Experimental evaluation of the performance degradation of a solar PV plant operating in a Sahelian climate

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ABSTRACT

Niger, a Sahelian country, is known for its extreme climatic conditions and its wealth of solar deposits. In Niger, the average duration of sunshine is 8.5 hours per day and its average level is estimated at about 5 to 7 kW/m² per day. However, the rate of access to electricity in Niger remains very low. To address this problem, a 7MW solar photovoltaic power plant has been built by the authorities in the town of Malbaza (13°58.54 N and 13°58.54 E). It has a capacity of 7 MW and is composed of monocrystalline photovoltaic solar panels. In this study, we propose a method for analysing the degradation of a solar photovoltaic power plant under its operating conditions. The study will help to assess the performance and efficiency of PV systems installed in this geographical area. For this study, we use annual energy production data, recorded at the site, from 2019 to 2021. The method is based on the performance ratio values measured during these three years of operation. An hourly I_R energy production index was introduced to study the degradation and reliability of the system. The performance ratio values obtained from the measurements in 2019, 2020 and 2021 are 73.22, 72.73 and 70.84 respectively; the calculated hourly energy production index values are 0.921, 0.914 and 0.891 respectively. The PVsyst software was used to estimate the value of the performance ratio. The value obtained is 79.50%. Thus, a degradation of 1% per year over the three years of operation is estimated. Finally, a comparison was made with other studies.

Keywords: Performance ratio, degradation rate, monocrystalline technology, energy generation index.

1. INTRODUCTION

With the growing challenges of global resource depletion, global warming and environmental degradation, increasing attention has been given to renewable energy production, particularly solar photovoltaic energy production, as it is less harmful to the environment [1],[2],[3]. An additional problem in Africa is economic poverty, including energy poverty. At the same time, this part of the world has the greatest potential for solar energy, which is an inexhaustible resource.

Niger, a vast landlocked country in the Sahel (Africa continent), has an important solar resource. The average insolation time is 8.5 hours/day and the average power received is between 5 and 7 kW/m²/day [4]. Thus, to improve the country's energy production, the Nigerien authorities have thought of developing solar photovoltaic power plants. In 2018, a first 7 MW solar photovoltaic plant was built by the State of Niger, in the town of Malbaza. However, forecasting the production of electricity from PV systems is a complex task [5]. It takes into account the impact of weather conditions and the effect of degradation of PV system performance. This degradation is most often due to shadows, temperature, dust and defects in the system components. A degraded PV system loses its performance over time. This paper investigates the degradation of this plant after three years of operation. A collection of actual measurement data from the site was carried out over a three-year period: 2019, 2020 and 2021. The theoretical model was implemented using PVsyst software. Several studies have shown that this software gives a good estimation of meteorological and electrical data [6], [7].

2. MATERIAL AND METHODS

The present study is based on measurements of the solar PV plant, located in Malbaza, in the Tahoua region of Niger (13°58',54 N and 13°58',54 E). The data was collected over a three-year period from 2019 to 2021. Tables 1 and 2 show the characteristics of the plant and its components. An integrated data acquisition system monitors the main parameters of the PV system. Data is recorded every minute by a SCADA system.

Table 1. Characteristics of the inverters and PV panels used.

Inverter specification	Value	PV Module Specifications	Value
Max Power DC	1200 kW	Rated power at STC	330 Wp
Max Input Voltage	1100 V	Module efficiency	17.07 %
MPP voltage range	600–850V	Max voltage (Vmpp)	36 V
Max Input Current	1710 A	Max current (Impp)	9.17 A
AC Power Range	1000 kW	Open circuit voltage (Voc)	45.6 V
Rated AC voltage range	160–280 V	Open circuit current (Isc)	9.65 A
Frequency	50 HZ	NOCT	46 ±˚C
Max output current	1732 A	Temperature coefficient at Pmax	−0.3845 %/˚C
Max. frequency	98.30%	Temperature coefficient at Voc	−0.2941 %/˚C
Weight	61 kg	Temperature coefficient at Isc	0.0681 %/˚C

Table 2. Characteristics of the Malbaza PV plant.

N°	Parameter	Value
1	Rated power at STC	7 MW
2	Number of PV modules	21231
3	Number of inverters	7
4	Number of modules/strings	42
5	Number of strings	1011
6	Number of strings/inverters	144
7	Output voltage	3 phases 415 V AC

In order to evaluate the degradation of this system, a method based on the values of performance ratios was used. It consists in determining the energy generation index I_R, defined as the ratio between the actual values of the output performance ratios and the expected values of these same performance ratios, at the output. This index is calculated from formula (1) :

$$\mathbf{I_R} = \frac{\textbf{Actual PR}}{\textbf{Simulated PR}} \quad \textbf{(1)}$$

Where :

- I_R is the energy generation index ;
- Actual PR, the values of the measured performance ratios ;
- Simulated PR, the values of the theoretical performance ratios obtained from the PVsyst software.

This index is used to quantify the degradation and assess the reliability of the PV system.

In the present study, the theoretical model was simulated under the PVsyst software. A high I_R index indicates a good agreement between the actual performance ratio value and the measured one. It can therefore be stated that the PV system has a high reliability, when the actual and theoretical values are very close. A low I_R index means that the actual ratio value is lower than the theoretical ratio value due to performance losses caused by shading effects, temperature, failure or partial or total failure.

Matlab software was used to obtain the correlation curves and Excel software was used for comparisons.

3. RESULTS AND DISCUSSION

The PVsyst software was used to monitor the meteorological data and then resample it to obtain hourly meteorological data. The analysis was performed on filtered data, without including the records available during the night.

Figure 1 shows the evolution of the performance ratio (PR) of the plant in the years 2019, 2020 and 2021 and the one estimated from PVsyst. A decrease in performance over the years indicates a degradation of the system. Thus, it can be observed that, apart from the month of September 2020, the monthly averages of the performance ratios measured over the three collection years are low compared to the estimated monthly values. The lowest value of the ratios is observed in May 2019, with an average of 52.55% and the highest is 84.47%, observed in September 2020. There is a drop in the performance of the system in May. This drop can be justified by the fact that this month is one of the hottest in Niger

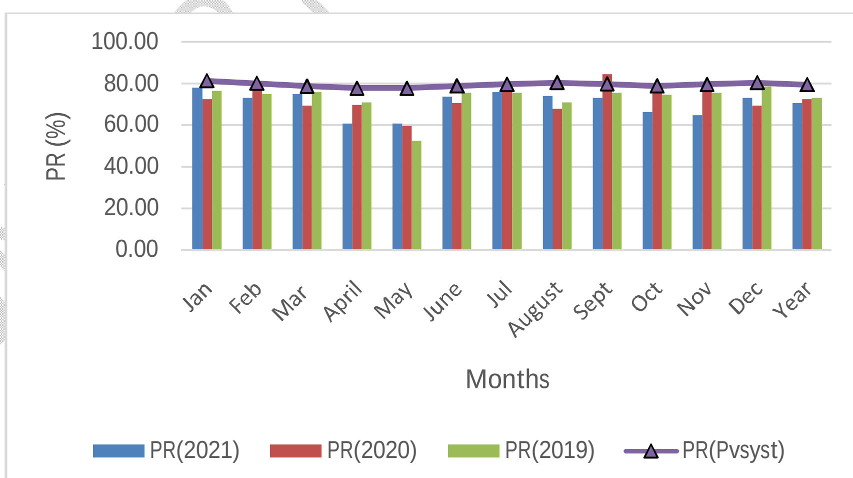

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Fig. 1. Simulated and measured PR for the years 2019, 2020 and 2021.

Figures 2, 3 and 4 show the correlations between the values of the performance ratios obtained from the measurements and those obtained from the PVsyst data. The correlation coefficient R^2 has been calculated for each case. This is one of the most commonly used coefficients. It measures the linear relationship between two variables. Its value varies from 0.14 to 0.58 over the years. The high coefficients show that the actual ratio is very close to the predicted ratio, which would demonstrate that the PV system is working well.

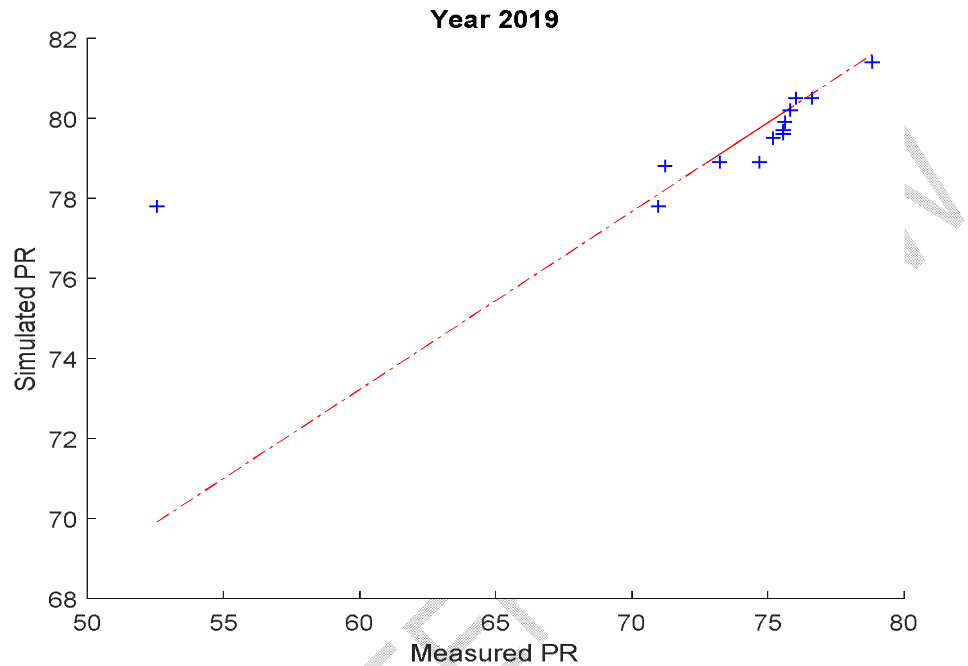

Fig. 2. Correlation between measured and simulated PR for the year 2019, *R^2=0.34*

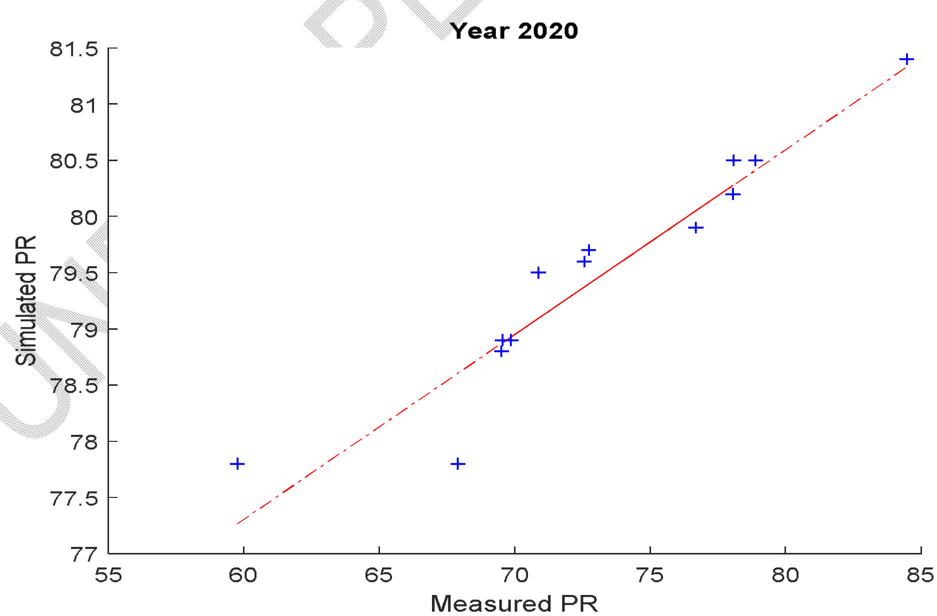

Fig. 3. Correlation between measured and simulated PR for the year 2020, *R^2=0.14*

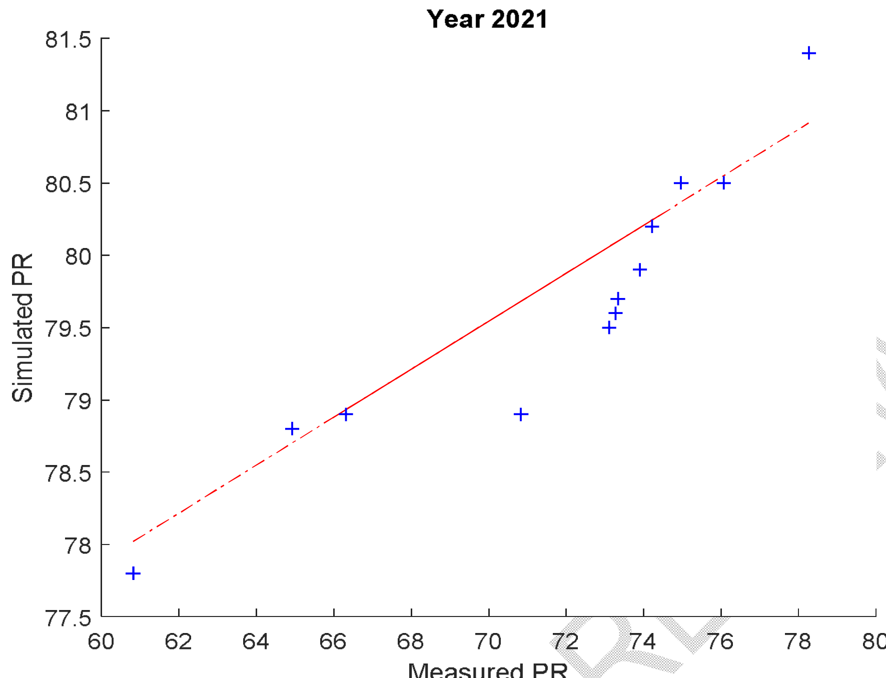

Fig. 4. Correlation between measured and simulated PR for the year 2021, *R^2=0.58.*

Figures 5, 6 and 7 illustrate an approach to identifying the effects of ambient conditions on the reliability of the PV system, where the expected hourly energy production index I_R is plotted against incident solar irradiance. These values are 0.018, 0.023 and 0.04 in the years 2019, 2020 and 2021 respectively. These low R^2 values mean that there is a low correlation between the two variables. This shows that the measured performance ratio and solar irradiance have a positive but weak relationship, i.e. when irradiance increases (or decreases), the performance ratio is less influenced. By Therefore, the differences between the measured ratios and the theoretical ratio, if they exist, are not due to the solar irradiance of the site, but their causes must be sought in the PV components and the operation of the system as a whole.

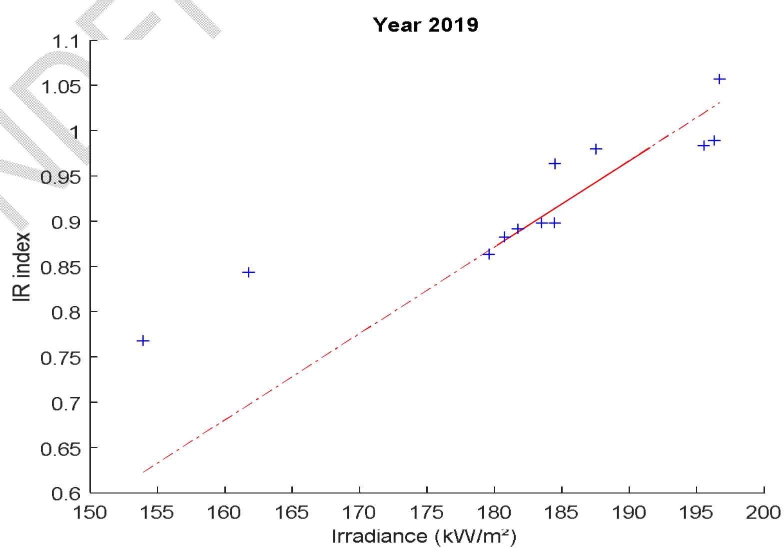

Fig. 5. Correlation between I_R index and irradiation for the year 2019, *R^2=0.018*

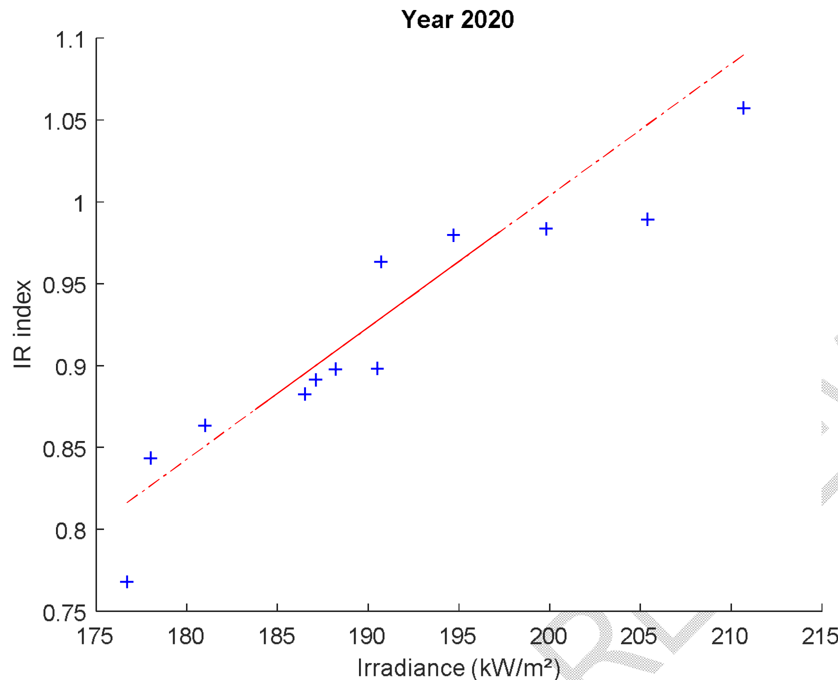

Fig. 6. Corrélation between I_R and irradiation for the year 2020, *R^2=0.023*

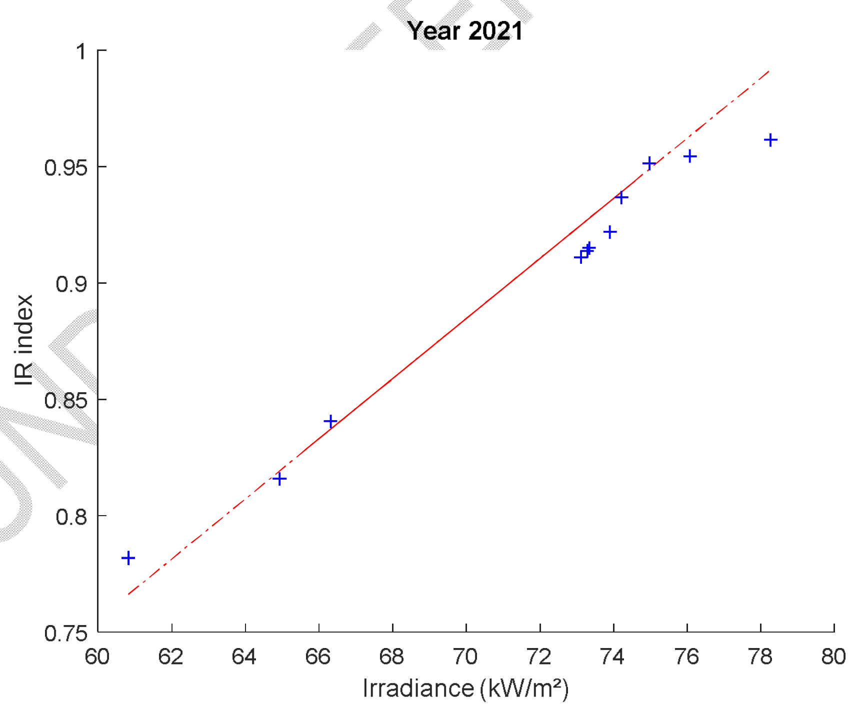

Fig. 7. Correlation between I_R and irradiation for the year 2021, *R^2=0.046*

Figure 8 shows the variations in the RI. These values range from 0.67 to 1.06. There is also a drop in this index in the month of May. This decrease can be justified by the fact that this month is one of the hottest in Niger.

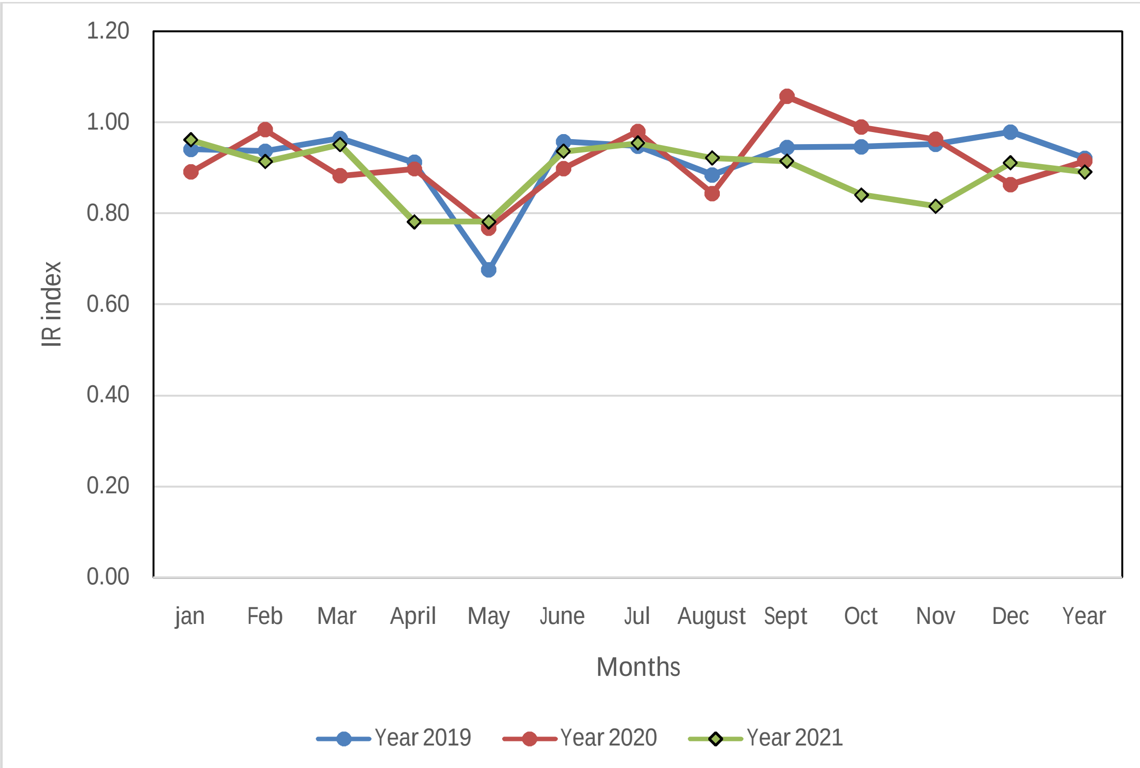

Fig. 8. Annual variation of the I_R index.

Table 3 presents the annual average of the I_R for each year. The results show that the annual averages of the I_R are close to 1 (perfect case). This means that there is a difference between the theoretical and the actual PR. This difference is due to the unfavorable operating conditions, it does not depend on the solar irradiation of the site. Moreover, the I_R index is very close to 1 and it is always higher than 0.91, which implies a good agreement between the actual and the theoretical PR.

Table 3. Average annual I_R index

Year	2019	2020	2021
IR	0,921	0,914	0,891

The I_R index therefore represents the reliability level of the PV system, which is 91% on average per year. Moreover, we can see that this index decreases over the years. This decrease shows that the PV system is degrading over time. The annual degradation rate can be estimated at about 1% per year. The values of I_R are shown in Table 3.

Table 4 summarizes the previously published degradations of PV systems studied in the literature and the results of this work.

Table 4. Comparison of degradation rates per year with some other studies

Locality	Rate of degradation by year (%)	Methodology	Reference
Italie	1.2	Ratio of power	[8] : Malvoni et al., 2017
Djibouti	1.01	PV-USA	[9] : Daher and Gaillard., 2018
Inde	0.55 to 0.95	Linear least-squares regression (LSS)	[10] : Kirmani and Kalimullah, 2017
Thailand	0.5	Simple linear regression model (SLR)	[11] : Limmanee *et al, 2015*
Saida, Algeria	0.58	Linear least-squares regression (LSS)	[12] : Silvestre et al., 2018
Alkmaar, Netherlands	0.92	Seasonal and trend decomposition using loess (STL)	[13] : Tabatabaei et al., 2017
Lecce, Italy	0.52	Linear least-squares regression (LSS)	[5] : Malvoni et al., 2017b
Bolzano, Italy	1.48	Classical seasonal decomposition (CSD)	[14] : Lindig et al., 2018
Tsukuba, Japan	2.35	Linear least-squares regression (LSS)	[15] : Ishii et al., 2011
Golden, CO, USA	0.71	Classical seasonal decomposition (CSD)	[16] : Huang et al., 2016
Ankara, Turkey	0.40	Linear least-squares regression (LSS)	[17] : Ozden et al., 2017
Netherlands	0.923	Seasonal and Trend decomposition using Loess (STL)	[18]: Chawla et al., 2021
Malbaza, Niger	**1**	**Report of performance ratio values**	**Our result**

From the collection of degradation studies shown in Table 4, it can be seen that LSS (5 studies) is the most widely used method in the literature for estimating degradation. It estimates a DR between 0.40% per year [17] and 2.35% per year [15]. The CSD method (2 studies) estimates a DR of 0.71% per year [16] and 1.48% per year [14]. The STL method (2 studies) estimates the same DR of 0.92% per year [13], [18]. The other methods (1 study), SLR, Power Ratio and PV-USA estimate DRs of 0.5% per year, 1.2% per year and 1.01% per year respectively [11], [8], [9].

This result is in line with the reference degradation rates calculated by the authors of other studies (1%/year), as shown in Table 4.

4. CONCLUSION

PV system degradation and reliability studies are strategic tools to evaluate the performance of a PV system [2]. This study contributes to the study of the performance of PV systems in the Sahelian climate. It also allows a comparative study with other climatic zones. The objective is to study the degradation and reliability of the solar PV power plant, located in Malbaza, Tahoua region, Niger, through a comparative analysis of measured and simulated performance ratios. The theoretical model of the PV system was implemented using the PVsyst software. The expected ratio generation index I_R was introduced to perform the evaluation. The results show that the reliability of the PV system depends on the operating conditions. It is not directly due to variations in solar irradiance at the site. A good agreement between the theoretical and actual energy production allowed to quantify the reliability of the PV system up to 91%. Furthermore, the degradation can be estimated at 1% per year over the three years of operation.

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