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Research article

Degradation and performance analysis of a monocrystalline PV system without EVA encapsulating in semi-arid climate

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ABSTRACT

The objective of the current paper is to evaluate the performances drop of a photovoltaic system composed of a new PV module conception without EVA encapsulation. After three years of operation under harsh atmospheric condition at Green Energy Park research facility, in the mid-south of Morocco, the system shows an energy drop around 1.8kWhe in one of its strings. For this reason, an inspection (in-situ and at the lab level) to evaluate and detect the source of this energy drop has been done using the IV-Curve, IR thermal and Electroluminescence. Results show that the Performance Ratio (PR) of the affected string reaches 13%. Besides, two modules from this last one showed a degradation rate (Rd) greater than 4.12 %. It has been found that the main cause of this energy drop is due to the presence of breakages and crack at the modules cells. Those deceases are caused by a bad manual cleaning, as well as, for the nature of the modules, without EVA protection against the mechanical shocks.

1. Introduction

Nowadays and due to the lack of the conventional energy sources, the investment in renewable energy become a necessity for Morocco. Indeed, the country imports more than 93% of its energy needs from abroad [1], which dramatically affects its economy. Nevertheless, Morocco has a great solar potential [1, 2, 3] that can be used to produce electricity from both Photovoltaic (PV) and Concentrating Solar Power (CSP) technologies [4, 5, 6] with high efficiency [7, 8, 9, 10]. For that reasons, the country launched a huge project to produce 2000MW of electricity from solar. This project starts by the construction of NOOR solar complex located in Ourzazate and having a capacity production of 500MW. The first phase of this project, which is a 160MW CSP power plant based on parabolic trough collectors and 3 h of thermal storage system, is already operational since the beginning of 2017. However, because of the high investment costs, CSP alone is no longer considered as optimal solution for electricity production and the hybridization with other energy sources is a necessity for a relatively low electricity cost.

Among the most compatible energy sources for hybridization with CSP, PV presents the best solution. Indeed, PV is cheap, modular, and easy on its installation and maintenance. Furthermore, photovoltaic has already proven its performances if installed in Morocco [11, 12]. Nevertheless, the country has a harsh atmosphere that can influence the efficiency of the PV modules and their durability. In fact, soiling, dust storms, high temperature values, humidity and temperature gradients are the most reported parameters causing the degradation of the PV modules [13, 14, 15, 16, 17, 18, 19, 20].

Even though the degradation of the PV modules can be exposed in different forms (cracks, discoloration, corrosion, hotspot, delamination …) the most reported defect in hot-dry climate is the hotspot [20]. The

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Figure 1. The studied monocrystalline PV system.

hotspot occurs when a part of the panel is shaded due to soiling, shade, or birds dropping, etc. This causes a power dissipation in this localized part, which causes a local temperature elevation, thus, a drop in the module's efficiency and production.

Cracks and breakages of the PV modules is also an important degradation cause in arid climate as involved in our recently published paper [21]. Indeed, the presence of a PV installation in arid climate is directly linked to the presence of soiling and dust, which requires frequent cleaning. The cleaning if not performed carefully, might break some part of the cells, thus, causes a drop in the module's performances.

In this paper, the degradation ratio of a Monocrystalline PV system, installed for three years at Green Energy park research facility located at Benguerir (mid-South of Morocco), has been evaluated after the detection of a drop in the production of one of its strings. For this reason, we firstly assessed the drop on the electrical parameters of the modules using an IV curve device. After that, IR thermal camera has been used to detect the presence of any hotspot on the affected modules. Finally, indoor Electroluminescence technique has been used to detect if any other degradation mode, rather than hotspots.

Results show that the affected string provides lower energy than the other with ~1.8 kWhe during the sunny days and 0.25kWhe during the cloudy ones. As for the Performance ratio (PR), the 2nd string show an average daily drop of 7%. This drop can reach 13% in clear sky conditions. To detect the degradation sources, IR thermal and Electroluminescence imaging techniques have been used. It has been concluded that the main source of the system performance drop, is the presence of breakages and cracks at the modules cells. Those defects are mainly due to the bad cleaning and the nature of the modules (without EVA protection).

The benefit of this study is the in-situ investigation of a new PV module encapsulation (Without EVA) in the case of a semi-arid climate. Furthermore, the identification of the several degradations forms which appeared on this PV technologies.

2. Methodology and experimental setup

In this part we will discuss the methodology used to evaluate the environmental impact on the performance drop of a monocrystalline PV system. This system is composed of three identical strings with a capacity of 16.6kWhe, and it was exposed for three years under a harsh semi-arid weather, at Green Energy Park research facility. Furthermore, a description of the material used to detect the degradation modes will be discussed.

2.1. Methodology

After three years of operation, a drop on the electrical production of the PV system (described below) has been detected. In fact, starting from December 2017, a significant energy drop has been monitored on the second string of this system. For this reason, an inspection on the affected string has been launched to: (i) detect the affected panels, (ii) understand the reasons behind this energy drop. The first approach used in our inspection campaign, is the field visual investigation. This approach is recommended in the literature and it is used to identify the presence of any visible degradation in the PV modules like: heavy front surface soiling, junction box failure, bus bar oxidation and corrosion, glass breakage [22, 23, 24]. After that, to detect which one of the modules is affected, their electrical parameters were measured using the I-V curve tracer PVPM1040CX. Then, the degradation rate (Rd) for each one of the modules and for each electrical parameter was calculated analytically using the following expression (Eq. 1):

$$Rd(\%) = \left(\frac{X - X_0}{X_0}\right) * \frac{1}{\Delta t} * 100 \quad (1)$$

X and X_0 present respectively, the values of the measured parameter and its value at the STC (Standard Test Conditions) conditions. Δt (in years) is the field exposure duration of the PV modules starting from their initial operation until the measurement time.

Finally, and after the detection of the affected modules, Infrared (IR) and electroluminescence (EL) imaging have been conducted to identify the sources of their performances drop.

2.2. Experimental setup

2.2.1. Photovoltaic system and site exposition's description

The PV system investigated in the current study is a new silicon PV conception without EVA encapsulation (Figure 1). The system's nominal capacity is 16.5 kW_p and it's exposed at GEP research facility (Latitude

Table 1. Main characteristics of the PV modules.

Module technology	Monocrystalline silicon
Maximum power at STC (Pmax)	240 [W]
Optimum operating voltage (Vmp)	30.1 [V]
Optimum operating curent (Imp)	7.9 [A]
Open circuit voltage (Voc)	37.3 [V]

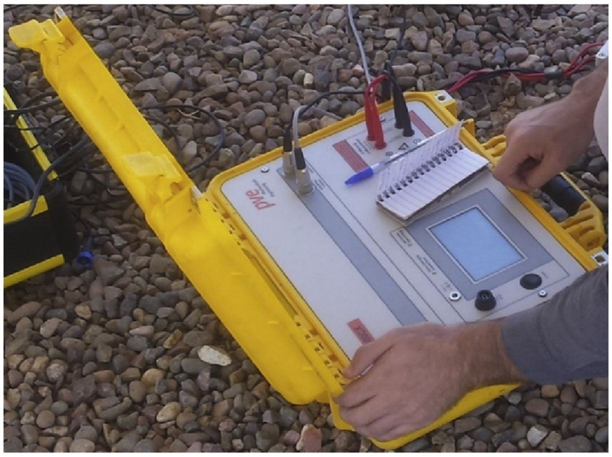

Figure 2. The used I-V curve tracer PVPM1040CX.

32.22N, Longitude -7.94E, altitude 449 m) with a tilt angle of 31° and facing south for a period of three years. This site has a semi-arid climate with a daily global horizontal irradiation (GHI) records between 1.2 and 8.89 kWh/m^2/day, a humidity in the range of 12–93.95 % and an average ambient temperature of 24 °C.

The PV system is composed of three PV strings of 23 modules each, connected to the grid via SB5000TL-21 inverters. These inverters are equipped with a monitoring system that collects the whole electrical parameters: Energy, Power, Current, Voltage, as well as, the modules temperature. The modules specifications at standard conditions are listed in Table 1.

2.2.2. I-V curve tracer PVPM1040CX

To measure and evaluate the performances of the PV modules, a well calibrated I-V curve tracer PVPM1040CX (Figure 2) has been used. This device measures the main electrical parameters for either a single or a string of modules. To do so, the I-V curve tracer uses as a parameter's the irradiation and the PV module temperature values (measured via a monocrystalline reference cell and a PT1000 thermal sensor) to converts the measured electrical values to STC (Standard Test Conditions) and NOCT (Nominal Operating Cell Temperature) conditions. This process is important to provide reproducible measurements regardless the variability of the irradiance and the temperature values during the measurement period. The characteristics of the device are listed in Table 2.

2.2.3. Infrared thermal images

Infrared thermal imaging is a non-destructive method to identify non-visual defects in the PV modules, especially, hot spots. This technique consists of using a camera sensitive to infrared radiation range, by using the concept of localized heat generation due to Joule heating effect. In this study, the FLIR T440 Infrared thermal camera (Figure 3) has been used to investigate the modules of the 2nd string. The technical specifications of the thermal camera are given in Table 3 (see Figure 4).

2.2.4. Electroluminescence images

One of the major degradation sources in a PV field are the panels crack and the micro-cracks. These cracks are generally hard to be detected visually and they occur due to shocks during cleaning events or strong mechanic shocks like wind loads on the panels surfaces.

To detect these degradation forms, the Buchanan Electroluminescence EL-MES chamber has been used. A DC voltage is applied to the module, typically near or equivalent to the open-circuit voltage of the module. Photon emission due to radiative recombination within the PV cell is then detected by the EL camera. The characteristics of the Buchanan EL-MES are summarized in Table 4.

3. Results and discussion

This section will discuss the result of this study. We will firstly present the energy behaviour of the PV system and highlight the amount of energy drop in the 2nd string. After that, the results of the IV-curve measurements will be presented, and the panels performances drop will be discussed. Finally, to detect the source of the electrical performances drops, the modules with high Degradation rate (Rd) were taken for indoor Electroluminescence (EL) to investigate the presence of any cracks

Figure 3. Flir T440 thermal camera used in this study.

Table 2. Technical characteristics of the I-V curve tracer PVPM1040CX.

Sampling rate	Max. 100kHz
Resolution	0.01V–0.25V, 0.005A–0.01A
Accuracy Peak power measurement	±5%
Temperature	-40 °C - +100 °C with Pt1000
Irradiance	0 - 1300W/m^2 (Standard sensor)

Table 3. Technical specifications of the used FLIR T440 infrared thermal camera.

Parameters	Range
Temperature Range	-4°F–2192°F (-20 °C–1200 °C)
Thermal sensitivity	<0.045 °C at 30 °C
Frame rate	60 HZ
Detector Type (FPA)	320 × 240 pixels
Spectral range	7.5–13μm

Figure 4. BUCHANAN electroluminescence.

or non-functional cells. Besides, IR thermal images have been taken to inspect the presence of hotspots. The results of the EL and IR imaging will be presented in this section as well.

3.1. Energy of the PV system

As mentioned above, the system inspected in this study is composed of three identical strings. After evaluating the system's data records of

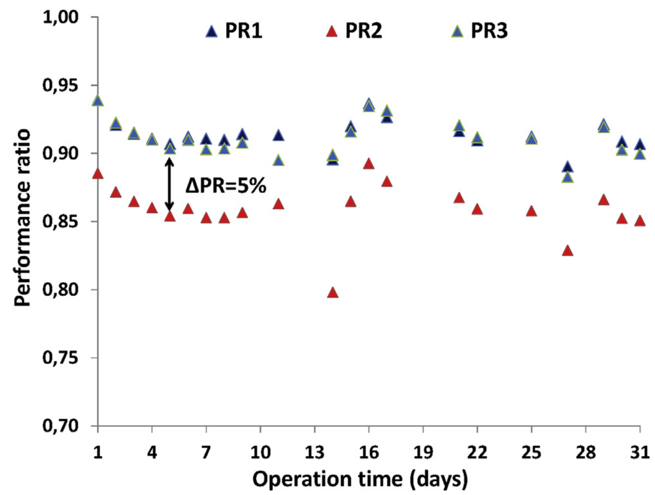

Figure 6. Performance ratio difference between investigated strings in December 2017.

Table 4. Technical specifications of the used EL-MES Buchanan Electroluminescence chamber.

Defects to detect	Cracks, microcracks, finger gaps, dislocations
Max. power output	1.5 KW
Max. voltage	360V DC
Max. current	15A
Requirements	230V/50 Hz, 220V/50 Hz or 110V/60 Hz

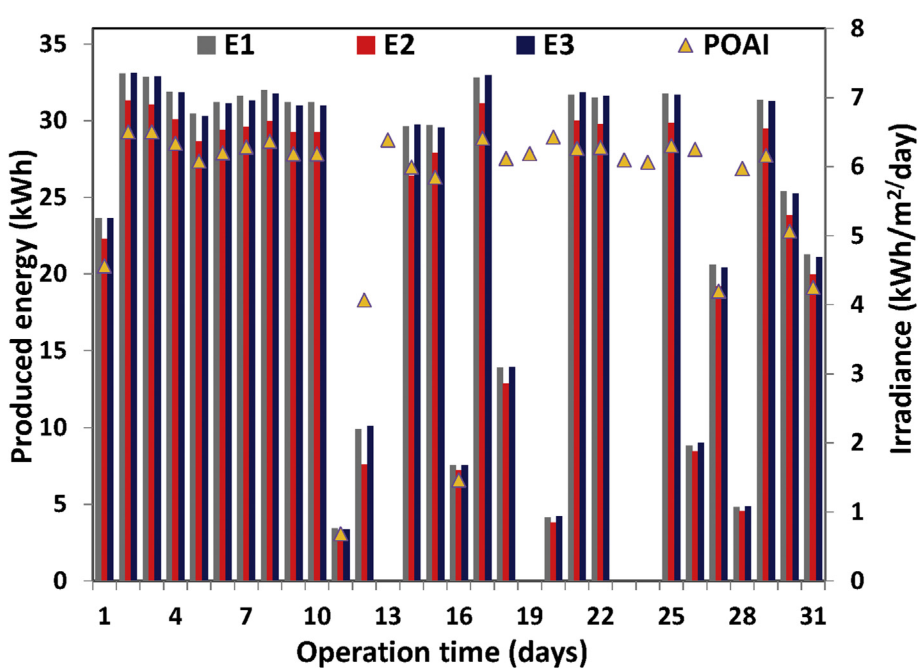

Figure 5. Daily energy of the three strings in December 2017.

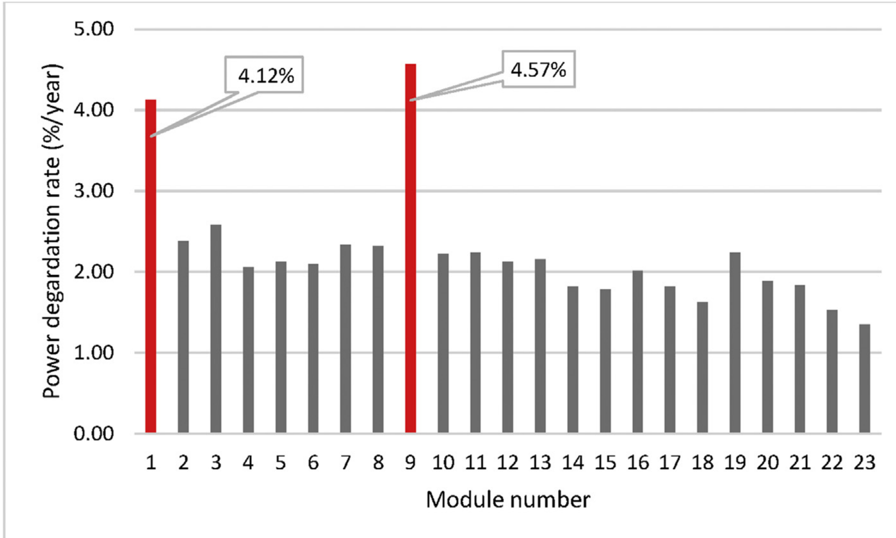

Figure 7. Power degradation rate for each individual photovoltaic panel of the 2nd string.

Table 5. Electrical parameters degradation rate of PV photovoltaic modules.

Module number	Degradation rate (%)					
	P	I_{SC}	V_{OC}	I_m	V_m	FF
1	**4.13**	**0.56**	**0.92**	**1.10**	**2.88**	**2.52**
2	2.38	0.36	0.55	0.93	1.22	1.17
3	2.58	0.24	0.62	0.80	1.55	1.48
4	2.06	0.04	0.51	0.63	1.22	1.26
5	2.13	0.60	0.34	1.05	0.78	0.91
6	2.10	0.68	0.29	1.10	0.78	0.82
7	2.33	0.08	0.43	1.14	1.00	1.56
8	2.32	0.01	0.50	0.80	1.22	1.56
9	**4.57**	**0.36**	**0.45**	**1.60**	**2.88**	**3.60**
10	2.22	0.12	0.49	0.80	1.22	1.56
11	2.24	0.12	0.33	1.05	0.89	1.52
12	2.13	0.04	0.31	0.93	0.89	1.52
13	2.15	0.12	0.31	0.76	1.11	1.65
14	1.82	0.08	0.21	0.84	0.78	1.39
15	1.78	0.08	0.14	0.76	0.78	1.43
16	2.01	0.16	0.38	0.80	1.00	1.22
17	1.82	0.32	0.26	0.51	1.00	1.61
18	1.63	0.04	0.22	0.55	0.78	1.09
19	2.24	0.36	0.33	0.72	1.22	1.26
20	1.89	0.32	0.23	0.80	0.78	1.04
21	1.83	0.08	0.25	0.68	0.89	1.22
22	1.53	0.32	0.29	0.38	0.89	0.65
23	1.35	0.16	0.06	0.59	0.44	0.82

The bold numbers are shows the electrical values of the PV modules most affected by the degradation.

December 2017, we noticed that the production of the 2nd string is lower than the other two left. As it can be seen in Figure 5 the 2nd string always provide less energy than the 1st and the 3rd regardless the sky conditions. Indeed, for a sunny day (*e.g.*, Day 3 of December) the energy produced by the 1st and the 3rd strings were of 32.83 and 32.87kWhe respectively, while, the 2nd one produced an energy of 31.05 kWhe, which is lower by 1.8 kWhe than the others. Correspondingly, for the cloudy days (e.g., Day 11 of December) the energy generated by the 2nd string was of 3.25 kWhe while the 1st and the 3rd produced 3.44 and 3.4 kWhe respectively. Here again, the production by the 2nd string is lower than the other strings by around 0.25kWhe. We need to mention that the system was non-operational on the 13th,19th,23rd and the 24th because we disconnecting it in purpose for conducting indoor IR and IV-curve measurements.

3.2. Performance ratio assessment of the PV plant

To further investigate the performance drop of the affected string, the use of standard comparison metrics like the performance ratio (PR) is recommended. The performance ratio is defined as the ratio of the actual to the theoretical value of the energy output (Eq. 2). In our study, the PR

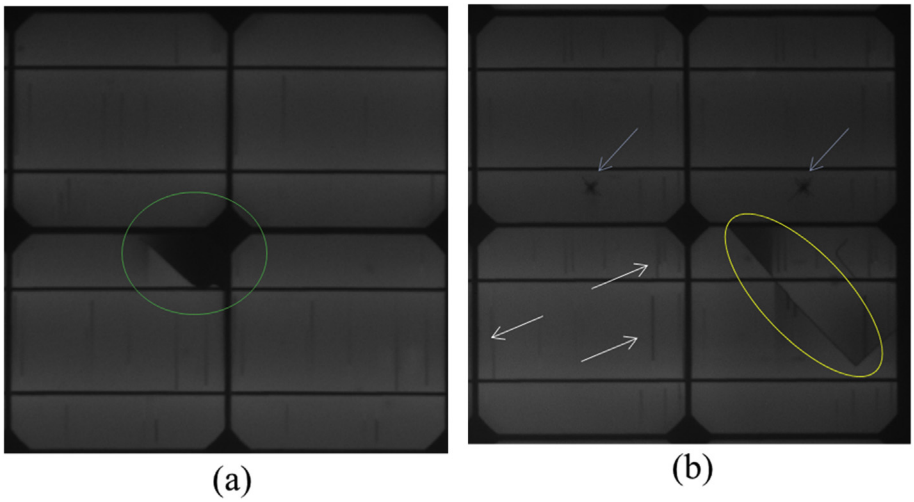

Figure 8. Cracks and breakages in some cells of affected PV modules. (a): cell breakages; (b): white line.

values of the three strings was calculated and plotted in Figure 6. Here again we can clearly notice that the PR of the 2nd string is much lower in comparison to the other strings. Indeed, the daily average difference is around 5% in comparison to both other strings. This deviation can reach 13% especially under clear sky conditions. As for the 1st and the 3rd strings, we can clearly notice that they produce electricity with almost the same performance, with a slight deviation of +/-1%.

$$PR = \frac{Y_f}{Y_r} \qquad (2)$$

Where Y_f is the net energy output of the system and Y_r presents the peak power of the installed PV array at standard test conditions.

3.3. Outdoor measurements of electrical parameters

To detect which are the modules with the highest performances drop, and to quantify the degradation rates of their electrical parameters, the I-V curve tracer has been used. Figure 7 illustrates the degradation rate of the power output measured for each module of the 2nd string. As it can be seen, after three years of exposition, the power drop is of 2% in average for all modules. Whereas, the 1st and the 9th modules are the most degraded ones with a drop in the power of 4.12% and 4.57% respectively.

The same process has been used to evaluate the Rd of the other electrical parameters: power output (Pm), short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum current (I_m), maximum voltage (V_m) and fill factor (FF). The results were summarized in Table 5. As it can be noticed, the power degradation of the 1th and the 9th modules (already presented in Figure 7) is mainly due to the reduction in both current (I_m) and voltage (V_m) with 0.84 % and 1.14 % in average and respectively. This can be explained by the possibility of the presence of some problems at the cell levels like cracks or breakages, especially, knowing the fact that the studied PV system is composed by PV modules without EVA production. These degradation forms can be detected effortlessly using EL imaging.

The power degradation rate was of 4.57%/year in the modules with breakage and cracks. This drop in the power is mainly due to the drop on both the Im and Vm with 0.84 and 1.14%/year respectively.

3.4. EL inspection

As discussed above, with the EL imaging technique and a qualitative analysis we can identify easily the shunted areas, cracks and finger interruption in the cells. In order to detect the source of error in the modules 1 and 9, EL images have been taken (Figure 8). As it can be seen, reveal inhomogeneous EL emission, where several breakages cracks gridline interruption and shunt area are detected. Some of these defects isolate a part of the cells and decrease their efficiency, consequently their power output.

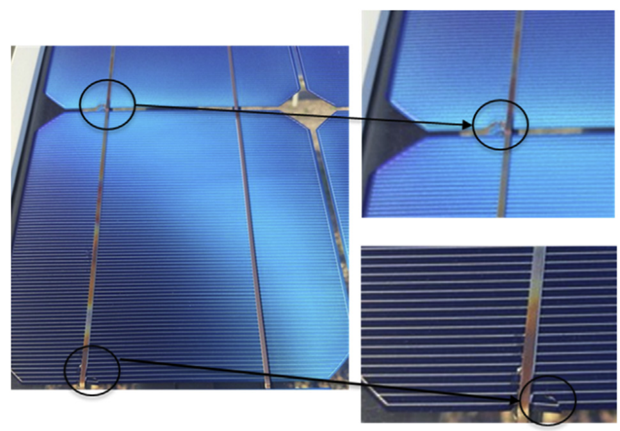

Figure 9. Visual Cracks and breakages in some cells of affected PV modules.

Indeed, the resultant power loss is strongly dependent of the defect patter such as size, geometry and orientation. These cracks can propagate and damage the contact fingers and resulting the development of cell breakages. This is mainly due to some problems of manufacturing and operation like cleaning events. In the EL image, these defects are easily detectable in the form of dark line perpendicular to the bus bar, which reveals the interrupted finger (Figure 8b –white line).

In turn, cell breakages (like to the one detected on, Figure 8a) causes the isolation of a part of the cell area which leads to significant current drop. The cell breakages are detected on the EL images as dark areas.

In the 1st and the 9th modules, the cracks of the cells can also be detected visually (Figure 9). This lead us to conclude that the power drop on these modules is mainly due to the breakage of some of their cells. This breakage is very likely due to a bad cleaning event, because we are using manual cleaning and the performances drop in the power output were recently detected.

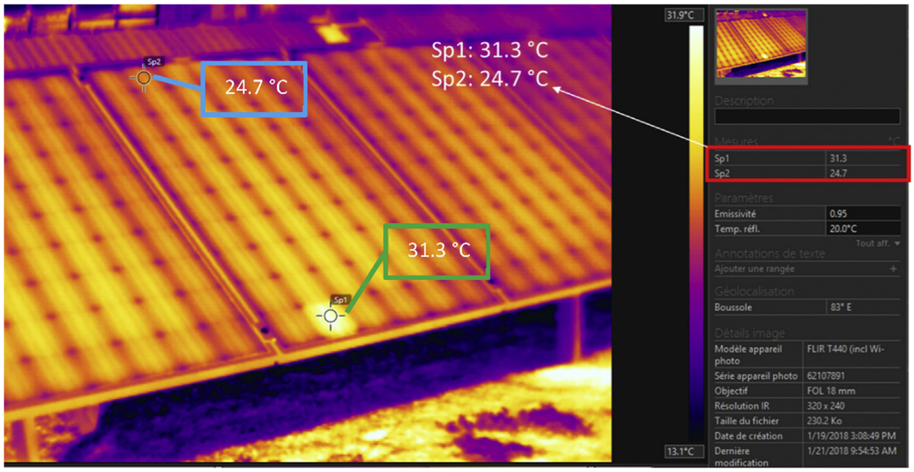

Figure 10. Infrared thermal image of PV module number 7.

3.5. Infrared thermal inspection

In order to further investigate the drop on the 2nd string performances, In-situ IR thermal imaging inspection has been done. This inspection is important to detect any hotspot in the modules. This degradation form occurs if one cell is shaded by the accumulation of dust on the bottom of the PV modules, knowing the fact that the exposition site is a highly soiled one.

Figure 10 presents an IR thermal image of a part of the 2nd string. As it can be seen, only one of the modules (the module 7) reveals a cell exhibiting a temperature difference greater than 7 °C from the neighbouring cells.

For the other modules we could not detect any hot spot. Therefore, we can say that the main source of the energy drop in our PV system is the presence of cracks and breakages in the cells and it's due to a bad cleaning and the nature of the PV modules (without EVA protection).

4. Conclusion

The goal of this paper is to present the effect of the climatic conditions on the crystalline photovoltaic modules' performance in the semi-arid conditions after the detection of an energy drop in one of its strings. For this reason, an experimental performance evaluation of has been carried out through visual inspection, I-V characteristic, degradation rate calculation, as well as, EL and thermal imaging.

The key results of this study are summarized below:

- Through visual inspection, some cracks are observed which are associated to the absence of EVA encapsulating that protects the modules from the mechanical shocks and stresses.
- The power degradation rate has been found to be of 2.22%/year which is higher than the usually reported values in the literature.
- It was also found that, the power degradation rate was of 4.57%/year in the modules with breakage and cracks. This drop in the power is mainly due to the drop on both the Im and Vm with 0.84 and 1.14%/year respectively.
- With the EL imaging technique, we proved that the main cause of the measured energy drop is the presence of cracks at the cells.
- Using the IR thermal camera, we could not detect any hotspot, except in one module with a temperature difference of 7 °C.

Finally, in arid regions with high soiling rates and frequent cleaning event, we highly recommend the use of PV modules with EVA encapsulating to protect the cells against any breakage or mechanical shocks.

Declarations

Author contribution statement

Charaf Hajjaj, Abdellatif Bouaichi, Houssain Zitouni: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Ahmed Alami Merrouni: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Abdellatif Ghennioui, Badr Ikken: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Mohammadi Benhmida, Messaoudi Choukri, Mohammed Regragui: Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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