ANALYSIS OF WEATHERED c-Si PV MODULES

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ABSTRACT

The LEEE-TISO testing centre for PV components has, since 1991, carried out systematic tests, under real operating conditions, on the most important modules currently on the market. PV c-Si modules coming from production shows a typical degradation in performance when exposed to light of up to -5%. This initial degradation of c-Si modules takes place during the first hours of exposure. During the first year of operation some of the tested modules shows almost no further degradation and some a very small degradation. The long term degradation of c-Si modules has been extensively studied on one of the LEEE-TISO plants. In 21 years of service, the Arco Solar ASI 16-2300 modules of the 10 kW TISO plant showed several signs of physical degradation. Yellowing of PVB encapsulant and hot-spots affected the module efficiency. Nevertheless, the results of the indoor performance measurements of all plant modules indicate that the ASI 16-2300 modules are still working in a very satisfactory manner.

1 INTRODUCTION

At the LEEE-TISO Test Centre, the most commonly sold modules on the market undergo a series of tests in order to examine their quality and reliability in terms of energy production and power degradation over time [1,2]. The laboratory is also monitoring the oldest grid-connected PV power plant in Europe (TISO 10kWp sc-Si).

The two test installations allowed to observe degradation mechanisms that take part in c-Si modules in short- medium- and long-term.

1.1 The LEEE-TISO Test Stand

In the test stand (see Figure 1), the modules were selected from those most commonly found on the Swiss market or which had interesting innovations. In order to guarantee impartiality and neutrality regarding measurements, the modules were purchased anonymously. Two modules for each type were acquired.

The LEEE-TISO testing procedure includes regular indoor measurements at standard test condition (STC). The performance measurements of all modules are repeated every 3 months. Before 2001 the indoor measurements has been executed at the ESTI laboratory of the Joint Research Centre in Ispra. Since 2001 The LEEE-TISO laboratory has his own class A solar simulator, accredited ISO 17025, to execute indoor measurements at STC.

The modules of the test stand are measured indoor before installation (Pa), after a first outdoor exposure of 20kWh/m2 (P_0) and then every 3 months. A complete test cycle, executed under real environmental conditions and at maximum power point operation, has a duration of 15 months.

In this paper results about performance degradations of the test cycles 5, 6, 7, 8 and 9 will be presented. In the test period going from 1997 until 2003 98 modules of 48 different types has been tested for at least 1 year.

1.2 The 10kWp TISO plant

In May 1982, the first European grid-connected PV plant came into operation (see Figure 1). The first objective of this array was to provide a technologically advanced facility of medium size, giving practical information for the planning of future photovoltaic plants.

In April 2000, in proximity to the 20-year design life of the plant, a collaboration between the LEEE-TISO and the ESTI Laboratory (JRC Ispra) started to determine the Mean Time Before Failure (MTBF) of the system and to investigate the physical degradation mechanism in action.

Figure 1: Test stand of the LEEE-TISO testing centre (left) and the TISO 10kWp grid-connected PV power plant (right).

2 DEGRADATION AFTER FIRST EXPOSURE

Almost all standard c-Si PV modules tested in cycle 5 to 9 showed a degradation in performance when exposed for the first time to sun light. Such power degradation occurs during the first hours of exposure (H=2.5 kWh/m2)

In order to avoid first degradation effects influences the determination of module energy yield, the test procedure of the LEEE-TISO laboratory, has been modified in 2001 adding a period of light soaking of 20kWh/m^2 followed by 3 months of stabilisation [1]. In this first outdoor exposure period the mean degradation of the 98 c-Si modules tested at the LEEE-TISO is -3.0%. The degradation is between -0% and -5% with respect to the initial power P_a [1]. The performance loss is mainly due to degradation of the short circuit current Isc (see

Figure 2). Considering the measurement precision, for degradations up to -5% a linear relation between power and Isc degradation can be observed. Modules with a larger degradation (>5%) shows no direct correlation with Isc, they seems to be influenced by other factors as the open circuit voltage Voc a the fill factor FF (Figure 3 and 4). In the last two tests cycles (8 and 9 i.e. 2001-2003) the measured mean degradation was -1.9%, ranging from -5.2% to +0.1%.

Prior sunlight exposure and storage time and subsequent pre-degradation of the modules purchased is not known, so the initial power Pa measured at LEEE-TISO could correspond to the power of already degraded c-Si modules.

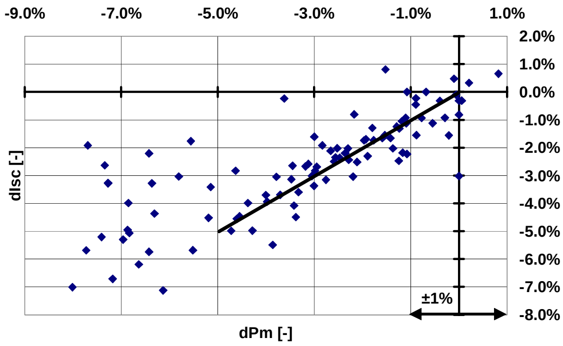

Figure 2: degradation of Isc vs. degradation of Pm after 3 months of exposure, for 98 c-Si modules (1997-2003).

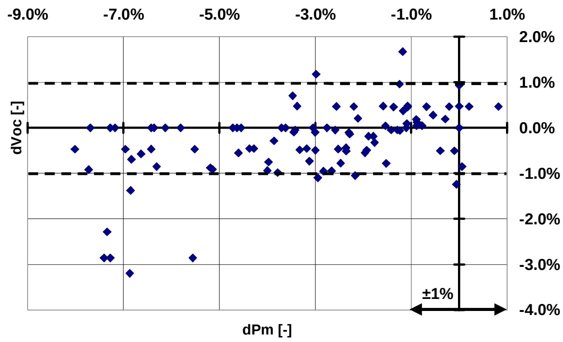

Figure 3: degradation of Voc vs. degradation of Pm after 3 months of exposure, for 98 c-Si modules (1997-2003).

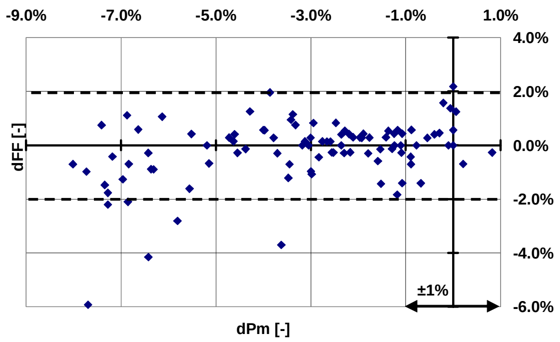

Figure 4: degradation of FF vs. degradation of Pm after 3 months of exposure, for 98 c-Si modules (1997-2003).

3 ONE YEAR DEGRADATION

During the first year of outdoor exposure under real climatic conditions and after the initial degradation, the weathered modules shows a further average degradation of -1.2%. The relative average degradation of the short circuit current was -0.6%, of the open circuit voltage -0.2% and of the fill factor -0.4%.

Even if the reproducibility limit of the measurements does not permit to see a real degradation in Isc, Voc or FF, the negative trend of Pmax is slightly larger than the measurement uncertainty (Figure 5, 6 and 7).

The average degradation between mc-Si e sc-Si modules shows no significant difference and does not permit a subdivision into two separate categories with characterized by different degradation behaviors.

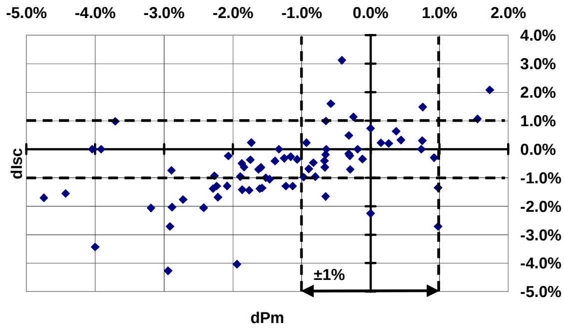

Figure 5: degradation of Isc vs. degradation of Pm after 1 year of exposure, for 76 c-Si modules (1997-2002).

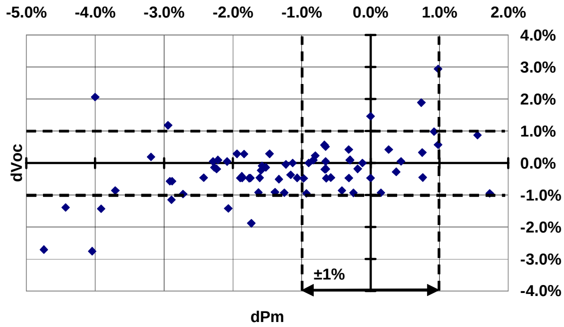

Figure 6: degradation of Voc vs. degradation of Pm after 1 year of exposure, for 76 c-Si modules (1997-2002).

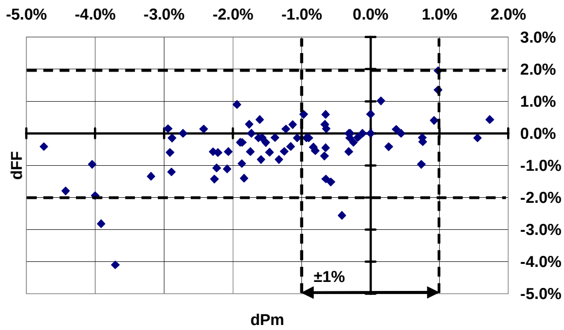

Figure 7: degradation of FF vs. degradation of Pm after 1 year of exposure, for 76 c-Si modules (1997-2002).

4 LONG-TERM DEGRADATION

The study of the 21-year old 10 kWp TISO plant, allows to determine the different degradation mechanisms influencing the module performance. Besides the initial degradation relating to the incapsulated cells, other defects have been found compromising the module efficiency: yellowing of the encapsulant, delamination and hot-spots.

4.1 Description of modules and array

The plant consists of 288 Arco Solar ASI 16-2300 modules distributed in 3 sub-arrays of 12 horizontal per 8 verticals panels each (see Figure 1). Since the plant realization in 1982, the system configuration has been changed three times because of inverters substitutions. At the beginning the plant was organised in 24 series of 12 modules each; at present there are 12 series of 21 modules. In the near future, the inverter unit will be substitute and the new plant configuration will consist of 12 series of 24 modules each.

The ASI 16-2300 are sc-Si modules with 35 round cells (∅ 102.5mm), using PVB (poly-vinyl-butyral) encapsulant and tedlar/aluminium/tedlar backsheet.

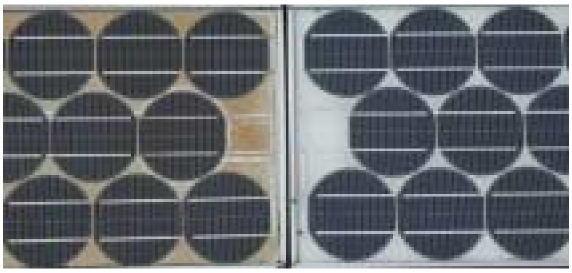

Figure 8: 21-year old module ASI16-2300 (ARCO Solar Inc.).

4.2 Mechanical degradation

Several types of defects were detected during intensive visual inspection of all plant modules. A comparison with previous visual analysis results showed that some defects were present during the first years of module exposure. For example, a 1985 TISO publication stated that 20% of modules had cracked cells and that this aspect did not affect the plant performance [2]. At present, this percentage has increased to 22%; with the new breakages corresponding to hot-spotted cells.

4.2.1 Yellowing

The most evident visual defect is the yellowing of encapsulant; present, in 1985 [2], on 50% of modules, it currently affects, with different intensities, the 98% of the plant. The reason why some modules have remained completely white is unknown. The correlation between electrical characteristics and encapsulant discoloration showed that completely yellowed modules present higher loss in Isc (10-13% less than the nominal value) with respect to the white or partially yellowed ones (6-8% less than the nominal value). Effect of PVB yellowing on module power degradation is less precisely quantifiable, due to the presence of additional defects, which could affect module efficiency.

Spectral response measurements on white and yellow modules were performed; even if results gave no significant differences in mismatch factor (0.9994 non-yellowed and 0.9993 heavily yellowed), the comparison of the two absolute spectral responsivity graphics, showed a lower response of discoloured module between 400nm and 700nm. The I-V characteristics of the same two modules shows differences of 4.5% in Pmax and 1.3% in Isc.

4.2.2 Hot spot

The junction box located in correspondence of the back surface of one cell, provokes a higher thermal insulation and leads to a cell temperature increase of about 4°C. This cell is heavy stressed not only by the higher temperature, but also by the possible presence of umidity in the junction box. In fact, a quite frequently detected defect is the bad seal of the junction box on the tedlar backsheet with the consequent risk of detachment when opening, loss in insulation resistance and water penetration.

All these aspects justify the presence of several hot-spots (67 modules corresponding to 26% of actual plant) exclusively on the cell in front of the junction box. The overheating is about 10°C with respect to the rest of the module surface, whose temperature distribution is very regular.

4.2.3 Repeated accelerated ageing tests in comparison to ageing in field conditions

In 2001, the comparison between the defects appeared after damp heat test and thermal cycles (according to the International Standard IEC 61215) [4] and the ones provoked by ageing in field conditions, evidenced two significant differences:

a) thermal cycles and damp heat did not provoke delamination,
b) no naturally aged modules exhibited tedlar detachment [5].

After one year, in October 2002, the backsheet detachment in the bottom part of two naturally aged modules (0.8% of the plant) has been detected. At present, this phenomena affects 31 modules (12.3% of the plant - +11.5% after 7 months). Even if tedlar is still attached along the edges, the eventual exposition of the aluminium foil has to be kept under control, as it could represent an electrical safety hazard. For the moment, modules with such a defect do not present power degradation.

The comparison between results obtained from the two ageing "methods" evidences that accelerated ageing tests (according to IEC61215) partially reproduce the effects of natural ageing.

4.2.4 Delamination

One of the major disadvantages of PVB as a module encapsulant was its propensity for water absorption, which complicated handling procedures and occasionally produced voids on lamination. Moisture sensitivity dictated the use of a metal foil backsheet, as was made for ASI 16-2300 modules. Such a precaution did not prevent PVB delamination; since 1986, the presence of water infiltration and sealant penetration in some modules was documented [3]. At present, 233modules (92% of the actual plant) show encapsulant delamination along edges and 191 (76% of the actual plant) sealant diffusion.

Figure 9: water penetration corresponding to the tedlar backsheet detachment in a 21-year old ASI16-2300 module.

4.3 Performance degradation

Even if in 69 modules (27% of the plant) delamination represents a major defect, as it forms a continuous path between frame and circuit (as defined by IEC 61215), no insulation failures was detected both in wet and dry conditions. However, in some modules, cells delamination has to be kept under control, as it could lead to electrical performance degradation.

4.3.1 Effect of delamination on cells/module efficiency

One of the plant modules (AA005) presenting several differently delaminated cells has been subjected to repeated visual inspection and performance measurements. During three years, the progressive electric degradation related to the cells deterioration has been detected.

Figure 10: Delamination affecting cells nr. 5 and 6 of the ASI16-2300 module A005.

Electrical characterization of differently delaminated cells showed that performance losses of single cells are proportional to their affected area [1]; the Fill Factor decrease show the effects on series resistance Rs.

Delaminated cells show a temperature increase leading to hot-spots formation.

Table I: I-V characteristics evolution (2001-2003) of 4 differently delaminated cells (module AA005).

Cell nr.	5	6	7	8
Pmax	-4.1%	-3.6%	-3.9%	-3.6%
Isc	-2.8%	-3.8%	-3.0%	-2.4%
Voc	1.8%	1.8%	0.7%	1.0%
FF	-2.5%	-2.2%	-1.0%	-1.1%

Cells delamination also affects the overall module efficiency, but it involves different parameters. In the last three years, the module power degradation has been equal to -2.5%, while the power loss of the cells affected by delamination has been -3.8% (Table I and II). While for single cells, delamination affects the short-circuit current Isc and the Fill Factor, for the overall module only the Fill Factor FF shows a decrease (Table II).

Table II: I-V characteristics evolution of the overall module AA005.

	2001	2002	2003		Diff. 01/03
Pmax	32.76	32.56	31.94	W	-2.5%
Isc	2.20	2.20	2.19	A	-0.1%
Voc	21.05	21.01	20.97	V	-0.4%
FF	70.9%	70.5%	69.4%	-	-2.1%

The effect of humidity penetration is probably restricted to the temporary current flow between the frame and the active area of damaged cell. In fact the presence of delaminated cells does not prevent the module to function as long as the short circuit between frame and the active area occurs.

Particular attention has to be paid to modules where delamination affects the entire area of hot-spotted cells. In 20 years, 3 modules (1.2% of 252) presented such a defect: 1 of them was replaced in 1997, while 2 are still working and have a maximum power respectively of 26.4W and 28.2W (-20.2% and –14.8% with respect to the actual mean module power).

4.3.2 Long-term power degradation

The initial nominal plant power was equal to 10.7 kW (24 string of 12 modules). In 1983, the outdoor I-V characteristics of the 24 strings were performed, giving a total power output, after STC correction and comparison with indoor measurements of a batch of modules, equal to 9.8 kW [1].

Having no data of initial strings measurement or measured maximum power value of each module before exposition to the light, it has not been possible to state if the –8.4% difference from the nominal power existed at the beginning, or it is attributable to module degradation and/or wiring losses.

In January 2002, measurement of the 12 strings was performed (plant configuration: 12 string of 21 modules). The sum of the power output of all strings, after correction at STC, was equal to 8.33 kW. Due to the change of the plant configuration, which occurred in 1992, a comparison between the current results and the ones obtained in 1983 was not possible. However, a rough estimate of the annual degradation rate of the module power, since 1983, is shown in Table III.

Table III: estimate of module power degradation based on outdoor string measurements performed in 1983 and 2002.

Year	**Measured plant power [kW]**	**N° of modules**	**Module power (calculated) [W]**
1983	9.8	288	34.0
2002	8.3	252	32.9
Δ module power 2002-1983			- 3.2%
Module power degradation/year (since 1983)			**- 0.2%**

In March 2001, the entire plant was dismantled to perform indoor electrical characterization of all 252 modules. The mean maximum power was equal to 33.1 W, which is in good agreement (Δ = +0.6%) with the 32.9 W obtained through power estimation of 2002 outdoor measurements (Table III).

Figure 10 shows the performance behaviour of 18 reference modules of the 10 kWp TISO plant. In the last 5 years, a slight power degradation occurred. The difference between the power measured in 1982 and the one obtained in 2003 is equal to about -3%. This result is confirmed by the data from outdoor measurements results. However, such a result does not allow to determine the modules long-term stability, due to changes in the measurement system during 20 years.

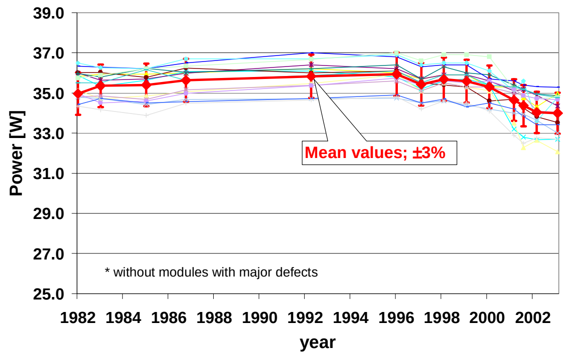

Figure 10: Power (STC) evolution of 18 reference modules during 21 years of outdoor exposure.

5 CONCLUSIONS

- The initial light exposure of c-Si modules caused a mean power degradation of about -3% (from -0% to -5%).
- In particular, it is an Isc degradation occurring during the first hours of exposure.
- In some modules the initial degradation lasts several months.
- After one year of exposure, in absence of particular defects, all the modules became stable.
- After 20 years, the Arco Solar of the 10 kWp TISO plant, show a first sign of power degradation.
- Results from outdoor and indoor measurements indicate a power degradation, after 20 years, equal to about -3% (annual power degradation equal to -0.2%).
- Yellowing of encapsulant, delamination and hot-spots are the principal causes of power degradation of ASI 16-2300 modules.
- Cells affected by delamination show a decrease in Isc proportional to their damaged area.
- Even if cells delamination affects modules efficiency, its influence on the overall plant operation is limited.
- Cell delamination can lead to hot-spots formation, so increasing cell degradation.
- The cells located in front of the junction box are subjected to a high stress caused by higher thermal insulation and humidity penetration inside the terminal box. This justifies the presence of several hot-spots.
- To avoid such a phenomena, junction box should not be placed in correspondence of PV cell and should be as small as possible.
- During last months, the tedlar backsheet detachment in some plant modules has been observed. This phenomena is rapidly increasing (0.8% of the plant in October 2002, 12.3% after 7 months).
- The same defect appeared on modules subjected to repeated damp heat test (accelerated ageing tests, International Standard IEC 61215).
- Nevertheless, the results of the indoor performance measurements of all plant modules indicate that the ASI 16-2300 modules are still working in a very satisfactory manner.

Crystalline silicon PV modules represent the 85% of world module production and, within it, the most well-known technology. Their components are reliable and have a high level of durability. However, the study of weathered modules' failure mechanisms could lead to an improvement of actual PV modules quality

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