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Long-term performance analysis of operational efficiency of a grid-connected solar power plant under Mauritania climate

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ABSTRACT

This work examines a solar power plant connected to the Nouakchott electricity grid in Mauritania. Operating since 2013, the 15 MWp plant's reliability and energy yield have been evaluated using a performance index. The assessment involves three phases. First, the plant's meteorological environment and technical indicators are presented. In the second phase, mathematical performance models specified by the International Energy Agency (IEA) are applied to calculate performance indices using data from the data acquisition system (SCADA). The third phase compares actual production data for 2015, 2017, and 2020 with results simulated for PVsyst for the same years. The obtained results are thoroughly analyzed to highlight relevant physical phenomena. The analysis focuses on the plant's 7-year operating period and its impact on performance indicators for electricity production fed into the grid. This study provides insights into the solar power plant's reliability and energy yield, aiding future operational enhancements. It underscores the importance of performance monitoring and assessment in optimizing solar power generation systems.

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1. INTRODUCTION

It is important to note that most current research is done on stand-alone photovoltaic (PV) systems. To a lesser degree, there are some studies on PV systems that are connected to the grid [1]–[3]. However, for simulations, these solar power plants are studied through simulation software such as PVsyst, PV*SOL, Helioscope, hybrid optimisation model for electric renewable (HOMER), RETScreen, photovoltaic geographical information system (PVGIS), SISIFO, PVWatts, and PVOnline. In the studies in [4]-[7], the authors have carried out investigations on hybrid power generation systems using the software HOMER. The optimization results of the considered system were obtained by comparison with other configurations [8], [9]. The same papers proposed the optimal planning of the hybrid system. Similarly, the authors conducted a sensitivity analysis on the variation in load and the price of diesel. Upon closer examination of the simulation software's bibliographic references, it becomes clear that these works are either associated with feasibility studies of solar systems, solar component modeling, techno-economic analysis, or environmental analysis.

Some of the researchers also gave special attention to the software PVsyst. This software allows the estimation of energy losses and yields in solar conversion chains, as described in [10]. Belmahdi and Bouardi

[11] used the PVsyst software to evaluate the feasibility and viability of the installation of a 1 MWp PV network connected with different cities. Next, they obtained the operational results of the PVsyst software implementation, which included recommendations for two fixed tilts of the PV panels. Mohammed *et al.* [12] focus on the same topic. This paper used PVsyst to find the performance coefficients on the economic part of grid-connected systems. Furthermore, in the other paper [13], the factors that determine the optimal performance of a PV module are presented. However, in all the papers [10], [14]–[20], it was noted that the environment of the solar systems is one of the parameters that directly affects the performance of the PV systems. It is important to note that the various results of the proposed modeling, simulation, and software can help improve solar systems and offer more opportunities for their operation. In the study that will be conducted, a literature review will be carried out whose work has similar objectives to those of this article, then the solar power plant in its environment and its technical specifications will be presented, and the data will be recorded from the data acquisition system SCADA. Furthermore, we will conduct a comparison and analysis of the actual production data from 2013 with the data acquisition system values from 2015, 2017, and 2020. PVsys also used the data from 2013 as a reference for the simulation. Finally, the study provides an analysis and the actual operating results to highlight the performance indices of the solar power plant in operation on the Mauritanian grid.

There is a scarcity of research on grid-connected solar plants in Africa, with most studies focused on standalone systems or simulations. Also, there is an absence of long-term performance analysis in the coastal African climate, making it challenging to optimize solar power systems. In this paper, comparing simulated results with real-world data over an extended period is conducted with an extensive 7-year performance analysis of a 15 MWp solar power plant connected to the Nouakchott grid in Mauritania, shedding light on performance in this unique climate. The paper used real production data gathered over a long period of time to give a full picture of the plant's performance. It also did a detailed comparison between real production data and PVsyst simulations to show that the simulation models work in Mauritanian conditions. The paper has identified performance degradation trends over time that are crucial for maintenance and optimization strategies. Also, insights into how the desert climate impacts solar system performance in Mauritania are valuable for similar environments. In summary, this paper bridges research gaps by offering a comprehensive analysis of a grid-connected solar power plant's long-term performance in Mauritania using real data and comparing it with simulations. This contributes to understanding and optimizing solar power systems in this specific region.

2. LITERATURE REVIEW

First of all, it is important to note in this section that in addition to the reviews already listed in the introduction they have addressed solar power plants, simulation software, and the environment of solar systems. There is also a growing body of work whose objectives are similar to those of this article. This literature has analyzed the parameters of the monitoring data to determine the degradation rates, or the performance rates of PV plants, In addition, the literature review has also been provided, in Table 1, the performance data of solar power plants in different countries.

Table 1. The performance of solar power plants in different countries

Location	Installed capacity (MWp)	Type of PV	Y_f	PR	Reference
El-Bayadh, Algeria	23.92	PC-Si	4.95	82.02	[21]
Ghana	20.00	PC-Si	3.68–5.06	72.80–80.20	[22]
Sohar, Oman	1.40	PC-Si	5.13	82.60	[23]
Irbid, Jordan	5.00	PC-Si	4.60	80.00	[24]
Niš, Serbie	2.00	MC-Si	3.18	93.60	[25]
Dublin, Ireland	1.72	MC-Si	2.41	88.50	[26]
Nouakchott, Mauritania	15.00	A-Si and µA-Si	4.62	79.95	This study

*PC-Si is poly-crystalline silicon, MC-Si is mono-crystalline silicon, A-Si is amorphous silicon, and µA-Si is micro-amorphous silicon

The proposed reviews study the evaluated factors of solar power plants in different parts of the world. The parameters that are studied and compared of solar power plants include energy output, reference yield (Y_r), PV array yield (Y_a), final yield (Y_f), capture losses (Lc), system losses (Ls), and ratio performance (PR). In addition, the Middle East and African areas have yields (Y_f) that are high compared to Europe. Indeed, for the Middle East and Africa, these average values are higher than 4.5 kWh/kWp/d due to the high level of daily solar energy irradiation. On the other hand, the performance (PR) values reach on average higher values in Europe compared to the Middle East and Africa. These average performance values are above 88%. This is due to these areas' low average ambient temperature and irradiation. However, for the

Middle East and Africa, they are lower than 86% due to the high ambient temperatures. Furthermore, it should be noted that the methods used in these reviews are based on both measurement and simulation results. All these reasons pushed to combine the methods of measurements, calculation, and simulation through the recorded data to bring out the advantages of solar power plants on the Mauritanian coast.

3. MATERIALS AND METHOD

The 15 MWp solar power plant was initiated in Mauritania in the year 2013, and it is located north of the capital Nouakchott. As shown in Tables 2 and 3, data from the acquisition system provides the production parameters at each level of the energy discharge bars. Measurements are taken every 5 minutes and over the long term give a vision of the performance of the existing solar system. It is also measured in addition to the production parameters: solar radiation, ambient temperature, and module temperature. It should also be noted that maintenance operations in the usual format that is dedicated to PV systems are performed regularly such as visual inspection of strings from the ground (every year) to detect broken modules, delaminated modules, and the state of fixation of the PV modules. In addition, the electrical part must be inspected, especially after the inverters and the relays, and the protection circuit breakers in their room (at least once a year). It is possible to add an important part that concerns periodically cleaning the panels of dust deposits on their surface.

Table 2. Environmental parameters of the tested power plant

Parameters	Values
Climatic zone	Hot and dry
Annual minimum and maximum temperatures (°C)	18.6 °C; 42.5°C
Average min and max relative humidity (%)	51.2%-84.7%
Annual average hours of insolation	10 h
Annual average global horizontal irradiation	4.2 à 6.6 kWh/m^2/days

Table 3. Technical specifications of PV modules given by the manufacturer at STC (a-Si and µ-Si)

Classification	Wc	Quantity	Power (Wc)	I_{MPP}	I_{SC}	V_{OC}	V_{MPP}
a-Si	410	1,296	531,360	2.57	3.25	197.0	160.0
a-Si	420	3,690	1,549,420	2.61	3.30	198.0	161.0
µ-Si	470	72	33,840	2.17	2.64	283.4	217.0
µ-Si	480	198	95,040	2.20	2.67	284.3	218.0
µ-Si	490	936	458,640	2.22	2.71	285.2	220.0
µ-Si	500	2,754	1,377,000	2.23	2.61	290.0	225.3
µ-Si	510	6,678	3,405,780	2.24	2.64	292.0	227.7
µ-Si	520	5,670	2,948,400	2.37	2.81	283.5	219.8
µ-Si	530	2,916	1,545,480	2.39	2.83	285.2	221.8
µ-Si	540	3,384	1,827,360	2.41	2.84	287.0	223.8
µ-Si	550	1,962	1,079,100	2.43	2.85	288.7	225.7
µ-Si	560	270	151,200	2.46	2.87	290.4	227.7
Total	29,826	15,003,000					

4. MATHEMATICAL MODELS OF PERFORMANCE

The performance parameters have been specified by the International Energy Agency (IEA) and are described in the standardized norms International Electrotechnical Commission (IEC) 61724 [27]. These parameters are used to define the performance of the whole system including the efficiency of the solar power plant concerning the energy production, the solar resources, and the overall effect of the losses of the PV system. Mathematical models of these parameters are proposed as follows:

- Performance ratio

  Equations should be placed at the center of the line and provided consecutively with equation numbers in parentheses flushed to the right margin, as in (1). The use of Microsoft equation editor or MathType is preferred.

$$PR = \frac{Final\ \ Yield\ \ (Y_f)}{Reference\ \ Yield\ \ (Y_r)} = \frac{E_{ac} \times G_{STC}}{P_O \times G_{POA}} = \left(Y_f = \frac{E_{ac}}{P_O} in\ \ kwh/kw_p, Y_r = \frac{G_{POA}}{G_{STC}}\right) \tag{1}$$

Where E_{ac} is net energy output AC in kWh, P_o is the nominal output power of the PV generator at STC in kWp; GpoaTotal solar radiation in the plant in kWh/m^2, G_{STC} IS Solar reference radiation at STC=1 kW/m^2, Y_r is reference yield (kWh/kWp/day), and finally Y_f is Final yield of the PV system (kWh/kWp/day).

- Capacity utilization factor
  Capacity utilization factor (CUF) means the ratio of the annual output of the plant in kWh versus installed plant capacity for the number of days, i.e., CUF is defined as the ratio of the actual output from a solar plant over the year to the maximum possible output from it for a year under ideal conditions.

$$CUF = Energy\ measured\ (kWh)\ /\ (365 * 24 * installed\ capacity\ of\ the\ plant) \quad (2)$$

- Efficiency of system
  The expressions for evaluating the efficiency of PV modules and system, (η_{pv}) and (η_{sys}), are given by (3) and (4):

$$\eta_{PV} = \frac{E_{dc}}{G_{POA} \times A} \quad (3)$$

$$\eta_{sys} = \frac{E_{ac}}{G_{POA} \times A} \quad (4)$$

  Where E_{dc} is the output energy DC of the PV generator in kWh and A is the surface of the photovoltaic field in m^2.

- Capture losses system losses
  The Lc represents the losses in the PV array due to the available irradiation intensity, module operating temperature, humidity, partial shading, wiring, and the Ls represent the losses due to the efficiency of the inverter operation [28]. Lc and Ls are given by (5) and (6) in [29]:

$$Lc = Yr - Ya \quad (5)$$

$$Ls = Ya - Yf \quad (6)$$

  Where Y_a is the PV array yield (kWh/kWp/day).

5. SOLAR POWER PLANT IN OPERATION

This section presents the following information: an analysis of the performance of the solar power plant, a comparison between and analysis of the results of the real data and those of the simulation, a discussion of the different results, specific conclusions, and a general conclusion. Several factors affect the performance of photovoltaic systems, such as solar irradiation, ambient temperature, dust accumulation, installation configuration, wind speed, and the area where the solar plant is located. These factors, cited in [30]–[34], lead to the degradation of the solar system and its performance. Therefore, this part of the study offers a method of presentation and analysis of the performances, which are implemented and adapted to our specific case, and which could be generalized for similar cases on the coast. This method is based on the processing of real data from the plant's data acquisition system in real-time operation during 8 consecutive years 2013 (reference), 2015, 2017, and 2020.

5.1. Solar power plant 2015 performance analysis

The data has been studied monthly, to assess the performance trends of the solar plant under the different climatic conditions of the Mauritanian coast. Finally, the impact of the climatic parameters as well as the losses is estimated in Figure 1. Thanks to the mathematical models, the performance parameters of the solar power plant are calculated under the meteorological data of the site. The measured or calculated parameters of the solar power plant have the following units of measurement: EGi: tilted global insolation (kWh/m^2); Ta: ambient temperature; E_{DC}; E_{AC}: direct and alternative energy; and η(%) is inverter efficiency. Solar radiation and ambient temperature have been collected by the data logger providing hourly average values. The months of April, May, June, July, August, and September are considered the months with the highest solar potentials. For example, the month of May records the maximum data EGi=195.8 kWh/m² and Ta=34.90 °C. On both sides of May, the values of these data start to drop to a minimum for January EGi=124.6 kWh/m² and for December EGi=123.4 kWh/m². The periods related to high radiation are May, June, July, August, and September.

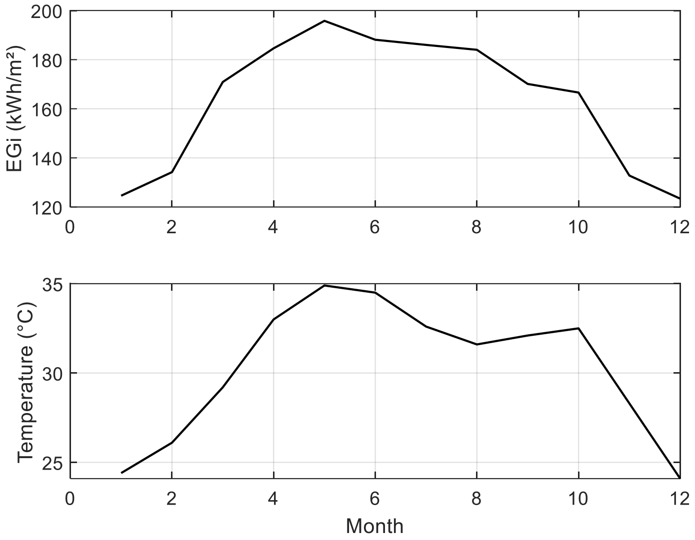

Figure 1. Meteorological data EGi (kWh/m²) and Ta (°C)

As shown in Figure 2, the average monthly energy E_{DC} and the average monthly energy E_{ac} are generated by the solar power plant and are represented. The months (of March, April, May, and June) are considered with the highest peak energy production. For example, the peak energy production was reached in April to be 967007.92 kWh for E_{DC} and 940021.87 kWh for E_{AC}. Similarly, a minimum of energy was generated in December, with the value E_{DC} of 480598.80 kWh and the value EAC of 465027.79 kWh.

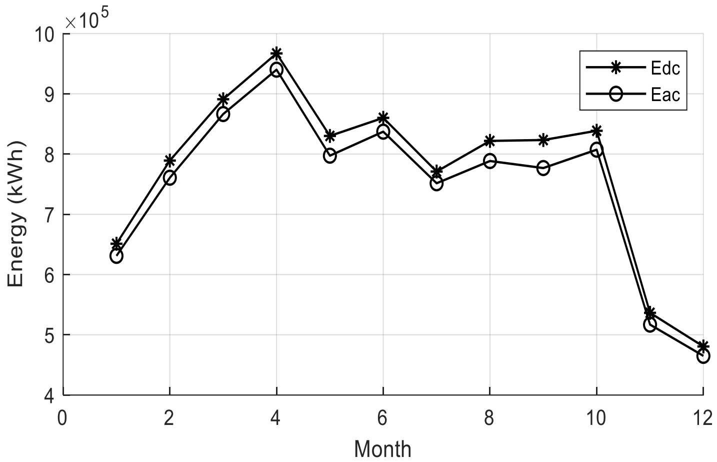

Figure 2. The energy produced E_{DC} (direct energy in kWh)) and E_{AC} (alternating energy in kWh))

In Figure 3, the performance parameters of the solar system are illustrated, which include the yield Y_r, Y_a, and the average final yield (Y_f). Therefore, the evaluation gives the maximum values for the months of (March, April, May, June, July, August, September, and October). Indeed, if we take the example of May, it shows the maximum of the values for Y_r=6.86, Y_a=5.40, and Y_f=5.48.

The decrease in this type of value starts on both sides of this month. These values show a trend for the values as follows: $Y_r > Y_a > Y_f$. In this case, the (Y_r, Y_a, and Y_f) give an overview of the performance when the months of May, December, July, August, and September show the best performance in terms of yields (Y_r, Y_a, and Y_f) at the solar power plant site which is explained by the increase in solar radiation during these months. It can also be deduced that the values of the coefficients of performance are proportional to that of the illumination.

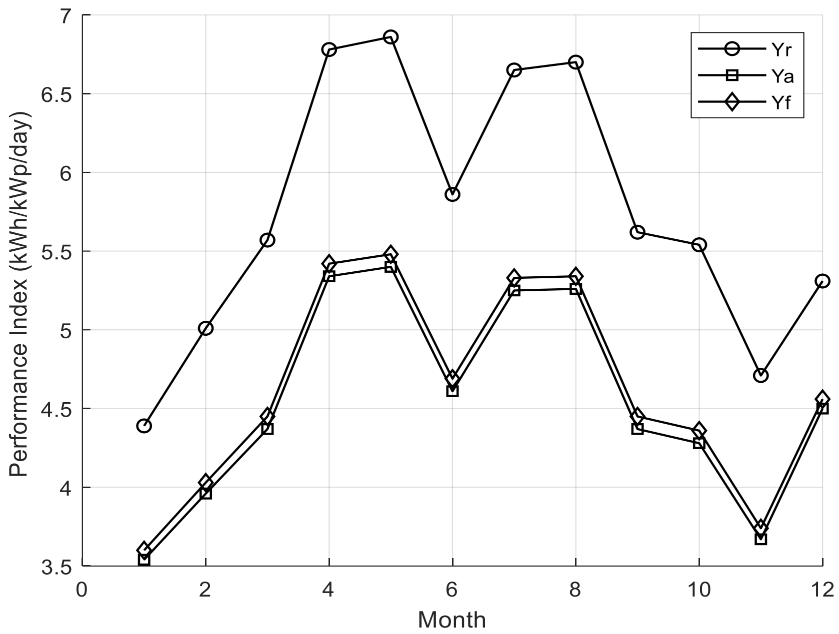

Figure 3. Performance index (Y_r, Y_a, and Y_f (kWh/kWc/day))

Figure 4 shows the Ls and miscellaneous Lc of the solar power plant operation. The grid Lc represents the uncaptured part of the total radiation striking the modules of the solar power plant. Ls represents the losses that occur in the inverters. These losses are significant for March, April, May, June, July, August, and September. They were at their maximum for May, with Lc=1.460 and Ls=0.080. These losses are minimum for December, with Lc=0.810 and Ls=0.060. The significant losses of Lc and Ls take place in periods of high temperatures.

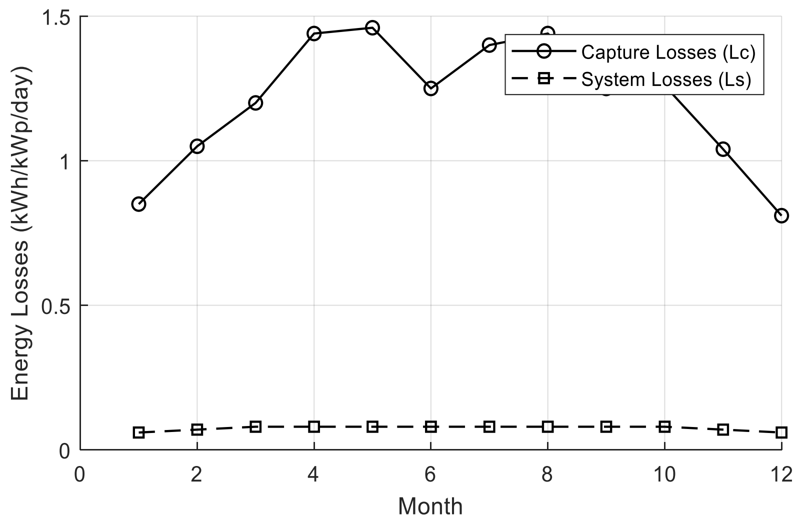

Figure 4. Energy losses Lc and Ls in kWh/kWp/day

In Figure 5, the instantaneous efficiency of the PV module (η PV) is given in December for the important values in February, March, April, May, June, July, August, and September. The example of December shows performance values of PR=0.802 and η (%)=98.4. In addition, these values are at a minimum for October: PR=0.788 and η (%)=98.2. Finally, it is not difficult to see that Feb, Mar, Apr, May, Jun, Jul, Aug, and Sep also have the best PR and inverter efficiency η (%) at the solar plant site. Solar radiation is the main parameter directly linked to energy generation. In fact, in our case, the month of April and May record the highest values of solar radiation. Therefore, it is observed that the energy that is generated is at its maximum in these two months. Thus, the peak of energy production is reached for example for April (2015) with E_{DC}=967007.92 kWh and for May with E_{DC}=830060.08 kWh. In line with what has been mentioned, the losses are also at a maximum for these two months, e.g., May (Lc=1.460 and Ls=0.080). Therefore, the solar plant shows an efficiency of η (%)=98.4 with PR=0.802 for May. In December, the lowest insolation was recorded, therefore, which resulted in the lowest energy produced. Thus, solar radiation directly affects the energy produced by the solar power plant.

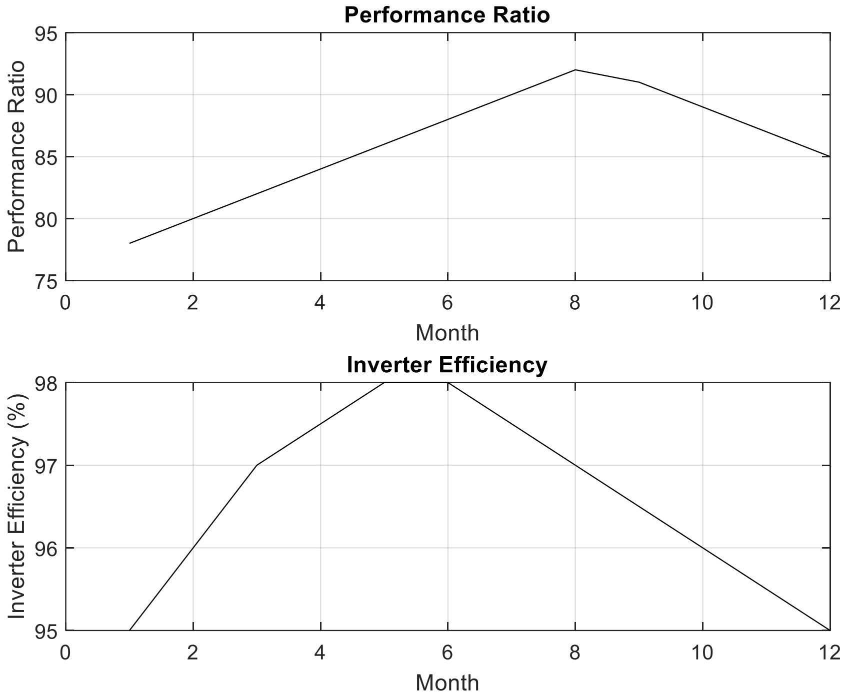

Figure 5. Performance ratio and inverter efficiency η (%)

5.2. Comparison between the results of the real data and the simulation data

It is necessary to present the functioning of the software (PVsyst), which is at the center of the comparison between real and simulated production [35]–[38]. For this purpose, a brief description of the PVsyst simulation procedure is given, which was carried out in 4 phases as follows: (1st phase): providing the geographical and meteorological data of the site in PVsyst and the type of solar installation, (2nd phase): providing the power of the installation, the inclination of the collector plane and the orientation information, the string configuration, the characteristics of the inverter and the transformer, (3rd phase): providing the information on various losses and power factor information that has been provided and the simulation that has been carried out, and (4th phase): providing the normalized productions, PR, annual irradiation, the efficiency of the photovoltaic panels and the system. In Tables 4 and 5, the results show that the energy produced by the solar power plant and the energy fed into the grid is strongly affected by the operating time. Indeed, for example, the simulation by PVsyst for January gives the values (E_PV=662755.1 kWh and E_Grid=652083.4 kWh (energy simulated by PVsyst at the origin of the design), and the values for January 2015, it is given E_PV=651130.61 kWh and E_Grid=631017.46 kWh. It is noted that the energy produced by the solar power plant and the energy fed into the grid has continued to undergo a gradual decrease from 2015 to 2020 to reach the values in January: (E_PV=488650.42 kWh and E_Grid=467527.17 kWh). The PR was impacted by this aging degradation which was evaluated as follows: PR (parameter simulated by PVsyst at the origin of the design): 0.835, PR (2015): 0.821, PR (2017): 0.795, and PR (2020): 0.768.

Table 4. The actual production of 2015, 2017, and 2020 the simulated results in KWh

	2015 measured		2017 measured		2020 measured		PVsyst simulated	
	E_PV	E_grid	E_PV	E_grid	E_PV	E_grid	E_PV	E_grid
Jan	651130.61	631017.46	620124.39	600969.01	488650.42	467527.17	662755.10	652083.4
Feb	789196.04	760710.93	775732.15	751479.63	756338.85	732692.64	691476.80	680459.8
Mar	890950.71	866377.99	866229.11	829470.33	824980.11	789971.74	845957.10	832088.1
Apr	967007.92	940021.87	940638.07	907102.47	917695.68	884978.02	880449.90	866639.8
May	830060.08	797292.63	771676.39	751269.44	752855.02	732945.79	905931.90	892082.9
Jun	860119.17	837119.72	757956.01	728293.42	739469.28	710530.17	862685.01	849211.2
Jul	770966.58	751541.10	649417.22	623774.36	618492.59	594070.82	858931.90	845586.4
Aug	821812.57	788456.04	767343.12	747641.44	748627.43	729406.28	865378.50	852050.2
Sep	823242.46	776748.76	637542.87	616466.29	607183.69	587110.75	819764.60	806848.8
Oct	838622.48	807236.46	796691.36	766874.64	769997.43	738611.41	833397.60	819942.8
Nov	536466.20	516883.12	500590.03	479636.13	467841.15	448258.07	689893.40	678851.8
Dec	480598.80	465027.79	440811.91	424150.93	411973.75	396402.74	655818.80	645798.9

Table 5. Comparison of PR for the years (2015, 2017, and 2020) the simulated results

	Simulation PR	2015 mesured PR	2017 mesured PR	2020 mesured PR
Jan	0.835	0.821	0.795	0.768
Feb	0.831	0.804	0.778	0.751
Mar	0.825	0.798	0.772	0.745
Apr	0.826	0.799	0.773	0.746
May	0.825	0.798	0.772	0.745
Jun and Jul	0.827	0.801	0.775	0.748
Aug	0.824	0.797	0.771	0.744
Sep	0.818	0.791	0.765	0.738
Oct	0.815	0.788	0.762	0.735
Nov	0.822	0.795	0.769	0.742

The degradation is a decrease in the value of the energy produced in the form of losses due to the imperfections of the solar system or its aging over the years of operation with direct or indirect causes. The degradation in production has occurred on several levels and is directly followed by the degradation in the PR. This decrease in energy production is unexpected because it occurred in an area with high irradiation, which records an annual average of global horizontal irradiation: of 4.2 to 6.6 kWh/m^2/d. This shows that the PR is influenced by the meteorological parameters that are associated with the location of the operation. This decrease in energy output is close to 7% for every two years. Table 6, it is proposed the calculation of the data in two phases for the comparison of the projected output (baseline) with the energy from the PV system and the energy fed into the grid as follows: (1st phase): highlights the energy losses between the projected PVsyst production with the energy produced at the PV system's discharge bar and (2nd phase): highlights the energy losses between the projected PVsyst production and the energy fed into the grid each year. The year 2015 shows a very small difference of 3.62% between the simulated energy and the energy at the output of the PV system and a difference of 5.13% compared to the simulated energy and the grid energy.

Table 6. Difference between the PV projected production and actual energy fed into the grid in KWh

	2015		2017		2020	
	E-PV	E-grid	E-PV	E-grid	E-PV	E-grid
Annual average	312266.98	483210.33	735420.99	711305.78	1156068.22	1125928.27
Difference (%)	3.62	5.13	7.94	7.96	12.48	12.60

This very small difference is explained by the state of the solar system being considered new, after only two years of operation. However, the difference will increase in 2017. Indeed, the output energy of the PV system is 7.94% and the output energy of the grid is 7.96%. These differences in data between 2015 and 2017 are impacted by aging factors. The energy losses increase with the years of operation and become more and more important. It should be considered that this increase in losses is related to the last 4 years of operation. In the end, for 2020, the difference will increase, so the energy at the output of the PV system is 12.48% and the energy at the output of the grid is 12.60%. Paradoxically, this area of the Mauritanian coastline is perhaps one of the most suitable locations for the use of solar energy due to the high levels of solar radiation that are recorded on an annual average (4.2 to 6.6 kWh/m^2/d). However, the desert climate of the coastline negatively influences the performance of solar systems. From the information, the performance of a solar power plant as shown in the tables can be influenced by the presence of meteorological disturbances.

6. CONCLUSION

In this paper, performance data have been analyzed monthly, to assess the performance trends of the solar power plant under the climatic conditions of the Mauritanian coastline. The impact of the climatic parameters as well as the energy losses are estimated through the proposed mathematical models. The results showed that April, May, June, July, August, and September are the months with the highest solar potential and ambient temperatures. The energy of inverter input and output increases steadily with increasing solar irradiation. The calculations Y_r, Y_a, and Y_f gave an overview of the performance of the solar PV plant for the operating year 2015. May, June, July, August, and September have shown the best performance. Then, the losses Lc and Ls are considered important for sunny months which also have the best performance and efficiency ratios at the solar power plant site. Furthermore, the actual data is compared with the simulation data showing small differences. The average difference is around 7%. Finally, there is a difference between the projected production and the energy fed into the grid since losses increase as the plant is operated every year.

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