YC, YF) in this our article are all lower than the 7.25 kWh/kWp/day, 6.5 kWh/kWp/day and 5.09 kWh/kWp/day obtained by Yahya et al. (26) and the 6.98 kWh/kWp/day, 5.68 kWh/kWp/day and 5.22 kWh/kWp/day obtained by Komoni et al [55], respectively for YR, YC and YF. These differences are not only explainable by weather conditions (between Mali and Kosovo) but also by the lack of system maintenance for our modules. Much is true that YC depends on solar radiation availability, site weather conditions and modules conversion efficiency [26].

Lastly, the angle of inclination of this system is very low (6°). Indeed, according to Lu and Zhao [56], the deposition rates increase whenever the angle of inclination approaches the horizontal of the Earth's surface. Combination of a high dry dust deposition rate with a lack of cleaning frequency results in the low ratio of performance and the bad system efficiency we are encountering.

All in all, we demonstrate in this investigation that dust deposits have a considerable impact on the performance of our photovoltaic system. Therefore, to have a PV system working efficiently, especially in the Sahelian climate, the modules must be cleaned regularly, especially during the dry season.

5. Conclusion and Prospects

The performance analysis of the PV system grid-connected installed in 2020 on the roof of a building of USTT-B was performed in this article. The effect of orientation and inclination of the surface plane of the modules was first analyzed. It shows that the annual radiation on the surface of the modules is a little higher for a standard orientation and inclination (due south and latitude of the place) than for an east or west orientation and a 6° inclination as is the case with the system under consideration. The total annual electricity production delivered to the grid was 114801.57

kWh.

Regarding the performance parameters, the following results are obtained:

1) The annual system efficiency, capacity factor and annual performance ratio were 10%, 13% and 70% respectively.
2) The final yield varied from 2.37 kWh/kWp/day to 4.09 kWh/kWp/day. Its daily annual average was found at 3.18 kWh/kWp/day.

We found out that the system is not performing well as it should be. The system performance is significantly affected by dust deposits more than other environmental parameters. Therefore, regular cleaning of the modules needs to be done to increase the performance of the system.

By taking into account this recommendation which proposes a reliable dust cleaning frequency and respecting appropriate installation, solar photovoltaic systems can play a vital role in the adoption of a more sustainable, clean and reliable electricity production system.

Acknowledgements

This manuscript is part of the doctoral research activities of the first author which falls within the continuity of the scope of the RARSUS-SEMALI project. The activities were fully supported by the International Science Program (ISP/IPPS) at Uppsala University through the Laboratory of Optics, Spectroscopy and Atmospheric Sciences (LOSSA) of the University of Technical and Bamako Technologies (USTT-B), Mali. Sacko thanks the member of LOSSA and the member of the renewable energy agency for their collaboration for enlightening discussions over time.

References

[1] DNE. Politique energetique nationale. Bamako: DNE, 2006.

[2] (BVG), Bureau du Vérificateur Général. GESTION DE LA SOCIETE ENERGIE DU MALI: VERIFICATION DE PERFORMANCE, - Période du 1er janvier 2016 au 30 septembre 2019. Bamako: Bureau du Vérificateur Général (BVG), 2020.

[3] Effect of tilt angle on the performance and electrical parameters of a PV module: Comparative indoor and outdoor experimental investigation. M. A. A. Mamun, M. M. Islam, M. Hasanuzzaman, Jeyraj Selvaraj. 2022, Energy and Built Environment, Vol. 3, pp. 278–290.

[4] A. Danu, V. Tanasiev Influence of tilt and orientation angle of the PV panels on high-energy production in Romanian climate conditions during cold season. A. Danu, V. Tanasiev, C. Ionescu, A. Badea. 2015, IEEE Environment and Electrical Engineering (EEEIC), in: Proceedings the 15th International Conference, 2015, pp. 1599–1604.

[5] Analysis of the optimum tilt angle for a soiled PV panel. R. Xu, K. Ni, Y. Hu, J. Si, H. Wen, D. Yu. 2017, Energy Convers. Manag, Vol. 148, pp. 100–109.

[6] Determination of the optimal tilt angle and orientation for solar photovoltaic arrays. E. D. Mehleri, P. L. Zervas, H. Sarimveis, J. A. Palyvos, and N. C. Markatos. 11, 2010, Renewable Energy, Elsevier, Vol. 35, pp. 2468–2475.

[7] The disagreement between anisotropic-isotropic diffuse solar radiation models as a function of solar declination: computing the optimum tilt angle of solar panels in the area of southern-Italy. Emanuele, C. 2012, Smart Grid and Renewable Energy, Vol. 3, pp. 253-259.

[8] Optimum tilt angles for photovoltaic panels during winter months in the Vaal triangle, South Africa. A. Osamede, S. James, P. Christo. 2012, Smart Grid and Renewable Energy, Vol. 3, pp. 119-125.

[9] Investigation of soiling effects, dust chemistry and optimum cleaning schedule for PV modules in Lahore, Pakistan. Ullah A, Amin A, Haider T, Saleem M, Butt NZ. 2020, Renewable Energy, Vol. 150, pp. 456-468.

[10] Effects of soiling on photovoltaic (PV) modules in the Atacama Desert. Cordero RR, Damiani A, Loroze D, MacDonell S, Jorquera J, Sepulveda E, Ferron S, Llanillo P, Labbe F, Carrasco J, Ferrer J, Torres G. 1, 2018, Scientific reports, Vol. 8.

[11] Floating photovoltaic powerplant: A review. Alok Sahu, Neha Yadav, K. Sudhakar. 2016, Renewable and Sustainable Energy Reviews, Vol. 66, pp. 815–824.

[12] IEA. Renewables 2019: Analysis and Forecast to 2024, www.iea.org/renewables2019. s.l.: IEA, 2019.

[13] Performance analysis of a grid connected photovoltaic system in northeastern Brazil. Lutero Carmo de Lima, Leonardo de Araújo Ferreira, Francisco Hedler Barreto de Lima Morais. 2017, Energy for Sustainable Development, Vol. 37, pp. 79-85.

[14] PERFORMANCE ANALYSIS OF GRID-CONNECTED PV SYSTEMS. Jahn, Stefan Mau and Ulrike. Dresden, Germany: s.n., 2006. 1st European Photovoltaic Solar Energy Conference and Exhibitions, 4-8 September.

[15] Improved Energy Capture in Series String Photovoltaics Via Smart Distributed Power Electronics. L. Linares, R. W. Erickson, S. MacAlpine and M. Brandemuehl. Washington, DC, USA, 2009, pp. 904-910: s.n., 2009. 2009 Twenty Fourth Annual IEEE Applied Power Electronics Conference and Exposition.

[16] Performance analysis of a 3 MWp grid connected solar photovoltaic power plant in India. Daniel, K. Padmavathi and S. Arul. 6, 2013, Energy for sustainable development, Vol. 17, pp. 615-625.

[17] Monitoring of Photovoltaic systems: good practices and systems analysis. Achim Woyte, Mauricio Richter, David Moser, Stefan Mau, Nils Reich and Ulrike Jahn. 2013, Proc. 28th European Photovoltaic Solar Energy Conference, 3686-3694.

[18] Analysis of the outdoor performance and efficiency of two grid connected photovoltaic systems in northern Italy. Diego Micheli, Stefano Alessandrini, Robert Radu and Losto Casula. 2014, Energy conversion and management, Vol. 80, pp. 436-445.

[19] An investigation of the Energy Efficiency of a Grid Connected Photovoltaic System. Koev, Konstantin. 2022, 8th International Conference on Energy Efficiency and Agricultural Engineering (EE& AE) 1-4.

[20] Recent advances in failure diagnosis techniques based on performance data analysis for grid-connected photovoltaic systems. Andreas Livera, Marios Theristis, George Makrides and George E. Georghiou. 2018, Renewable Energy, p. doi: 10.1016/j.renene.2018.09.101.

[21] Marios Theristis, Venizelos Venizelou, George Makrides and George E. Georghiou. CHAPTER II-1-B: Energy Yield in Photovoltaic System. Kalogirou, S. A. (Ed.), McEvoy's Handbook of Photovoltaics, third ed. Academic. 2018, pp. 671–713.

[22] Photovoltaik-Anlagen – Bewährung und Herausforderung. Jahn, Ulrike. 2003, FVS-Themen, pp. 28-35.

[23] THE EFFECT OF SOLAR IRRADIATION ON SOLAR CELLS. K. A. Ibrahim, P. M. Gyuk, S. Aliyu. 1, 2019, Science World Journal, Vol. 14, pp. 20-22.

[24] Dynamic thermal model of solar PV systems under varying. Diego Torres Lobera, Seppo Valkealahti. 2013, Solar Energy, Vol. 93, pp. 183–194.

[25] Dynamic thermal modelling of PV performance and effect of heat capacity on the module temperature. B. Tuncel, T. Ozden, R. S. Balog, B. G. Akinoglou. 100754, 2020, Case Studies in Thermal Engineering, Vol. 22.

[26] Performance analysis of a 48kWp grid-connected photovoltaic plant in the Sahelian climate conditions of Nouakchott, Mauritania. Ahmed Med YAHYA, Abdel. Kader. MAHMOUD, Daha Hassan DAHER, Léon GAILLARD, Christophe MENEZO, IssakhaYOUM, Adel. MELLIT. 2021, Preprints, Vol. 2021020275 (doi: 10.20944/preprints202102.0275.v1), pp. 1-24.

[27] Review of the performance of residential PV systems in France. Jonathan Leloux, Luis Narvarte, David Trebosc. 16, 2012, Renewable and Sustainable Energy Reviews, pp. 1369– 1376.

[28] IEC, International Standard. Photovoltaic system performance monitoring –Guidelines for measurement, data exchange and analysis. 1998.

[29] Performance evaluation and economical analysis of three photovoltaic systems installed in an institutional building in Errachidia, Morocco. Abderrazzak Elamim, Bouchaib Hartiti, Amine Haibaoui, Abderrazak Lfakir and Philipe Thevenin. 2018, Energy procedia, Vol. 147, pp. 121-129.

[30] DIRECTION NATIONAL DE L'ENERGIE, DNE. PLAN D'INVESTISSEMENT SREP-Mali Pour la Valorisation à Grande Echelle des Energies Renouvelables, Volume 1: Plan d'Investissement. Bamako: DNE, 2011.

[31] EPIA, (European Photovoltaic Industry Association) and the Photovoltaic Technology Platform. SOLAR EUROPE INDUSTRY INITIATIVE IMPLEMENTATION PLAN 2010-2012. s.l.: EPIA, 2010.

[32] Evaluation experimentale des performances d'une centrale solaire photovoltaique de 300 KWc a Djibouti. Daha HASSAN DAHER, Léon GAILLARD, Mohamed AMARA, Bernard LIPS, Christophe MENEZO. 27, 2014, Science et Envioronnement, pp. 16-22.

[33] Performance Parameters for Grid-Connected PV Systems. B. Marion, J. Adelstein, K. Boyle, H. Hayden, B. Hammond, T. Fletcher, B. Canada, D. Narang, A. Kimber, L. Mitchell, G. Rich and T. Townsend. 2005. Photovoltaic Specialists Conference.

[34] Review of Photovoltaic Performance Influencing Factors. Bhogula Navothna, Sri Chandan Kondamudi and Sandhya Thotakura. 10, 2020, Journal of Green Engineering, Vol. 10, pp. 9052-9067.

[35] Council, Australian Energy. Solar report Septembre 2016. Auatralie: s.n., 2016.

[36] EnergySage. Evaluating solar panel quality, https://www.energysage.com/solar/decision-guide/solar-panel-efficiency/#:~:text=Solar%20cell%20efficiency,-Solar%20panel%20efficiency&text=The%20most%20efficient%20solar%20panels,panel%20efficiency%20just%20under%2023%25.&t. 2020.

[37] Preliminary assessment of a small-scale rooftop PV-grid tied in Norwegian climatic conditions. Vågnes, Muyiwa S. Adaramola and Emil E. T. 2015, Energy Conversion and Management, Vol. 90, pp. 458–465.

[38] Performance analysis of a 190 kWp grid interactive solar photovoltaic power plant in India. Sharma V, Chandel SS. India: s.n., 2013, Energy, Vol. 55, pp. 476–485.

[39] IEA-PVPS. Performance of New Photovoltaic System Designs. s.l.: IEA-PVPS, 2021.

[40] A Critical Appraisal of PV-Systems' Performance: Review. Zainab Usman, Joseph Tah, Henry Abanda and Charles Nche. 192, 2020, Buildings, Vol. 10, pp. 1-22.

[41] Assessment of soiling impacts and cleaning frequencies of a rooftop BAPV system in composite climates of India. Satish Kumar Yadav, Nallapaneni Manoj Kumar, Aritra Ghosh, Usha Bajpai, Shauhrat S. Chopra. 2022, Solar Energy, Vol. 242, pp. 119–129.

[42] Performance analysis of a 11.2 kWp roof top grid-connected PV system in Eastern India. Goel, Renu Sharma and Sonali. 2017, Energy Reports, Vol. 3, pp. 76-84.

[43] Effect of dust deposition on the performance of photovoltaic modules in Taxila,. Hafiz Muhammad ALI, Muhammad Abdullah ZAFAR, Muhammad Anser BASHIR, Muhammad Ali NASIR, Muzaffar ALI and Aysha Maryam SIDDIQUI. 2, 2017, Thermal Science, Vol. 21, pp. 915-923.

[44] Performance and feasibility assessment of a 1.4 kW roof top grid-connected photovoltaic power system under desertic weather conditions. Hussein A. Kazem, Tamer Khatib, K. Sopian, Wilfried Elmenreich. 2014, Energy and Build, Vol. 82, pp. 123-129.

[45] Experimental investigation and modeling of photovoltaic soiling loss as a function of environmental variables: A case study of semi-arid climate. Houssain Zitouni, Alae Azouzoute, Charaf Hajjaj, Massaab El Ydrissi, Mohammed Regragui, Jesús Polo, Ayoub Oufadel, Abdellatif Bouaichi, Abdellatif Ghennioui. 2020, Solar Energy Materials and Solar Cells, Vol. 221, 110874. DOI: https://doi.org/10.1016/j.solmat.2020.110874

[46] An empirical study of performance characteristics of BIPV (Building Integrated Photovoltaic) system for the realization of zero energy building. J. B. Lee, J. W. Park, J. H. Yoon, N. C. Baek,& U. C. Shin. 2014, Energy, Vol. 66, pp. 24-34.

[47] Nouar Aoun. Performance Analysis of a 20 MW Grid-Connected Photovoltaic Installation in Adrar, South of Algeria. Advanced Statistical Modeling, Forecasting, and Fault Detection in Renewable Energy Systems. s.l.: Intechopen, DOI: http://dx.doi.org/10.5772/intechopen.89511, 2020, pp. 1-12.

[48] Performance Analysis of the Mini-Grid Connected Photovoltaic System at Algiers. F. Cherfa, A. Hadj Arab, R. Oussaid, K. Abdeladim, S. Bouchakour. 83, 2015, Energy Procedia, pp. 226 – 236.

[49] Performance Analysis of PV Grid-Connected in Four Special Months of the Year. Mustapha Adar, Zakaria Khaouch, Amin Benouna, Mustapha Mabrouki, Ahmed Chebak. Tanger: s.n., 2017. International Renewable and Sustainable Energy Conference (IRSEC'2017).

[50] Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco. Kamal Attari ∗, Ali Elyaakoubi, Adel Asselman. 2, 2016, Energy Reports, pp. 261-266.

[51] Performance of 1.4 kW Grid connected desert type PV. A. H. Al-Badi. Tenerife (Spain): s.n., 2019. International Conference on Renewable Energies and Power Quality (ICREPQ'19) Tenerife (Spain).

[52] The effect of dust on solar photovoltaic systems. F. Mejia, J. Kleissl, J. L. Bosch. 49, 2014, Energy Procedia, pp. 2370 – 2376.

[53] Experimental Study on the Effect of Dust Deposition on a Car Park Photovoltaic System with Different Cleaning Cycles. Khaled M. Alawasa, Rashid S. AlAbri, Amer S. Al-Hinai, Mohammed H. Albadi, and Abdullah H. Al-Badi. 7636, 2021, sustainability, Vol. 13, pp. 1-16.

[54] Investigation of fly ash soiling effects on solar modules performances. Ivana Radonjic, Tomislav Pavlovic, Dragoljub Mirjanic, Lana Pantic. 220, 2021, Solar Energy, pp. 144–151.

[55] A comparison of the performance of mono-Si and poly-Si photovoltaic modules operating under Kosovo climate conditions. Vjollca Komoni, Alemayehu Gebremedhin and Njomza Ibrahimi. 013504, 2018, Journal of Renewable and Sustainable Energy, Vol. 10, pp. 1-11.

[56] Effects of particle sizes and tilt angles on dust deposition characteristics of a ground-mounted solar photovoltaic system. Hao Lu, Wenjun Zhao. 220, 2018, Applied Energy, pp. 514-526.