30 YEARS OF EXPERIENCE WITH A 10 KW PV PLANT

Thomas Friesen[*], – thomas.friesen@supsi.ch
University of Applied Sciences and Arts of Southern Switzerland, SUPSI-ISAAC, 6952 Canobbio, Switzerland

ABSTRACT: *This paper reports the results obtained in 30 years of measurements, testing and monitoring of a PV TISO 10 kW plant installed at SUPSI in Southern Switzerland. The plant was connected to the grid in May 1982, the first in Europe. The system operated for 27 years with virtually no interruptions; the plant underwent configuration changes on only a few occasions, mainly because of inverter breakdowns. Due to a change in location at the end of 2008, the the system began to be disassembled, and 18 months later the plant was reinstalled in a new configuration on a different roof. Between 1982 and 2010 the IV curves of 18 selected modules were measured regularly. Performance measurement, visual inspection and insulation testing was performed on all modules of the plant in 2001 and 2009/2010. The average degradation of all modules of the plant over the 28 years is 0.38 %/year. In the first period (1982-2001), the degradation was 0.27%/year and in the second period (2001-2009) 0.64% / year. The performance ratio of the system decreased by about 20% in the 27 years of operation, and increased 10% after maintenance and reinstallation of the plant.*

Palavras-chave: *Lifetime, Degradation, Reliability, PV module, Performance*

1. INTRODUCTION

The durability and reliability of PV modules represents an important concern for module manufacturers, PV system installers and investors, who are interested in a cost-competitive system with reliable and predictable energy production during the entire lifetime of the module. At present, photovoltaic module manufacturers guarantee 80% of the nominal power after a 25-year lifetime, but the performance and the reliability of PV modules in real operating conditions over this guaranteed period of time can be verified for only a few plants.
In 1982 TISO (TIcino SOlare) started a research project to install grid connected PV power plants. The primary objective of the project was to provide technical information for planning larger systems in the future, and in particular to study the potential safety and technical problems involved in the connection of a photovoltaic plant to the electrical grid. The 10 kW plant with c-Si PV modules was connected to the grid on 13th May, 1982, the first in Europe. Two smaller PV plants with thin film modules were installed at a later date. The TISO 10 kW plant operated for 27 years with virtually no interruptions; the plant underwent configuration changes only a few times, mainly because of inverter breakdowns. The plant therefore provides an exceptional set of data that can be used to verify the electrical and mechanical durability of the modules in real operating conditions.

2. APPROACH

The TISO monitoring and measurement campaign consists of two parts: the monitoring of the PV system in operation, and the indoor measurements and testing of the PV modules. The system monitoring data acquisition process changed during the history of the plant, due to breakdowns and changes of technology. In particular, the data acquisition systems and data formats changed very rapidly in the past, causing problems today in terms of reprocessing old files with formats which are no longer in use. Electrical parameters, such as DC Voltage, DC Current for each string and power to the grid were acquired. The PV modules were tested in line with IEC 61215 [1] standards by means of visual inspection – insulation and wet leakage tests. Performance measurements in line with IEC 61904 [2] standards were conducted at the ESTI laboratory in Ispra (Italy) from 1981 to 2003. In 2000 the PASAN IIIa flash sun simulator was installed at SUPSI ISAAC (SWISS PV Module Test Centre), and the performance measurements were taken in-house.

3. PV MODULE DESCRIPTION

The PV modules installed in the TISO plant were manufactured by ARCO Solar. The PV module consists of 35 series-connected, mono crystalline Si cells with 102.5 mm diameter. The manufacturer gives a nominal power of 37 Wp, currently not at STC conditions, but with a module temperature of 28°C, AM1.5 and 1000 W/m2 and initial degradation was not considered.

It is not certain if PVB is the polymer used for encapsulation in all the modules, or whether ethyl-vinyl-acetate (EVA) was also utilized. It seems that some modules were manufactured from EVA by one of the two suppliers of Arco Solar. A query made in 2000, to a former collaborator of ARCOR Solar, remained unanswered. A publication by ENEA (Italy) [3] reported that PV modules manufactured by ARCO Solar in 1980 were encapsulated with PVB, and in 1983 the same module type was encapsulated with EVA, which confirms that the 1981/82 period covers the transition time when production was switched from PVB to EVA.
The rear of the module is made from a multilayer of Tedlar® - metal sheet - Tedlar® sheets, in order to increase the barrier properties of the moisture-sensitive PVB. The front is made from 3mm thick tempered glass. The aluminum frame is glued to the laminate with hot melt butyrol sealant. The junction box shown in Figure 1 is a moisture proofed plastic box in which a single bypass diode is mounted.

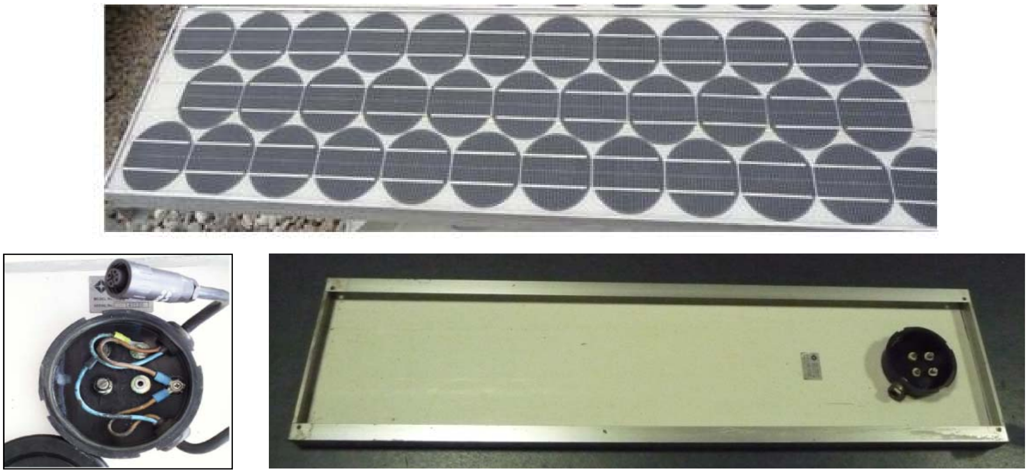


Figure 1: PV module installed in the TISO 10kW plant, manufactured by ARCO Solar ASI 2300–16: front of the module – junction box and terminal - rear of the module

Table 1: Technical details of ARCO SOLAR ASI 2300 – 16 PV modules installed in the TISO 10 kW plant

Pmax	37 Watt
Tolerance Pmax	± 10 %
Cell technology	Mono crystalline Si
Number of cells	35
Cell size	Ø 102.5 mm
Module efficiency	10.6 %
Front glass	3 mm – tempered
Encapsulant	PVB / EVA
Rear sheet	Tedlar® – metal – Tedlar®
Junction box	Moisture proofed plastic box
Edge sealant	Butyrol - hot melt
Frame	Al

4. HISTORY OF TISO 10 kW PLANT CONFIGURATIONS

The TISO 10 kW PV plant is installed on a roof at the Trevano Campus of SUPSI (Professional University of Southern Switzerland), where ISAAC (Institute for Applied Sustainability to the Environment) is located. The climate is moderate with temperatures from 1.1°C to 20.8°C (monthly average) and a relative humidity of between 80% and 57% (monthly average). The elevation of the site is 350 m with moderate snow loads. The annual global irradiance is 1243 kWh/m2.
In 1982 the installation cost for the TISO 10 kW plant was 46.30 CHF per Watt (value corrected to 2012), 34 CHF for the PV module and 12.30 CHF for the BOS. In Switzerland, in 2012, module costs were around 1.50 CHF/W and the installation price was about 5 CHF/W.
Configuration changes made to the plant since its installaion in 1982 have been due mainly to the replacement of inverters.

4.1. 1982 ÷ 1989 first plant configuration

In the initial configuration, 288 ARCO Solar modules were installed. They were lined up in three arrays of 96 modules each; the tilt angle was 65° in order to maximize energy production in winter. The plant was cabled in 24 strings, each with 12 series connected modules. The DC power produced was fed directly into the utility grid by means of an automatic 10 kW inverter, type Sunverter 714-3-200 from Abacus Controls Inc., USA. A maximum power system and the necessary safety and control features were implemented inside the inverter. The electrical and meteorological parameters, and data acquisition, were scanned every 2 minutes with a Solartron 35 data acquisition system.

4.2. 1989 ÷ 1991 second plant configuration

In 1989 the Abacus inverter broke down. From October 1989 to November 1991, a third of the plant (16 strings, each with 6 modules) was used to test the operation of the SOLCON inverter prototype, a 3.3 kW unit developed by the Biel School of Engineering (Switzerland). The rest of the modules were exposed in Voc condition.

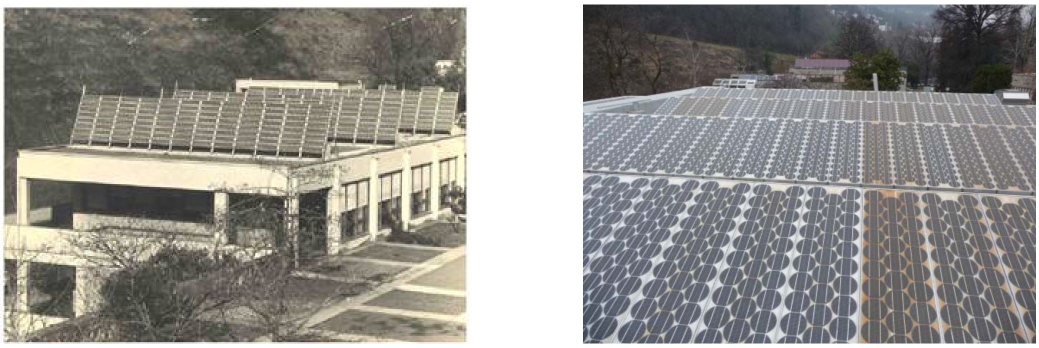


Figure 2: TISO 10 kW PV plant. (a) plant configuration in 1982 (b) plant in 2010 in the new location

4.3. 1992 ÷ 2003 third plant configuration

A new 15 kW inverter manufactured by ECOPOWER® (Invertomatic SA, Riazzino, Switzerland) was installed in 1992, and the module cabling was reorganized. The characteristics of the new plant configuration are described below:

Plant nominal power: 9.3 kWp
Number of modules: 252 (3 arrays of 84 modules each)
Array tilt angle: 55° since 1995
Module cabling: 12 strings, each 21 series connected modules

36 modules, the difference between 288 and 252, remained mounted in the plant, but held in Voc.

In 1995, the Solartron 35 data acquisition system was replaced by a new data logger Campbell CR10 in order to precisely monitor the overall plant behaviour. Mean and maximum values were recorded every hour from data measured twice a minute. It was also possible to record measurements every two minutes on an additional separate memory.

4.4. 1995 roof insulation replacement

In 1995 the plant was completely dismantled in order to re-lay the flat roof, and was then reassembled with a tilt angle equal to 55°. New terminal boxes for the parallel setting of the strings were also installed.

4.4. 2003 ÷ 2008 fourth configuration

In 2003 the ECOPOWER inverter had to be replaced because of technical problems. All 288 modules were re-connected to the grid, with inverters manufactured by SMA, type SUNNYBOY 2500. The tilt angle was not changed.

4.5. 2009 ÷ 2010 measurements campaign

Dismantling of the PV plant started at the end of 2008, and the modules were stored under dark conditions. IV curve measurements of some modules taken before and after cleaning verified that soiling had not deteriorated the power of the modules, although all modules were cleaned before testing. When necessary, the junction boxes were repaired by replacing wires and terminals. In 2009, measurements and tests were performed on all the modules, at the SWISS PV Module Test Centre – accredited ISO 17025 with the SAS number STS 531. Installation on the roof of another building at the Trevano Campus started in October 2010. In January 2011, the TISO PV plant in the new configuration was connected to the grid and data acquisition began in August.

4.6. 2010 ÷ Fifth configuration

In the fifth configuration, in 2010, all 288 modules were installed in 24 strings of 12 series connected modules divided into 6 fields. The inverters are manufactured by SMA, type SUNNY BOY 1200. The tilt angle in the new configuration is 22°, in order to minimize the visual impact of the PV plant, as requested by the owner of the building.

4.7. Replaced modules

After a few months, three modules were replaced under warranty. In the following years five modules were replaced with spare modules – four modules due to junction box failures and one module due to cracked cells.
Unfortunately, two modules of those selected were damaged during transportation.

5. RESULTS OF THE IV CURVE MEASUREMENTS OF 18 SELECTED MODULES

When the plant began operating in 1982, a batch of 18 field exposed PV modules was selected from the plant for regular IV curve measurements. These modules were measured at ESTI – JRC until 2003, and have been measured at ISAAC since 2000. Both laboratories measured IV curves in line with IEC standards. The overlapping measurements during the three years from 2000 – 2003 allowed a good comparison and measurement alignment between the two laboratories.

Table 2: Pmax values of the 18 selected modules and degradation rate related to the first measurement in 1982

	1982	1992	2004	2008
Pmax avg. (W)	35.56	35.49	31.58	28.37
Pmax min (W)	34.34	32.40	16.10	0.00
Pmax max (W)	36.49	37.00	34.00	32.59
Pmax deviation	5 %	12 %	52 %	100 %

In 2001, two modules of this batch were damaged during transport, and in 2008 one was lost in the disassembly process. One module degraded to 16 W in 2004, and to 0 W in 2008. For the average, this degraded module is calculated as 0 W, while the three damaged modules were no longer considered for the average after having been damaged.

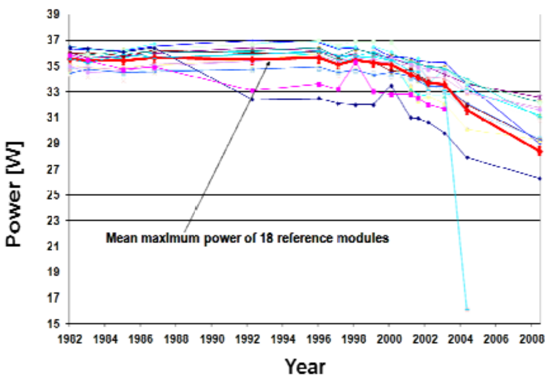


Figure 3: Pmax of the 18 selected modules of the TISO plant plotted in dependence of the year

The initial average power of the selected modules measured in 1982 was 35.56 W, with a spread of 5%. Two modules have shown degradation since 1986, as seen in Figure 3, while the power of the remaining 16 modules has not recorded any significant changes for almost 18 years. The average annual degradation between 1982 and 2001 was 0.1%.
After this point the average power decrease became greater. In 2001, after 20 years of outdoor operation, the annual degradation rate was 0.18%. In 2004 the annual degradation rate increased to 0.51%, which was still below the limit of the warranty given by the manufacturer of PV modules: usually 20% in 25 years or 0.8% / year.
After 27 years of operation the annual degradation rate increased to 0.75%, still within the warranty limit. Considering only the last 4 years the annual degradation rate is 1.8%, and so greater than the warranty limit.

6. INSPECTION AND MEASUREMENT RESULTS OF THE COMPLETE SET OF TISO 10 kW MODULES

The complete set of 288 modules from the TISO 10 kW plant was inspected, tested and measured in 2001 and 2009.

Visual inspection results

The purpose of the inspection was to dedect any visible defects in the module. With reference to the International Standard IEC 61215 [1], each module of the plant was carefully inspected in order to check the presence of any visible defects. The results were compared with the reports from 2001 [2].

Yellowing of encapsulant

Yellowing is the major visible change which was already registered in 50% of the modules in 1985. In 2001, 97 % of the modules were yellowed and this high level remained stable in 2008. Unfortunately, no distinction between light and dark yellowing – browning – was made.

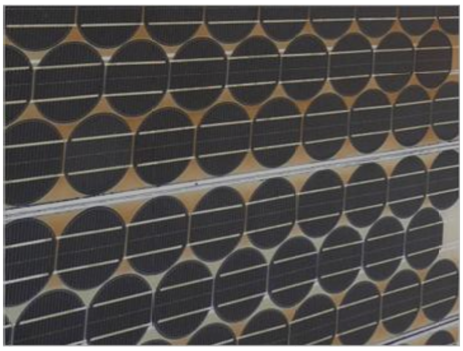


Figure 4: Yellowing of ARCO Solar modules in 2010: the upper one with dark yellowing – the lower one with light yellowing

Oxidation of terminals and junction box

Oxidation of the terminal and in the junction box, as shown in figure 5, was always a more serious issue of this module type, due to the design. The first reports described the defects as early as in 1983. Oxidation on the terminals and in the junction boxes involved 92% of the modules in 2001, and all the modules in 2008.

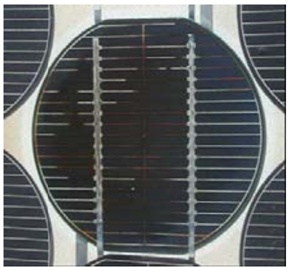


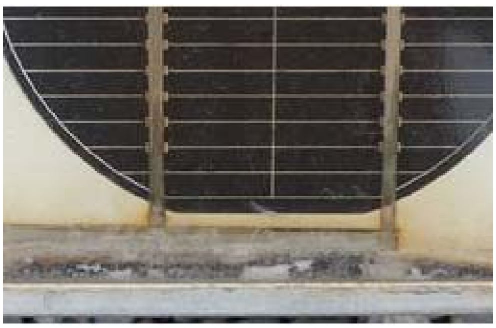
Figure 5: Visible defects of ARCO Solar module - typical oxidation in junction box (left) and grid oxidation on PV cells

Oxidation of grid

In 2001, almost all the modules already demonstrated cells with grid oxidation, as shown in Figure 5. In 2008 all the modules showed cells with grid oxidation.

Sealant penetration

In 2008, 90% of the modules demonstrated penetration of the sealant from the edge of the module, as shown in Figure 6.



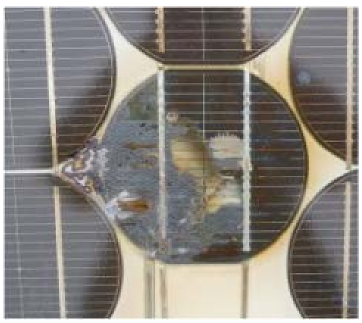


Figure 6: ARCO Solar module with sealant penetration from the edge (left) and hot spot on the cell over the junction box (right)

Modules with cracked cells
The number of modules with cracked cells did not increase. Most of the cells were already cracked during delivery and, due to the thickness the cells, very resistant to breakage.

Table 3: Summary of the results of the visual inspections in 2001 and 2008

DEFECT	2001	2008
Yellowing	97%	97%
Oxidation JB	93%	100%
Hot spot	26%	33%
Cracks	22%	22%
Rear sheet	20%	95%
Delamination	92%	92%
Sealant	76%	90%
Grid oxidation	93%	100%

Modules with hot spots
One major quality issue of this module design (Figure 6) consists of the hot spots located over the junction box. The soldering technique used to attach the terminals to the PV cell causes a high resistance with heating effects on the cells. As early as in 2001, 26% of the modules were affected by hot spots, and in 2008 this percentage increased to 33%.

6.2. Results of insulation tests
The scope of the insulation test was to verify whether or not current carrying parts and the frame of the modules are sufficiently well insulated from each other. Insulation tests were performed in line with IEC 61215 Chapter 10.2 [1].
After 28 years, 9 out of 288 modules failed the test. These failing modules presented heavy delamination defects or sealant penetration at the edges.

6.3. Results of wet leakage tests
The scope of the wet leakage test was to verify the insulation of the current carrying parts of the module from the external environment in wet conditions. Insulation tests were performed in line with IEC 61215 Chapter 10.16.
41 modules failed this test.

6.4. IV curve measurement
All IV curve measurements were executed in accordance with the relevant IEC standards, with the class AAA simulator PASAN IIIa installed at ISAAC in 2000. This same reference cell was used in both measurement campaigns. The whole measurement system and procedure were accredited ISO 17025 in 2001.
In Figure 7 the decrease of the relevant Voc and Isc module parameters, and the fill factor FF are plotted in function with the Pmax decrease. The mean 35.56 W power for the 18 selected modules was chosen as the nominal power for all modules. The graph shows that the Voc is not correlated to the Pmax degradation. Visual inspection showed oxidation of the grid on all the modules, but this does not appear to have made a significant impact on the Voc.

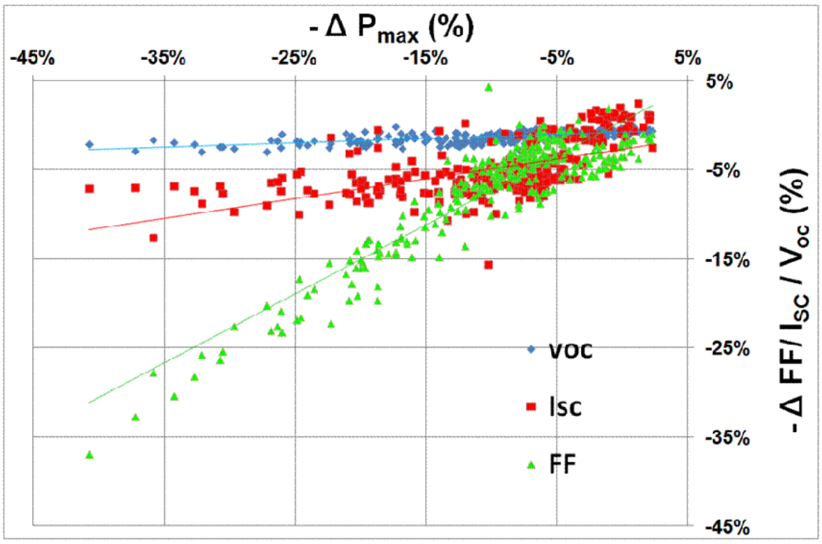


Figure 7: FF (green), Isc (red) and Voc (blue) degradation plotted in function with the Pmax degradation (nominal power of all modules : 35.56W)

The Isc has a moderate correlation with the Pmax decrease. Only some modules with heavy hot spots and delamination showed a significant decrease in Isc values.
Figure 7 shows that the fill factor FF degradation has a strong correlation with the Pmax decrease. This is an indication that major power degradation is caused by the shunt and series resistance decay of the module.
Figure 8 plots the FF, Voc and Isc values lost in 2001 and in 2008, in accordance with the power degradation for the whole set of modules. The Voc plot (c) shows no change in degradation in 2001 and 2008.
The Isc distribution broadened slightly in the second measurement campaign and presented some outliners. This broadening was caused by increased delamination defects and increased sealant penetration at the edges of the module. The outliners are attributed to heavy hot spots, as shown in Figure 6.

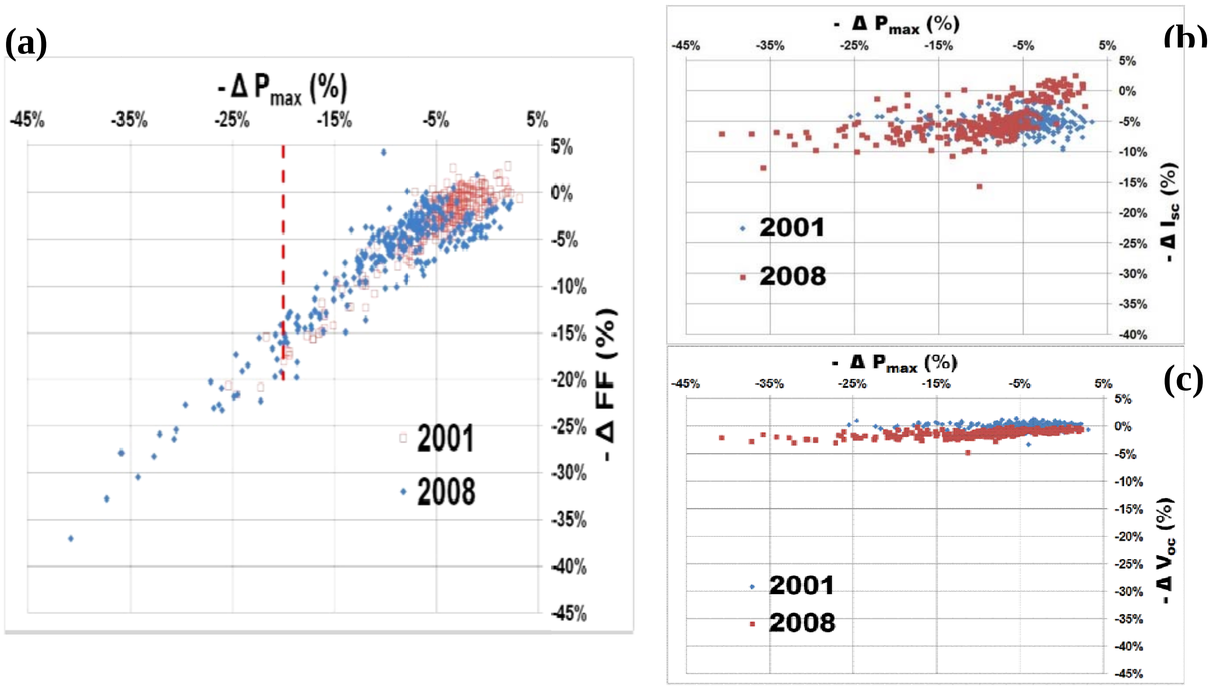


Figure 8: (a) FF, (b) Isc and (c) Voc degradation plotted in function with the Pmax degradation, with initial reference power 35.56W. All graphs have the same scale

The FF fill factor shows a further degradation from 2001 to 2008, with a significant increase in the spread. This is due mainly to the degradation of the series and shunt resistance of the modules.

Table 4: relevant electrical values of the complete module set in 2001 and 2008

	2001			
	Pmax (W)	Isc (A)	Voc (V)	FF
Max	36.10	2.37	21.30	0.74
Min	28.10	2.16	20.31	0.60
Average	33.67	2.27	21.03	0.70
Dev %	23.47%	9.24 %	4.71%	20.36%

	2008			
	Pmax (W)	Isc (A)	Voc (V)	FF
Max	35.87	2.45	20.98	0.75
Min	22.46	2.02	19.98	0.57
Avarage	32.29	2.28	20.75	0.68
Dev	41.35 %	19.08 %	4.75%	33.93%

Table IV summarises the average, minimum and maximum electrical values measured in 2001 and 2008. In particular, the Pmax and FF values decayed and the spreads increased significantly from 2001 to 2008.

Figure 9 (a) shows the distribution of the annual degradation rate from 1982 to 2008, for the whole set of TISO modules. Annual degradation rates are calculated in relation to the assumed nominal power, Pn of 35.56 W, calculated as the average of the 18 modules selected in 1982 at ESTI. The annual degradation rate over whole operation period is

0.38 %, below the warranty limit of 0.8% / year. In 2008, 24 out of 288 modules recorded annual degradation rates higher than the limit of 0.8% given as warranty by most module manufacturers.

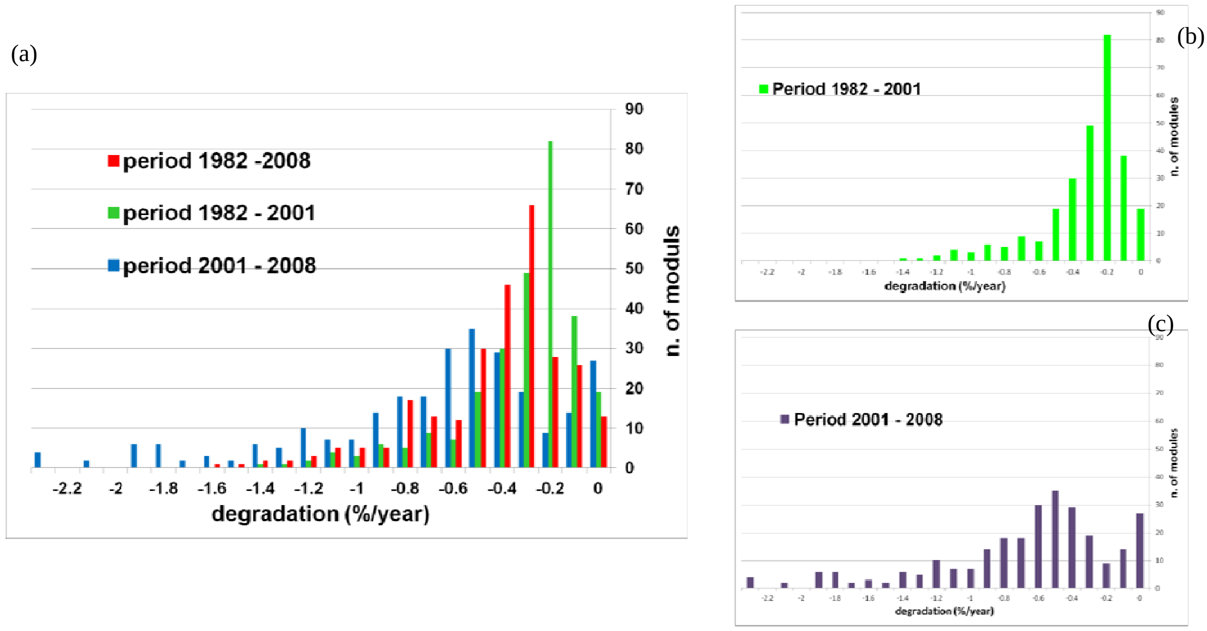


Figure 9: degradation rates of the PV modules for the three operating periods: (a) 1982 – 2001 – (b) 2001 - 2008 –(c) 1982 - 2008 (presumed nominal value: 35.56 W in 1982).

The distribution of the initial power and of the degradation rate, together with the increase in the annual degradation rate, caused the power distribution to broaden in the different years, as shown in Figure 10. Due to missing initial power measurements, or unreliable nominal power declarations, the distribution in 1982 is extrapolated from the 18 selected modules to all 288 modules.

Plot (b) shows the annual degradation rate for the first 20 years of plant operation, from 1982 to 2001. For this first period the values were distributed around the average of 0.27 %. During this period 17 out of 288 modules recorded annual degradation rates greater than 0.8%/year.

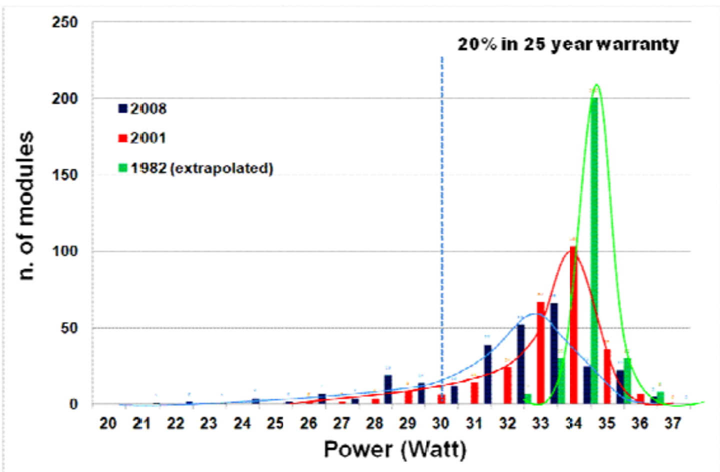


Figure 10: Distribution of the power Pmax for 1982 – 2001 and 2008 - values from initial distribution in 1982 are extrapolated from Pmax of selected module batch

In the second period, from 2001 to 2008, the distribution of the annual degradation rate broadened significantly and the average value increased to 0.64 %. The annual degradation rate increased from the first period to the second period for 229 modules, and decreased or remained stable for 46 modules. Over the 7 years, 74 out of the whole set of modules recorded annual degradation rates higher than the industry warranty limit.

The trends of the annual degradation rate of the 18 selected modules, and of the whole set of 288 modules, are comparable and confirm that the degradation increased significantly over the last few years.

7 CONCLUSIONS

The most important lesson given by the TISO 10 kW system is the good and reliable performance of PV modules. In the first 20 years of plant operation, most breakdowns were caused by inverter breakdowns. Today's inverters are much more reliable and have caused fewer breakdowns in the TISO plant.

The module degradation rate was low in the first 20 years of outdoor operation but has increased since 2001. The overall average annual degradation rate of 0.64% is still below the warranty limit given by most module manufacturers. The annual module degradation rate has increased constantly from 2001, so we can state that the degradation of the modules installed in the TISO plant is not constant over time but increases particularly after 20 years.

The plant performance ratio reflected the degradation of the modules. Over the course of almost 20 years, the PR degraded very slowly and degradation only increased after 2001.

After maintenance, the PR of the plant increased 10%. Data monitoring on the new plant, and analyses of the old raw data, are continuing and should produce new results in the coming years.

Acknowledgements

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REFERENCES

[1] Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approuval, CEI/IEC 61215 second edition: 2005, IEC Geneva, Switzerland, 2005

[2] A. Realini, E. Burà, N. Cereghetti, D. Chianese, S. Rezzonico; " Mean Time before Failure of PV Modules", Final report BBW 99.0579, June 2003

[3] Photovoltaic devices – Part 1: Measurement of photovoltaic current – voltage characteristics, CEI/IEC 60904-1:2006-9, IEC Geneva, Switzerland, 2006

[4] Domenico Coiante, "La durata dei moduli fotovolatici al silicio cristallino" – published on www.aspoitalia.it in decembre 2010