Early degradation factors of solar 33 kV grid connected power plant, a comparative study

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Article Info

Article history:

Received Jun 16, 2023
Revised Jul 5, 2023
Accepted Jul 29, 2023

Keywords:

Degradation rate
Early degradation
Grid-tied PV system
PV module inspection
Solar power plant

ABSTRACT

This paper identifies and analyses early degradation mechanisms observed in photovoltaic (PV) modules of power plants over 7 years of operation on the coast power grid in Mauritania. Performance degradation takes place due to several reasons such as material degradation following dust accumulation, high temperature, and humidity. Also, mismatch of electric power parameters such as increasing loads above projected values of the plant. Therefore, this paper analyses and studies the degradation in four phases. First, the visual inspection detects the degradation of materials and defects such as the presence of dust, cracks, browning (discoloration), and connection corrosion. The second phase proposes a mathematical model to calculate the early degradation rate (DR) of different components, such as short circuit current (Isc), open circuit voltage (VOC), the maximum yield power (Pmax), and the fill factor (FF) of the PV module. The third phase is a MATLAB modeling of the measured real-time data of the operating PV system to test Power versus voltage curves (with and without degradation) to examine the presence of failure of PV modules. Finally, compare the evolution of real-time production data for three measured years (2015, 2016, and 2017) with the simulation curves of this study.

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1. INTRODUCTION

In recent years, solar energy has symbolized renewable energy as the most favorable resource in the Sahel countries [1]–[3]. Therefore, to understand the degradation mechanisms, the authors [4]–[8] gave an overview of the principle of operation of PV modules, the main degradation phenomena that reduce their efficiency, and the different characterization techniques. First, Chianese *et al.* [9] and Saeed *et al.* [10] considers the PV module's performance as related to the conditions of the operating environment. They believe collecting real-time electrical performance data is the best test for PV modules. It goes further to include studying long-term performance in actual working conditions. The mathematical degradation models developed by Aboagye *et al.* [11] resulted in power degradation rates of 0.99% per year and 1.15% per year for both monocrystalline and polycrystalline, respectively, after six years of exposition. Piliougine *et al.* [12] also used the I-V curve plotter and the infrared camera, in addition to tools, to collect data. These results are higher than those proposed by the authors [13]–[15], who also found degradation rates at 0.8% per year with a median value of 0.5% per year. Hasan *et al.* [16] noted that initial exposure to light of the c-Si modules caused a degradation of the average power of about (0 to -5%). Then, he described this degradation as the initial type. He explained that in some modules, the initial degradation lasts several months. Then, he gave the main signs of the initial power degradation of the PV modules by ASI 16-2300, following the yellowing of the encapsulant, delamination, and the presence of hot spots. In addition, studies [17]–[20] have shown that photovoltaic module degradation varies in different locations. The discoloration of encapsulation materials is observed as the predominant mode of degradation mechanism of polycrystalline in hot semi-arid climatic conditions. In contrast, the browning of encapsulation materials follows as the dominant mode in tropical savannah regions. Thus, the work cited showed degradation to different degrees for PV modules. Furthermore, a particular type of behavior may predominate depending on the site and its environment [21]–[24]. As part of the organization of this paper, it presented: i) A visual inspection for the visual detection of material degradation; ii) A mathematical model to calculate the early degradation rate of the components of the short-circuit current (Isc), open circuit voltage (Voc), maximum power of the module (Pmax) and fill factor (FF) of the module (PV); iii) A simulation degradation study with MATLAB using real-time on-site measured data. It also proposes the characteristics curves to assess the failure; and iv) A validation of the work by comparing the evolution of the production data for three measured days of operation in real-time data for three years (2015, 2017, and 2020), with the simulation curves that carried out by PVsyst simulation results of 2020.

For the nature of the contribution to research, the following points should be mentioned: i) The research carried out is related to a theme of the degradation of PV modules, of which very few studies in the Sahelian zone on the northern coast; ii) The lifetime operation of large PVsyst, it is impossible to predict by these evaluation methods the degradation of the power output of the plant, which allows early decision-making to fill the power gap at the output; iii) The validation of mathematical degradation assessment models coupled with software such as MATLAB and PVsyst; iv) The apparent need to create a database on the impact of degradation on PV modules and the early performance of PV modules that located in the Sahel; and v) The PV modules in this work were used partly in a grid-connected solar power plant, while the works [25]–[28] carried out on individual modules.

Finally, this work also makes it possible to predict planned maintenance. In this sense, it allows the adoption of concrete actions such as cleaning, corrosion monitoring, and deterioration monitoring on glass surfaces or other materials to predict future failures. The analysis database creates the failures of photovoltaic systems in this world.

2. METHODOLOGY

To set up the practical and theoretical part of this work under standard conditions of 1000 (W/m^2) radiation and 25 °C temperature. It is proposed in this paper to study a real-time solar production system in operation during the interval (2013 to 2020) under the meteorological conditions of the site. The interest brought to the solar power plant is to deduce the characteristics of early degradation of the PV modules. With this in mind, the methodology presented consists of setting up the following steps about the objectives: the objective that determines the visual impacts of bad weather and those related to maintenance of the photovoltaic modules of the solar production system, the aim that establishes the mathematical models that govern the influence of degradation as a function of time, the objective that makes it possible to compare production data of the solar power plant during its new state (without degradation) and operating data over several years with degradation, establishing these original characteristic curves of the photovoltaic modules under the conditions of the site and the objective that allow to carry out and validate the simulations through mathematical models and compare them with the data recorded during time operation accurate.

Finally, the goal is to make it possible to compare the production data of 2015 (reference year), 2017, and 2020 with the data of the same years simulated using PVsyst. Thus, monitoring an actual installation makes it possible to understand, know and evaluate the degradation for the control to enhance or maintain electricity production. Similarly, it makes it possible to achieve the objectives of eliminating the causes cited in the context of power losses. Table 1 [29]–[34] (see in Appendix) summarizes the bibliography of degradation types by climatic zone. Indeed, the bibliography and studies seek to touch on aspects of this theme. In this bibliography, the early degradation elements are looked at to a lesser degree in the literature studied. Explains the importance given to degradation aspects in our case.

3. SYSTEM DESCRIPTION AND CONFIGURATION

The mauritanian electricity company (SOMELEC) built the solar power plant in 2013 on the northern part of the coast (Sahel). A total of 29,826 Masdar PV modules use for the project. Two different thin-film technologies use namely amorphous silicon (a-Si) and silicon micromorph (a-Si/μc-Si), each with several power ratings [35]. The solar power plant has been operated to date nine years. Therefore, the data used for this work covers seven years. the solar power plant that should inject about 10% of Nouakchott's energy capacity into the grid. The total power of the solar power plant is 15 MWp. The solar plant uses PV modules in (a-Si and µc-Si). On the other hand, it is shown the characterization bench of the photovoltaic modules and part of the meteorological parameters measured.

4. MATERIAL AND METHODS

It is essential to remember that it is possible to divide the degradation of any product into three categories according to the period of life of the product in which they appear. We are thus talking about early degradation at the beginning of use, random degradation in the living environment, and wear degradation at the end of its life. Therefore, it proposes to study and analyze the early degradations during the first seven years of operation of the solar power plant in depth to evaluate the performance in the hot climatic conditions of Mauritania. The data collected at this plant include the layout of the PV panels, site conditions, ambient and module temperatures, and solar radiation intensity. The methodology adopted for the evaluation of the performance of a 15 MWp solar photovoltaic plant over seven years divided into several stages: site inspection, understanding of the construction and layout of the entire plant, technical and financial information of the plant, modeling, and simulation of the plant in PV system, collection of SCADA data, estimation of losses by software and discussion with the plant manager, identification of different degradation modes and defects, their causes and impact, measurement of production curves in real time and comparison with simulation results.

4.1. Climatic data

The 15 MWp solar power plant's data acquisition system and measuring instruments provide temperature, solar radiation, relative humidity, wind speed, and direction every 50 minutes. Figure 1 shows the temperature and irradiation recorded at the plant site by the data acquisition system. Data on climate values (solar irradiation, temperatures) propose for the photovoltaic conversion chain according to Figure 1.

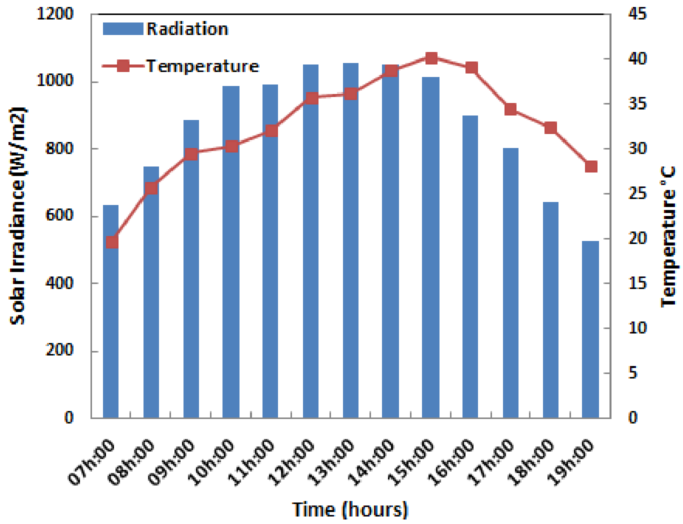


Figure 1. Temperature and daily solar radiation on site of the plant

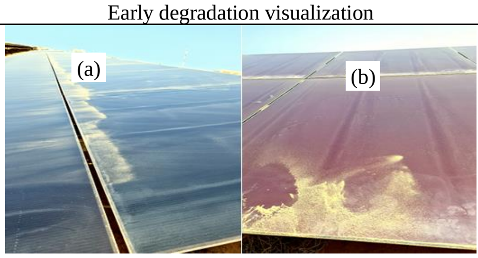
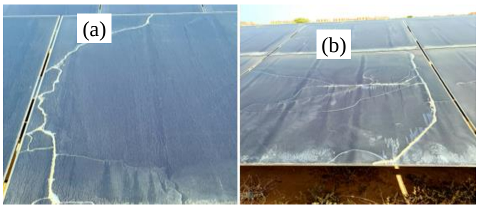
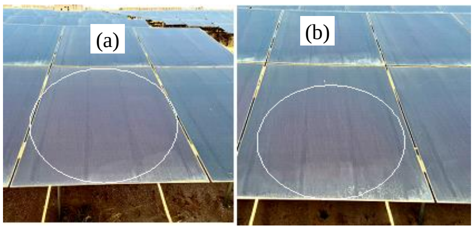
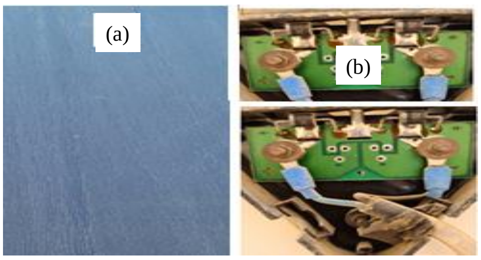
4.2. Degradation of PV modules

The current decomposition range can be lower than the nominal value by 6% to 8% and for complete discoloration, it can range from 10% to 13%. The performance of photovoltaic modules degrades due to the following factors [36]–[38]: temperature, humidity, irradiation, dust, and mechanical shocks. Indeed, these different factors can induce one or more types of degradation. Modes of degradation of photovoltaic modules: encapsulant, delamination, encapsulant discoloration, corrosion, broken cells, junction box failures, broken interconnects, and hot spots. Therefore, the degradation of the photovoltaic module can affect the different parts of the PV module, such as glass, interconnections between cells, encapsulating material which of ethylene vinyl acetate (EVA), protective polymer film, which of Tedlar and glues that ensure adhesion between the different components of the module.

4.3. Visual inspection of PV modules

The early aging of these modules is a degradation process that evolves, considering years of operation (2013-2023). This early degradation results in progressive damage to the characteristics of a component or system, which may alter its ability to function within the limits of the acceptability criteria and which is caused by service conditions. The visual inspection cited in Table 2 of this part sought to determine the impacts of bad weather on the PV modules.

Table 2. Solar module degradation inspection at the plant site

N°	Early degradation visualization	Comments
N°1	 PV modules: (a) µc-Si (530 Wp) and (b) a-Si (410 Wp)	Dust accumulation on PV modules: Dust reduces the properties of glass and initiates the degradation of PV modules. Indeed, the sand wind causes the deposit of sand on the solar modules, thus reducing the surface receiving solar radiation. In addition, dust can penetrate the boxes of the modules generating wrong contacts. Not to mention that the combination of moisture and grains of sand can create dangerous short circuits for the electrical system.
N°2	 PV modules: (a) µc-Si (510 Wp) et and (b) µc-Si (540 Wp)	Photovoltaic modules with early cracks: Parts of materials such as glass are sensitive to temperature changes (night and day) that break the glass and cause the degradation of the module's power generation capabilities. At sunrise, the incident rays on the module lead to a sudden change in temperature, which in the long term leads to early cracking of the glass. As a result, the PV module has cracks. Glass cracks are a vital degradation factor.
N°3	 PV modules: (a) µc-Si (500 Wp) and (b) µc-Si (470 Wp)	PV Modules affected by early browning (discoloration): Some PV modules have a color (brown) attributed to the EVA's fading. In the literature [39], [40], the leading causes of the degradation of EVA are UV rays combined with water at temperatures above 50 C. In addition, discoloration may appear in different and not adjacent areas of a PV module; This may be due to polymers used with other characteristics.
N°4	 PV modules: (a) µc-Si (520 Wp) et and (b) Connexions	Early corrosion of junction box interconnections: Corrosion is an early degradation phenomenon affecting the PV module's electrical production. Corrosion occurs via electrochemical reactions due to the migration of electrons in the metal part. The PV module has corrosion at the interconnect tape and junction box. Corrosion can cause fatal damage to the photovoltaic generator. In addition, corrosion can increase leakage currents and, thus, a loss of performance. This mode also degrades the adhesion between the cells and the metal frame.

The visual inspection informed the status of PV modules for different technologies. The visualization of the defects revealed four types of early visible defects: the accumulation of dust on the PV modules, the presence of cracks on the modules, the browning effect (discoloration) on the PV module, and the corrosion of the junction box interconnections. This part also proposed an analysis of the early degradation of PV modules. The modules of the solar power plant degrade by losing their electrical performance. Furthermore, premature degradation reveals the failure modes of solar modules. Finally, identifying the degradation of PV modules and assessing their importance is a challenge because a high degradation rate leads directly to a loss of power and, therefore, to a reduction in the return on investment. In addition, the aging of the PV modules also leads to different alterations in their life.

4.4. Early degradation rate calculation model

The evaluation of the early degradation rate of the short-circuit current (Isc), the open circuit voltage (Voc), the maximum power of the module (Pmax), and the fill factor (FF) of the module managed by comparing the standardized value and the initial value before commissioning of the photovoltaic module. The difference expressed as a percentage represents the rate of early degradation of the parameter under consideration. The early degradation rate of the short-circuit current (Isc), the open-circuit voltage (Voc), the maximum power (Pmax), and the factor of the early degradation rate DR% of FF of the module are given respectively by the (1)-(4), where:

- $D_R I_{SC}$: The early degradation rate of short circuit current.
- ISCo: The short-circuit current at the initial time under standard conditions.
- I_{SC}: The short-circuit current at the time of test execution under standard conditions.
- $D_R V_{OC}$: The rate of early degradation of the open circuit voltage.
- V_{OC}: The open circuit voltage at the initial time under standard conditions.
- VOC: The open circuit voltage at the time of test execution under standard conditions.
- D_RPmax: The rate of early degradation of the maximum power.
- $Pmax_0$: The maximum power at the initial time under standard conditions.
- Pmax: The maximum power at the time of the test execution under standard conditions.
- D_RFF: The rate of early degradation of the fill factor.
- FF_0: The fill factor at the initial time under standard conditions.
- FF: The fill factor at the time of the test execution under standard condition.

$$D_R I_{SC}(\%) = \frac{(I_{SC_0} - I_{SC})}{I_{SC_0}} \times 100 \tag{1}$$

$$D_R V_{OC}(\%) = \frac{(V_{OC_0} - V_{OC})}{V_{OC_0}} \times 100 \tag{2}$$

$$D_R P(\%) \frac{\left(P_{max_0} \quad - P_{max}()\right)}{P_{max_0}} \quad _{max} \tag{3}$$

$$D_R FF(\%) = \frac{(FF_0 - FF)}{FF_0} \times 100 \tag{4}$$

5. RESULTS AND DISCUSSION

In general, evaluated the early degradation of a PV module in Table 3 by measuring the decrease in basic parameters and power. To better understand these early degradations, tests using a specially designed platform have made it possible to reproduce them. Indeed, these tests are under temperature, radiation, wind speed, and pressure conditions. As in our case, we should also note the interest in having a test model to evaluate early degradations numerically and their evolution. Table 3 shows the measured electrical parameters such as open circuit voltage (V_{OC}), short-circuit current (I_{SC}), fill factor (FF), and maximum output power (Pmax) for PV modules. These parameters use to evaluate the performance of each PV module type. In the case of dust on PV modules: The dust caused early degradation, which has more impact on the modules (a-Si and μc-Si) characteristics curves. It noted that this is an early degradation mechanism specific to windy areas. It is visible in Table 2 (N°3). For the case with cracks: there are early cracks visible on the PV modules in Table 2 (No. 2), which highlight the early impact in terms of current and power drop in the modules' characteristics. This degradation lowers the current hence the power and D_R value given in Table 3. In addition, the characteristic curves show visible degradation mechanisms on PV modules shown in Table 2 (N°3), based on (a-Si and μc-Si), is the discoloration of the encapsulant visual (a and b), generally known as EVA polymer. This type of early discoloration degradation by a decrease in the current and power produced by the module. This deterioration is marked in D_R% in Table 3. This early discoloration can cause corrosion of the grid or embrittlement of the encapsulant resulting in cracks.

This work summarizes the calculation of the early degradation rates D_R % of the electrical parameters of the PV modules (Types 1, 2, and 3) compared to the technical specifications and the estimation of the measurements of the annual degradation rate of the installation. The electrical parameter most influential by degradation is the short-circuit current (Isc) and the voltage (Voc), which also degrade. The quantified degradation mechanism can measure by parameters (Isc and Voc). Thus, the current produced by the module is proportional to the luminous flux. Therefore, it can deduce that degradation reduces the ability of the PV module to capture light radiation. Consequently, it also influences the degradation of the power produced by the PV module.

Table 3. Calculating early degradation rates relative to the reference for the described modules

Module Description	Electrical characteristics before degradation	Degradation mechanisms	Electrical characteristics after degradation	D_R (%)	D_R (%)/Years
MPV410-SXL amorphous silicon (a-Si)	Isc = 3.25 A Voc = 197 V Pmax = 411.2 W FF = 0.6422	Natural accumulation of dust	Isc = 3.1 A Voc = 194 V Pmax = 379.94 W FF = 0.6317	3.84	0.548
MPV500-MXL Micromorph silicon (μc-Si)	Isc = 2.62 A Voc = 290 V Pmax = 500.16 W FF = 0.6583	Cracks on the glass	Isc = 2.5 A Voc = 287 V Pmax = 480.858 W FF = 0.6506	2.66	0.380
MPV510-MXL Micromorph silicon (μc-Si)	Isc = 2.64 A Voc = 292 V Pmax = 510.04 W FF = 0.6616	Discoloration (browning)	Isc = 2.54 A Voc = 289 V Pmax = 466.83 W FF = 0.6550	2.09	0.298

5.1. Degradation results on PV modules simulated by MATLAB

The modeling simulated the characteristics of the manufacturer (I (V) and P (V)) of the PV module of the solar power plant in the MATLAB environment. Then, these characteristics are considered as references and compared with the degraded modules' characteristics. Then, in this part, we focus on the electrical characterization of two photovoltaic modules, the first of which is the degraded module following early degradation after seven years of operation of the solar power plant (15 MWp), and the second is a reference module. Figures 2, 3, and 4, show the impact of degradation on PV module characteristics curves.

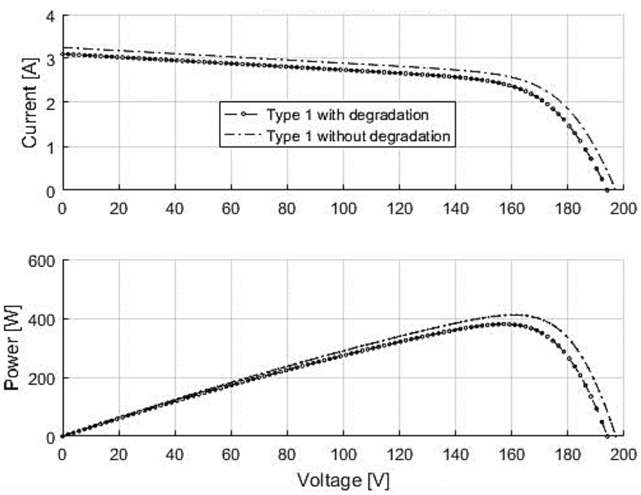


Figure 2. Characteristic I(V) and P(V) for the module (MPV410-SXL) with and without degradation

The conditions for these one-diode characteristics are G=1000 W/m^2, T=298.15 K. In this context, a solar power plant integrates a photovoltaic system consisting of a field of modules with these different mixed connections (series, parallel) to produce electricity for the other loads. Similarly, it should note that this work compares modules without degradation with modules with early degradation to identify the type of solar panels best suited for operation in this coastal area.

The characteristic curves of the PV module (a-Si and μc-Si) show the current failure. Then it is given an overview of the operational behavior of these two technologies under the same conditions represented in the figures below. The performance of PV module analysis after seven years of operation allows the identification of early failure modes. These early failure modes affect PV modules. Overall, the work shows that several design aspects need to improve for the PV module in (a-Si and μ-Si). Thus, this desired improvement of PV modules links to the qualification of the solar system for targeted geographical regions such as the northern Sahelian coast.

5.2. The simulation versus actual measured data

SMA-COM (SMA Data logger) serves an essential role in photovoltaic (PV) system management and monitoring. By continuously gathering and storing data from the inverters, the system operators can keep track of the system's status in real-time. Three power curves of PV production of the solar power plant for three days (same day for the three years) are shown in Figure 5, which retain in agreement with the three types of degradation (accumulation of dust, presence of cracks, and browning (discoloration) on the PV modules). These degradations were noted during the visual inspection. 2015 and 2017 the production and degradation are depicted in blue and orange curves. On the other hand, the 2020 curve gives the production and degradation curves compared to the PVsyst simulations. Table 4 shows the impact of degradation on the power curves of the power generation of the solar power plant for three days.

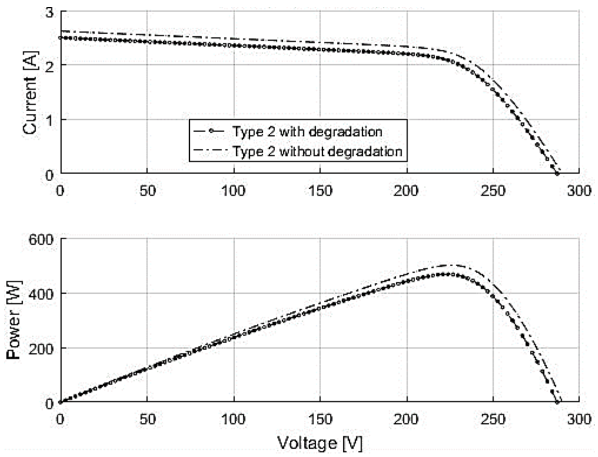


Figure 3. Characteristic I(V) and P(V) for the module (MPV500-MXL) with and without degradation

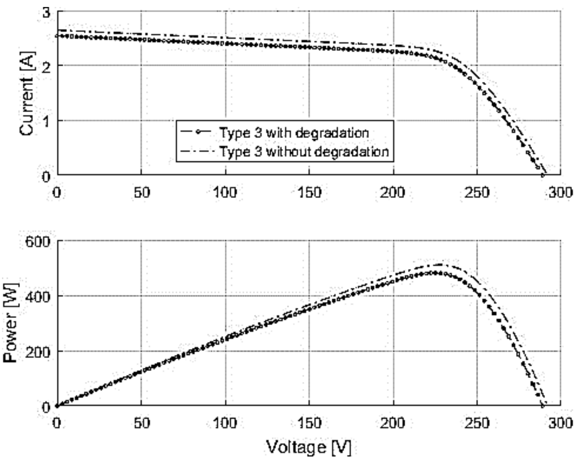


Figure 4. Characteristic I(V) and P(V) for the module (MPV510-MXL) with and without degradation

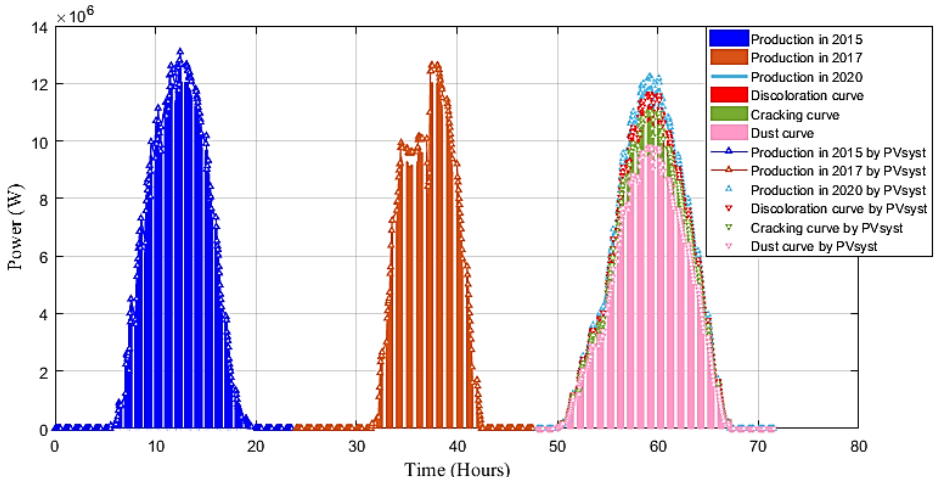


Figure 5. The real-time operation (2015, 2017, and 2020) versus simulation results of the PV system for 2020

The physical impact related to the environment of the site, according to the years of operation (degradation) of the solar power plant. Thus, for the year (2020) it is possible to consider, for example, that it is the most impacted by degradation. It is also affected by the influence of dust. In addition, it has a degradation rate of 3.09% or an annual value of 0.44% per year. Indeed, this dust phenomenon is very present on the northern coast of Mauritania. Therefore, we must take this impact on electricity production into account. Then, the dust effect follows by the cracks, which give a degradation rate of 2.90% or an annual value of 0.41% per year. Cracks are second only to the degradation factor "dust," which has the most impact on electricity production. Subsequently, the discoloration, set in the third position with a degradation rate, is worth 2.86% or an annual value of 0.40% per year. Finally, on the one hand, the inspection of dust and cracks are very present in the solar power plant. On the other hand, the impact on electricity production is meaningful. Therefore, it deserves to include in the factors influencing the sizing of solar systems.

Table 4. Impacts of degradation on the power curves of the solar plant's electrical production

Date	Without degradation		Degradation mechanisms	With degradation		
	Measured real production power	Production power simulated by PVsyst		D_R %	Measured real production power	Production power simulated by PVsyst
04 April 2015	12.47 MW	13.09 MW	Natural accumulation of dust Cracks on the glass Discoloration (browning)	--	--	--
04 April 2017	12.04 MW	12.65 MW	Natural accumulation of dust Cracks on the glass Discoloration (browning)	--	--	--
04 April 2020	11.27 MW	12.25 MW	Natural accumulation of dust Cracks on the glass Discoloration (browning)	3.09 2.90 2.86	11.27 MW 10.70 MW 9.51 MW	11.63 MW 11.02 MW 9.79 MW

5.3. Discussion

The electric production curves undergo a degradation of the product injected into the grid according to these few years of operation. In our case, these curves went from 2015 for a value (Pmax = 12.47 MWp) to 2017 for a value (Pmax = 12.04 MWp) to reach 2020 value (Pmax = 11.87 MWp). Indeed, it is possible to say that the performance of the solar power plant in actual conditions with the least likely degradation was achieved in the year 2015 (the beginning of the operation of the solar plant). However, in 2020 in natural operating conditions, the parameters were affected by certain environmental factors, such as solar energy (irradiation), ambient temperature, humidity, dust accumulation, and wind speed. So, taking a closer look at the electricity production curve (2020). It noted that the last turn considered is the most impacted by the leading degradation actor, dust. The dust reduced production to a lower power of 9.51 MWp (Reference power: 11.27 MWp). Thus, it is possible to say that dust has the most significant impact on the operation of solar power plants. It causes production to decrease more than any other early degradation factor. Then, the dust effect follows the cracks, which gives a maximum power of 10.70 MWp. Therefore, cracks position as the 2nd factor of early degradation with the most impact on the production of the solar power plant. Finally, the discoloration is placed in the third position with a production level close to 10.70 MWp compared to the reference power, which is 11.27 MWp. We must not forget that another factor that can cause damage to the operation of the plant is corrosion. Corrosion considers in work as the result of the interactions of all these environmental and physical phenomena mentioned above. Table 5 compares actual and simulated production values for 2015, 2017, and 2020.

Table 5. Compare actual and simulated production values for 2015, 2017, and 2020

	2015		2017		2020	
	Real (MWp)	Simulated (MWp)	Real (MWp)	Simulated (MWp)	Real (MWp)	Simulated (MWp)
Max value	12.47	13.09	12.04	12.65	11.27	12.25
Difference	0.62 MWp		0.61 MWp		0.98 MWp	
Difference (%)	4.73		4.82		8.0	
Difference between the base year and other years for both cases (actual and simulated) (%)			3.44	3.36	9.62	6.41

Table 5 compares the actual production on the site (2015, 2017, and 2020) and that simulated. In addition, it shows the reduction in the difference in MWp between actual measurements and PVsyst simulations (2015 records 0.62 MWp or about 4.73% difference, 2017 records 0.61 MWp or 4.82% difference, and 2020 records 0.98 MWp or 8% difference). These data prove the performance of the simulation software that can replace the measurements if the measurements are absent. On the other hand, Table 6 shows a comparison with the actual measured data and the estimated simulations for a type of degradation for the year 2020. The actual measured and simulated values indicate the relative values of each kind of degradation. For example, the two values (measured and simulated) show a difference of 0.01% for discoloration. For cracks, always considering both values, they record a difference of 0.19%, and for dust, a difference value of 0.2%.

Table 6. Percentage of actual and simulated degradation for the year 2020

Type of degradation	Discoloration	Cracks	Dust
Actual value (%)	5.05	9.85	19.88
Simulated value (%)	5.06	10.04	20.08
Difference (%)	0.01	0.19	0.2

The values show how close the simulations are to the fundamental values. Thus, they can replace the measurements during the sizing. In our case, the PV module has already lost an average of 5.6% following an early degradation rate that subsequently translates into the output power. In this sense, we can say that the PV module will probably not work during the 30-year warranty. The climate significantly impacts module performance over time as shown in Figure 6. The high rate of early degradation means less output, shorter lifetime of the modules, unable to function flawlessly and efficiently to provide the required power. It is, therefore, essential to have maintenance methods in sites where the environment is aggressive to maintain the quality assurance of the modules.

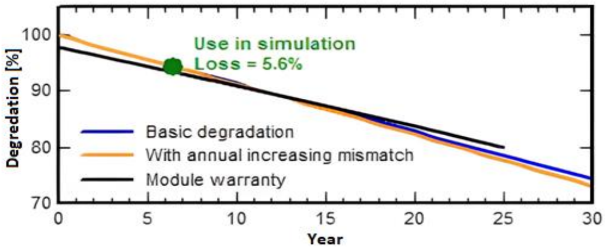


Figure 6. Degradation curves with respect to time

6. CONCLUSION

This paper presents an experimental and comparative study of the early degradation factors impacts on the performance of a 15 MWp PV plant connected to a 33 kV grid after seven years of operation. Climatic conditions, such as dust, high temperatures, and humidity leading to dust accumulation, early cracking, early browning (discoloration), and corrosion significantly impact the premature degradation of PV module performance. For the degradation rate, the module of type 1, the D_RPmax, has a value of 7.6% or an annual value of 1.08% / year. In contrast, it gives type 2 module D_RPmax with a value of 3.86% or a yearly value of 0.55% / year, and finally, for type 3, a D_RPmax of a value of 2.59% or an annual value of 0.37% / year. Thus, dust is the worst among other types of degradation. The simulation assessment of degradation through characteristic curves simulations is implemented to show a comparison between the characteristics of the reference modules with those of the PV modules prematurely degraded in connection with the tests. This simulation to estimate future degradation due to the local environmental conditions, compared with the actual past measured data, is proved to be efficient and can replace the measures if the measurements are absent.

APPENDIX

Table 1. The impact of climate on the degradation rate of photovoltaic installations in different countries

Country	Type of climate	Operation Years	Module Type	Capacity	Mean Annual Degradation Rate	Reference
Algeria	The Saharan environment	3	Monopolycrystalline	Module-based	0.83% for poly & 0.79% for mono	[29]
Morocco	Temperate climate	6	Monopolycrystalline	2.04 Kwp	0.53% and 0.41% for mono, 0.36% and 0.2% for poly	[30]
Djibouti	Desert maritime climate	5	Polycrystalline	302.4 Kwp	PVUSA 0.96%/year & PR 1.01%	[31]
Australia and UK	Different Weather Conditions	10	Polycrystalline	3.960 Kwp	1.05–1.16% UK and 1.35–1.46% Australia	[32]
Germany	Moderate climate	7	Monopolycrystalline	1 Kwp	0.1–1%	[33]
India	Tropical semi-arid environment	4	Monocrystalline	1 Mwp	0.27% LLS and 0.32% CSD & 0.50% HW and 0.27% STL	[34]

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