DEGRADATION OF CRYSTALLINE SILICON MODULES: A CASE STUDY ON 785 SAMPLES AFTER TWO YEARS UNDER OPERATION

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ABSTRACT: : This article reports on the results obtained regarding the quality control performed in our IEC 17025 accredited laboratory on 785 crystalline silicon modules after two years under operation. The measurements were carried in 2008 on the modules before installation, and on 2009 and 2010 to verify the performances after one and two year under real operation, respectively. Photovoltaic modules belong to six different manufacturers from two large PV plants. The overall results show that the peak power decreases between 1.0% and 3.5%within the first year and between 0.4% and 1.3% in the following year. The same trend is followed by the Isc and Voc values; on the contrary, the most noticeable change appears in the Vmpp value, which keeps almost constant within the first year, but dramatically drops at the end of the second year, indicating an increase in the modules' series resistance.

Keywords: PV Modules, Quality Control, Testing and Characterization

1 INTRODUCTION

The main purpose of all photovoltaic installation is obtaining the highest energy production according to the received irradiation, and consequently, the highest economic profit for the owner. In all economic models, in Feed-in Tariff (FIT) or Purchase Power Agreements (PPA) schemes, the annual energy production is calculated considering a certain annual degradation of the output power of the PV modules. It is clear and important that a deeper knowledge of the annual degradation of PV modules results in more precise economic modelling. In many cases, the technical assessors assume, based on manufacturers´ warranties (typically 90% performance during first 10 years and then 80% performance until 25 years), an initial degradation of 1% and annual degradation of 0.5%. The most accurate assessments have into account previous results of degradation based on the experience. Due to importance in the knowledge of the annual degradation of PV modules, the well-operated PV plants have, assigned in their maintenance services, a certain number of modules which are tested every year to monitor the annual degradation. This is a fundamental approach used to estimate the energy production of the PV plants.

Exhaustive studies of PV modules degradation have been reported in the past. For example, studies carried out by the NREL show module performance losses of 1-2% per year in systems tested over ten-year period [1] and the LEEE-TISO has measured losses ranging from -0.7 and -8.2% respect nominal power after first 15 month of exposure [2].

In general, these of investigations have been carried out with short amount of samples. LEEE-TISO, for instance, have measured power degradation on 98 c-Si modules between -0% and -5% after first exposure (initial degradation) with respect to the initial power and -1.2% during the first year [3].

To the best of the authors' knowledge, this paper reports on the largest set samples available in the literature: there exist other articles on the same subject, as mentioned above, but always based on a limited quantity of modules. In this work we will present an analytical and statistical study on the measurements performed on 785 modules from 6 different manufacturers.

Due to the large dataset available in our laboratory, this analysis provides a practical tool for both the scientific and business members of the PV community as our study can be considered as brand-independent. It is important to specify that the purpose of our study is to objectively analyze the reliability of crystalline silicon modules through their complete operative life. In any case the intent is not to find out the best manufacturer, but to evaluate the performances of crystalline silicon modules after the first operation year (when it is supposed to reach their initial performance expectations) and then every year after, to ascertain their power degradation, and, whether is possible to find out the mechanisms responsible for.

Furthermore, as we do not exclusively focus on maximum peak power (that is a fundamental key to evaluate the productivity of PV plants), but also report on several other module parameters (Voc, Isc, Vmpp), this paper can be useful for the engineering sector, allowing substantial cost reduction in the design phase.

This study has been elaborated with the results obtained in the periodic quality control of PV modules from two large PV plants in the southern Spain, carried out in the IEC 17025 accredited laboratory of ENERTIS SOLAR. This laboratory, pioneer in the implementation of PV modules quality control on large scale, has carried out the quality control of PV modules of more than 90 PV projects with overall power capacity above 700 MW from 2007 until 2011.

The degradation after first operation year in a portion of these modules were analyzed and published in previous works [4, 5]. The present article extends the study to the second operation year.

The tests used for the analysis are included in the quality control of PV modules which was exposed in a previous publication [6]. Tests are: peak power measurement and infrared thermographic inspection (see Figure 1). Peak power measurement gives information regarding electrical performance of the modules and thermographic inspection regarding concerning hot-spots, broken cells and non active areas in cells.

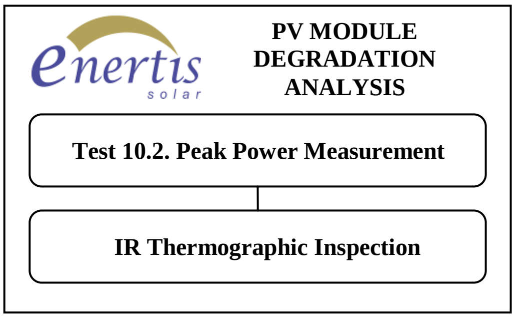

Figure 1: Tests included in the degradation analysis

2 SAMPLING PROCEDURES

According to the annual modules´ quality control of PV plants, 785 modules were extracted from two large PV facilities located in the South of Spain, one of 19 MWp and the other of 13 MWp. A total of six manufacturers have been analyzed. The name of the manufacturers is concealed in this work for two reasons: one the one hand, we cannot break the confidential agreements with our clients, and on the other hand, the purpose of this work is not to evaluate manufacturers and find the best one.

Table I shows details of selected modules and sampling percentage respect of total modules per manufacturer. The sampling procedure has been carried out following ISO 2859-1 standard.

Table I: Sampling details

Manufacturer	Total modules	Selected modules	Percentage (%)
A	14133	100	0.70
B	48634	257	0.53
C	19350	82	0.42
D	7611	32	0.42
E	37943	200	0.53
F	33025	114	0.35
TOTAL	160696	785	0.49

In table we can see that the samples of manufacturer A have been increased in 50 modules respect of the previous works.

3 RESULTS

3.1 Peak power

The I-V curves of the modules have been obtained by means of a Class AAA solar simulator according to IEC 60904-9 manufactured by OPTOSOLAR. Temperature and irradiance corrections have been performed according to IEC 60891. Test area of the simulator is 2×2 m^2 and it is situated in a black tunnel with a distance between xenon flash lamp and test plane of 6 meters. This equipment has a flash plateau of 10 milliseconds. Ambient temperature in the black tunnel is always kept to a value of 25±2 ºC in order to minimize errors that can be introduced by extrapolations. The expanded uncertainties, for a confidence level of 95% (k=2), are: peak power measurement ±2.6%, open circuit voltage ±1.0% and short circuit current ±2.0%.

Tables II, III and IV show the annual electrical parameters losses, expressed as absolute percentages. These losses correspond to difference between values in the initial test and test performed after one and two years under operation. Reported values have been obtained averaging the results of each batch of modules of table I.

Table II: Difference of electrical parameters in the first year (2008-2009)

Manufacturer	ΔI_{SC} (%)	ΔV_{OC} (%)	ΔP_m (%)
A	-1.0	-1.4	-1.7
B	-1.3	-1.4	-1.0
C	-2.7	-2.0	-2.6
D	-	-	-
E	-3.0	-0.7	-3.5
F	-1.9	-1.0	-1.5

Table III: Difference of electrical parameters in the second year (2009-2010)

Manufacturer	ΔI_{SC} (%)	ΔV_{OC} (%)	ΔP_m (%)
A	-0.8	-0.9	-0.4
B	-0.8	-0.4	-0.7
C	0.0	-1.0	-1.3
D	-	-	-
E	0.3	-0.4	-0.5
F	1.1	-0.5	0.3

Table IV: Difference of electrical parameters in the whole period (2008-2010)

Manufacturer	ΔI_{SC} (%)	ΔV_{OC} (%)	ΔP_m (%)
A	-0.2	-2.3	-2.1
B	0.1	-1.6	-1.0
C	-2.5	-3.0	-4.0
D	1.2	-1.8	-1.0
E	-2.7	-1.1	-3.8
F	-0.8	-1.6	-1.3

Tables show that the performance loss in the first two years is not exclusively due to Isc degradation. Results show significant Voc after two first operation years.

Note that values of table II are higher than table III because, obviously, the first year contains the initial degradation (produced during the first weeks) and the annual degradation. The values of table III are related corresponds with the annual degradation during second year. With these results, we can consider for simulation of PV plants that the maximum power of modules during first year could decrease between 1.0% and 3.5% (initial degradation included), and between 0.4% and 1.3% during the second year.

Figures 2 and 3 show the annual degradation trend of Isc and Voc as a function of power in samples of Manufacturer E for the second operation year, while

Figures 4 and 5 show degradation considering the whole operation period (2008-2010). We can see in figure 2 high dispersion in ΔIsc, even with positive values. This tendency is not usual and a possible explanation is that in 2009 different connectors where used in the solar simulator which increased the series resistance. In 2008 and 2010 measurements, the same connector type was used.

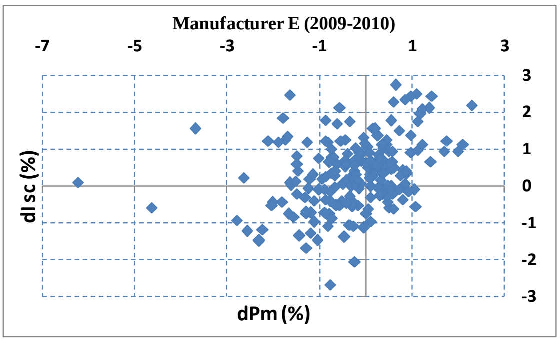

Figure 2: Degradation of Isc vs. degradation of Pm during second operation year in samples of Manufacturer E.

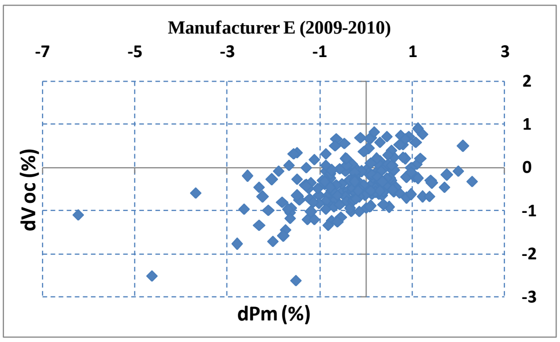

Figure 3: Degradation of Voc vs. degradation of Pm during second operation year in samples of Manufacturer E.

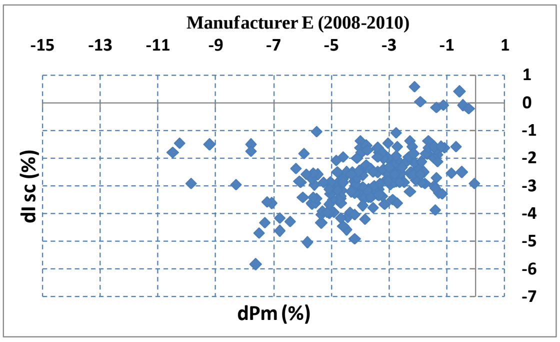

Figure 4: Degradation of Isc vs. degradation of Pm after first two operation year in samples of Manufacturer E.

Figure 4 shows that the performance loss in the first two years is mainly due to Isc with decreases up to 6.0%. Moreover, Figure 5 shows the Isc degradation is not the only cause of the performance losses. Voc decreases mainly between 0.0% and 2.0%, however degradation values over 3% have been reported after two first operation years.

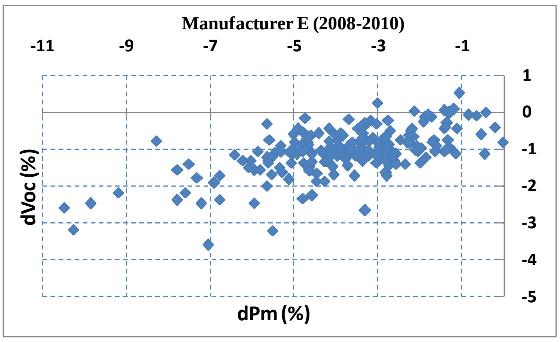

Figure 4: Degradation of Voc vs. degradation of Pm after first two operation year in samples of Manufacturer E.

The most noticeable change appears in the Vmpp value, which keeps almost constant within the first year, but dramatically drops at the end of the second year, indicating an increase in the modules' series resistance. This circumstance can be observed in Table V.

Table V: Percentage difference of Vmpp during first 2 operation years

	ΔV_{MPP} (%)		
Manufacturer	**1st year**	**2nd year**	**2 years**
A	-0.8	-1.3	-2.1
B	+ 0.1	- 1.7	- 1.6
C	- 0.6	- 1.7	- 2.4
D	- 0.3	- 2.0	- 2.3
E	+ 0.1	- 1.2	- 1.1
F	+ 0.4	- 1.1	- 0.7

3.2 IR Thermographic Inspection

The purpose of this study is to analyze the possible correlation between power degradation and internal defects detected by thermographic inspection. The infrared thermographic inspection permits to detect defects which are not visible with a naked eye: cracked or broken cells, hot-spot in cells or their connections and soldering, non active cells or region which do not contribute to photogeneration. The test was performed in a black room with the modules forward-biased.

No new thermographic defects have been detected after two operation year. Table VI shows percentage of defects per manufacturer after test. Note that percentage for manufacturer A has changed in comparison with previous publications because its number of samples has been increased.

The analysis has been carried out with the modules from manufacturer E and F. Table VII summarizes the results: in this table we calculate the increase in the losses of the electrical parameters of defective modules respect to the rest of the modules without defects. Exposed values correspond to absolute percentages.

Table VI: Percentage of thermographic defects per manufacturer

Manufacturer	Percentage of thermographic defects
A	8,9%
B	18,7%
C	9,8%
D	3,1%
E	34,5%
F	13,0%
AVERAGE	16,2%

Table VII: Increment of electrical losses in defective modules in comparison with non defective ones

ΔI_{SC} losses (%)		
Manufacturer	**1st year**	**2nd year**
E	+ 0.7	+ 0.2
F	+ 0.2	- 0.1
ΔV_{OC} losses (%)		
Manufacturer	**1st year**	**2nd year**
E	+ 0.2	+ 0.3
F	+ 0.1	- 0.1
ΔP_{M} losses (%)		
Manufacturer	**1st year**	**2nd year**
E	+ 1.0	+ 0.9
F	+ 0.6	+ 0.8

Results of Table VII show that, after second operation year, modules with internal defects detected by thermographic inspection suffer a higher degradation of the Isc, Voc and Pm. However, in spite of the higher degradation in the defective modules, the increase of power losses keeps constant respect of the first year.

Here, we keep in mind that the maximum power measurement is carried out during 10 ms and this time is not enough to observe anomalous behaviors caused by continuous sun exposition as, for instance, excessive warming of the defective cells. The substitution of the modules with thermal defects is highly recommendable to avoid energy losses in the PV plant during its operation.

4 CONCLUSIONS

This paper studies the degradation of the electrical parameter in a sample of 785 photovoltaic modules from two large PV plants after first two operation years. Moreover, the correlation between power degradation and internal defects detected by thermographic inspection is analyzed.

The overall results show that the peak power decreases between 1.0% and 3.5% within the first year (initial degradation included) and between 0.4% and 1.3% in the second year. The performance loss in the first two years is not exclusively due to Isc degradation. Results show significant Voc drop after two first operation years. The study has detected a change in the trend of Vmpp values, which which keeps almost constant within the first year, but dramatically drops at the end of the second year, indicating an increase in the modules' series resistance.

In the first and the second year, modules with internal defects detected by thermographic inspection suffer a higher degradation of the Isc, Voc and Pm in respect of the non defective modules. Results show that that increase of power losses in the second year keeps constant respect of the first year.

6 ACKNOWLEDGEMENTS

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