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ACTA IMEKO
ISSN: 2221-870X
December 2018, Volume 7, Number 4, 75 - 81

In-field monitoring of eight photovoltaic plants: degradation rate over seven years of continuous operation

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ABSTRACT
The results of more than seven years (October 2010-December 2017) of continuous monitoring are presented in this paper. Eight outdoor photovoltaic (PV) plants were monitored. The monitored plants use different technologies: mono-crystalline silicon (m-Si), poli-crystalline silicon (p-Si), string ribbon silicon, copper indium gallium selenide (CIGS), thin film, and cadmium telluride (CdTe) thin film. The thin-film and m-Si modules are used both in fixed installations and on x-y tracking systems. The results are expressed in terms of the degradation rate of the efficiency of each PV plant, which is estimated using the measurements provided by a multi-channel data acquisition system that senses both electrical and environmental quantities. A comparison with the electrical characterization of each plant obtained by means of the transient charge of a capacitive load is also made. In addition, three of the monitored plants are characterized at module level, and the estimated degradation rates are compared to the values obtained with the monitoring system. The main outcome of this work can be summarized as the higher degradation rate of thin-film based PV modules with respect to silicon-based PV modules.

Section: RESEARCH PAPER

Keywords: Photovoltaic power systems; degradation; electric variables measurement; data acquisition; uncertainty

Citation: Alessio Carullo, Antonella Castellana, Alberto Vallan, Alessandro Ciocia, Filippo Spertino, In-field monitoring of eight photovoltaic plants: degradation rate over seven years of continuous operation, Acta IMEKO, vol. 7, no. 4, article 13, December 2018, identifier: IMEKO-ACTA-07 (2018)-04-13

Editor: Alexandru Salceanu, "Gheorghe Asachi" Technical University of Iasi, Romania

Received April 24, 2018; **In final form** September 21, 2018; **Published** December 2018

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1. INTRODUCTION

The continuous worldwide increase in installations of photovoltaic (PV) plants [1] demands a reliable estimation of their long-term performance. The main parameters of interest are the payback time (PBT) and the energy payback Time (EPBT) [2-6]. Such parameters are largely affected by the actual degradation to which the PV modules are subject, which reduces efficiency during their lifetime. As an example, for a small-size 3 kW plant whose expected energy production is 4500 kWh/year, in the conditions defined in the web tool [7], a payback time of nine years and eight months is estimated using a PV module decay of 0.70 %/year, as suggested in the IEA document [8] for mature module technologies. However, if the PV modules used exhibit a degradation rate of 2.40 % per year, the estimated payback time becomes 10 years and 4 months.

With the aim of estimating the degradation rate of the commercially available PV technologies, the authors monitored eight different outdoor PV plants between 2010 and 2017. Electrical and environmental quantities were continuously monitored by means of a specifically conceived data acquisition system, which is subject to a metrological confirmation program [9]. This allows for measurement traceability to be ensured and uncertainty to be stated for each of the measured parameters. Preliminary results are reported in [10-12]. The results reported here refer specifically to the degradation rate of the monitored PV plants, estimated from October 2010 to December 2017.

Furthermore, three of the plants based on thin-film technologies, which exhibited the worst degradation rate, have been characterized at module level in order to verify the average degradation of all the involved PV modules and to highlight the presence of possible "outliers." This characterization was undertaken in March 2018.

In Section 2, the test facility is described, providing information about the monitored PV plants, the experimental setup, and the estimated parameters. In Section 3, the results obtained in terms of the degradation rate at plant level are provided for each of the monitored PV plants, while Section 4 reports the results in terms of the degradation rate at module

Table 1. Main characteristics of the monitored PV plants.

Plant	PV technology	A_{PV} (m²)	P_{nom} (kW)	P_{act} (kW)	η_{nom} (%)	η_{act} (%)
A	m-Si	11.2	2.03	1.93	18.1	17.2
B	p-Si	13.8	1.85	1.80	13.4	13.1
C	String ribbon Si	17.9	2.28	2.16	12.7	12.1
D	CIGS	17.5	1.70	1.68	10.3	9.6
E	CdTe	17.3	1.74	1.61	10.1	9.3
A_{ts}	m-Si	11.2	2.03	1.93	18.1	17.2
D_{ts}	CIGS	17.5	1.70	1.68	10.3	9.6
E_{ts}	CdTe	17.3	1.74	1.61	10.1	9.3

level for three of the monitored plants. Finally, in Section 5, the main outcomes related to the obtained results are summarized.

2. TEST FACILITY

2.1. Monitored PV plants

The eight PV plants that were monitored are located in Piemonte (Italy) at a latitude of about 45 °N, in the Cwc Köppen-Geiger climate zone [13]. Table 1 summarizes the main characteristics of the monitored PV plants, which include silicon-based modules (plants A, B, C, and A_{ts}) and thin-film based modules (D, E, D_{ts}, and E_{ts}). The subscript "ts" denotes the plants whose modules are installed on a x-y tracking system, while the others are oriented towards South (azimuth angle of about 0°) and mounted in a fixed position with a tilt angle of 35°.

In Table 1, A_{PV}, P_{nom}, and η_{nom} refer to the nameplate area (m²), power (kW), and efficiency (%), respectively. Immediately after the installation of the PV plants, their *I-V* electrical characteristics were measured in natural sunlight by means of the acquisition of the transient charge of a capacitive load [14], and the actual power P_{act} and efficiency η_{act} in the standard test conditions (STCs) were then estimated and are also reported in Table 1. The relative expanded uncertainty (coverage factor k = 2) for both parameters is about 3.5 %.

2.2. Monitoring system

The monitoring system is able to measure direct voltage V_{dc} and direct current I_{dc} (to upstream the inverter) and temperature t_m of a PV module for each of the eight PV plants. Solar irradiance G_m was also measured on the plane of the PV modules by means of two secondary-standard pyranometers: The first one was mounted with the same orientation as the fixed plants, while the second one was mounted on the x-y tracking system of the plant A_{ts}. A measurement of each quantity was carried out every 10 s and stored in a daily file. The architecture of the monitoring system is described in [10], and its metrological confirmation process is described in [9]. The calibration is performed with a periodicity of one year and includes the initial verification of each measuring chain, the adjustment that allows offset and gain drifts to be compensated, and the final verification. The maximum admitted errors used during the verifications are:

- (0.5 % *reading* + 0.2 V) for voltage V_{dc} in the range of 100 V to 450 V;
- (0.4 % *reading* + 5 mA) for current I_{dc} in the range of 0.5 A to 7 A;
- (2.0 % *reading* + 5 W/m²) for irradiance G_m in the range of 500 W/m² to 1200 W/m²; and
- (0.6 % *reading* + 0.55 °C) for temperature t_m in the range of 10 °C to 80 °C.

2.3. Data processing

The efficiency η of each plant at STC is obtained by:

$$\eta = \frac{P_{\max,\mathrm{STC}}}{A_{\mathrm{PV}} \cdot G_{\mathrm{STC}}} \tag{1}$$

where G_{STC} = 1000 W/m² is the reference irradiance value, A_{PV} is the area of the PV modules as reported in Table 1, and $P_{max,STC}$ is the maximum measured power reported at STC through the simplified model:

$$\begin{aligned} P_{\max,\mathrm{STC}} &= \left(I_{\mathrm{dc}} + I_{\mathrm{SC,act}} \cdot C_{\mathrm{G}} + \alpha \cdot C_{\mathrm{t}}\right) \cdot \\ &\cdot \left[V_{\mathrm{dc}} + \beta \cdot C_{\mathrm{t}} - R_{\mathrm{S,act}} \cdot \left(I_{\mathrm{SC,act}} \cdot C_{\mathrm{G}} + \alpha \cdot C_{\mathrm{t}}\right)\right] \end{aligned} \tag{2}$$

where $I_{SC,act}$ and $R_{S,act}$ are the short-circuit current and the series resistance of each plant obtained during the preliminary *I-V* characterization; α (A/°C) and β (V/°C) are the absolute current and voltage temperature coefficients, respectively; and the correction coefficients C_G and C_t are obtained by:

$$C_{\mathrm{G}} = 1 - \frac{G_{\mathrm{m}}}{G_{\mathrm{STC}}}; \quad C_{\mathrm{t}} = t_{\mathrm{STC}} - t_{\mathrm{m}} \tag{3}$$

Starting from the available data, a clear day was selected in each month in the period from January 2014 to December 2017, and Equations (1)-(3) were calculated for each plant using the measured parameters that correspond to the values of irradiance G_m that are greater than 800 W/m². During the initial monitoring period (from September 2010 to December 2013), the same procedure was implemented, but with different sampling, since a clear day was selected for each couple of months.

The standard uncertainty $u(P_{max,STC})$ of each PV plant was estimated according to the procedure described in [11], which takes into account both the repeatability contributions and the uncertainty of each measuring chain. The last contribution corresponds to the maximum admitted errors that are periodically verified.

One should note that the uncertainty of the efficiency η obtained by means of Equation (1) mainly depends on the uncertainty of the parameter $P_{max,STC}$, since G_{STC} is a conventional reference value, while A_{PV} is known with a negligible uncertainty.

3. PLANT DEGRADATION RATE

An example of the obtained results that refer to the selected day, 17 January, 2016, is reported in Table 2, where $u_A(P)$ represents the standard deviation of the set of values $P_{max,STC,i}$, corresponding to the G_{mi} values that are greater than 800 W/m². Meanwhile, $u_{Bx}(P)$ is the uncertainty contribution related to the measured quantity x. Among the different contributions, the one that mainly accounts for the uncertainty of the parameter $P_{max,STC}$ and, in turn, of the estimated efficiency η is that related to the correction coefficient C_G, which depends on the measured quantity G_m. Since this quantity is sensed through a secondary standard pyranometer, this contribution cannot be significantly reduced for monitored outdoor PV plants. In the same table, the estimated efficiency η at STC is reported for each plant with the corresponding standard uncertainty $u(\eta)$. Similar uncertainty values for the parameters $P_{max,STC}$ and η were obtained during the whole monitored period.

3.1. m-Si based plants

The estimated efficiency η of plant A (fixed installation) based on m-Si PV modules during the monitored period is reported in Figure 1, while Figure 2 refers to the plant A_{ts} (x-y tracking system). The red circles represent the estimated η values, the black squares are the values obtained after the adjustment of the

Table 2. An example of the uncertainty budget, selected day: January 17, 2016.

Plant	$u_A(P)$ (W)	$u_B^{Idc}(P)$ (W)	$u_B^{Vdc}(P)$ (W)	$u_B^{CG}(P)$ (W)	$u_B^{tm}(P)$ (W)	$u(P_{max,STC})$ (W)	$P_{max,STC}$ (W)	η (%)	$u(\eta)$ (%)
A	8.2	5.0	5.7	26	3.2	28	1940	17.33	0.25
B	8.4	4.4	5.0	40	4.1	42	1725	12.50	0.21
C	11.7	5.4	6.2	27	4.9	31	2110	11.77	0.16
D	10.9	3.4	4.1	14	3.2	19	1375	7.95	0.16
E	4.9	3.0	4.3	8.5	3.1	12	1415	8.07	0.16
A_{ts}	8.0	5.9	5.7	24	3.2	26	1990	17.78	0.25
D_{ts}	3.7	4.0	3.8	10.8	3.5	13	1350	7.70	0.16
E_{ts}	3.9	3.9	3.9	11.0	2.6	13	1360	7.84	0.16

monitoring system, and the black stars represent the value obtained after the PV modules were washed. The former intervention does not show significant effects on the estimated efficiency, thus highlighting that the drift of the measuring chain characteristics during the calibration period is acceptable. In Figure 1 and Figure 2, the efficiency values obtained with the capacitive load technique in months 1 and 78 are also reported (black diamonds), and they demonstrate behavior that is in agreement with the observed season variability. The black triangles identify invalid results, due to a fault in the monitoring system in the month-interval (80-85) and a fault in the plant A_{ts} during months 46, 47, and 48. The continuous straight line is obtained by fitting only the valid η values through a least square algorithm. One should note that for plant A_{ts}, the straight line was fitted from month 40, since previous efficiency estimations were affected by a fault in the board that connects the positive pole of the PV modules to ground. Due to this improper grounding of the PV modules, the two poles of the plant were floating, thus exposing the modules to potential induced degradation (PID) [15], one of the causes of efficiency loss. After the grounding board was replaced (month 40), plant A_{ts} exhibited efficiency values very similar to plant A.

The fitted straight line can be represented as:

$$\eta(t) = \eta(t_0) + S_\eta \cdot t \tag{4}$$

where t is the time (months), while S_η is the slope of the fitted line (%/months).

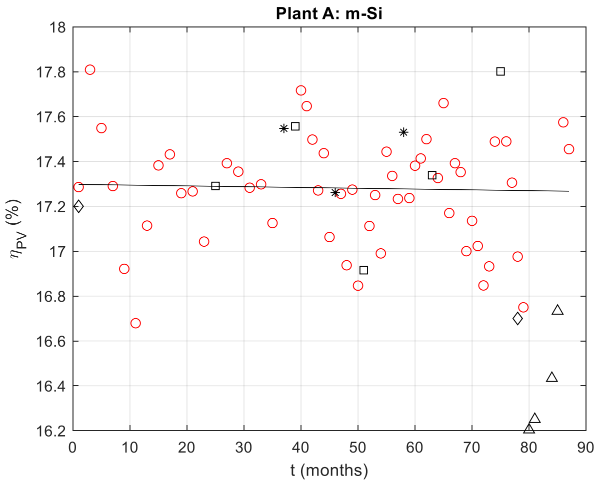

Figure 1. Estimated efficiency of plant A based on m-Si PV modules in a fixed installation (red circles); black squares: values after adjustment of the monitoring system; black stars: values after module washing; black diamonds: values obtained by means of the capacitive load technique; black triangles: invalid data.

The parameter S_η and its standard uncertainty $u(S_\eta)$ were obtained according to the procedure described in [11], taking into account the standard uncertainty $u(\eta_i)$ corresponding to each monthly estimation. Starting from the obtained values, the yearly percentage degradation rate DR (%/year) was estimated following:

$$DR = 100 \cdot \frac{12 \cdot S_\eta}{\bar{\eta}} \tag{5}$$

For the m-Si based plant A, a degradation rate DR_A equal to -0.03 %/year, expanded uncertainty (95 % confidence level) $U(DR_A)$ = 0.35 %/year, was obtained. These values are summarized in Table 3, where the degradation rates and the corresponding uncertainties of the PV plants under investigation are reported for different monitoring periods [11-12]. Taking the uncertainty into account, the estimated degradation rates of plant A are compatible during the different monitored periods, thus showing excellent behavior of the plant based on m-Si PV modules in fixed installations. For plant A_{ts}, the obtained value is DR_{Ats} = -0.78 %/year, and the expanded uncertainty is $U(DR_{Ats})$ = 0.40 %/year. This updated value is significantly different from the previous one (+0.20 %/year at the month 72, as indicated in Table 3), thus highlighting an important degradation of the m-Si modules installed on the x-y tracking system.

The obtained results are in good agreement with the efficiency values estimated for month 78 with an independent measuring system (black diamonds in Figure 1 and Figure 2).

3.2. CIGS-based plants

Table 3. Summary of the degradation rates of the plants under investigation estimated during different monitored periods

Plant	34 months [11]		72 months [12]		87 months	
	DR (%/year)	*U* (*DR*) (%/year)	*DR* (%/year)	*U* (*DR*) (%/year)	*DR* (%/year)	*U* (*DR*) (%/year)
A	-0.20	0.80	-0.03	0.30	-0.03	0.35
B	-0.08	0.80	-0.52	0.46	-0.87	0.35
C	-0.50	0.80	-0.64	0.28	-0.68	0.25
D	-1.20	0.80	-2.08	0.16	-1.83	0.20
E	-3.10	0.80	-2.06	0.26	-2.36	0.30
Ats	n.a.	n.a.	0.20	0.80	-0.78	0.40
Dts	-1.80	1.0	-3.34	0.26	n.a.	n.a.
Ets	-3.50	1.0	-2.56	0.14	-2.41	0.20

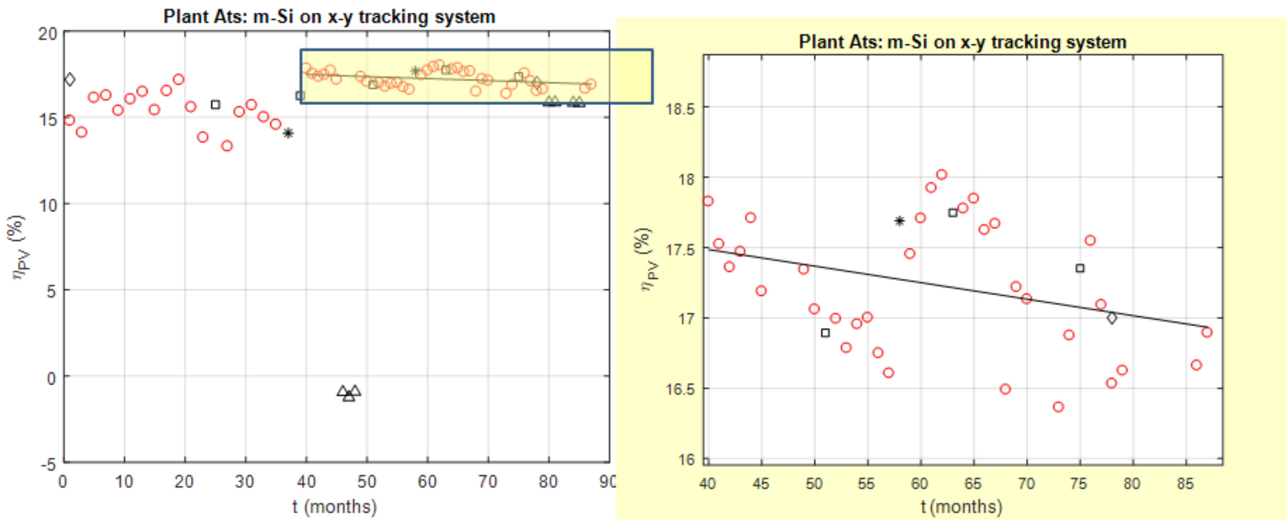

Figure 2. Estimated efficiency of plant A_{ts} based on m-Si PV modules on an x-y tracking system (red circles); black squares: values after adjustment of the monitoring system; black stars: values after module washing; black diamonds: values obtained by means of the capacitive load technique; black triangles: invalid data.

The results in terms of efficiency η of plant D (fixed installation) based on CIGS thin-film PV modules are reported in Figure 3. The meaning of the symbols is the same as in Figure 1, and the invalid results are the same as those of plant A. Furthermore, there is good agreement with respect to the values obtained using the capacitive load technique (black diamonds for months 1 and 78), and the results obtained after the adjustment of the monitoring system (black squares) do not significantly differ from the others. The estimated degradation rate DR_D is equal to -1.83 %/year (expanded uncertainty $U(DR_D)$ = 0.20 %/year), which is compatible with the values obtained in the previous monitored interval (see Table 3).

Unfortunately, the results obtained after month 65 for plant D_{ts} that was installed on a x-y tracking system are unreliable. This is due to a misalignment between the tracking systems of plants A_{ts} and D_{ts} in the month-interval (65-72) [12] and to a fault in the electrical measuring chain of this plant in the month-interval (73 - 87) that the plant owner has not fixed. For this reason, the estimated degradation rate for plant D_{ts} is the same as the value stated in [12], i.e., DR_{Dts} = -3.34 %/year, $U(DR_{Dts})$ = 0.26 %/year.

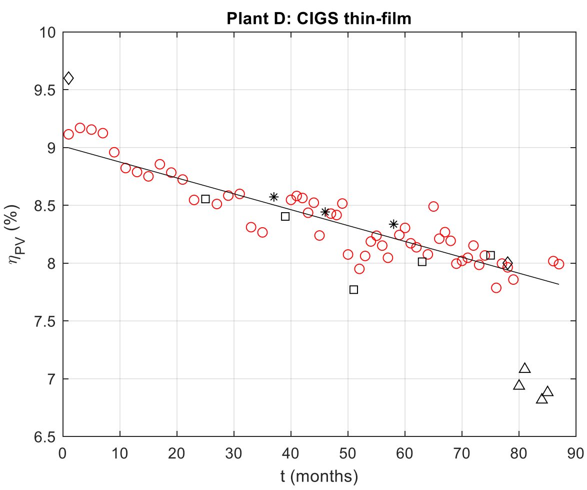

Figure 3. Estimated efficiency of plant D based on CIGS thin-film PV modules in a fixed installation (red circles); black squares: values after adjustment of the monitoring system; black stars: values after module washing; black diamonds: values obtained by means of the capacitive load technique; black triangles: invalid data.

The obtained uncertainty is low enough for us to confidently state that CIGS modules are subject to an important degradation and that the modules installed on the x-y tracking system exhibit a larger degradation than the same modules in a fixed position.

3.3. CdTe-based plants

Figure 4 shows the efficiency η of the plants based on CdTe thin-film PV modules. The left chart refers to plant E (fixed position) and the right chart to plant E_{ts} (x-y tracking system). The same symbols used in the previous figures are used here, and the reasons for the invalid results (black triangles) are the same as for the other plants. The efficiency values obtained by means of the capacitive load technique for months 1 and 78 (black diamonds) are in good agreement with the observed season variability.

The estimated degradation rates are DR_E = -2.36 %/year, $U(DR_E)$ = 0.30 %/year, and DR_{Ets} = -2.41 %/year, $U(DR_{Ets})$ = 0.20 %/year. As summarized in Table 3, these values are in agreement with the degradation rates estimated during the first 72 months of operation, while they seem better than the values estimated after 34 months of operation. However, the large uncertainty of the first estimated values does not allow us to distinguish the degradation rates estimated during the different monitored periods, since they are compatible.

Furthermore, in this case, we can conclude that the degradation of the CdTe thin-film modules is higher than the degradation exhibited by the m-Si modules. However, due to the uncertainty, it is not possible to clearly distinguish between the behavior of the modules in a fixed position with respect to the modules installed on the x-y tracking system.

3.4. p-Si and string ribbon Si based plants

The results of the last two monitored plants are shown in Figure 5: the left chart refers to the plant based on p-Si PV modules, while the right chart refers to the plant that uses string-ribbon Si modules. The same symbols used in the previous

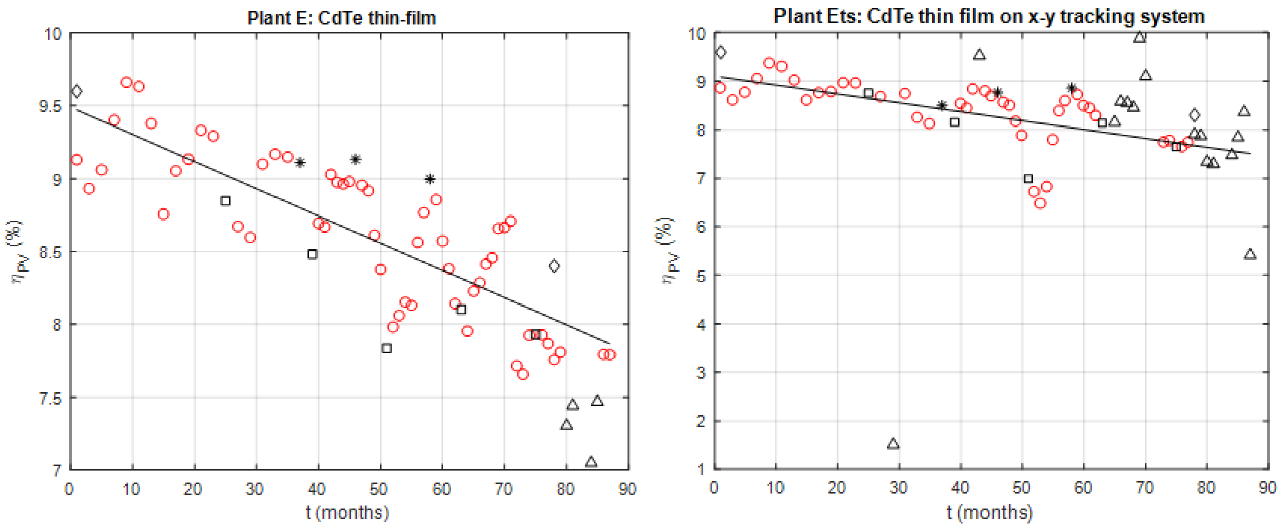

Figure 4. Estimated efficiency of the plants based on CdTe PV modules: E in fixed installation, E_{ts} on an x-y tracking system (red circles); black squares: values after the adjustment of the monitoring system; black stars: values after module washing; black diamonds: values obtained by means of the capacitive load technique; black triangles: invalid data.

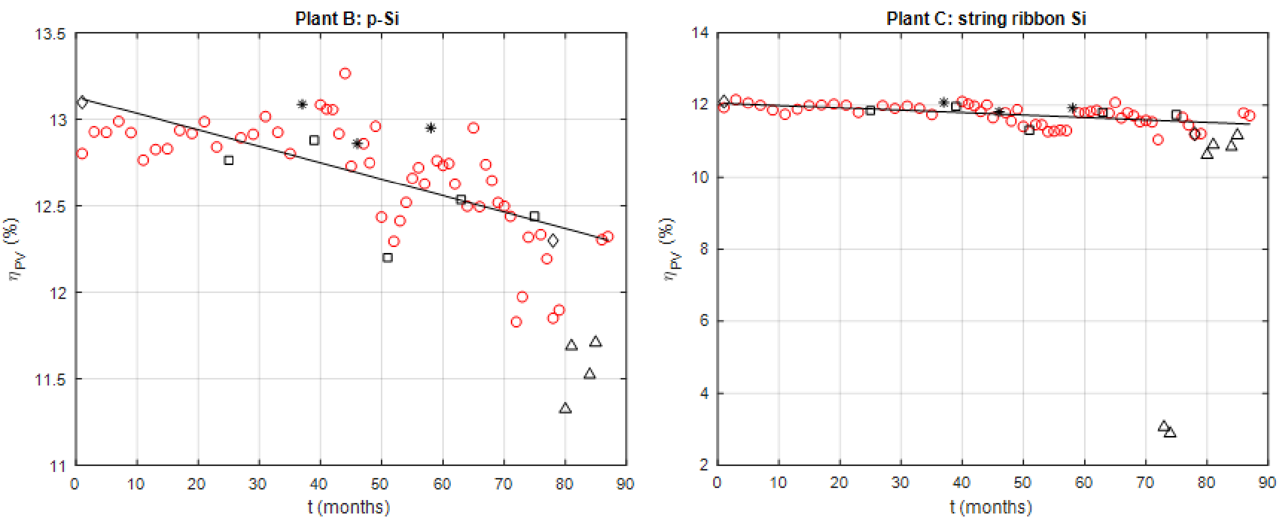

Figure 5. Estimated efficiency of the plants based on p-Si modules (left chart) and string ribbon Si modules (right chart) (red circles); black squares: values after adjustment of the monitoring system; black stars: values after module washing; black diamonds: values obtained by means of the capacitive load technique; black triangles: not valid data.

figures are used here, and the reasons for the invalid results (black triangles) are the same as for the other plants in fixed positions. One should note that the adjustment of the monitoring system does not significantly change the efficiency estimations. The fitted straight lines of the two plants are very similar, which is confirmed by the numerical results: for the p-Si based plant, the estimated degradation rate DR_B is -0.87 %/year, $U(DR_B)$ = 0.35 %/year, while for the string-ribbon Si-based plant, the obtained value is DR_C = -0.68 %/year, $U(DR_C)$ = 0.25 %/year. Both degradation rates are very similar to the values previously estimated (see Table 3), thus confirming a medium degradation for these plants.

4. MODULE DEGRADATION RATE

With the aim of confirming the estimated degradation rates for the plants that exhibited the worst behavior, an electrical characterization at module level was performed for plants D and D_{ts}, which are based on CIGS thin-film modules, and for plant E_{ts}, which is based on CdTe thin-film modules.

The *I-V* characteristic of each of the 24 modules that made up each plant was obtained by means of an experimental setup that is based on a programmable electronic load connected to the PV modules under test. Each *I-V* characteristic is obtained at the measurement conditions (air temperature in the range of 15.3 °C to 18.0 °C and irradiance in the range of 800 W/m² to 1030 W/m²) and then reported to STC in order to obtain the parameter $P_{max,STC,i}$ of each PV module. The experimental setup and the correction algorithm are the same as those described in [16].

This operation was performed on March 23, 2018, approximatively 90 months after the installation of the PV modules. Once the parameter $P_{max,STC,i}$ was obtained, the actual degradation rate of each PV module was obtained as:

$$DR_i = 100 \cdot \frac{P_{max,STC,i} - P_{nom,i}}{P_{nom,i}} \cdot \frac{12}{90} \quad (\%/\text{year}), \tag{6}$$

where $P_{nom,i}$ is the nameplate power of the investigated PV modules, which is 70 W for CIGS thin-film modules and 72.5 W for CdTe thin-film modules.

The obtained results are summarized in Figure 6 in the form of a histogram of occurrences of the parameters DR_i, which were obtained according to (6).

The top histogram, which refers to the PV modules of the plant D (CIGS thin-film in fixed position), shows the lowest standard deviation (about 0.7 %/year) and an average value of -2.43 %/year. This value is very similar to the degradation rate estimated at plant level, which is -2.35 %/year, thus confirming the obtained outcomes.

The middle histogram refers to the PV modules of the plant D_{ts} (CIGS thin-film on x-y tracking system) and exhibits a standard deviation of about 0.8 %/year and an average value of -2.90 %/year. In this case, the average value is lower than the degradation rate estimated at plant level (- 3.34 %/year), but the two values are not comparable, since the monitoring of the plant D_{ts} only refers to the first 65 months of operation, for the reasons described in subsection 3.2.

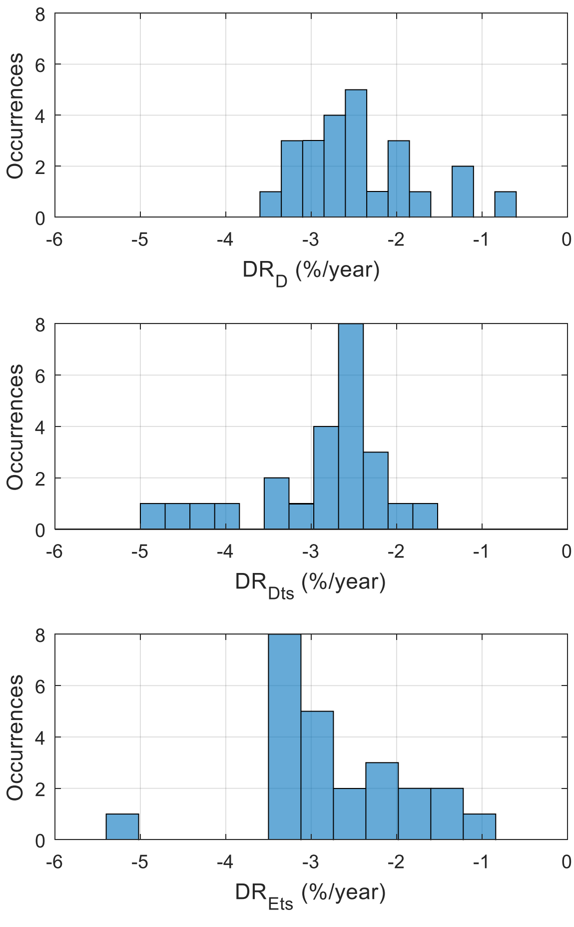

Figure 6. Degradation rate (%/year) of the 24 PV modules of plants D, D_{ts}, and E_{ts} expressed in the form of a histogram of occurrences.

Figure 7. Detail of the broken module in plant E_{ts} (CdTe thin-film on an x-y tracking system).

The bottom histogram, which refers to the PV modules of the plant E_{ts} (CdTe thin-film on x-y tracking system), shows the highest standard deviation (about 0.9 %/year) and an average value of -2.72 %/year, which is comparable with the degradation rate at plant level (-2.41 %/year). The high standard deviation is mainly due to a PV module that shows a degradation rate of about -5.0 %/year. However, this is a biased value, since this PV module, which is positioned at the lower-left corner of the plant, presents a visible break, as shown in Figure 7. The average value of the degradation rate recalculated after the broken module has been excluded does not change significantly.

5. CONCLUSION

The results of the monitoring of eight outdoor PV plants based on different technologies along a period longer than seven years have been presented in this paper. The parameters that have been taken into account in order to assess the performance of the PV plants under investigation are the maximum power and the PV efficiency at STC. The latter parameter allowed the degradation rate of each plant to be obtained, which provided interesting information related to the behavior of the different types of plants.

The plants that use silicon-based PV modules are subject to a degradation rate that is significantly lower than the plants based on thin-film PV modules. Taking the estimated uncertainty into account, the PV plants that use m-Si, p-Si and string-ribbon Si PV modules exhibited a degradation rate that is in agreement with the indication given in [8] for mature module technologies. On the contrary, the plants based on thin-film PV modules exhibited degradation rates that exceed the typical value for mature technologies. The estimated uncertainty does not allow significant conclusions to be made about the different behavior of the same PV modules installed in fixed positions and on tracking systems.

An estimation of the degradation rate at module level was also performed for three of the eight monitored plants, obtaining results that are in good agreement with the degradation rate at plant level.

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