Investigation of Degradation in Crystalline Silicon Photovoltaic Modules After 10 Years Exposition in Senegal by Infrared (IR) and Electroluminescence (EL)

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Abstract. The effects of a sub-Saharan coastal climate on PV modules degradation was studied in this paper. A Mono and a polycrystalline-silicone solar PV module exposed in Dakar, dry and coastal climate, at the extreme West of Senegal was studied. As first inspection in this region, the electrical parameters of two PV modules A and B operated during about 10 years, are measured under standard testing condition (STC) and their I-V characteristics were fitted. The initial I-V characteristics was performed under real conditions and translated to STC and compared to the measured I-V characteristics at standard test conditions (STC) obtained in PV Laboratory after exposition. After the operating years, the main important parameters of the studied PV modules: short-circuit current I_{SC}, open circuit voltage U_{OC}, maximum power P_{MPP}, nominal current I_{MPP} and Voltage VMPP are evaluated and then compared to the initial parameters obtained during initial exposition to estimate their degradation.

Moreover, the defects that affected the PV module are explored by visual inspection, Electroluminescence (EL) and thermography (IR) imaging methods. The results show absolute degradation of maximum power (ΔP_{MPP}) nearing −5.35% and −2.92% for the mono and polycrystalline silicon operating about 10 years. The inspection reveals many degradations in both modules. Most of the degradations due to the climate are found in the mono and a very advanced I_{SC} mismatch is found with the IR image. The polycrystalline has many mechanical defects that's does not too much affect the performance characteristics.

Keywords: Photovoltaic · Degradation · Performance
Electroluminescence imaging · Thermography imaging

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1 Introduction

The use of Renewable Energies becomes more and more necessary for the satisfaction of the world Energy demand, with less negative effects on the environment. Global warming and fossil fuels depletion force the world to seek for solutions to ensure our survival and those of future generations. Africa in particular is facing a critical energy scenario. According to the World Bank, 25 countries in sub-Saharan Africa are in energetic crisis. Only 32% [1] of the population has access to electricity in 2012 with a very high average price of US $ 0.13 [2] per kilowatt hour.

However, the continent can rely on its significant renewable energy resources to improve its situation. Several renewable energy sources are available in different localities. East Africa is known for its large geothermal deposit. The extremities are marked by the presence of remarkable wind potential with an estimated power of 1,300 GW. Hydropower with an available capacity of 238 GW is the most exploited clean energy in the continent. But solar energy remains the most abundant source on the continent. Africa is the sunniest continent of the world. An average radiation of 2650 kWh/m^2/year, with an estimated sunshine duration of 3500 h/year could enable the continent to satisfy its energy needs.

Several energy projects based on solar photovoltaic are planned or executed on the continent. Nevertheless, for better exploitation of solar resources, adaptation of technologies to the African environment is essential. The technical characteristics of the existing solar panels are given under the standard testing conditions (STC) corresponding to a mild climate of 25 °C and a sunshine of 1000 W/m^2.

These conditions are totally different from the ambient exposure conditions of panels in Africa. In this context, it is pertinent to identify, quantify and compare the major defects or expected modes of failure for the various climates that can be encountered in sub-Saharan Africa (arid, continental, wet or coastal monsoon) and which are Very different from the climate of central Europe.

The study is about degradation of the performance of mono and polycrystalline solar panels after about ten (10) years of exposure in a coastal climate precisely at the Polytechnic superior school of Dakar (ESP).

The analysis focuses on data collected using electroluminescence (EL) and infrared imaging methods.

2 Location and Platform Test Presentation

2.1 Presentation of the Experimental Environment

2.1.1 Temperature

The photovoltaic platform shown in Fig. 2 is used in this study. It is installed at Dakar in Senegal. Dakar is located on the extreme western Africa with geographic coordinates 14.61° North latitude and 17.37° West longitude. In Senegal, the climate is of sub-desert tropical type punctuated by damp summers and dry winters. On the other hand, the DAKAR region, which has an advanced position in the Atlantic Ocean, is characterized by a coastal microclimate. This is strongly influenced by the trade winds and the monsoon coming from the sea. On average, the temperatures are always high.

the average daily maximum temperature is 24 °C from January to March and between 25 and 27 °C in April, May and December. From June to October, temperatures reach 30 °C (Fig. 1) [3].

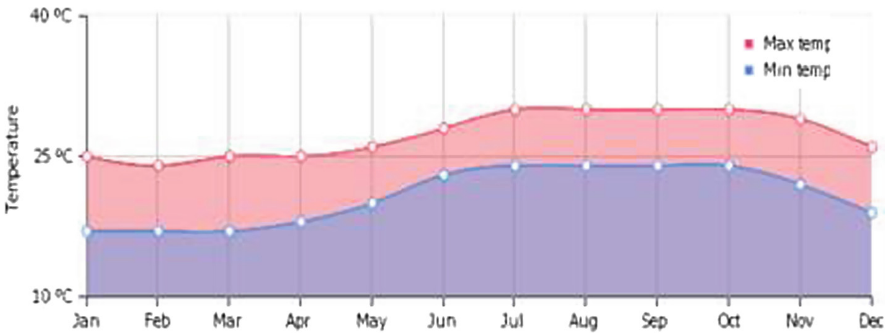

Fig. 1. Average min & max temperature in Dakar.

2.1.2 Radiation and Insolation

Radiation and insolation are key parameters, among others, in the quantification of the producible energy but also of the effects of radiation on the photovoltaic material. The radiation is expressed in kWh/m^2 while the insolation is expressed in hours. High radiation and insolation values correspond to very high temperatures and low values at low temperatures and vice versa. The average sunshine varies from 7.3 h/d during the rainy season when the sky is always cloudy at 9 h/d during the dry season when the sky is clear [4]. The highest average monthly value for radiation is 6.92 kWh/m^2/d and is in the period from March to June, while the lowest is 4.57 kWh/m^2/d corresponding to the months from July to February.

2.1.3 Humidity

Variations in relative humidity depend in part on the air temperature and the hygrometric characteristics of the air masses. The annual evolution of the relative humidity of the air is also tempered by the maritime influence and the annual average is around 70%. The highest values coincide with the heart of the rainy and low season in the months of April-May and October-December-January. Main climatic characteries are presented by Table 1 [5].

2.2 Platform and Modules Presentation

The platform used is composed of four (4) modules. Two monocrystalline manufactured by WAAREE in the left. The Two polycrystalline modules in the left are BP Solar products. One module on each technology have been chosen (A & B) to evaluate and analyze the degradation affecter about 10 years of operation. The two modules A & B fielded have been installed in same period 2007. The PV modules initial characteristics have been measured using the analyzer IV-400. The obtained IV curve initially designed and the characteristics obtained in exposition location and translated to STC are detailed for each module.

Table 1. Main climatic characteristics of Dakar.

Months	Temperature	Relative humidity	Daily solar radiation-horizontal
	°C	%	$kWh/m^2/d$
January	20.7	70.2%	4.89
February	20.7	74.9%	5.80
March	21.0	78.5%	6.57
April	21.4	83.0%	6.92
May	22.8	82.9%	6.71
June	25.6	82.3%	6.21
July	27.1	79.7%	5.60
August	27.4	83.0%	5.34
September	27.6	84.7%	5.34
October	27.6	81.8%	5.53
November	25.8	73.8%	4.98
December	23.4	68.6%	4.57
Annual	**24.3**	**78.6%**	**5.70**

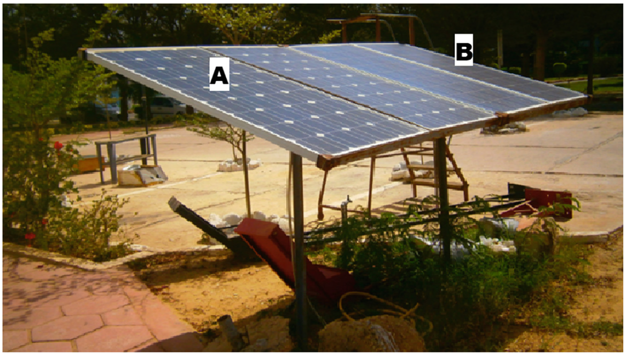

Fig. 2. Photovoltaic platform installed in Dakar University.

A monocrystalline solar panel of 106 W_P (given by manufacturer) was used as a reference model for experimentation and simulation. However, the data used for degradation assessment are those measured on-site. The measurement cared out just after the installation of the system on the site, have been done under local conditions and automatically "translated" to the standard testing conditions (STC). The main performance characteristics are extracted are gathered in following table. The maximum current and voltage have been used to obtain the P_{MPP}. The maximum power obtained initially is equal to 114 W_P.

The second module used (B) is a polycrystalline also of 110 W_P according to the data given by the constructor. Like the module A, the initial measurements were established using the IV-400 analyzer. These measurements on site and "translated" to the STCs determine the different performance parameters grouped in Table 2. With its 36 polycrystalline cells connected in series, the measured power on site for the poly is equal to 114 W_P.

Table 2. Technical characteristics of the PV modules.

Modules	Technology	Manufacturers	References	Characteristics	Values
Module A	Monocrystalline silicon	WAAREE	WS-110	Maximum power (P_{MPP})	114 W
				Nominal voltage (V_{MPP})	16.22 V
				Nominal current (I_{MPP})	7.04 A
				Open circuit voltage (U_{OC})	21.41 V
				Short-circuit current (I_{SC})	8.56 A
				Fill factor (FF)	62.20%
Module B	Polycrystalline silicon	BP Solar	WS-110	Maximum power (P_{max})	114 W
				Maximum voltage (V_{max})	17.31 V
				Maximum current (I_{max})	6.59 A
				Open circuit voltage (V_{OC})	21.76 V
				Short-circuit current (I_{SC})	7.43 A
				Fill factor (FF)	70.50%

3 Data Acquisition and Analysis Methodology

3.1 Data Acquisition

The main objective of this work is to evaluate and analyze the degradation on two crystalline modules exposed for about 10 years. But the main element in all that being to have the effects of the environment on the panel and the consequences generated on the electrical characteristics. For this, the main data used are: the electrical characteristics initially obtained and after the years of exposure, the EL and IR images.

- The initial Electrical performance characteristics are obtained using the analyzer IV-400. Photovoltaic module analyzer I-V 400 carries out the field measurement of the I-V characteristic and of the main characteristic both of a single module and of module strings. The acquired data are then processed to extrapolate the I-V characteristic at standard test conditions (STC). Output current or voltage from the module is measured with the 4-terminal method, which allows extending the measurement cables without requiring any compensation for their resistance, thus always providing accurate measures.
- IV curve and electrical characteristics obtained after exposition, have been measured using a lab solar simulator. The PASAN solar simulator is equipped with 4 Xenon flash tubes that generate a pulsed, calibrated and time-steady light. The light travels through a black tunnel and illuminates the module, which is positioned 8 m away on a uniformly illuminated 3 $\times$ 3 m surface. Different irradiance levels can be reproduced, however in our case the teste was carried out under STSs. A tracer records the electrical response of the module measuring up to 4000 points of the I-V curve, along with other electrical parameters (Fig. 3).

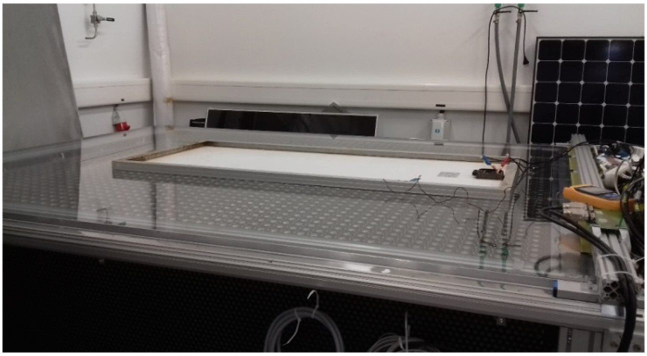

Fig. 3. IV measurements on the module.

– The set-up for PV EL Imaging is simple, consisting of: shortwave infrared (SWIR) camera with lens darkened enclosure solar cell/module Power Supply. An SWIR camera with In GaAs sensor and a spectral range from 0.9 to 1.7 μm was used in this study for capturing the EL image. Two different EL images have been made using different current. The first with a current equal to I_{SC}, the second was made with just I = 10% I_{SC} which allows to clearly identify the most affected surfaces (Fig. 4).

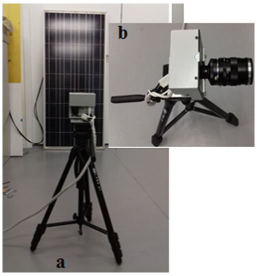

Fig. 4. (a) Module during EL imaging - (b) Close-up of the EL camera.

– For IR Imaging, the measuring device is a thermal imaging camera with a surface temperature measurement range of −20 °C to 250 °C and a 31° × 22.5° field of view, the user can view and save a quick snapshot of temperature patterns in any given area, thus quickly identifying unusual hot or cold spots. With ≤ 80 mK thermal sensitivity, temperature differences of just 0.8 °C are visualized on the 3.5″ cooler screen via the 160 × 120-pixel thermal sensor. Three different color palettes give added functionality whilst hot and cold spots can be activated to immediately highlight hot and cold spots in the field of view. A digital read out of the surface temperature at the measurement point is shown alongside both the thermal image and the visible-light picture from the camera (Fig. 5).

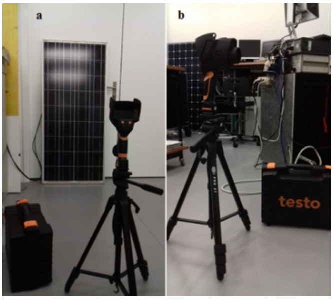

Fig. 5. (a) Module during IR imaging - (b) Close-up of the IR camera.

– The percentage of the surface affected by the different types of degradation is obtained with the GeoGebra software. GeoGebra is a dynamic mathematics software that combines geometry, algebra, spreadsheet, graph, statistics and infinitesimal calculus into a single easy-to-use software. It allows, according to a chosen scale, to quantify the selected surfaces and to put them in color. Thus, these surfaces in comparaison with the total surface gives the percentage of the surface affected by the degradation.

3.2 Analysis Approaches

In this study, degradation phenomena observed in PV modules operating in the field for about 10 years are presented. Nondestructive diagnostic techniques including I-V curve analysis, infrared (IR) thermography and electroluminescence (EL) are employed here to assess PV performance and identify the defects. And the software Geogebra with the EL image give important information on the percentage of affected surface. Two Modules that have undergone different stages of degradation, from mechanical and manufacturing defects to severe visual degradation phenomena due to environmental effects, are analyzed, and performance characteristics degradation estimates are given for the 2 different technologies tested, revealing the need for a deeper understanding of PV degradation phenomena that occur under real conditions of operation. The diagnostic methodology of degradation is presented in Fig. 6.

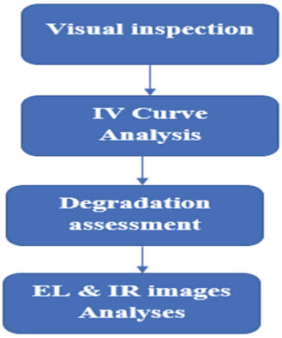

Fig. 6. Degradation diagnostic methodology.

4 Analysis of Electrical Characteristics

In this section, the aim is to assess, quantify and analyze the degradation of the two PV modules that operated during nearly ten (10) years in the tropical climate of Dakar located at the extreme west of Senegal. This locality, as described in Sect. 3 is marked by a tropical and semi-arid climate. We investigated the degradation of the main important electrical parameters (P_{MPP}, I_{SC}, U_{OC}, I_{MPP}, U_{MPP} and the FF) of two PV modules installed in the University of Dakar.

For further details in addition to the visual inspection, both modules were analyzed by Electroluminescence (EL) and Infrared (IR) imagery. This inspection allows to identify the different defects in the module, quantify the affected surface and analyze the temperature distribution to understand the different performance characteristics degradation that affected the two PV modules.

4.1 Photovoltaic Modules Degradation Assessment

4.1.1 Monocrystalline Module (A)

4.1.1.1 Characteristics After 10 Years of Exposure

After using the module for about 10 years, the performance characteristics were again measured. These measurements obtained at PV LAB in Switzerland are carried out directly in the STC with a simulator. The PASAN tester TC 1.1.3 used, is a pulsed solar simulator, for current-voltage (IV) characterization of photovoltaic modules. The results obtained are plotted in the curve IV in blue in Fig. 7 (Table 3).

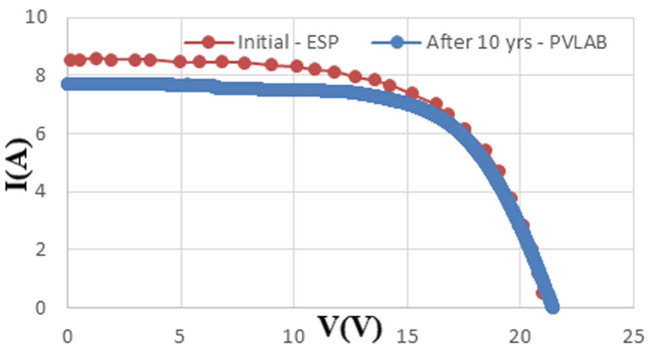

Fig. 7. I-V characteristics of monocrystalline module (A). (Color figure online)

Table 3. Performance characteristics comparison after about 10 years.

Measurements	P_{MPP} [W]	U_{OC} [V]	U_{MPP} [V]	I_{SC} [A]	I_{MPP} [A]	FF [%]
Initial - Measured at ESP	114	21.405	16.24	8.56	7.020	62.2
After 10 yrs - Measured at PVLAB	107.905	21.44	16.178	7.750	6.670	**64.9**

The realization of this curve IV in comparison with the initial curve already shows degradation of certain performance characteristics. The short-circuit current I_{SC} from 8.56 A to 7.75 A is the most affected characteristic. Therefore, the maximum power current I_{MPP} is affected. Initially the maximum power of 114 W obtained with I_{MPP} of 7.02 A decreases by 6.095 W. The maximum power current thus becomes 6.67 A.

4.1.1.2 Degradation Assessment

The measurements initially carried out with the natural sunlight and translated back to the STC with the IV400 analyzer; and those using a simulator in the STC conditions at PV LAB made are used to evaluate the different variations that occurs during the module exposition. The nominal (I_{MPP}) and short circuit (I_{SC}) current, the nominal (U_{MPP}) and the open-circuit (Uoc) voltage, and the PV module maximum power (P_{MPP}) degradation are evaluated by comparing each measured value after 10 years with the reference value obtained with the initial measurements given in Table 2. The degradation of these different parameters is expressed in percentage as a function of the difference between the initial normalized values and the obtained after exploitation [3].

The results obtained from the degradation calculations are summarized in the following graph (Fig. 8).

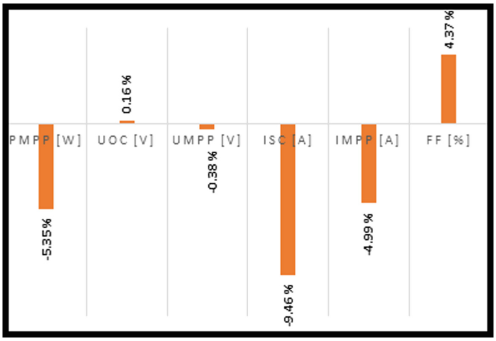

Fig. 8. Performance degradation of module A.

From Fig. 8, it can be seen that the open-circuit voltage is not affected because the calculated degradation is positive. The U_{MPP} also expresses a very slight degradation of just −0.38%. However, the nominal and short circuit current degradation is striking and equal to −4.99% and −9.46% respectively, which is generally caused by mismatched cells and increase sometimes series resistance increase. Such kind of IV distribution and I_{SC} reduction refer to irradiation decreases or shaded cells. In general, this is the consequences of operating area reduction or cells properties inhomogeneity. Also, a non-homogeneous temperature distribution could be expected by thermal imaging to confirm the aging of this module. The considerable degradation of I_{MPP} particularly affects the maximum power which is degraded by −5.35%. The fill factor degradation rate is also positive, meaning that the theoretical power degradation is more important than the maximum power diminution.

4.1.2 Polycrystalline Module (B)

4.1.2.1 Characteristics After 10 Years of Exposure

After 10 years of operation in hot and semi-arid climatic conditions, the PV module I-V curve were measured using pulsed solar simulator the comparison between measurements made initially and after exposition (Fig. 9) showed that, the short circuit current (I_{SC}) and the open circuit voltage (U_{OC}) did not change too much. However, the trend of the IV curve obtained after the operation years shows a slight decrease in the maximum power. In the literature [6, 7], such a change on curve IV is due to an increase in the series resistance R_S. This variation in resistance mainly affects the PV module operating voltage.

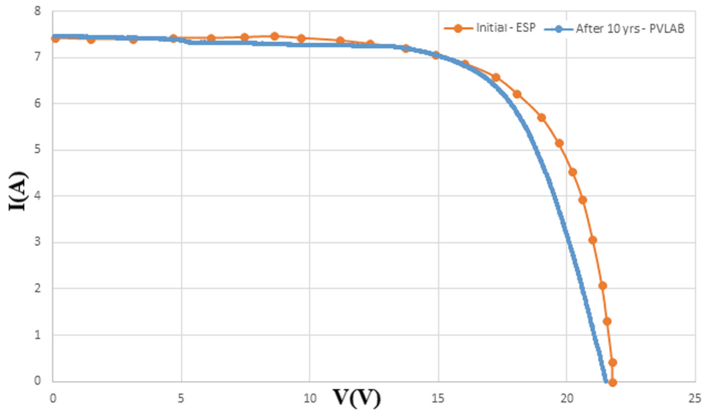

Fig. 9. I-V characteristics of monocrystalline module (B).

The comparison between the performance characteristics initially measured and that after the years of operation clearly shows that the nominal (I_{MPP}) and short-circuit (I_{SC}) current have not been affected. However, even if the variation is not too great, among all the parameters, voltage was the only electrical characteristic that deteriorated. The open-circuit voltage goes from 21.765 V to 21.5 V. The maximum power voltage has experienced the greatest variation, with an initial value equal to 17.3 V, it becomes 16.73 V, i.e. an absolute reduction of 0.6 V (Table 4).

Table 4. Performance characteristics comparison after about 10 years.

Measurements	P_{MPP} [W]	U_{OC} [V]	U_{MPP} [V]	I_{SC} [A]	I_{MPP} [A]	FF [%]
Initial - Measured at ESP	114.01	21.765	17.311	7.429	6.586	70.5
After 10 yrs - Measured at PVLAB	110.686	21.502	16.726	7.480	6.618	68.8

4.1.2.2 Degradation Assessment

The results obtained are summarized in Fig. 10. As expected with series resistance increase visible in the IV curve (Fig. 10), the maximum power voltage is the most affected characteristic, its absolute deterioration is −3.38%. Indeed, for a PV module exposed for almost 10 years, a degradation of only −2.92% of the maximum power is a good compatibility sign of this technology within the climate. However, it is always necessary to evaluate the different types of defects that affected the module to verify the material defects caused by the tropical climate. The Fill factor (FF) degradation is mainly due to the degradation nominal voltage degradation.

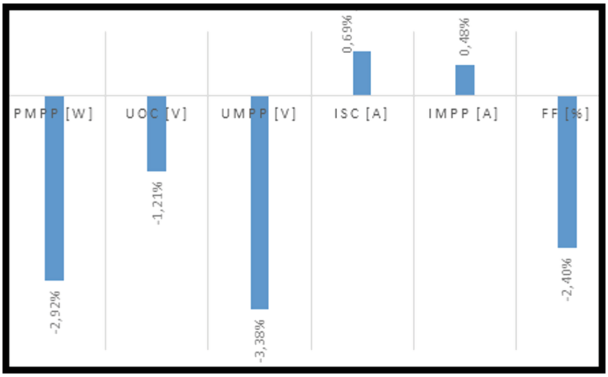

Fig. 10. Performance degradation of module B.

4.1.3 Comparative Study

The comparison between calculated degradation of the different characteristics for the two PV modules are summarized in Table 5. For the monocrystalline PV module (A), the short circuit current is the most affected characteristic with a degradation equal to −9.46%. The polycrystalline module (B) characteristics are slightly affected, but it is important to mention that the nominal voltage is the most affected parameter. This is to say that the drop in the maximum power output in the two PV modules does not have the same causes. The two modules than have different defects leading to such reduction of the maximum power.

The P_{MPP} degradation is equal to −5.35% for module A, and just −2.92% for module B. Thus, electrically the monocrystalline is more affected under such a climate.

Table 5. Performance characteristics degradation for the two PV Modules.

	P_{MPP} [W]	U_{OC} [V]	U_{MPP} [V]	I_{SC} [A]	I_{MPP} [A]	FF [%]
PV module A	−5.35%	0.16%	−0.38%	−9.46%	−4.99%	4.37%
PV module B	−2.92%	−1.21%	−3.38%	0.69%	0.48%	−2.40%

5 Analysis by Imaging Techniques

5.1 Module A: Monocrystalline

5.1.1 Electroluminescence Analysis (EL)

5.1.1.1 Degradation Types Identification

Defects in the material of the cell, micro-cracks, broken metallization, shunts, inactive regions are detected via Electroluminescence imaging in Fig. 11. This EL used to identify the defects is made under I_{SC} current. The fault types present in the modules are identified with different colors.

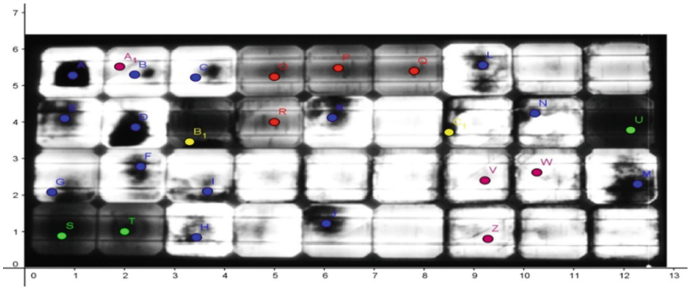

Fig. 11. Module A EL image with I = I_{SC}. (Color figure online)

- 15 cells (blue) have visual impairments such as discoloration and corrosion identified during visual inspection. These types of defects are directly related to climatic conditions mainly humidity.
- 2 cells with breakages which often occur during transport, packaging or installation of the modules. These types of mechanical damage are caused by insufficient packaging and vibration/shock.
- 4 cells with casting defects better known by the Contact finger interruptions. These types of defects are usually caused by insufficient screen printing during manufacturing. Because of their significant presence and non-uniform distribution, their remarkable effects on cells productivity are clearly evident.
- 4 other cells have microcracks, these types of defects such as breaks often occur during transport of the modules. The variation of the intrinsic manufacturing process can also be the cause of cells microcracks. But they are less serious and mostly invisible during visual inspection. However, they may cause deterioration in performance after several years of operation.
- 3 cells have unspecified dark areas. Several assumptions can be made about the origin of the dark shade: it may come from a local modification of the efficiency favoring non-radiative recombination of the charges, modification of optical proprieties of this zone and therefore the number of photons collected by the detector, or a modification of the contact resistance.

These assumptions mean that it is not possible to identify all the types of degradation present in an EL image on the simple visual criterion [5, 8].

In summary (Table 6), most of the defects identified on the module are due to the effects of the exposure climate conditions. 14 cells suffer from material degradation due mainly to contact of water with the cells. This water often present in moist air causes discoloration and corrosion. Given the climatic conditions of the operating site, it is evident that the high humidity of the hot location has effects on the cells. Indeed, Dakar is a very wet place with an annual average of 78.6%.

Table 6. Defects observed in module A.

Degradation type	Number of effected cells	Percentage relative to the total number of cell
Micro cracks	2	5.56%
Visual degradation	14	33.89%
Contact finger interruption	5	13.89%
Dark area	3	8.33%
Breakages	5	13.89%

The rest of the defects are for the most part mechanical. 6 cells have either microcracks or breaks due to poor handling during transport or laying. Manufacturing defects are fairly present. 4 cells with metallic hits severely affected are identified. 3 other cells have unidentified defects but often come from manufacturing.

5.1.1.2 Affected Area Evaluation

The use of the GeoGebra dynamic mathematics software allowed to quantify the total area affected by the different degradation types. The EL image used to determine the surfaces is the one supplied with a current equal to 10% of I_{SC}. An EL image taken at about 10% of the rated current of the photovoltaic module is more suitable for isolated cell parts quantification.

The maximum power (P_{MPP}) that the PV module can produce depends strongly on its productive surface as described in Sect. 1. Thus, the evaluation of the affected surface by the different types of degradation makes gives the opportunity to analyze the effects of productive surface decrease on the characteristics.

According to the chosen scale on the Fig. 12, the panel's total area is 75 cm^2. The fifteen (15) degraded areas evaluation gives a total dark surface of 20.97 cm^2 affected by the different types of defects cited above. Thus, 27.96% of the module's surface has been deteriorated. This materiel degradation of the surface leaded to a degradation of −5.35% in the maximum power (P_{MPP}). Then, the degradation of 1% of the surface causes a reduction of about 2% in the maximum power. Nevertheless, the black areas should not be interpreted as a totally zero emission, a black zone emits very little compared to the rest of the cell. And this is what causes electrical mismatches and reduce the I_{SC}.

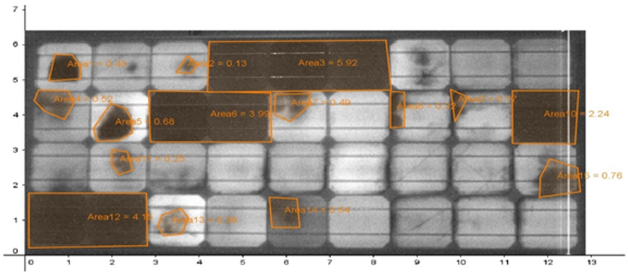

Fig. 12. Module A EL image with I = 10% I_{SC}.

5.1.2 Analysis by Infrared Imaging (IR)

In a normal PV module, all the cells are considered identical. For a defect less module, the temperature distribution is homogeneous because all the cells have the same characteristics. Thus, PV module thermography image visualization is a very useful tool to state a PV module. Infrared imagery specifically identifies hot spots and cold spots. Hot spots indicate a decline in productivity in these areas, which dissipates the surplus current from other parts as heat. This occurs when the cell is totally or partially shaded, fractured or electrically defective. The severity of this degradation is directly related the cell's the temperature. The cold zones highlight the visual degradations. The areas affected by these types of degradation act as insulators. The monocrystalline module IR image in Fig. 13 shows a striking thermal disparity. Temperatures range from 0 °C to 62 °C. Several hot points or surfaces are visible; Which proves that the different types of degradations identified previously decrease the electrical current. The cold parts identified represent the visual defects highlighted in the EL image. This photovoltaic module exposed for about ten (10) years shows a great thermal inhomogeneity, meaning an advanced electrical mismatch. This justifies the significant I_{SC} degradation and the decrease of the I_{MPP}.

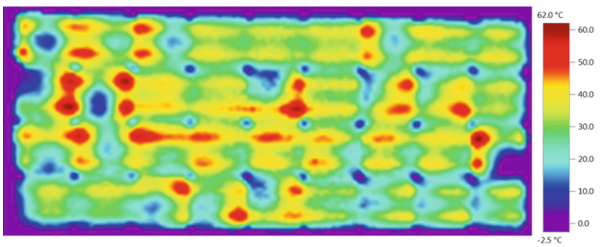

Fig. 13. Module A IR Image

5.2 Module B: Polycrystalline

5.2.1 Electroluminescence Analysis (EL)

5.2.1.1 Degradation Types Identification

The EL image for polycrystalline module was realized under the same conditions as the previous analyzed monocrystalline. For defects identification, the EL image used is realized under the short circuit current (I_{SC}) with different colors pointing fingers at the types of degradation present in the module (Fig. 14).

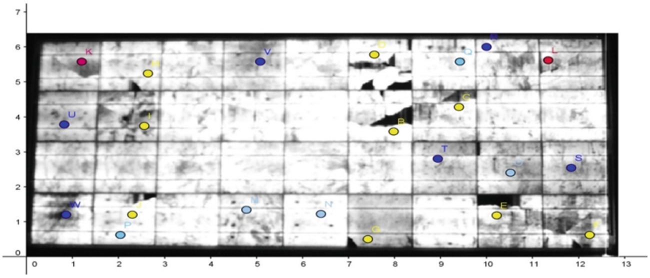

Fig. 14. Module B EL image with $I = I_{SC}$.

- 9 cells of the polycrystalline module experienced fairly extensive breaks which isolated the broken cell parts.
- 6 cells have visual defects due to the effects of the environment. During visual inspection, delamination of PV module's encapsulat has been identified. This probably justifies the presence of these dark surfaces indicating visual degradation.
- 5 cells have localized shunts. This type of defects is generally due to problems during cell's manufacturing (a particle, an anomaly in growth, etc.). It may also be a consequence of an external event such as electrostatic discharge or mechanical stress.
- 2 cells have micro cracks which elongated the list of mechanical defects.

For the polycrystalline module, mechanical defects due to physical constraints are the most present defects. Nine (9) cells in total have breakages often very advanced, and 2 others have micro cracks (Table 7).

Table 7. Defects observed in module B.

Degradation type	Number of effected cells	Percentage relative to the total number of cell
Micro cracks	2	5.56%
Visual degradation	6	16.67%
Localised shunt	5	13.89%
Broken cells	9	25.00%

Concerning the material or visual defects often due to the effect of the environment, they are present on 6 cells which are not nevertheless very affected. Indeed, since a polycrystalline module is not homogeneous in nature, it is sometimes difficult to identify the photoelectric effect. Manufacturing defects also are still present with many localized shunts.

5.2.1.2 Affected Area Evaluation

Using the same software, and with the EL image of the polycrystalline at $I = I_{SC}$, the results obtained show that the isolated surface is not very important. Seven (7) zones are isolated, representing a total area of 6.38 cm^2. So only 8.5% of the module's surface was severely affected, causing a degradation of −2.92% of the maximum power (P_{MPP}). Thus 3.5% of the power decreased to 1% of affected area.

However, it has always been pointed out that these isolated areas represent the consequences of all the defects identified. Similarly, they are not totally eliminated from the module, even if their participation is weak they slightly participate in the functioning of the module (Fig. 15).

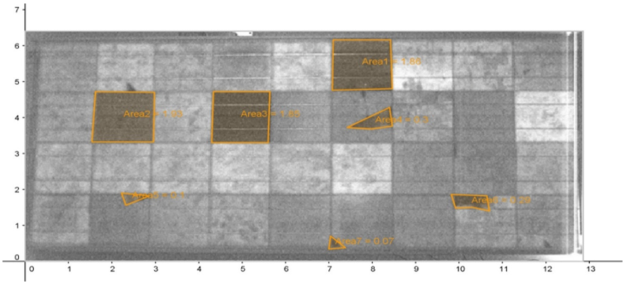

Fig. 15. Module B EL image with $I = 10\% \ I_{SC}$.

5.2.2 Analysis by Infrared Imaging (IR)

The IR image of the polycrystalline module shows a more homogeneous thermal distribution compared to the mono. Temperatures range from 29 to about 39 °C. The maximum temperature is not then so critical because it is less than the NOCT of 45 °C. the biggest part of the surface has a temperature of about 30 °C. Apart from 3 hot spots identified and some cold areas, the thermal disparity is not significant enough. Thus, the passage of the electric current is not too disturbed hence the low degradation of the current compared to the initial characteristics (Fig. 16).

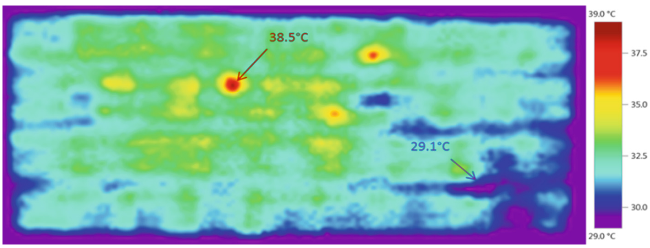

Fig. 16. Module B IR Image

6 Conclusion

The evaluation of the degradation already proves that the modules were affected after the years of exposure. The P_{MPP} degradation is equal to −5.35% for module A, and just −2.92% for module B. But it should be noted that the modules did not have the same degradation behavior. Module A experienced a significant drop in its short-circuit current (I_{SC}), while module B had a slight decrease in its nominal voltage U_{MPP}.

In this way, the visual inspection, EL and IR imaging allow to identify the different defects leading to such kind of degradation for the two modules. Even if there is not enough information on the degradation effects of each type of climate on the different crystalline technologies; defects due to the environmental conditions found in this study are much more present in the monocrystalline module than on the polycrystalline. The mechanical defects on the polycrystalline module are too advanced and will obviously be at the origin of most of the consequences on performance characteristics. The surface monocrystalline module isolated surface by the identified defects is much more important (27.96% of total area), compared to the poly (only 8.5% total area). Finally, EL images of the two PV modules in this study show that with the technology used, the environmental effects have been much more felt on the single-crystalline one. However, the affected surface analysis shows that the effect of percentage of affected surface on the P_{MPP} are more important for the polycrystalline than the mono.

The IR image for the monocrystalline module well justifies extensive degradation of the short circuit current and maximum power. The Module Isc mismatch clear shown in the thermography with many hot spots means that those parts can no more produce the short circuit current. So, the damage previously identified as corrosion and discoloration decreased the electrical output of several cells. Indeed, in the IR image analysis with a current equal to I_{SC} shows a large rise in temperature which reached 60 °C. This means that a big part of the module no longer produces enough power and transforms the surplus current coming from the healthy cells into heat. For the poly, the IR image shows that productivity is not too affected. The temperature distribution is almost homogeneous. We can then say that; the important mechanicals defects identified with the EL image do not affect too much the cells' production. Thus, by comparing the analyzes of the IR and EL images of the two modules it can be concluded that the defects caused by the climate on the mono module affect much more the production than the numerous mechanical defects on the poly.

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