Investigation on Performance Decay on Photovoltaic Modules: Snail Trails and Cell Microcracks

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I. Introduction

THE photovoltaic (PV) energy is one of the potential renewable energy that can provide a substantial contribution to the world energy demand in future. Since 2010, PV cost production has been reduced significantly, making PV electricity costs competitive with fossil fuels [1]. Together with costs, the assessment of PV modules degradation is very vital to enhance reliability, performance, and lifetime of the solar energy system [2]. Among PV degradation phenomena [3], [4], snail trails (also known as worm marks or snail tracks) are known as discoloration effect in the PV modules. Typically, the snail trails appear on the front side or the edge of the solar cells [5], [6]. The visual appearance of the snail trail phenomenon consists of small narrow dark line and discoloration on the surface of the cell, leading to the aforementioned names [7], [8].

The snail trail phenomenon may occur on different types of cells (i.e., mono- and polycrystalline silicon), and it appears on cells within several months after the installation of the PV modules [7]. Evidences of researchers showed that the snail trail phenomenon is not recent, but it dates back three decades [12].

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As shown by different authors, the snail trail discolorations within the cells can be strongly correlated with cell microcracks. The only exceptions are those snail trails which occur at the cell edges [5], [6]. Investigations have, in fact, shown that the snail trails can be also related to moisture reacting with PV module materials as polymers; this particular case is called "framing snail trails." The air moisture penetrates the PV modules from the back sheet foils. Once in the module, it can easily reach the edges of the PV cell surface or pierce through microcracks creating the discoloration effect described previously [5], [6], [8]. In the presence of an electrical field, temperature and UV irradiation corrode the interface between silver contact and encapsulation foil leading to a migration of silver into the EVA (Ethylene Vinyl Acetate) foil and forming Ag containing particles [5], [9]–[11].

Besides works focusing on the cause of snail trails formation in the PV modules, few publications investigated the impact of snail trails or microcracks on PV module performances. Results are contradictory since some papers showed that there is an actual decay of PV performances [9], while another states that there is no significant deviation of the actual performances compared with the predicted ones [13]. This issue stated also by manufacturers is supported by the formation mechanism of snail trails [8]: The discolorating silver nanoparticles were found only above the grid fingers within the encapsulant foil. Thus, neither the active area of the cell is impaired nor the conducting properties of the contact fingers are affected. Cell cracks, however, can lead to massive power losses after mechanical stress like wind, etc. [19].

The main purpose of this paper is to measure the effect of the snail trails phenomenon in both forms (the cell cracks and the incoming moisture) on PV modules performance, showing how they can be negatively affected. In order to do this, four modules were tested: The number of the PV modules involved in this analysis is not statistically relevant to draw a line on this subject; however, it can contribute to the evaluation of this phenomenon. Experimental tests on PV modules have been performed at SolarTech Lab [14] at Politecnico di Milano, Italy. Performances of PV modules affected by snail trails have been compared with the data available in the datasheets from the manufacturers. In addition, the PV energy production throughout August 2013 was monitored to determine the final yield as defined by IEC 61724 [15].

This paper is organized as follows: In Section II, the SolarTech Lab location, the facility overview, and the PV system considered in this study are described. Section III gives more details about the experimental procedure adopted. Moreover, the monitoring of experimental activities and their results,

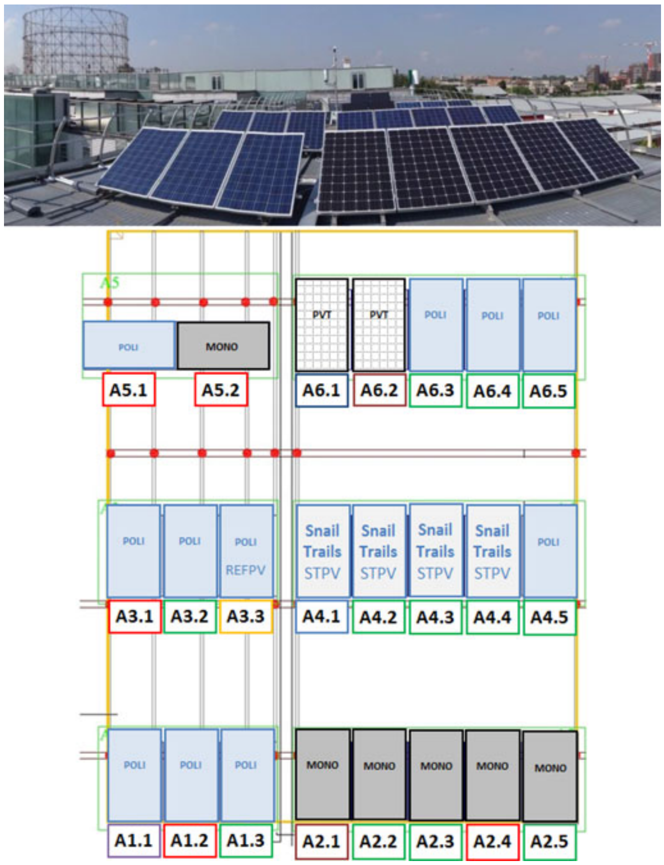

Fig. 1. Panoramic picture and layout of the PV Field in SolarTech Lab in August 2013.

TABLE I
METEOROLOGICAL STATION MAIN CHARACTERISTICS

Description	Net radiometer (LSI DPD504)	Pyranometer (LSI DPA253)
Measurements range	<2000 W/m^2	<2000 W/m^2
Spectral range	0.3–60 μm	305–2800 nm
Total achievable daily uncertainty	$<5\%$	$<5\%$
Nonlinearity	$<1.5\%$	$<4\%$
Thermal drift	$<2\%$	$<1.2\%$

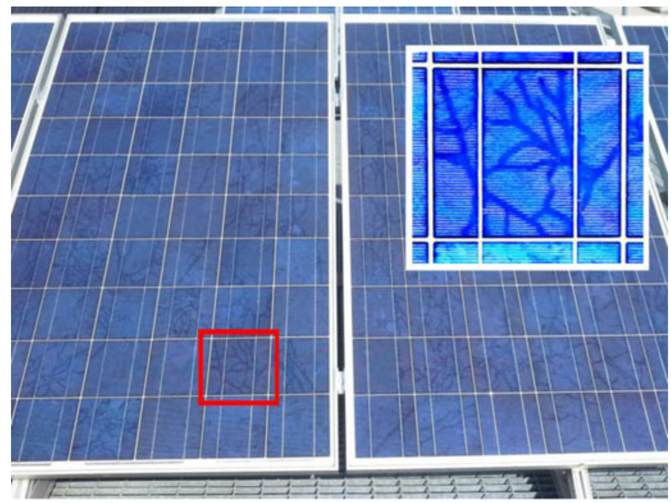

Fig. 2. Visible picture of STPV modules at SolarTech Lab and magnification of few cells affected by snail trails.

also considering instruments overall uncertainty, are presented. Our conclusions and general comments are reported in Section IV.

II. SolarTech Lab Location and Facility Overview

The SolarTech Lab has been founded at Politecnico di Milano, Italy in 2012. Its geographical coordinates are latitude 45.502941°N and longitude 9.156577°E. During the tests on PV modules affected by snail trails, 25 PV modules of different technologies and from several manufacturers were installed in the facility: 15 modules were polycrystalline type, six modules were monocrystalline, and four were PV-thermal modules. All of the PV modules face south with a tilt angle of 30°, except two of them which have tunable tilt angle. They have been under outdoor exposure for several months. PV modules are connected to the low-voltage distribution grid through commercial microinverters so that the operating conditions of every module can be optimized. Layout of PV modules at the SolarTech Lab is shown in Fig. 1.

Solar irradiance, air temperature, humidity, and wind (speed/direction) have been continuously measured by a meteorological station. Solar irradiadiance is measured by three different sensors: a net radiometer measuring the direct normal irradiance (DNI) and two pyranometers that measure the global on horizontal plane and diffuse irradiance.

The main characteristics of the solar radiation sensors at SolarTech Lab are summarized in Table I.

PV modules affected by the snail trail phenomenon are polycrystalline type and are named A4.1, A4.2, A4.3, and A.4.4 (see Fig. 1). For the sake of brevity, from now on, the modules affected by snail trails will be abbreviated as STPV (snail trails PV), while the PV module beside the investigated modules as REFPV.

The four STPV are made by the same manufacturer, while REFPV was made by another one. All the modules have been produced in 2011 and exposed to the sun light at the beginning of 2012 in similar environmental condition. Before installation, each module was tested showing good agreement in terms of performances with the corresponding datasheet. The STPV modules at that time did not show any problem in terms of the snail trail phenomenon or other issues. After less than six months, these PV modules started to show the snail trail phenomenon with simultaneous performance decay of the PV plant. Fig. 2 shows a picture of two PV modules affected by the snail trail phenomenon made at the time of installation at SolarTech Lab.

In terms of visual inspection, no yellowing, misalignment, delaminations, bubbles, and burnt cells could be observed in the STPV modules. Furthermore, the electrical wires and connections were working perfectly as well as the junction box or bypass diodes.

Reference PV module had constant performances throughout the 18 months of operation, and there were no problems.

III. Experimental Procedure

In this research, two different experimental analyses were carried out to evaluate snail trails effects on the PV modules performance under real condition. These are

1) measurements of the current–voltage and power–voltage characteristics at different operating conditions;
2) measurements of the energy produced by each PV module and analysis of the results in terms of "instantaneous final yield" and "daily final yield index."

The "instantaneous final yield" is the ratio between the output power of each PV module and its rated power (also known as peak power). It is defined by

$$y_f = \frac{P_{\text{out}}\,[\text{kW}]}{P_N\,[\text{kWp}]}. \tag{1}$$

The "daily final yield index" ($Y_{f,d}$) is defined, in accordance with the IEC 61724 [8], as

$$Y_{f,d} = \frac{E_{\text{out},d}\,(\text{kWh})}{P_N\,(\text{kW})}. \tag{2}$$

The relative difference of $Y_{f,d}$ between the STPV and reference PV modules is calculated as

$$Err = \frac{Y_{f,d}^{\text{ref}} - Y_{f,d}^{\text{mis}}}{Y_{f,d}^{\text{ref}}} \cdot 100 \tag{3}$$

where $Y_{f,d}^{\text{ref}}$ and $Y_{f,d}^{\text{mis}}$ refer to REFPV final yield and to STPV, respectively.

In addition to these analyses, thermal measurements of the PV module superficial temperature were performed to check whether hot spots occur in correspondence to the cell affected by snail trails. A qualitative thermal analysis is performed by means of a commercial thermal camera previously calibrated for the measurement of thermal field on the surface of PV module. The module temperature is measured by four thermocouples, placed on the back of the module as described hereinafter.

The aim of these tests is to measure eventual losses due to snail trails and cell cracks phenomenon in some PV modules in terms of power at the maximum power point and of the total energy production along a time period of around one month. From the technical point of view, it is really important to evaluate the reduction of the energy produced with consequent impact on the business plan. Therefore, this analysis does not investigate the influence of framing snail trails separated from the effect of cell cracks but the results of these phenomena as a whole. However, this is just not possible if samples contain two overlaying defects as cell cracks and framing snail trails. Further analysis as electroluminescence imaging would help to understand the type of defect actually present in the studied modules.

A. I–V and P–V Characteristics in Real Condition

The current–voltage and the calculated power–voltage experimental data of PV modules were measured at different operating conditions by electrical measurement equipment according to the IEC 60904-1 standard [16]. The IEC 60891 standard defines the procedure to correct the PV module characteristics at standard temperature and irradiance [17].

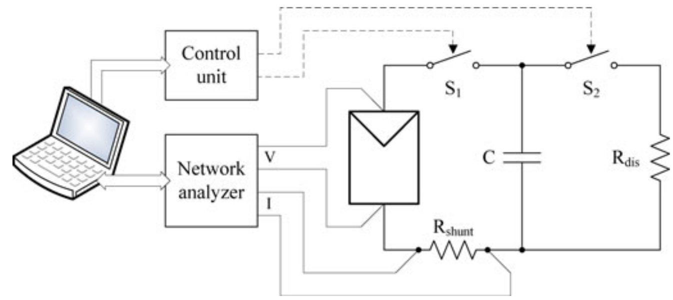

Fig. 3. Principle diagram of the instrument for the measurement and recording of the PV characteristics.

TABLE II
Metrological Characteristic of the Measurement Equipment

Description	Full scale (FS)	Accuracy: 1–10% of FS	Accuracy: 10–130% of FS	Accuracy: 130–150% of FS
Voltage input	100 V	1 V	100 mV	1 V
Current input from transducer	3 V	30 mV	3 mV	30 mV

The electrical measurements were performed using a prototype and market available equipment based on a network analyzer and a personal computer to lead and store the measured values. The operating principle of the measurement instrument is illustrated through the block diagram shown in Fig. 3 [18]. The accuracy of the network analyzer is reported in Table II. During the test, the pairs of voltage and current are measured and stored by a network analyzer. The analyzer is equipped with 12-bit A/D converters that simultaneously sample the voltage and current signals at the rate of 12.5 kSamples/s. The voltage measurement is direct, while current measurement is through the shunt resistor R_{shunt}. The instrument is programmed to perform a test in less than 0.5 s. The data were recorded with transducers within $\pm 1\%$ accuracy. At the beginning and in the end of the measurement campaign, the calibration of the network analyzer was verified with a voltage and current source whose accuracies are $0.25\% + 10$ mV and $0.25\% + 10$ mA, respectively.

Module temperature is measured by four thermocouples, placed on the back of the module as described in [17]. Each thermocouple has an accuracy of ± 1 °C, as indicated in [16]. The whole temperature acquisition system was calibrated at the beginning and checked at the end of the tests.

The irradiance measurement was made using a PV calibrated reference cell spectrally matched to the module under test, in conformance with [16]. Reference cell temperature is measured by its temperature sensor at the thermal steady-state condition. Reference cell is placed on the same plane of the tested modules.

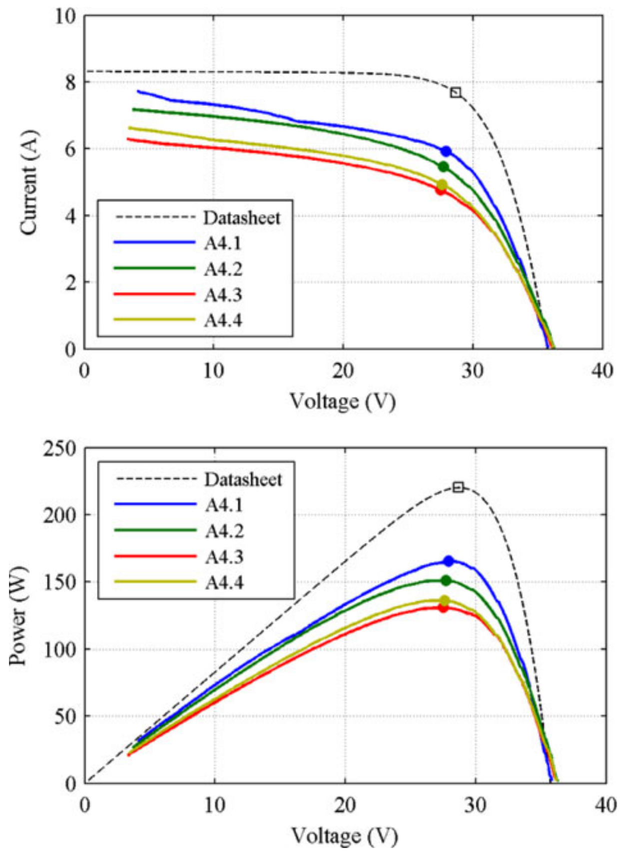

Fig. 4. Measured *I–V* and *P–V* curves of the four PV modules affected by the snail trail phenomena normalized at STC in comparison with datasheet curve.

Since the manufacturing datasheets are based on STC,[1] the measured *I–V* and *P–V* characteristics have carried out under real irradiance and temperature condition for all PV modules. In this investigation, it has been assumed that the temperature coefficients of short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and power at maximum power point (P_{MPP}) do not change in presence of snail trails phenomenon, and they are the same temperature coefficients reported in the datasheet by the manufacturer. During these tests, global irradiance on the PV module surface was stable, and it ranged between 940 and 950 W/m^2, while the average module temperature was between 52 °C and 54 °C. In each test, the global solar irradiance fluctuated within 1%, and the module temperature was stable within ±1 °C, in conformance with [16].

The measured *I–V* and *P–V* characteristics of the four polycrystalline PV modules affected by snail trails phenomenon and of the REFPV were normalized at STC and then compared with the manufacturer datasheet.

In Fig. 4, the measured curves for the four STPV modules are shown together with the curves calculated from datasheet. *I–V* curves have different values but from a quantitative point of view; they share the following aspects

1) They are all below the datasheet curve, in particular at maximum power point conditions.
2) The performance decay is mainly related to photo-generated current reduction.
3) The *I–V* curve has a significant slope at low voltages, suggesting a lower shunt resistance in the equivalent circuit.
4) The open-circuit voltage coincides with the reference value.

These results suggest that it is more likely the cell cracks instead of the snail trails are the reason for the performance loss. If the majority of the cells are isolated by breakage, they cannot contribute to the photo-generated current. This confirms what can be seen by the photos shown in Figs. 2 and 5: If massive ST became visible usually the affected cells are heavily broken.

In Table III, the measured values of the P_{MPP}, voltage at maximum power point (V_{MPP}) and current at maximum power point (I_{MPP}) for the PV modules affected by snail trails phenomenon are summarized and compared with rated values declared by manufacturer in the datasheet. Since any PV module has a performance decay for aging and exposure to ambient conditions, the REFPV measured data and datasheet values are also reported.

Performance loss of REFPV is about 3.4%, and this is assumed as standard degradation.[2] The power loss related to snail trails is then calculated as the difference between the overall power losses (datasheet power minus measured power) of each STPV and the standard degradation.

The maximum power point reduction of STPV respects the datasheet ranges between 24.8% and 40.5%; the range between 21.4% and 37.1% can be assumed because of snail trails phenomena. It is mainly related to the photocurrent generated and lower shunt resistance as also previously discussed.

Electric measurements of PV module performances were combined with a thermal analysis of modules surface to find out potential hot spots. Fig. 5 shows a thermal picture of PV modules. All modules shows nonuniform thermal behavior (lighter parts indicate higher temperatures).

Reference PV modules have uniform temperature distribution (besides marginal boundary effects). Hotter spots that coincide with cells affected by the snail trail phenomenon indicate that they have been damaged and are not working properly.

B. *Evaluation of Instantaneous Final Yield and Final Energy Index*

The latest test evaluates the energy production of PV modules affected by snail trails. The continuous monitoring of PV modules could be performed, thanks to the microinverter configuration adopted at the SolarTech Lab. Inverters were previously characterized in terms of efficiency at different operating conditions, showing a quite uniform behavior. Therefore, an eventual performance decay is certainly related to the PV module and not to the power conversion system.

The energy production by PV modules in August 2013 was recorded to assess the influence of snail trails in terms of daily

[1]Standard test condition: in plane irradiance of 1000 W/m^2 (perpendicular to the module plane), radiation spectrum equivalent to the solar spectrum at air mass 1.5, and a module temperature of 25 °C.

[2]This is due both to the aging of the modules and to the tolerance of the peak power of the modules.

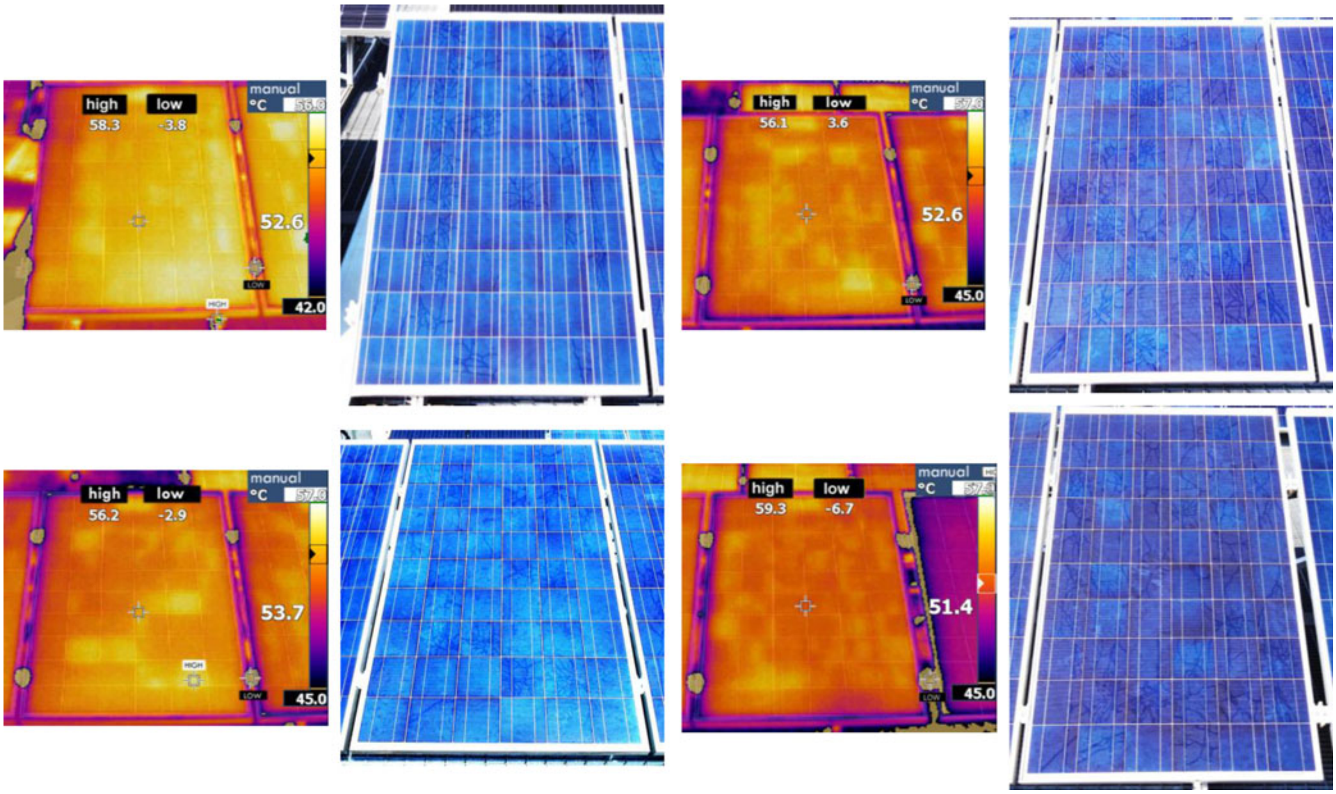

Fig. 5. Thermal image and picture of PV modules A4.1, A4.2, A4.3, and A4.4, starting from the top left, moving horizontally.

TABLE III
MEASURED AND DATASHEET VALUES OF P_{MPP}, V_{MPP}, AND I_{MPP} OF THE MODULES AFFECTED BY SNAIL TRAILS PHENOMENA AND REFPV

Module		I_{MPP} (A)	V_{MPP} (V)	P_{MPP} (W)
A3.3	Data Sheet	7.81	31.38	245
	Measured	7.64	30.97	236.61
	Difference (%)	−2.0%	−1.3%	−3.4%
STPV	Data Sheet	7.67	28.70	220
A4.1	Measured	5.93	27.90	165.39
	Difference (%)	−22.7%	−2.8%	−24.8%
A4.2	Measured	5.49	27.70	151.21
	Difference (%)	−28.4%	−3.5%	−31.3%
A4.3	Measured	4.76	27.50	131.01
	Difference (%)	−37.9%	−4.2%	−40.5%
A4.4	Measured	4.94	27.60	136.26
	Difference (%)	−35.6%	−3.8%	−38.1%

and total energy within the test period. The evaluation is performed in terms of Instantaneous Final Yield (y_F) and Final Yield Index (Y_F) which are compared with reference values of commercial PV modules of the same technology installed at the SolarTech Lab.

Instantaneous Final Yield of PV modules for three different randomly chosen days in August are shown in Figs. 6 and in 7. In Fig. 6, y_F of all PV modules oriented as STPV and in production at the SolarTech Lab on 13th August is reported. The thick curves distinguished by blue, green, dark yellow, and red colors represent the power production rate of the STPV, numbered A4.1, A4.2, A4.3, and A4.4, respectively. The other curves represent other PV polycristalline modules oriented as STPV at SolarTech Lab. Beside minor shading issues at sunrise and sunset of few modules (see the light blue of A4.5 and dark red of A1.1 and A3.1), Instantaneous Final Yield (y_F) of STPV is always the lowest. It could be noted in Fig. 6 that performance of the REFPV (A3.3) is representative of the other modules having an average behavior. This module is considered as the reference module in Fig. 7.

The difference of Instantaneous Final Yield (y_F) increases with the solar radiation achieving an absolute value between 18% and 30% at 12 A.M. solar time (about 1:30 p.m. local time).

When the solar radiation is low and the contribution of the diffuse radiation is higher (before 9:00 and after 18:00), the performances of STPV are close to the reference panel. This result suggests that snails trails negatively affect the conversion efficiency of the direct solar radiation; however, further investigation should be performed.

The same considerations can be extended to the curves reported for two additional days (August 5 and 6, respectively) in Fig. 7 where, only one reference PV module is shown, the one beside the investigated modules.

Finally, the daily energy generation—in term of final yield (Y_F)—by PV modules recorded from 3rd to 30th August 2013 is summarized in Table IV. The daily charts prove that the four STPV have a lower final yield ($Y_{f,d}$) ranging from 16% to 32% compared with the REFPV module. Since the final yield decay is referred to the reference PV module installed at the laboratory, the whole decay can be attributed to the snail trail phenomenon.

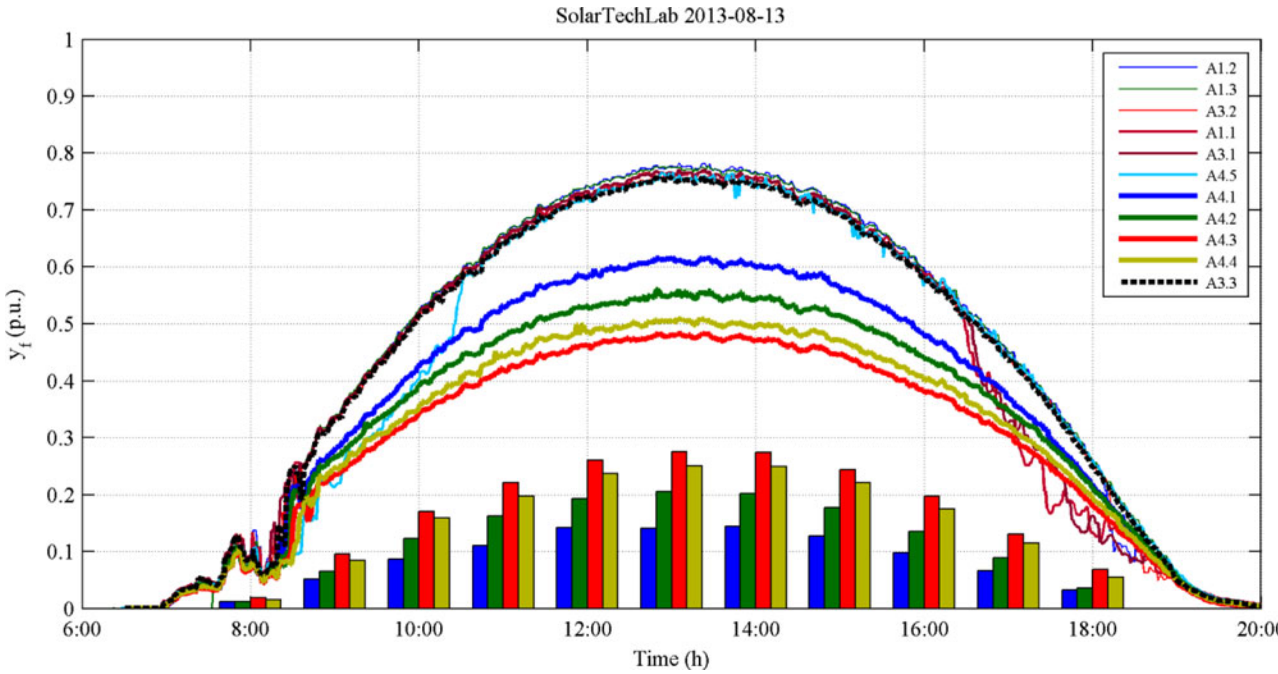

Fig. 6. Daily production of the all the polycrystalline PV modules present in the SolarTech Lab in August 13, 2013. The A4.1, A4.2, A4.3, and A4.4 PV modules were affected by snail trails phenomena. A4.5 and A1.1, A3.1 PV modules were affected by partial shading at sunrise and sunset, respectively. The PV module A3.3 is the polycrystalline one taken as the reference. The bar chart shows, hour by hour, the difference in term of power between STPV modules and REFPV one.

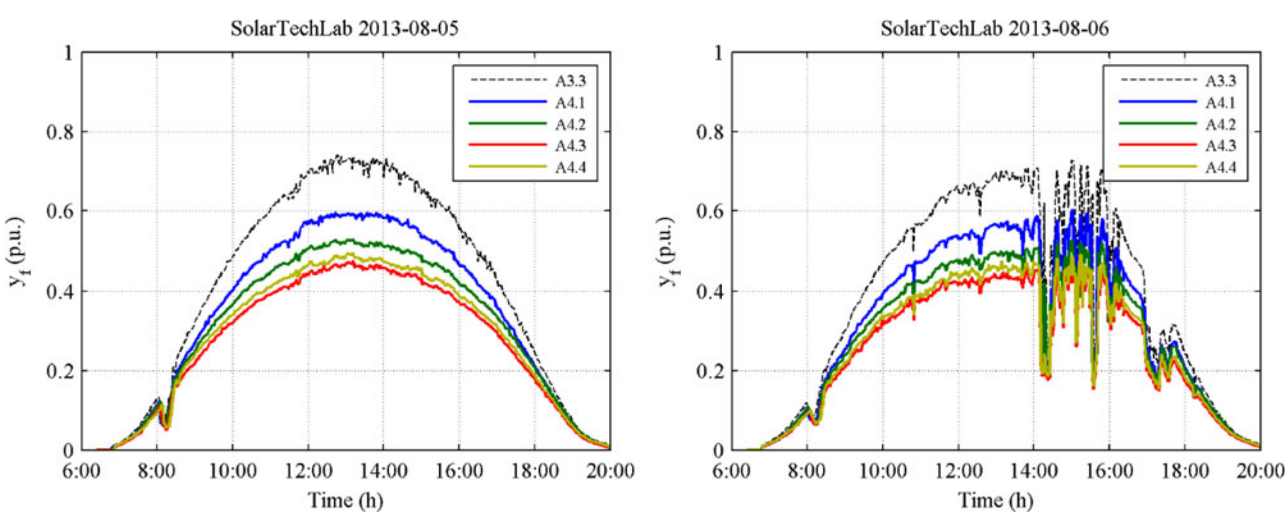

Fig. 7. Daily energy production of the four module affected by snail trails phenomena (A4.1, A4.2, A4.3, A4.4) in comparison with reference curves (A3.3), recorded in two days of August 2013 (August 5 is on the left, and August 6 is on the right).

Moreover, it can be outlined that performances decay is higher in days with high solar radiation for all STPV.

The comparison of STPVs before and after testing shows that neither the number of snail trails nor their length increased, and the efficiency of the PV modules did not decreased during one month of operation.

These results confirm that snail trails phenomenon affects PV performances reducing the electricity produced. However, the number of tested modules is not large enough to deduce further considerations.

IV. Conclusions

Performance reduction is one of the main concerns of PV systems due to solar cells modules degradation. Therefore, the investigation of potential defects on PV modules is an important issue to keep PV systems at the high performances.

This study was carried out to investigate the effect of snail trails phenomenon of both cell cracks and framing type on the PV modules which is often considered only an esthetic issue.

TABLE IV
DAILY FINAL YIELD INDEX ($Y_{f,d}$—WH/W) OF THE FOUR PV-AFFECTED MODULES BY SNAIL TRAILS PHENOMENA AND PERCENTAGE OF DIFFERENCES IN COMPARISON WITH THE REFERENCE MODULE DAILY FINAL YIELD

Day	Daily solar irradiance (Wh/m^2)	A3.3 $Y_{f,d}$ (Wh/W$_p$)	A4.1 $Y_{f,d}$ (Wh/W$_p$)	*Err.*	A4.2 $Y_{f,d}$ (Wh/W$_p$)	*Err.*	A4.3 $Y_{f,d}$ (Wh/W$_p$)	Err.	A4.4 $Y_{f,d}$ (Wh/W$_p$)	*Err.*
03/08/2013	6.5	5.3	4.4	17%	3.5	34%	3.7	30%	4.0	24%
04/08/2013	6.9	5.6	4.6	17%	3.7	35%	3.9	31%	4.2	25%
05/08/2013	7.0	5.6	4.7	17%	3.7	34%	3.9	31%	4.2	25%
06/08/2013	6.4	5.2	4.3	17%	3.4	34%	3.6	31%	3.9	25%
07/08/2013	3.2	2.6	2.2	15%	1.9	29%	2.0	25%	2.1	20%
08/08/2013	1.5	1.2	1.0	12%	0.9	23%	1.0	19%	1.0	13%
09/08/2013	6.9	5.7	4.8	16%	3.9	32%	4.1	29%	4.5	22%
10/08/2013	7.4	6.1	5.0	17%	4.0	34%	4.2	31%	4.6	24%
11/08/2013	6.3	5.2	4.3	17%	3.5	34%	3.6	31%	4.0	24%
12/08/2013	6.5	5.3	4.4	17%	3.5	34%	3.7	30%	4.0	24%
13/08/2013	6.9	5.8	4.8	17%	3.8	34%	4.0	30%	4.4	24%
14/08/2013	3.2	2.5	2.2	14%	1.8	27%	1.9	24%	2.1	17%
15/08/2013	6.8	5.8	4.8	17%	3.9	33%	4.1	30%	4.4	24%
16/08/2013	6.6	5.8	4.8	17%	3.8	34%	4.0	30%	4.4	24%
17/08/2013	6.7	5.7	4.7	17%	3.8	33%	4.0	31%	4.3	24%
23/08/2013	6.0	5.4	4.5	17%	3.6	33%	3.8	30%	4.1	24%
24/08/2013	4.8	4.3	3.6	17%	2.9	33%	3.1	29%	3.3	24%
25/08/2013	5.2	4.7	3.9	16%	3.2	33%	3.3	29%	3.6	23%
26/08/2013	5.5	4.9	4.2	15%	3.4	30%	3.5	28%	3.9	21%
27/08/2013	4.0	3.6	3.0	16%	2.5	30%	2.6	27%	2.8	21%
29/08/2013	3.2	2.7	2.4	14%	2.0	27%	2.1	23%	2.3	17%
30/08/2013	5.7	5.3	4.4	16%	3.6	32%	3.8	28%	4.2	21%
TOTAL	123.2	104.3	87.0	16%	70.3	32%	73.9	29%	80.3	23%

Two different experimental analyses were performed to evaluate the eventual perfomance decay of PV modules affected by the snail trail phenomenon by measuring the current–voltage characteristics and of the energy produced.

Results show that the snail trails phenomenon can indicate cell cracks on the PV module: Therefore, it can be considered as a serious defect for PV modules. Maximum power production and overall yearly energy production may be reduced up to 37% and 32%, respectively. It should be mentioned that this investigation was led on a limited amount of samples. Therefore, this study is not going to declare that the snail trails phenomenon can affect all PV modules in any condition, but it has to be seriously considered as a crucial issue for PV reliability.

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