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MTBF - PVm
Mean Time Before Failure of Photovoltaic modules

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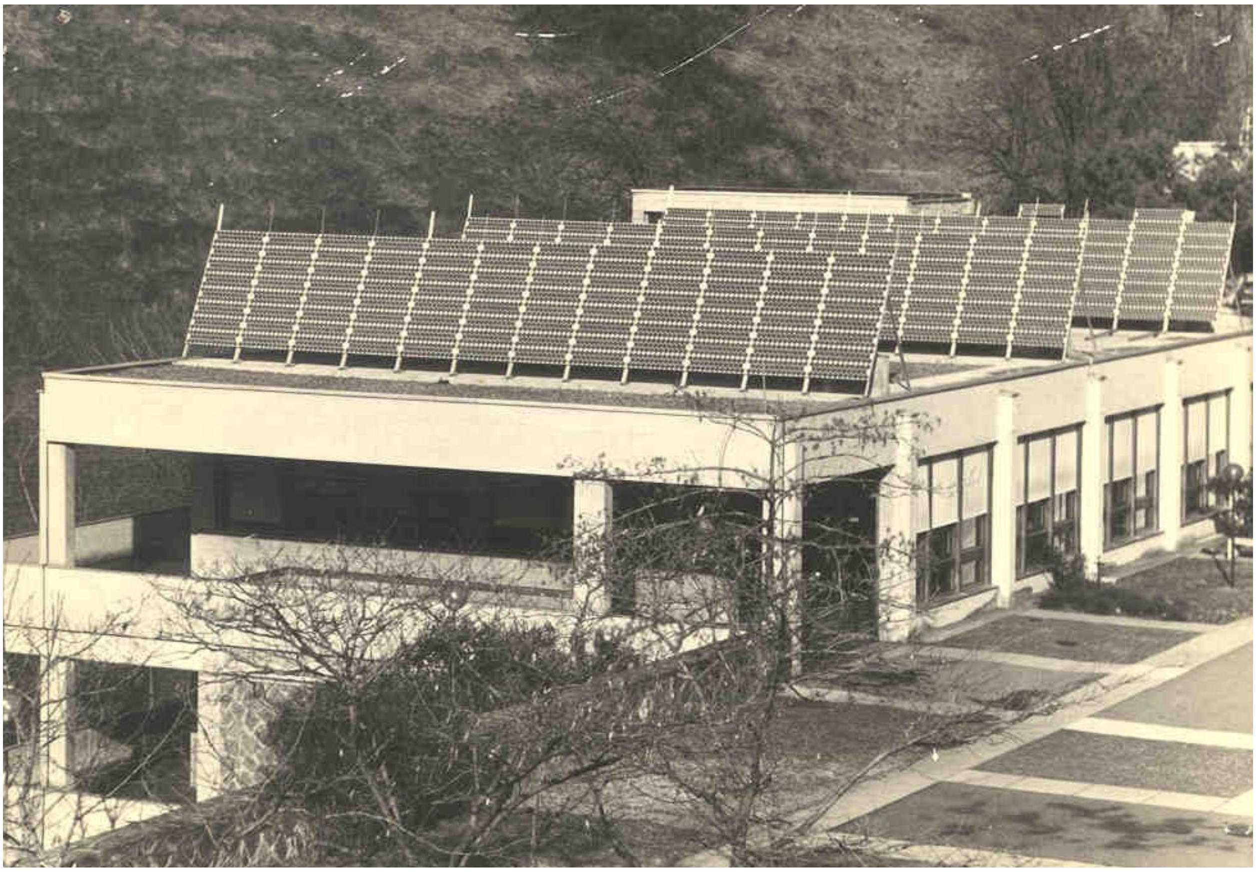

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1 Summary

The Mean Time Before Failure (MTBF) project is a collaborative research program between the Laboratory of Energy, Ecology and Economy LEEE-TISO (Scuola Universitaria Professionale della Svizzera Italiana, Dipartimento delle Costruzioni e del Territorio, Lugano) and the European Solar Test Installation (ESTI) laboratory (European Commission, Joint Research Centre, Institute for Environment and Sustainability, Renewable Energies Unit, Ispra); it is a 3-year project, started in April 2000.

The object of this collaboration is the study of the behaviour of a 21-year old photovoltaic plant, sited on the roof of the Scuola Universitaria Professionale della Svizzera Italiana, also seat of the LEEE-TISO. It's a 10kW array, installed in May 1982, representing the first PV system connected to the public electrical grid in Europe.

This report describes the aims of the MTBF project, the work performed, the results obtained and the conclusions that have been drawn after 3 years of analysis and monitoring.

2 Introduction

Durability of PV modules represents an important concern both for module manufacturers, interested in producing reliable and cost-competitive devices, and for consumers, willing to invest in this quite expensive technology in exchange of a guarantee of quality. Regarding c-Si technology, today's photovoltaic market offers modules qualified to survive 20-25 years, with guaranteed power production varying for different manufacturers. At present, one of the aims of PV industries is to produce commercial modules with lifetimes of 30 years or more.

Achieving 30-year life PV modules requires a systematic approach to the identification of failure mechanisms, to the establishment of allowable failure levels, and to the development of cost-effective solutions. The study of modules' failure mechanisms can aid this drive towards higher levels of durability. With this aim, several investigations have been carried out on field-aged and laboratory-aged modules utilising destructive and non-destructive techniques to analyse the degradation of various module components.

The Mean Time Before Failure project aims to study these effects through the analysis of the LEEE-TISO 10 kW PV plant.

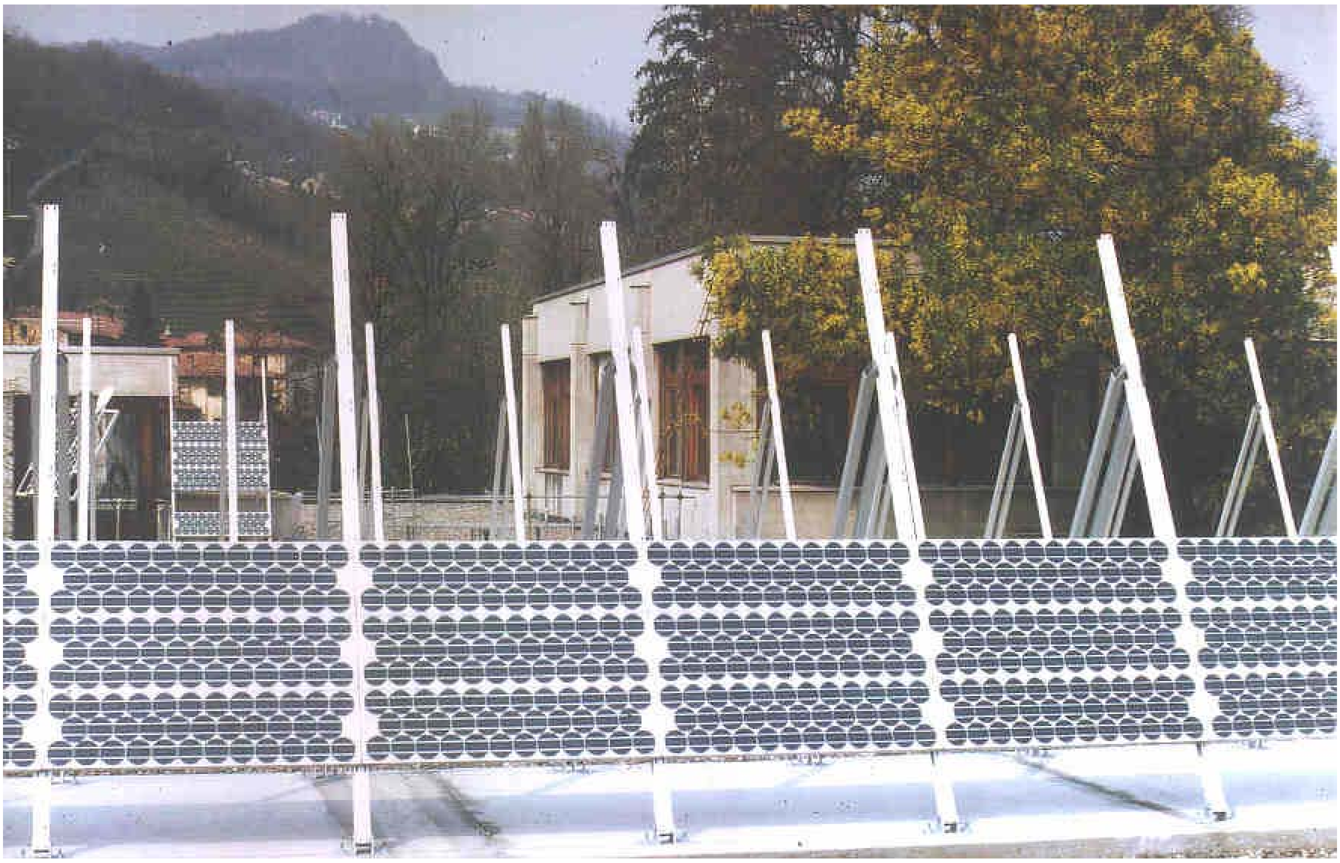


Figure 1: mounting structure of TISO 10 kW plant with some new ASI 16-2300 modules (1982).

3 Plant history

3.1 Initial scope

In 1982 the Department of Environment of Ticino (Switzerland) started a research project called TISO 15, to design, install and operate a 15 kW grid connected PV power plant. Primary objective of this effort was to provide a technologically advanced facility of intermediate size giving practical information for the planning of future larger PV plants.

The first part of the installation, with a peak power of 10 kW, started to operate the 13th May 1982. The second part, consisting of a new type of concentrating modules and a dedicated inverter unit was planned to come into operation one year later [1].

At that time, the 10kW plant represented the first PV installation connected to the public electrical grid in Europe, and it had a factor of 10 larger with respect to the other existing PV systems in Switzerland.

3.2 Plant description

Since its realization, the plant configuration has been changed three times because of inverters substitutions. At present, a new system organization is ongoing for the same reason.

3.2.1 1982÷1989: initial configuration

The initial plant configuration consisted of 288 ARCO Solar ASI 16-2300 single-crystalline silicon (sc-Si) modules, with a nominal power of 37 Wp each (Total power plant: 288 modules x 37 Wp ≅ 10.7 kWp). They were lined up in three arrays of 96 modules each (8 vertical x 12 horizontal); the tilt angle was 65° in order to maximize the power generation in winter. The plant was cabled in 24 strings of 12 series connected modules each (operating voltage 192 V). The produced DC power 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 (Figure 3). A maximum power system and the necessary safety and control features were implemented within the inverter. Scanning of the electrical and meteorological parameters and data acquisition was performed every 2 minutes (Solartron 35 - Figure 4). In seven years of operation the Abacus inverter performance was satisfactory; three short shut-downs occurred in the first three years. Equipment failure was caused, in turn, by insufficient power bridge insulation, electrical contacts (non-gold plated) deterioration, and overheating of one power supply resistor [2].

Figure 2: rear view of the TISO 10 kW plant during its installation (1982).

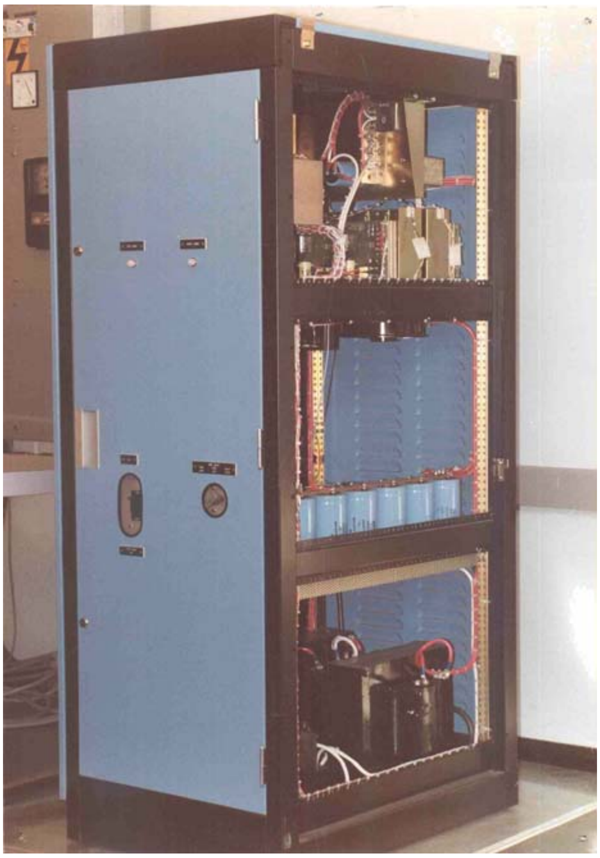


Figure 3: Sunverter 714-3-200 inverter.

Figure 4: Abacus inverter and Solartron 35 data acquisition system.

3.2.2 1989-1991: Solcon prototype inverter

In 1989 the Abacus inverter broke down. From October 1989 to November 1991, a third of the plant (16 strings of 6 modules each) 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 inverter suffered only one breakdown caused by incorrect handling during a test [2].

3.2.3 1992-2003: third plant reorganization

In 1992 a new 15 kW inverter was installed and the modules cabling reorganized. 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 (chapter 3.2.4)
Modules cabling:	12 strings of 21 series connected modules each
Working voltage:	2 fields (positive and negative) working at ± 380 V
Inverter :	ECOPOWER® 15 kW (Invertomatic SA, Riazzino, Switzerland)
	Pulsed-Width Modulation technology (PWM)
	Insulated Gate Bipolar Transistor (IGBT)
	Maximum Power Tracking (MPT) analogical control circuit

During the first year of operation the new inverter had a fault because the aluminium frame of the DC electrical board was not sufficiently insulated. Afterwards, no relevant problems were reported [3].

In 1995, the Solartron 35 data acquisition system was replaced by a new data logger Campbell CR10 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. Table 1 shows the measured and calculated characteristics.

Measured values	Measure
Back of module temperature (Tm)	°C
Positive field DC voltage (U+)	V
Negative field DC voltage (U-)	V
Positive field DC current (I+)	A
Negative field DC current (I-)	A
Irradiance on module surface (G)	W/m²
AC energy (Imp Eac) – n° of pulse in 30 seconds	1/s
Calculated values	**Measure**
Positive DC power (Pdc+)	W
Negative DC power (Pdc-)	W
Total DC power (Pdc tot)	kW
Total AC power (Pac tot)	kW
DC energy (Edc)	kWh
AC energy (Eac)	kWh
Inverter efficiency (η)	%

Table 1: plant characteristics recorded by Campbell CR10 data logger and elaborated data.

In addition, since June 2000, individual string energy production data has been recorded every minute from 5.00 a.m. to 10.00 p.m. (new data acquisition system wih Agilent 34970A datalogger), allowing analysis and comparison of string behaviour (Chapter 6.5, Figure 12).

In November 2001 an inverter anomaly, strongly influencing the plant performance, was detected (Chapter 13). At present, the inverter substitution together with the reorganization of the plant configuration is ongoing (Chapter 16).

3.2.4 1995: works for roof insulation

In 1995, the plant was completely dismantled for the re-laying of the flat roof insulation (Figure 5) and reassembled with a tilt angle equal to 55°. New terminal boxes for the parallel setting of the strings were also installed (Figure 6) [4].

A flat roof has a limited lifetime (about 30 years), hence plant supporting structures and ballasts have to be designed considering an eventual temporary dismantling. The use of connectors for modules cabling can also facilitate the plant mounting and dismounting.

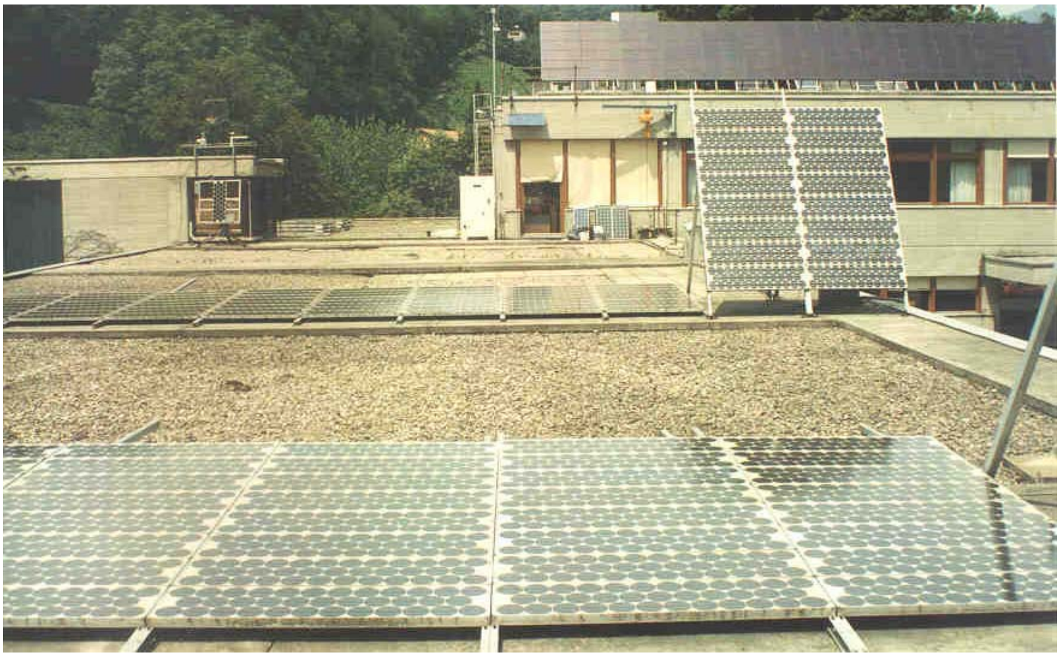


Figure 5: plant dismantling for new roof insulation (1995).

Figure 6: new field terminal box (1995).

4 SOLAREC – Mean Time Before Failure project (MTBF-PVm)

Within the 5th European Framework Program (1998-2002), the Photovoltaic Solar and Thermal Electricity Project SOLAREC aimed to the understanding, characterization and development of photovoltaic devices, its related integration components and selected technologies for solar thermal electricity concepts, monitoring and assisting in the development of cost-effective solar electricity applications from basic research through to the commercial product. The research focus covered three major lines:

- Material supply, Device Physics and Reference measurements;
- Integration of Solar Electricity Systems in centralized and decentralized supply;
- Cost reduction and Lifetime improvement of PV technology.

This last aspect represents an important concern both for module manufacturers, interested in producing reliable and cost-competitive devices, and for consumers, willing to invest in this quite expensive technology in exchange of a guarantee of quality. Regarding c-Si technology, today's PV market offers modules qualified to survive 20-25 years, with guaranteed power production varying for different manufacturers. At present, one of the aims of PV industries is to produce commercial modules with lifetimes of 30 years or more. The study of modules' failure mechanisms can aid this drive towards higher levels of durability.

Failure is defined as the termination of the ability of a product or system to perform a required function. The primary function of a photovoltaic module is to provide safe, useful electric-power. Since modules are typically deployed as components in systems, module degradation and failure may not be immediately recognized. System design can oftentimes mask the effects of module performance degradation and/or individual module failures. Conversely, some module degradation mechanisms can significantly degrade the operation and/or performance of the entire system.

The Mean Time Before Failure project aims to study the effects of modules' failure mechanisms through the analysis of the LEEE-TISO 10 kW PV plant.

The main objectives are:

- Determination of the Mean Time Before Failure (MTBF) of the modules and investigation on the physical degradation mechanisms in action;
- Correlation of field reliability with accelerated lifetime tests, to assess and refine existing standards for PV module reliability (e.g. IEC 61215);
- Correlation of field performance with indoor performance measurements, to define an energy rating scheme for PV modules;
- Analysis of the interaction with the electrical grid, to identify performance/reliability requirements for grid-connected inverters;
- Identification of strategies for fault-tolerant system design.

The combination of systematic monitoring and laboratory measurements provide a unique opportunity to study the system and the end of its life.

4.1 MTBF definition

In order to achieve a widespread application of PV technology, the costs will have to be substantially reduced and the versatility and reliability increased. In order to increase the PV system reliability it is essential to have a comprehensive system structuring, modularization and standardization of the functional units.

Mean Time Before (or Between) Failure – MTBF- is the mean (or average) time expected between failures of a given device. For electronic devices is normally measured in hours, while for photovoltaic modules and PV systems components is expressed in years.

MTBF is a statistical value meant to be applied to a large sample over a long period of time. It is neither a guarantee nor a prediction of how long any specific sample will last before failing. It is, however, a critical element in determining the probability-of-failure of a specific sample. Probability is a ratio, normally quantified as a percentage. Therefore, the question is not how long will this specific sample last, for that is unknown, but instead, what are the chances this sample will last a particular number of hours (or years).

5 Work distribution

The work between the two partners have been mainly distributed as follow:

LEEE-TISO

- Periodic electrical performance measurements on the 10 kW array (outdoor strings measurements and indoor performance measurements of individual modules);
- Periodic infra-red analysis and detailed visual inspections of the plant;
- Analysis of evolution of system performance ratio over the time;
- Recovery of original module construction data.

ESTI

- Periodic indoor electrical performance measurements on reference group of 18 modules (every 6 or 12 months) (Chapter 10.2);
- Repeated accelerated ageing test (according to the International Standard IEC 61215) on a batch of 8 modules of the plant (outdoor exposed from 1982 to 1997) (Chapter 6.6).

5.1 LEEE-TISO work organisation

The first step moved by the LEEE-TISO has been the organization of a detailed work program to achieve at best the main goals of the project.

Once a year, it has been established to execute a detailed **visual inspection** of all plant modules and an **infra-red analysis**, to detect the presence of physical defects, to follow their evolution and, in comparison with **electrical data**, to determine their influence on modules efficiency.

Regarding **performance measurements**, it has been decided to dismount the plant and perform the indoor current-voltage characterization of all individual modules to precisely correlate physical defects and electrical data of each device. Initially, this type of measurements was foreseen to be repeated every year, but as it took a lot of time, it has been decided to periodically measure only the modules with major defects (delaminated cells, hot-spots, etc.). Considering the risk of junction boxes and terminal connections detachment (Chapter 8.2.2), **new connectors** have been applied to each module, to make easier the module dismount and to avoid any breakage. In addition **measurements of the outdoor strings** have been planned.

Together with the outdoor/indoor performance measurements, the infra-red and visual analysis, and the continuous monitoring of the plant, it has been considered basic the **recovery of all available data and information** about the plant, recorded since 1982, to allow the reconstruction of the system history and, consequently, to better understand its actual state.

Another important aspect was the organization of a user-friendly database for all the results, data and information about the overall plant and the individual modules.

As some broken modules have been replaced and others removed from the plant for different reasons, the first step has been going back to all devices displacements and assign a position code at each module (previously only identified by its serial number).

Figures in the following pages show the present plant configuration (displacements are also indicated), both referring to the position codes (Figure 7) and to the serial numbers (Figure 8). In the file containing these tables a macro allows to switch directly from module position to the serial number and to other information (Figure 9 and Figure 10), such as visual inspection data and pictures of each device.

In 2001, the indoor performance measurements of all plant modules was executed (Chapter 10.2). As for visual inspection forms, the excel files containing the electrical data of each device has been linked to the other related documents. In such a way, it is possible to find all the information on a module starting from its plant position (Figure 10).

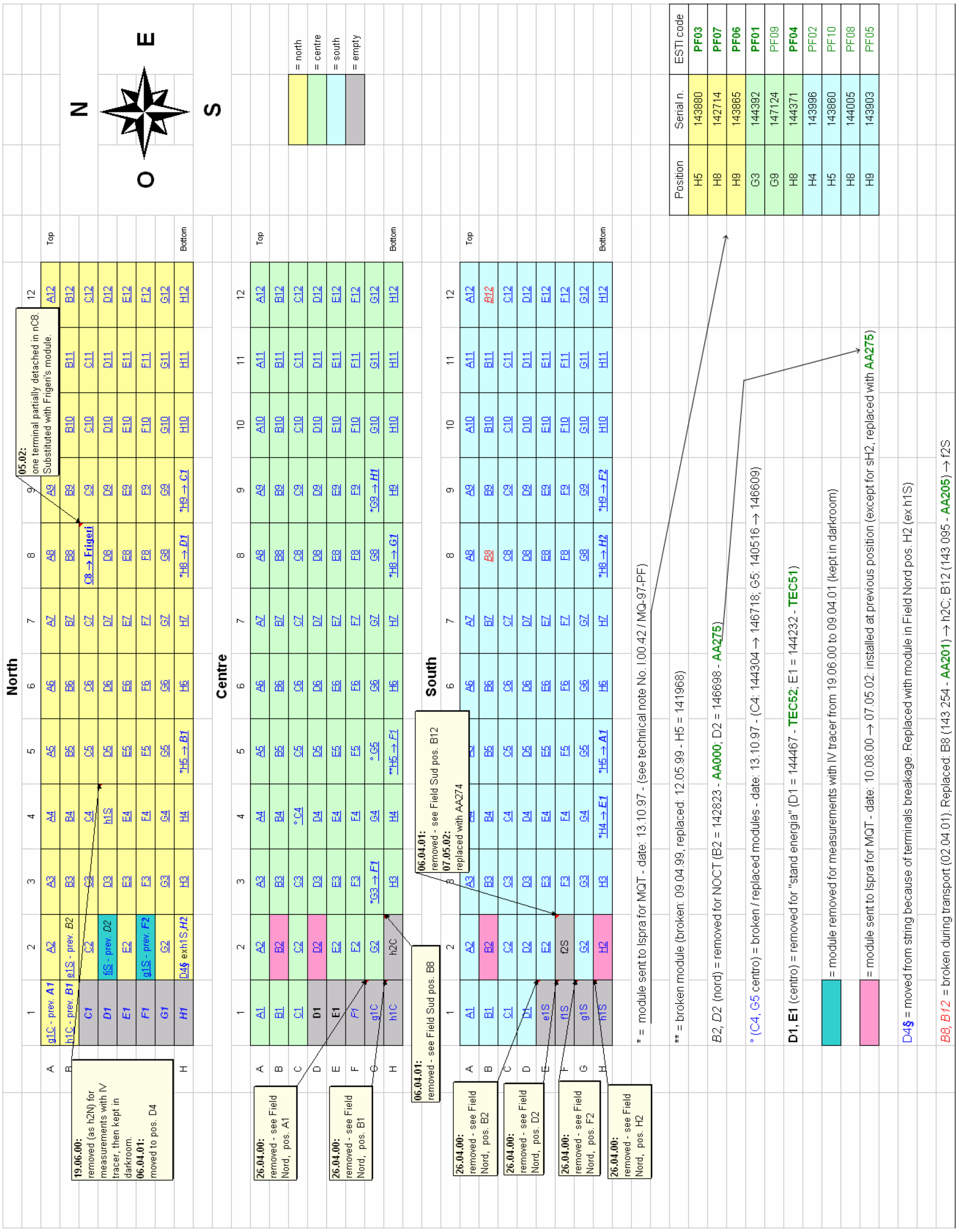


Figure 7: plant configuration (until July 2003) and previous modules displacements (with reference to position codes).

North

	1	2	3	4	5	6	7	8	9	10	11	12	
A	#144 275	143 138	147 152	139 703	147 147	144 156	142 795	145 741	143 693	145 159	145 961	143 036	Top
B	#143 150	#147 213	147 481	144 627	145 950	139 647	143 064	145 696	145 227	142 678	142 778	145 929	
C		144 350	147 595	142 814	143 156	145 754	143 695	141 927	142 558	142 718	143 263	140 394	
D		#142 756	143 217	#146 717	144 168	143 112	145 693	140 349	144 326	145 933	142 740	144 278	
E		144 319	143 859	147 527	147 153	143 011	143 215	145 784	145 959	140 398	145 729	143 857	
F		#144 018	144 297	145 158	147 448	146 693	147 160	140 469	146 707	145 689	145 169	140 426	
G		145 193	147 485	144 002	144 280	144 318	143 837	144 344	144 221	144 286	144 343	144 246	
H		#140 473	144 307	143 885	#142 791	143 067	147 413	#146 794	#144 355	143 856	143 070	146 594	Bottom

Centre

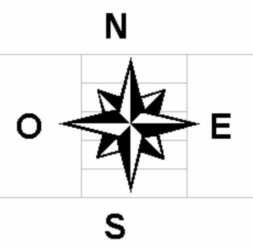
	1	2	3	4	5	6	7	8	9	10	11	12	
A	144 263	143 118	144 316	144 279	147 015	142 801	144 189	143 962	147 025	144 256	145 108	143 102	Top
B	144 008	143 407	143 128	147 519	142 904	147 580	144 328	146 526	144 376	144 390	143 967	143 923	
C	143 986	146 696	143 729	#146 718	144 265	143 958	143 081	143 957	143 736	144 281	142 575	147 391	
D		143 734	145 708	147 470	143 738	142 793	143 743	143 287	147 402	145 771	143 664	142484	
E		144 179	142 786	143 100	145 192	142 997	144 311	145 757	147 479	143 126	143 907	143 097	
F		143 089	142 738	143 599	144 360	144 285	144 414	144 195	143 990	142 562	145 166	145 163	
G		143 127	#142 737	146 639	#146 609	143 099	145 912	144 288	#139 509	147 483	140 415	145 687	
H			140 397	145 709	#143 116	142 721	143 661	#146 584	142 973	147 556	145 952	147 121	Bottom

South

	1	2	3	4	5	6	7	8	9	10	11	12	
A	144 277	145 214	145 725	146 677	147 542	144 006	144 175	144 027	145 132	145 229	144 166	144 039	Top
B	145 717	144 078	145 330	144 361	145 129	145 767	147 544	#144 391	147 606	146 870	144 056	#147 424	
C	142 945	144 430	143 993	143 723	145 242	146 685	146 634	143 074	143 998	142 950	145 327	147 499	
D	143 073	147 591	144 291	142 796	145 711	147 216	144 004	146 689	145 113	143 069	144 377	146 872	
E		142 803	142 948	142 842	146 636	145 190	147 077	147 331	142 109	146 660	147 328	142 820	
F			144 296	143 976	144 178	144 028	147 050	142 752	144 062	144 185	147 315	142 818	
G		147 061	147 027	144 635	144 183	142 903	146 869	145 733	145 185	147 600	142 949	142 811	
H		146 699	144 171	#142 479	#145 934	142 802	147 552	#144 226	#143 111	145 211	146 617	144 009	Bottom

[turquoise] = module removed for measurements with IV tracer from 19.06.00 to 09.04.01 (kept in darkroom)

[pink] = module sent to Ispra for MQT - date: 10.08.00



[yellow] = nord
[green] = centro
[light blue] = sud
[grey] = empty

Serial. N.	Now	1st pos.	2nd pos.
# 144 275	A1	g1	
# 143 150	B1	h1	
# 147 213	B2	e1	
# 142 756	D2	f1	
# 144 018	F2	g1	
# 146 717	D4	h1	
# 140 473	H2	D4	
# 142 791	H5	*B1*	H2
# 146 794	H8	*D1*	
# 144 355	H9	*C1*	
# 146 718	C4	/	
# 142 737	G3	*F1*	
# 146 609	G5	/	
# 139 509	G9	*H1*	
# 143 116	H5	*F1*	
# 146 584	H8	*G1*	
# 144 391	B8	h2	
# 147 424	B12	f2	
# 142 479	H4	*E1*	
# 145 934	H5	*A1*	
# 144 226	H8	*H2*	
# 143 111	H9	*F2*	

Figure 8: modules serial numbers and their position in the plant.

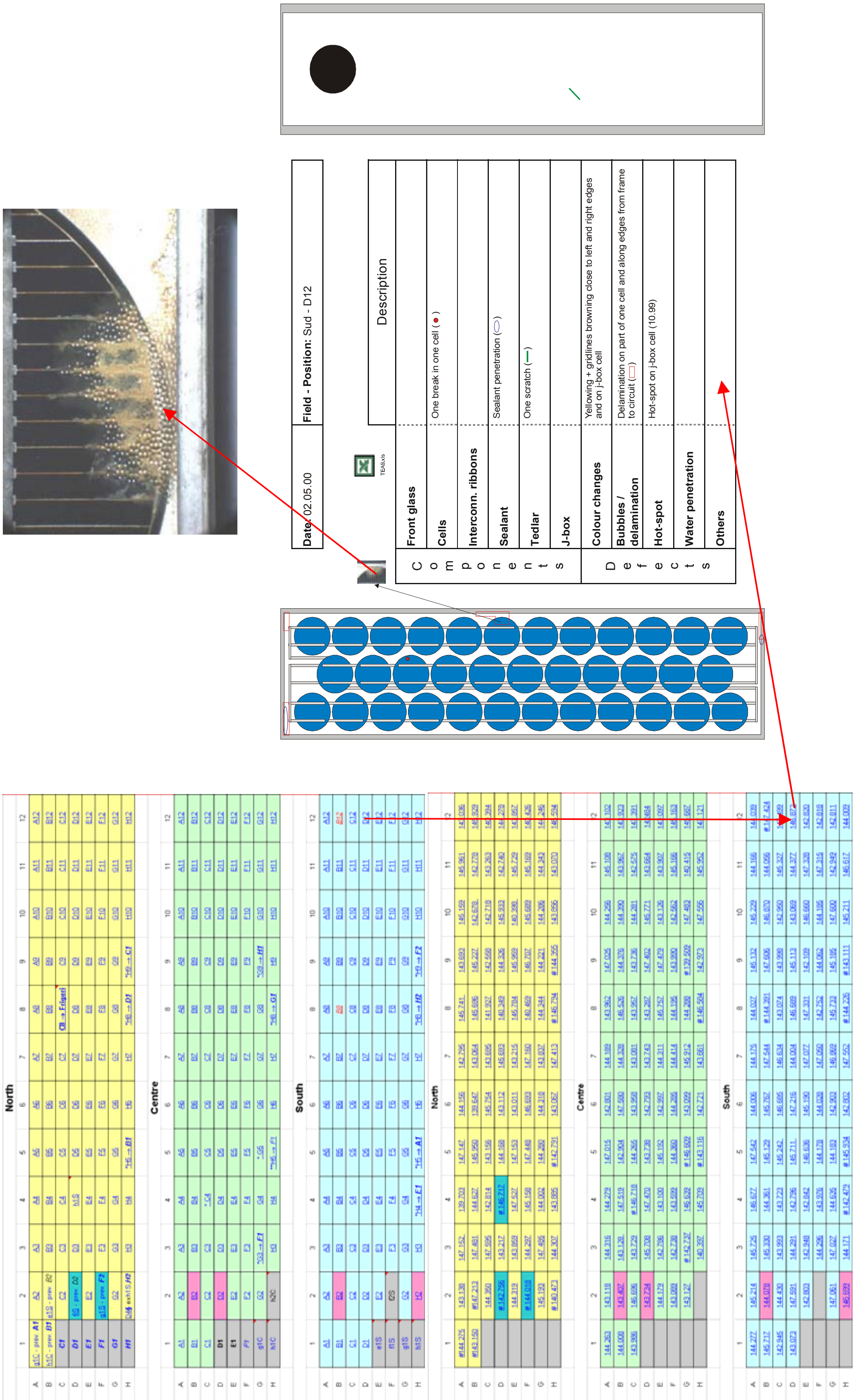


Figure 9: example of how to get to visual inspection data of each module starting from its position code.

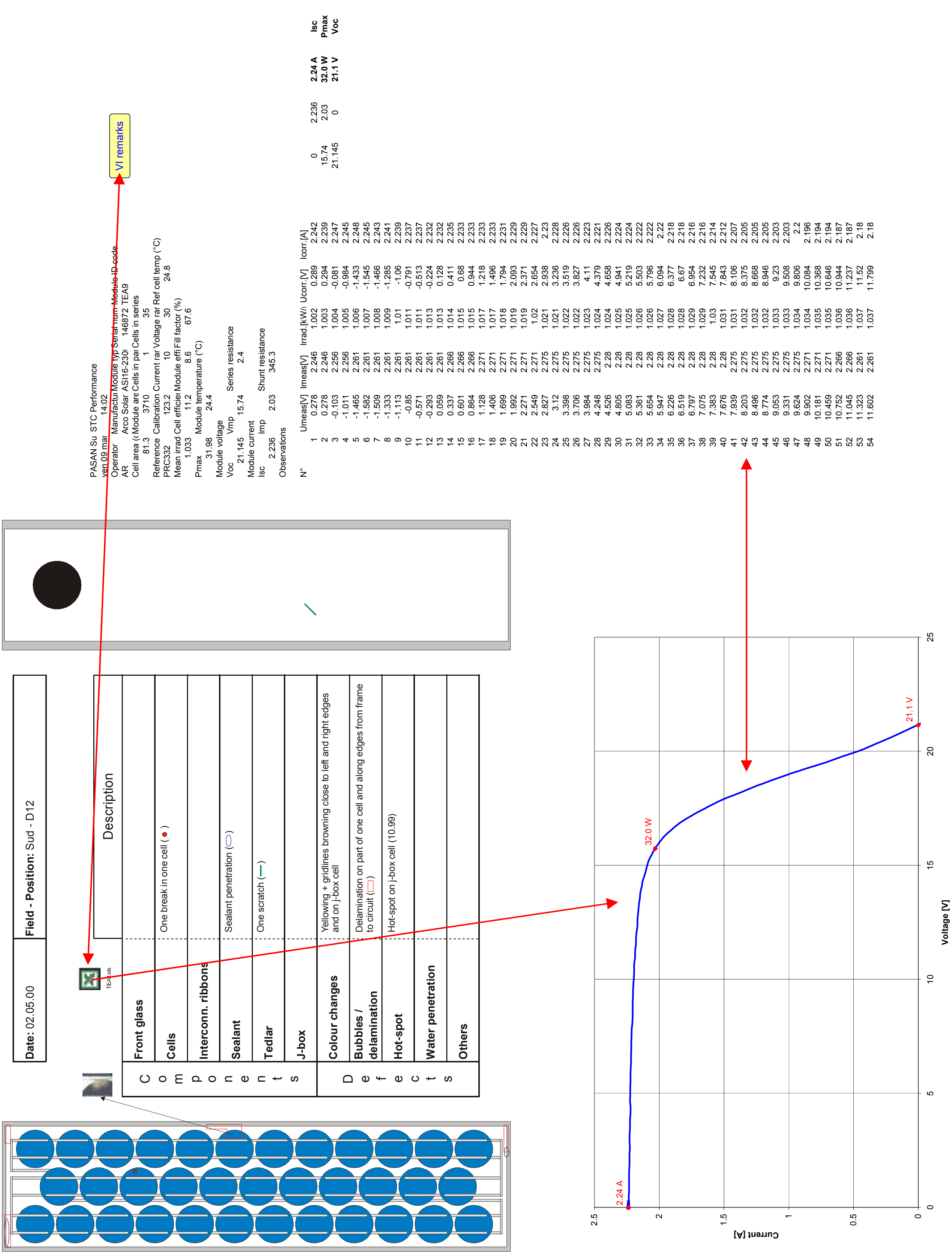


Figure 10: example of links between visual inspection data and performance measurements results.

6 Work programme description

In this chapter the description of the main work executed (measurements, inspections, etc.) is given.

6.1 Insulation test

The purpose of the insulation test is to determine whether or not the modules are sufficiently well insulated between current carrying parts and the frame.

The presence of encapsulant delamination close to edges could affect the module insulation. For this reason, heavy delaminated modules have been tested.

The procedure, as defined in the International Standard IEC61215 [5], is described below:

- Connect the shorted output terminals of the module to the positive terminal of a DC insulation tester with a current limitation
- Connect the exposed metal parts of the module to the negative terminal of the tester
- Increase the voltage applied by the tester to 1000 V plus twice the maximum system voltage. For ASI 16-2300: 1000 V + (500 V * 2)= 2000 V
- Reduce the applied voltage to zero and short-circuit the terminals of the tester for 5 minutes, while still connected to the module
- Remove the short circuit
- Apply a DC voltage of 500 V to the module and determine the insulation resistance.

The module is to be considered well insulated if no dielectric breakdown (less than 50 μA) or surface cracking occur during the application of higher voltage, and if insulation resistance is not less than 50 MΩ.

6.2 Visual Inspection

The purpose of the visual inspection is the detection of any visual defect in the module.

With reference to the International Standard IEC 61215 [5], each module of the plant has been carefully inspected to check the presence of the following visual defects:

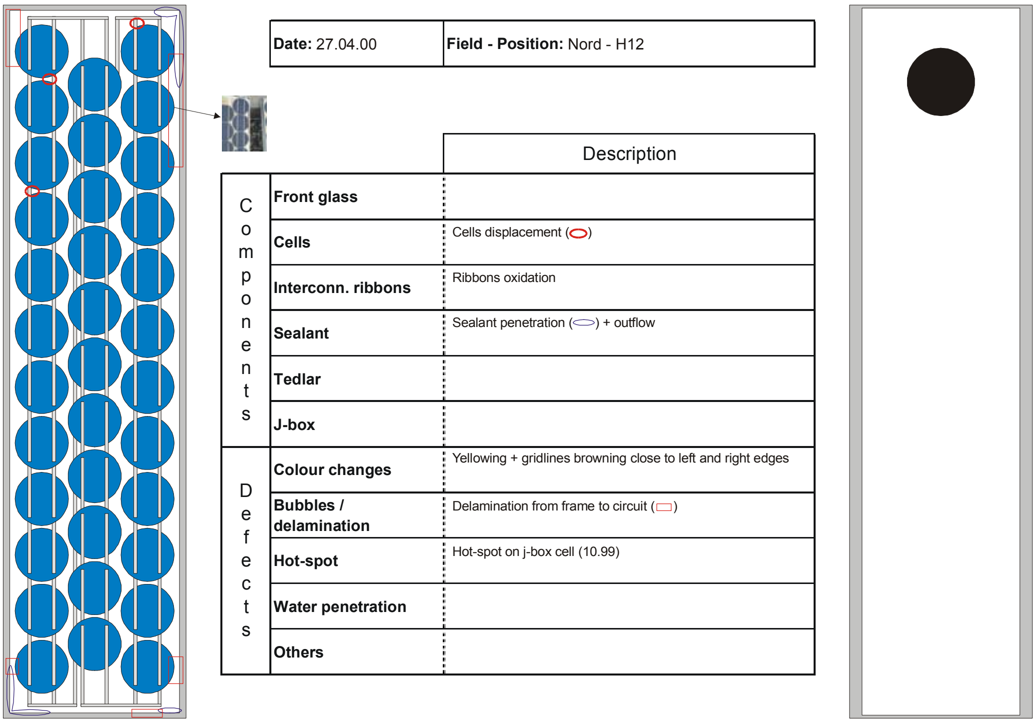
- Crack, bent, misaligned or torn external surface
- Broken cells
- Cracked cells
- Faulty interconnections or joints
- Cells touching one another or the frame
- Failure of adhesive bonds
- Bubbles or delamination
- Tacky surfaces of plastic materials
- Faulty terminations, exposed live electrical parts
- Any other conditions which may affect performance (e.g. changes in encapsulant transparency)
- Any other detected defects (colour changes, backsheet detachment, etc.) has been signalized.

The International Standard IEC 61215 [5] define the following anomalies as major visual defects, as they could compromise the good functioning of the module:

- Broken, cracked, bent, misaligned or torn external surface
- A crack in a cell whose propagation could remove more than 10% of that cell’s area from the electrical circuit of the module
- Bubbles or delamination forming a continuous path between any part of the electrical circuit and the edge of the module
- Loss of mechanical integrity, to the extent that the installation and/or operation of the module would be impaired.

Intensive visual inspection of all plant modules has been performed once a year mainly to define the state of the plant and, then, to follow the evolution of the modules physical degradation.

For each module a registration form was created to be filled with annotations of detected anomalies during every inspection (Figure 11). For relevant defects, like heavy delamination, pictures have been taken (their presence is indicated on the visual inspection form by an icon linked to the picture – Figure 11).



Date: 27.04.00	**Field - Position:** Nord - H12	
		Description
Components	**Front glass**	
	Cells	Cells displacement ( )
	Interconn. ribbons	Ribbons oxidation
	Sealant	Sealant penetration ( ) + outflow
	Tedlar	
	J-box	
Defects	**Colour changes**	Yellowing + gridlines browning close to left and right edges
	Bubbles / delamination	Delamination from frame to circuit ( )
	Hot-spot	Hot-spot on j-box cell (10.99)
	Water penetration	
	Others	

Figure 11: example of visual inspection registration form including remarks.

6.3 Performance measurements

Outdoor and indoor characterizations of the plant modules have been executed as described in the next sub-chapters.

6.3.1 Outdoor measurements

The LEEE-TISO owns an I-V Tracer Solar Systeme Schutt PVCT for the execution of outdoor performance measurements of individual modules and plants (strings of modules and subfields). Two loads are available: one electronic load (100V/20A) and one capacitive load (1000V/25A).

Measurements are performed as close as possible to the Standard Test Condition (1000W/m², 25°C), and results extrapolated with the Blaesser method [6].

Within the MTBF project, outdoor performance measurements of the 12 strings of the plant and of the 2 subfields (positive and negative) have been executed.

6.3.2 Indoor measurements

In January 2000, the LEEE-TISO acquired a Class A large area pulsed sun simulator PASAN III (), which enables to determine the I-V characteristics of PV modules. Measurements are performed at Standard Test Condition (1000W/m², 25°C) in accordance with the International Standard IEC60904-1.

Since June 2001 the I-V curve measurements with the LEEE-TISO sun simulator has been accredited (ISO 17025) by the Swiss Accreditation Service (STS 309).

The individual performance measurement of all plant modules has been executed once to determine the electrical state of each device and correlate it to the eventual presence of physical defects.

6.4 Infra-red analysis

The infra-red analysis of PV modules under normal operating conditions enables to verify their thermal uniformity and, consequently, to detect the presence of hot-spots.

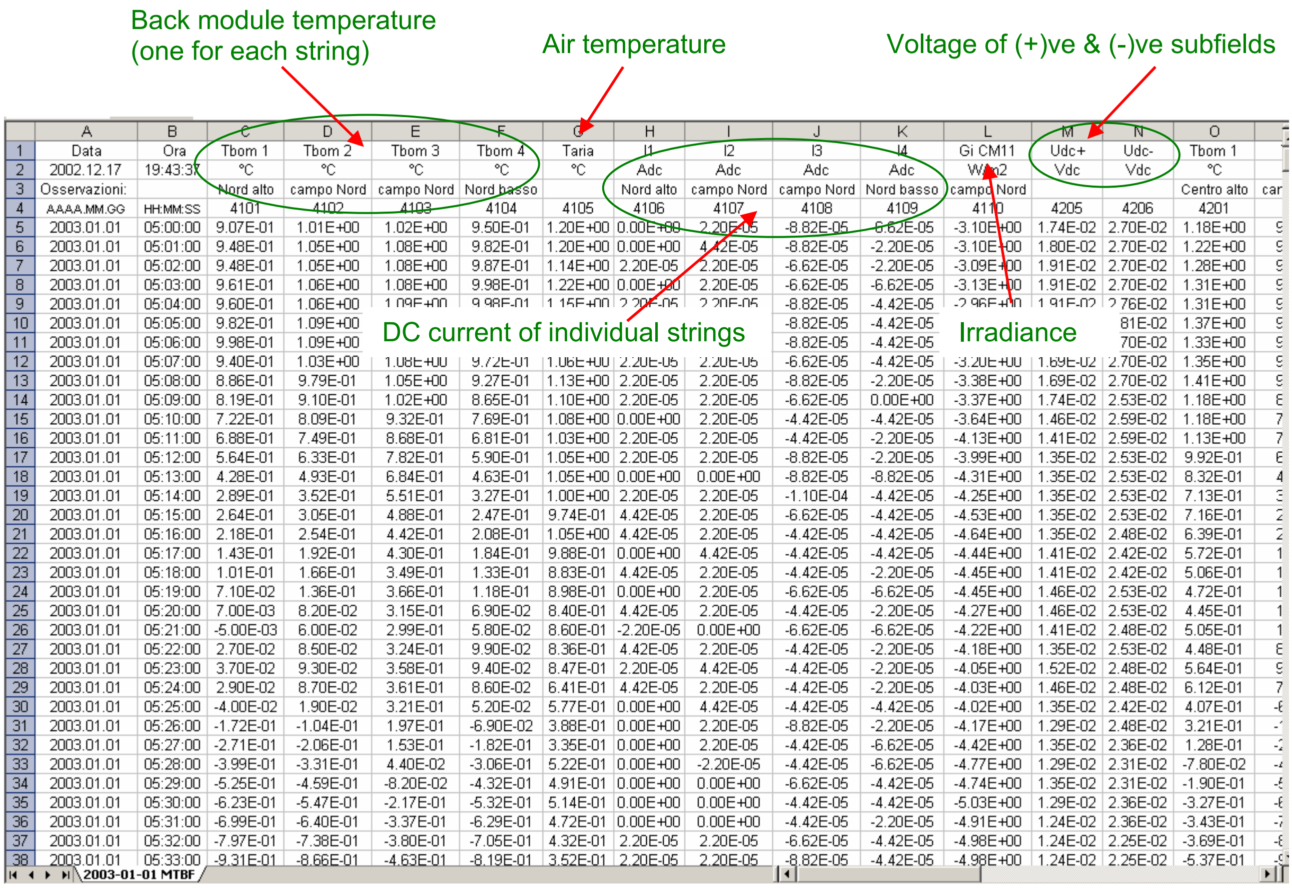
Hot-spots may occur in c-Si modules when one or more cells are mismatched in relation to the others. This may be when they are partially or entirely shaded; it can also be caused by cracked or mismatched cells and interconnection failures. In these situations, the electrical parameters of the affected cell are shifted into reverse bias mode and, instead of producing electrical energy, it dissipates that generated by the rest of the string. This could lead to a considerable local overheating and, consequently, provoke module damage, like solder melting or encapsulant deterioration. So hot-spot resistance of a PV module is a quality feature of the device and is essential to its lifetime.

For the execution of the infra-red analysis, the LEEE-TISO has at its disposal a Thermovision 570 Agema camera (sensitivity <0.15°C. accuracy ± 2%). As in the case of visual inspection, the thermal control of the plant has been performed once a year.

6.5 Daily production data acquisition

Since its installation, the plant production has been continuously monitored and recorded. The acquisition systems used since 1982 have been described in Chapters 3.2.2 and 3.2.3.

In June 2000 a new data acquisition system was set up (Agilent 34970A datalogger) allowing to record the individual strings production data every minute from 5.00 a.m. to 10.00 p.m.; an example of the type of the stored data is given in Figure 12.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Data	Ora	Tbom 1	Tbom 2	Tbom 3	Tbom 4	Taria	I1	I2	I3	I4	Gi CM11	Udc+	Udc-	Tbom 1
2	2002.12.17	19:43:37	°C	°C	°C	°C	°C	Adc	Adc	Adc	Adc	W/m2	Vdc	Vdc	°C
3	Osservazioni:		Nord alto	campo Nord	campo Nord	Nord basso		Nord alto	campo Nord	campo Nord	Nord basso	campo Nord			Centro alto
4	AAAA.MM.GG	HH:MM:SS	4101	4102	4103	4104	4105	4106	4107	4108	4109	4110	4205	4206	4201
5	2003.01.01	05:00:00	9.07E-01	1.01E+00	1.02E+00	9.50E-01	1.20E+00	0.00E+00	2.20E-05	-8.82E-05	-6.62E-05	-3.10E+00	1.74E-02	2.70E-02	1.18E+00
6	2003.01.01	05:01:00	9.48E-01	1.05E+00	1.08E+00	9.82E-01	1.20E+00	0.00E+00	4.42E-05	-8.82E-05	-2.20E-05	-3.10E+00	1.80E-02	2.70E-02	1.22E+00
7	2003.01.01	05:02:00	9.48E-01	1.05E+00	1.08E+00	9.87E-01	1.14E+00	2.20E-05	2.20E-05	-6.62E-05	-2.20E-05	-3.09E+00	1.91E-02	2.70E-02	1.28E+00
8	2003.01.01	05:03:00	9.61E-01	1.06E+00	1.08E+00	9.98E-01	1.22E+00	0.00E+00	2.20E-05	-6.62E-05	-6.62E-05	-3.13E+00	1.91E-02	2.70E-02	1.31E+00
9	2003.01.01	05:04:00	9.60E-01	1.06E+00	1.09E+00	9.98E-01	1.15E+00	2.20E-05	2.20E-05	-8.82E-05	-4.42E-05	-2.96E+00	1.91E-02	2.76E-02	1.31E+00
10	2003.01.01	05:05:00	9.82E-01	1.09E+00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-8.82E-05	-4.42E-05	[illegible]	[illegible]	[illegible]	1.37E+00
11	2003.01.01	05:06:00	9.98E-01	1.09E+00	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-8.82E-05	-4.42E-05	[illegible]	[illegible]	[illegible]	1.33E+00
12	2003.01.01	05:07:00	9.40E-01	1.03E+00	1.08E+00	9.72E-01	1.06E+00	2.20E-05	2.20E-05	-6.62E-05	-4.42E-05	-3.20E+00	1.69E-02	2.70E-02	1.35E+00
13	2003.01.01	05:08:00	8.86E-01	9.79E-01	1.05E+00	9.27E-01	1.13E+00	2.20E-05	2.20E-05	-8.82E-05	-2.20E-05	-3.38E+00	1.69E-02	2.70E-02	1.41E+00
14	2003.01.01	05:09:00	8.19E-01	9.10E-01	1.02E+00	8.65E-01	1.10E+00	2.20E-05	2.20E-05	-6.62E-05	0.00E+00	-3.37E+00	1.74E-02	2.53E-02	1.18E+00
15	2003.01.01	05:10:00	7.22E-01	8.09E-01	9.32E-01	7.69E-01	1.08E+00	0.00E+00	2.20E-05	-4.42E-05	-4.42E-05	-3.64E+00	1.46E-02	2.59E-02	1.18E+00
16	2003.01.01	05:11:00	6.88E-01	7.49E-01	8.68E-01	6.81E-01	1.03E+00	2.20E-05	2.20E-05	-4.42E-05	-2.20E-05	-4.13E+00	1.41E-02	2.59E-02	1.13E+00
17	2003.01.01	05:12:00	5.64E-01	6.33E-01	7.82E-01	5.90E-01	1.05E+00	2.20E-05	2.20E-05	-8.82E-05	-2.20E-05	-3.99E+00	1.35E-02	2.53E-02	9.92E-01
18	2003.01.01	05:13:00	4.28E-01	4.93E-01	6.84E-01	4.63E-01	1.05E+00	0.00E+00	0.00E+00	-8.82E-05	-8.82E-05	-4.31E+00	1.35E-02	2.53E-02	8.32E-01
19	2003.01.01	05:14:00	2.89E-01	3.52E-01	5.51E-01	3.27E-01	1.00E+00	2.20E-05	2.20E-05	-1.10E-04	-4.42E-05	-4.25E+00	1.35E-02	2.53E-02	7.13E-01
20	2003.01.01	05:15:00	2.64E-01	3.05E-01	4.88E-01	2.47E-01	9.74E-01	4.42E-05	2.20E-05	-6.62E-05	-4.42E-05	-4.53E+00	1.35E-02	2.53E-02	7.16E-01
21	2003.01.01	05:16:00	2.18E-01	2.54E-01	4.42E-01	2.08E-01	1.05E+00	4.42E-05	2.20E-05	-4.42E-05	-4.42E-05	-4.64E+00	1.35E-02	2.48E-02	6.39E-01
22	2003.01.01	05:17:00	1.43E-01	1.92E-01	4.30E-01	1.84E-01	9.88E-01	0.00E+00	4.42E-05	-4.42E-05	-4.42E-05	-4.44E+00	1.41E-02	2.42E-02	5.72E-01
23	2003.01.01	05:18:00	1.01E-01	1.66E-01	3.49E-01	1.33E-01	8.83E-01	4.42E-05	2.20E-05	-4.42E-05	-2.20E-05	-4.45E+00	1.41E-02	2.42E-02	5.06E-01
24	2003.01.01	05:19:00	7.10E-02	1.36E-01	3.66E-01	1.18E-01	8.98E-01	0.00E+00	2.20E-05	-6.62E-05	-6.62E-05	-4.45E+00	1.46E-02	2.53E-02	4.72E-01
25	2003.01.01	05:20:00	7.00E-03	8.20E-02	3.15E-01	6.90E-02	8.40E-01	4.42E-05	2.20E-05	-4.42E-05	-2.20E-05	-4.27E+00	1.46E-02	2.53E-02	4.45E-01
26	2003.01.01	05:21:00	-5.00E-03	6.00E-02	2.99E-01	5.80E-02	8.60E-01	-2.20E-05	0.00E+00	-6.62E-05	-6.62E-05	-4.22E+00	1.41E-02	2.48E-02	5.05E-01
27	2003.01.01	05:22:00	2.70E-02	8.50E-02	3.24E-01	9.90E-02	8.36E-01	4.42E-05	2.20E-05	-4.42E-05	-2.20E-05	-4.18E+00	1.35E-02	2.53E-02	4.48E-01
28	2003.01.01	05:23:00	3.70E-02	9.30E-02	3.58E-01	9.40E-02	8.47E-01	2.20E-05	4.42E-05	-4.42E-05	-2.20E-05	-4.05E+00	1.52E-02	2.48E-02	5.64E-01
29	2003.01.01	05:24:00	2.90E-02	8.70E-02	3.61E-01	8.60E-02	6.41E-01	4.42E-05	2.20E-05	-4.42E-05	-2.20E-05	-4.03E+00	1.46E-02	2.48E-02	6.12E-01
30	2003.01.01	05:25:00	-4.00E-02	1.90E-02	3.21E-01	5.20E-02	5.77E-01	0.00E+00	4.42E-05	-4.42E-05	-4.42E-05	-4.02E+00	1.35E-02	2.42E-02	4.07E-01
31	2003.01.01	05:26:00	-1.72E-01	-1.04E-01	1.97E-01	-6.90E-02	3.88E-01	0.00E+00	2.20E-05	-8.82E-05	-2.20E-05	-4.17E+00	1.29E-02	2.48E-02	3.21E-01
32	2003.01.01	05:27:00	-2.71E-01	-2.06E-01	1.53E-01	-1.82E-01	3.35E-01	0.00E+00	2.20E-05	-4.42E-05	-6.62E-05	-4.42E+00	1.35E-02	2.36E-02	1.28E-01
33	2003.01.01	05:28:00	-3.99E-01	-3.31E-01	4.40E-02	-3.06E-01	5.22E-01	0.00E+00	-2.20E-05	-4.42E-05	-6.62E-05	-4.77E+00	1.29E-02	2.31E-02	-7.80E-02
34	2003.01.01	05:29:00	-5.25E-01	-4.59E-01	-8.20E-02	-4.32E-01	4.91E-01	0.00E+00	0.00E+00	-6.62E-05	-4.42E-05	-4.74E+00	1.35E-02	2.31E-02	-1.90E-01
35	2003.01.01	05:30:00	-6.23E-01	-5.47E-01	-2.17E-01	-5.32E-01	5.14E-01	0.00E+00	0.00E+00	-4.42E-05	-4.42E-05	-5.03E+00	1.29E-02	2.36E-02	-3.27E-01
36	2003.01.01	05:31:00	-6.99E-01	-6.40E-01	-3.37E-01	-6.29E-01	4.72E-01	0.00E+00	0.00E+00	-4.42E-05	-2.20E-05	-4.91E+00	1.24E-02	2.36E-02	-3.43E-01
37	2003.01.01	05:32:00	-7.97E-01	-7.38E-01	-3.80E-01	-7.05E-01	4.32E-01	2.20E-05	2.20E-05	-6.62E-05	-4.42E-05	-4.98E+00	1.24E-02	2.25E-02	-3.69E-01
38	2003.01.01	05:33:00	-9.31E-01	-8.66E-01	-4.63E-01	-8.19E-01	3.52E-01	2.20E-05	2.20E-05	-8.82E-05	-4.42E-05	-4.98E+00	1.24E-02	2.25E-02	-5.37E-01

Figure 12: example of data recorded by the acquisition system in use since June 2000.

From the analysis of such a data it is possible to compare the different behaviour of individual strings in different temperature and irradiance conditions and, in presence of an electrical fault, to faster localize it.

Figure 13 and Figure 14 represent an example of analysis of recorded data. Figure 13 shows the production trend of the 12 strings of the plant during a sunny day (total irradiance = 7.15 k/m²) in summer (11th August 2001, mean air temperature = 22.9°C). For the same day, the positive and negative sub-fields behaviours are represented in Figure 14.

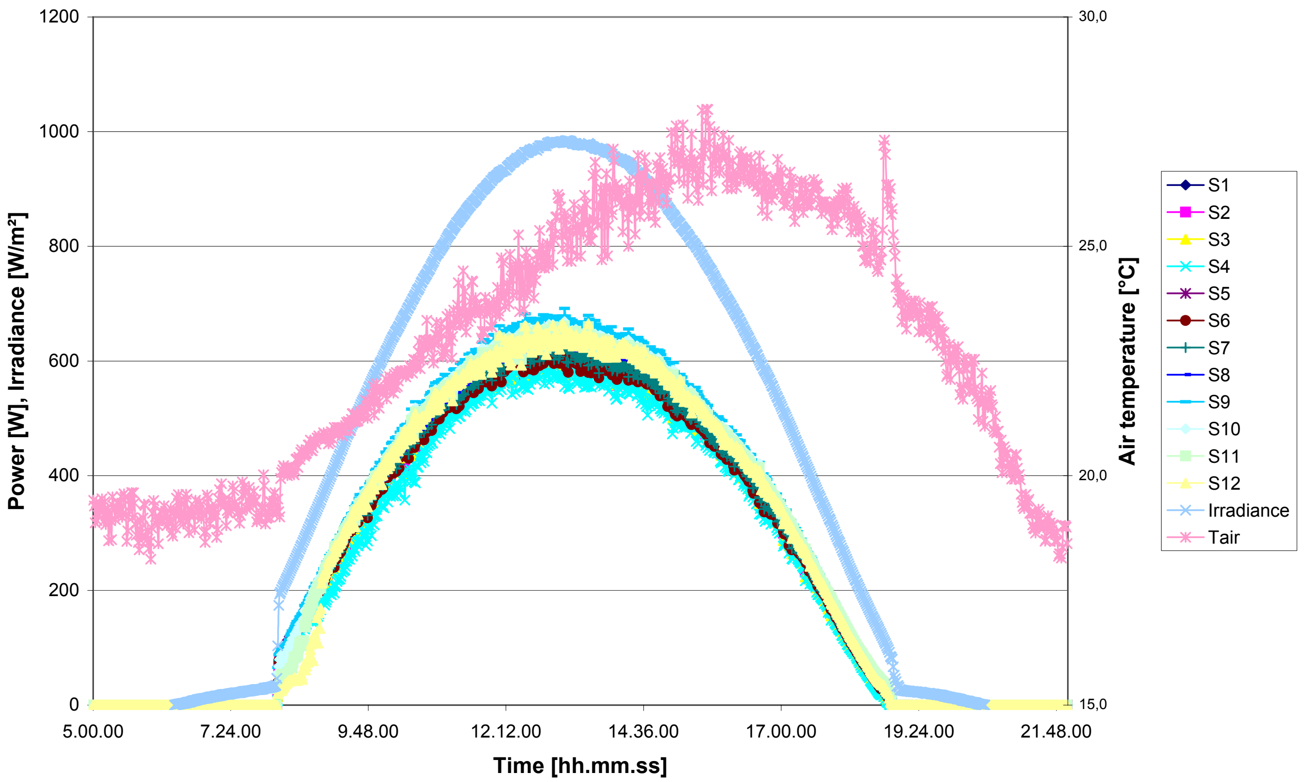


Figure 13: plant strings power production with reference to irradiance and temperature trends.

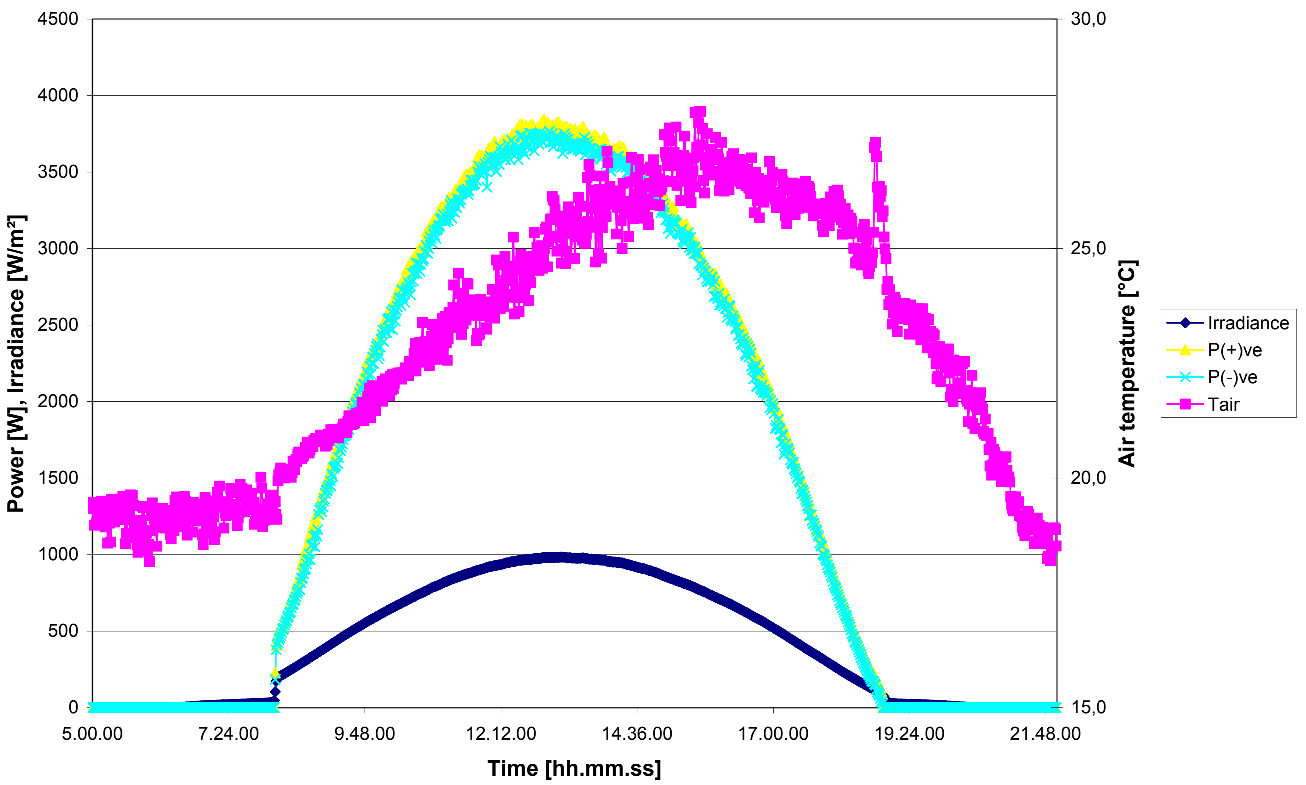


Figure 14: positive and negative sub-fields productions with reference to irradiance and temperature trends.

6.6 International Standard IEC 61215: crystalline silicon terrestrial PV modules – design qualification and type approval

In attempt to predict the failure mechanisms which could determine the lifetime of the ASI 16-2300, a batch of 10 modules has been removed from the plant and 8 of these have been subjected to repeated sequences of the IEC 61215 type approval tests.

One module has been kept as control device for performance measurements, while the remaining 7 modules have been divided into groups and subjected to different test sequences.

6.6.1 Summary of tests

- **UV exposure (UVE):** to determine the ability of the module to withstand exposure to ultra-violet (UV) radiation. Module subjected to 15 kWh/m² UV radiation in band from 280 – 400 nm. Module temperature maintained at 60°C ± 5°C.
- **Thermal cycling (TC50 – TC200):** to determine the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by repeated changes of temperature. Temperature range -40°C to +85°C, maximum rate of change of temperature 100°C/hour, repeated 50 or 200 times (depending on the tests sequence). Electrical continuity monitored throughout test.
- **Humidity freeze (HUF):** to determine the ability of the module to withstand the effects of high temperature and humidity followed by sub-zero temperatures. Cycle parameters: 85°C and 85% relative humidity for 20 hours, followed by cooling to -40°C; repeated 10 times. Maximum rate of change of temperature 200°C/hour. Electrical continuity monitored throughout test.
- **Damp heat (DAH):** to determine the ability of the module to withstand the effects of long-term penetration of humidity. Module stored for 1000 hours at 85°C and 85% relative humidity.
- **Robustness of termination (ROB):** to determine whether the terminations and the attachment of the terminations to the body of the module will withstand such stresses as are likely to be applied during normal assembly or handling operations.
- **Twist (TW):** to detect defects which might be caused to the module when mounted on an imperfect structure. Three corners of module fixed, fourth corner displaced perpendicular to module plane by distance $d=0.021*(l^2+w^2)^{1/2}$, where l=module length and w=module width. Electrical continuity monitored throughout test.
- **Mechanical load (MEL):** to determine the ability of the module to withstand wind, snow and ice loads. Load of 2400 Pa applied uniformly to front surface, while electrical continuity is monitored.
- **Hail resistance (HAR):** to verify that the module is capable of withstanding the impact of hailstones. Module subjected to 11 impacts of 25 mm diameter ice spheres with velocity 23 m/s.

Visual inspection, STC performance measurements and insulation test, already briefly described in, and, are repeated after each step of the test sequence.

The modules are judged qualified, so capable of withstanding prolonged exposure in normal open air temperate climate free rack mounted condition (about 20 years), if each test sample meets all the following criteria:

- the degradation of maximum output power at STC does not exceed the prescribed limit after qualification tests
- no sample has exhibited any open-circuit or ground fault during the tests
- there is no visual evidence of a major defect (Chapter 6.2)
- the insulation test requirements are met after the tests.

7 ASI 16-2300 technical data

Arco Solar Inc., purchased by Siemens Solar Industries in 1990, fabricated the ASI 16-2300 modules.

The principal modules characteristics are described below:

- Nominal power = 37 Wp
- 35 sc-Si cell (Ø 102.5 mm)
- texture-etched
- silver front grid contacts (screen printing)
- Tempered glass
- Poly-vinyl-butyral encapsulant (PVB)
- Tedlar / metal foil/ tedlar backsheet
- Edges sealed with butyral hot melt sealant
- Moisture-proof plastic junction box.

It is not certain if PVB is the polymer used for all the modules, or ethyl-vinyl-acetate (EVA) has also been utilized. Indeed, it seems that ASI 16-2300 were fabricated with EVA from one of two suppliers of Arco Solar. A list with the serial numbers of all modules with the request of specification about the used encapsulant was sent to a former-collaborator of Arco Solar, but no responses have been received.

The high propensity of PVB for water absorption dictates the use of an metal foil back-skin to avoid the intrusion of moisture and oxygen, which in presence of elevated temperatures could provoke encapsulant yellowing and/or delamination.

8 Visual inspection results

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, like broken cells and colour changes, were already present during the first years of module exposure.

8.1 Colour changes

Since the beginning, different types of colour changes affected ASI 16-2300 modules, such as yellowing of encapsulant and yellowing/browning of internal Tedlar foil.

The most evident visual defect is the yellowing of the encapsulant. A 1985 TISO publication reports the presence of this type of colour change on 50% of the modules and pointed out to its rapidly increasing during the last 12 months [7]. In 2003, it affected with different intensities the **98%** of the plant. The reason why some modules have remained completely white (Figure 15) could be due to the use of a different encapsulant (Chapter 7), but it is not certain, as both PVB and EVA could be affected by yellowing when exposed to UV light. Furthermore, from the gas chromatography analysis of white and yellow samples removed from two broken modules results the same compound (PVB).

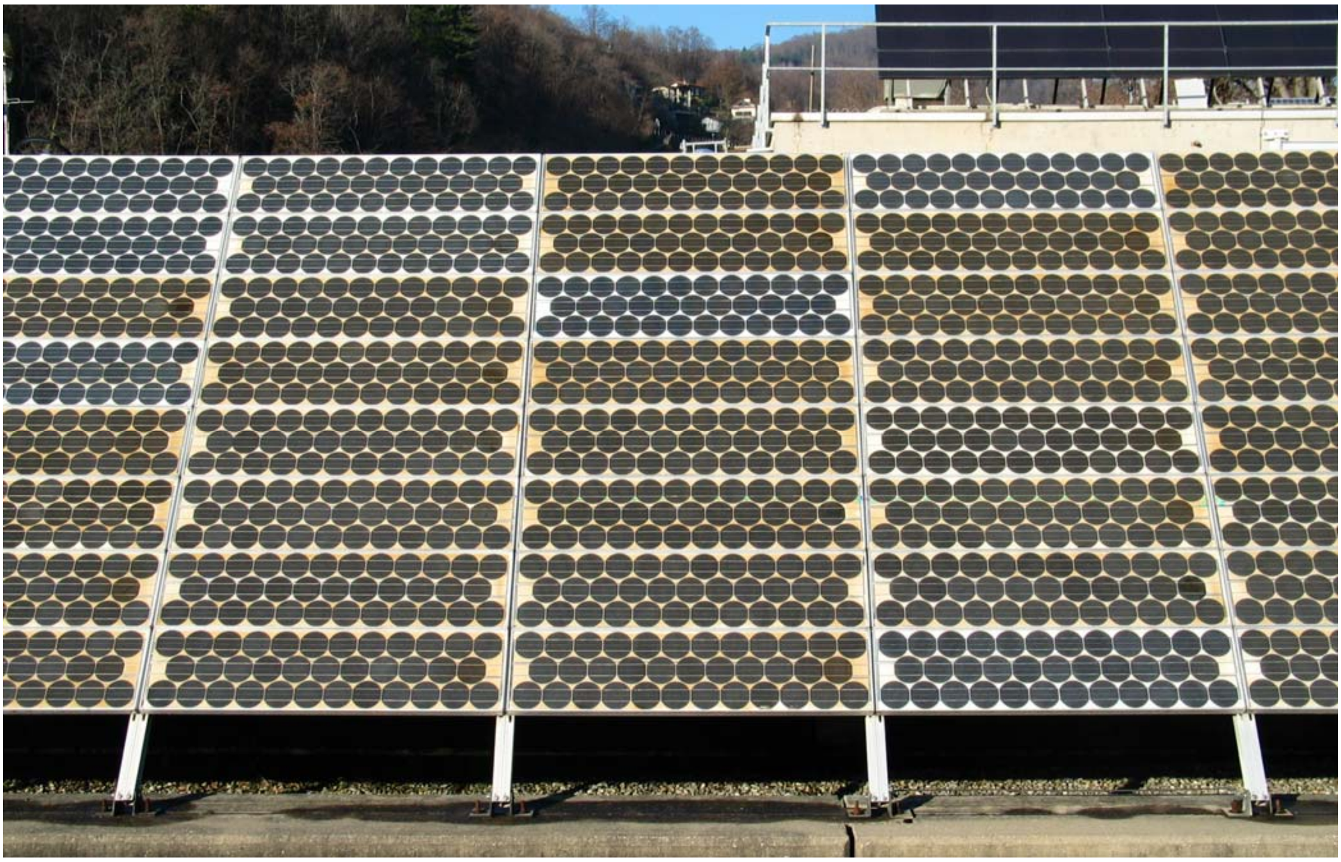


Figure 15: white and yellow modules in one field of TISO 10 kW plant (September 2002).

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 yellowed 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 (Figure 16). The I-V characteristics of the same two modules are compared in Figure 17 (ΔPmax = 4.5%, ΔIsc = 1.3%).

To screen out the UV light (wavelength less than 400 nm), since 1990, a small amount of the element cerium (Ce) has been added to glass formulations used for PV modules.

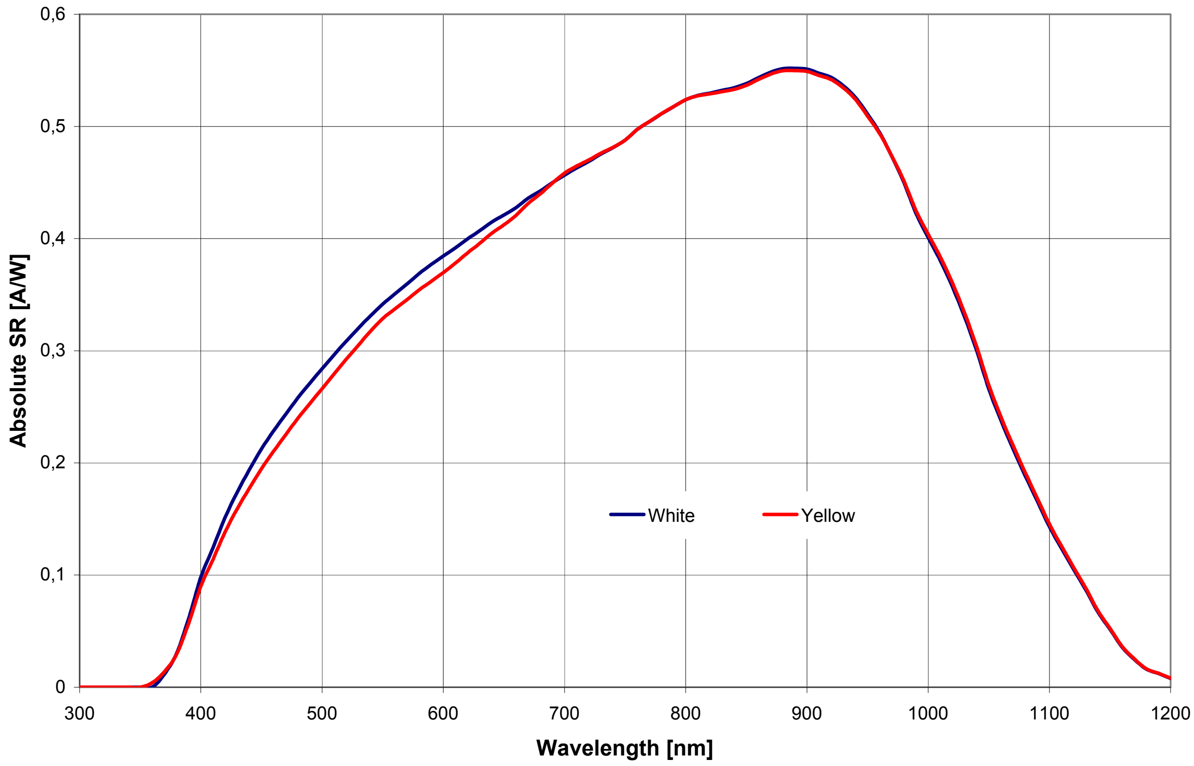


Figure 16: comparison of the absolute spectral responsivity of a white module and a yellow one.

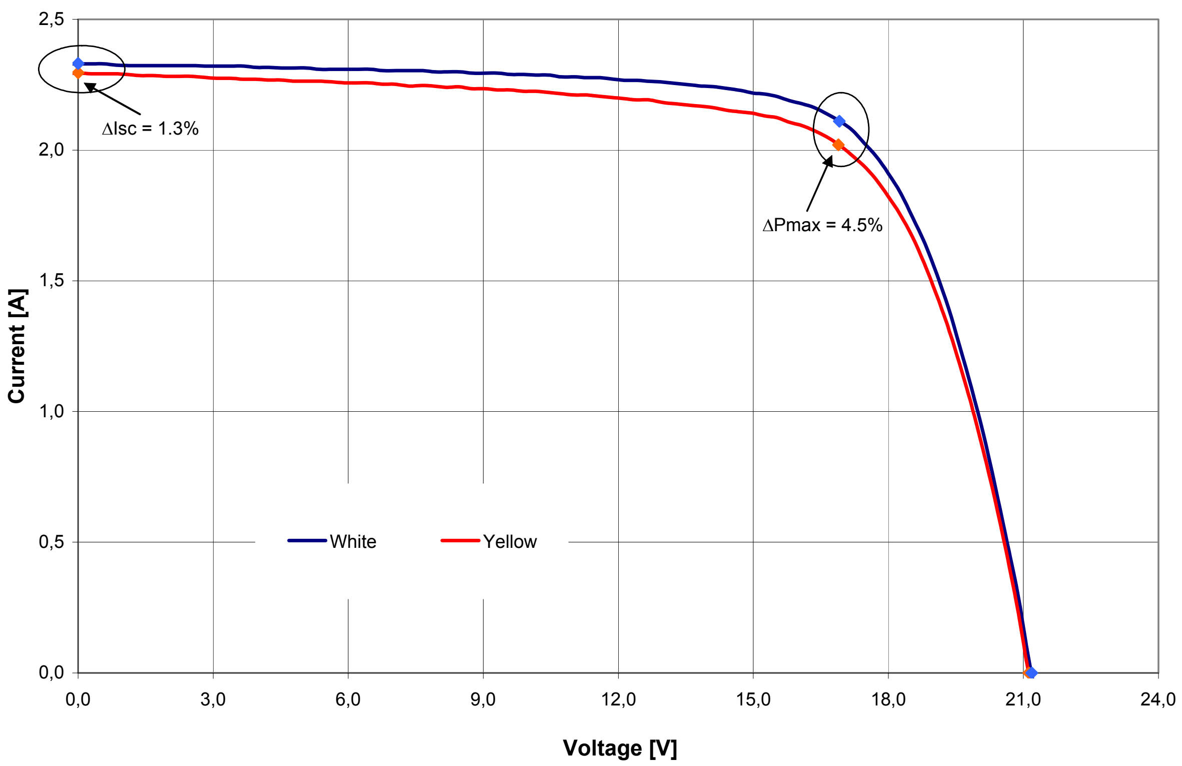


Figure 17: I-V characteristics of a white module and a yellowed one.

Other type of colour changes has been detected, such as browning of the internal Tedlar foil (Figure 18 and Figure 19), and the presence of red areas in correspondence of interconnection ribbons.

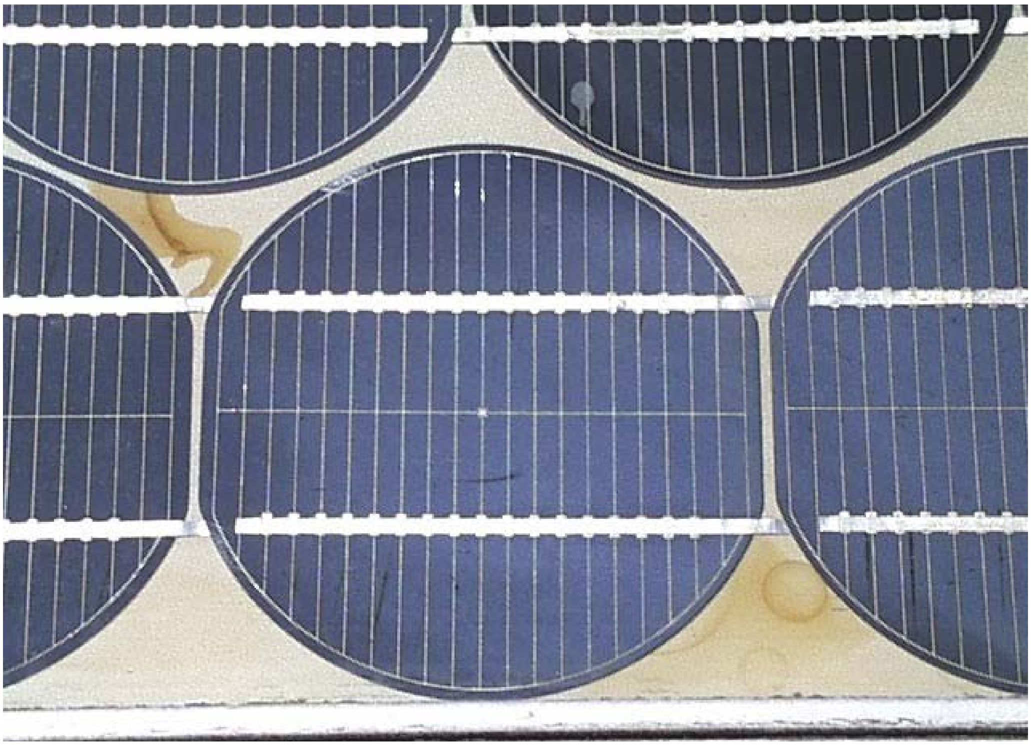


Figure 18: module presenting two different brown areas on internal Tedlar foil.

Figure 19: white module with one brown area on internal Tedlar foil.

8.2 Oxidation

Oxidation has been observed both on cell electrical grid and on the terminals in the junction box.

8.2.1 Cells gridlines

The browning of cells electrical grid was already detected in 1983 [8]; in particular, this phenomenon was associated with the cells sited in front of the junction box (Figure 20). A project final report dated 1984 [9] referred to a document, edited by Arco Solar, in which the browning of electrical grid, previously detected in other plants, was attributed to a PVB encapsulant oxidation accompanied with a catalytic reaction with decomposition products of poly-vinyl-alcohol (PVA). The manufacturer affirmed that this reaction did not involve the silver grid contacts; hence the cell electrical characteristics were not modified. No significant effects were mentioned in regard to PVB optical transmittances.

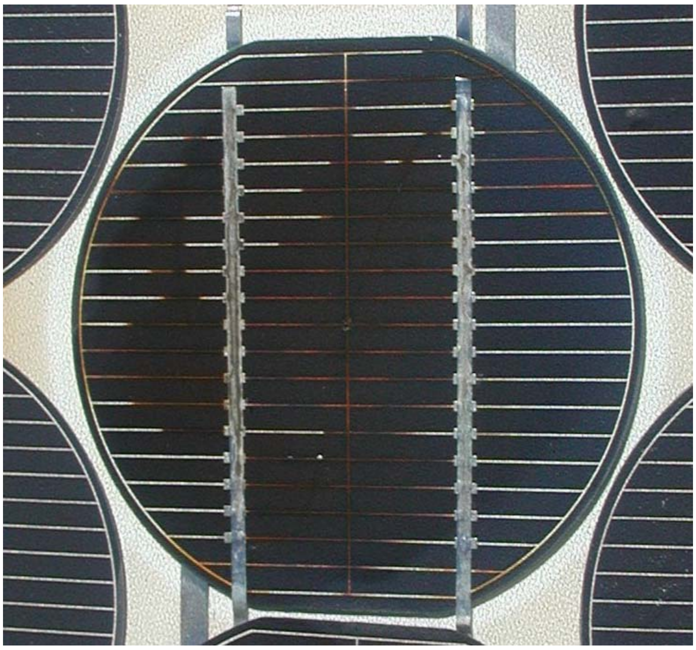


Figure 20: grid-lines oxidation on the cell corresponding to junction box.

In 2003, oxidation, detected on **93%** of the plant modules, also affected the cells close to the edges of the modules (Figure 21). It could be attributed to moisture permeation through the module edges.

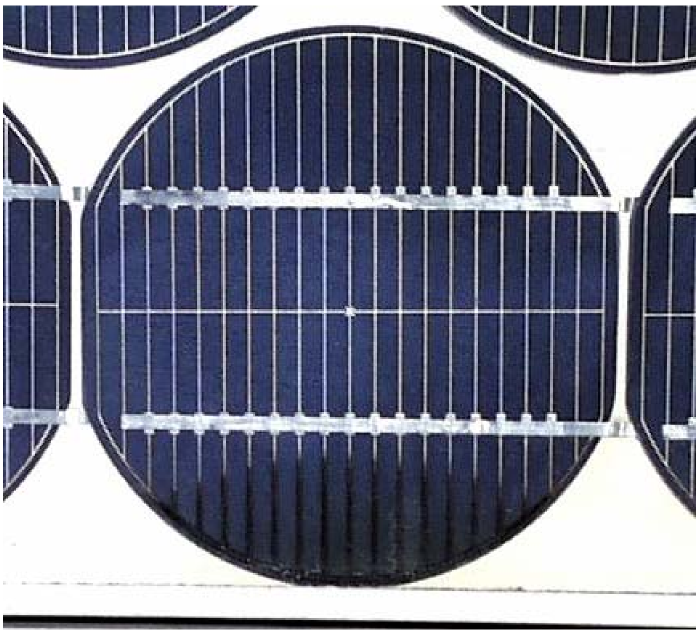


Figure 21: grid oxidation on cell close to module edge.

8.2.2 Terminals

The oxidation of terminals has been detected on **45%** of the plant modules. It is probably caused by the bad sealing of the junction box on the tedlar backsheet which, in turn, leads to loss in insulation resistance (Figure 22). Terminals oxidation results in higher electrical resistance, and could provoke detachment when wiring (Figure 23).

Figure 22: terminal oxidation (worst detected one).

Figure 23: oxidation inside junction-box and detachment of one terminal.

Partially detached terminals could affect module efficiency (hence, the overall plant production). For example, several consecutive indoor performance measurements (one flash about every minute) were executed on one module with a terminal partially detached. During the test no changes, such as settings and connections, have been applied. Results (Figure 24) always gave different electrical characteristics (fluctuating maximum power values).

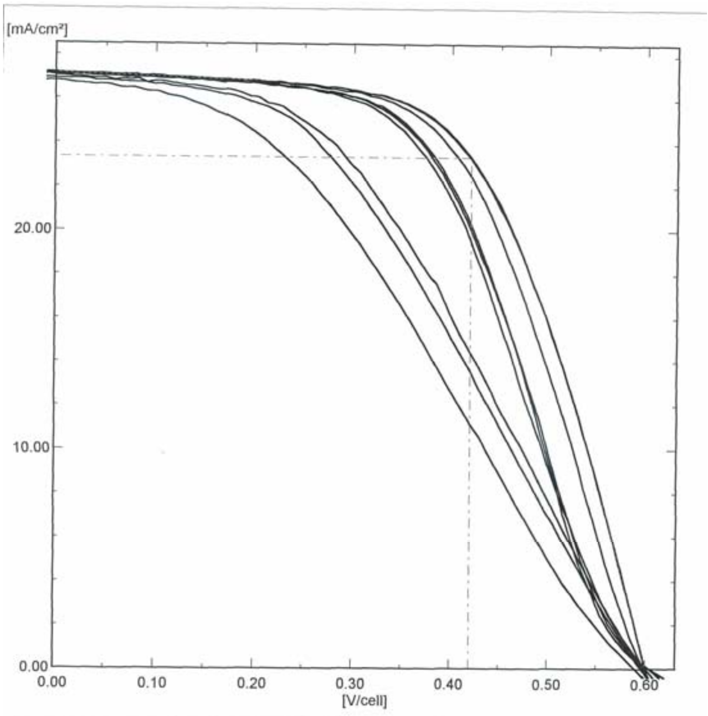


Figure 24: results of a series of I-V measurements on module with one partially detached terminal.

Having no spare modules, detached terminals have been replaced with simple soldered cables (Figure 25).

Figure 25: module with detached terminals repaired with soldered cables.

8.3 Delamination

The encapsulant's primary purpose is to bond the multiple layers of a module together. Delamination, resulting from loss of adhesion between the encapsulant and other module parts, is a degradation mechanism that has to be avoided to achieve 30-year product lifetimes.

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, which is why it has been subsequently substituted by EVA. The use of a metal foil backsheet (Chapter 7), as precaution did not prevent PVB delamination; since 1986 [10], the presence of water infiltration and sealant penetration in some modules was documented. In 2003, 233 modules (**92%** of the plant) showed encapsulant delamination along edges and 191 (76% of the plant) sealant diffusion.

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 were detected for these modules both in wet and dry conditions (Figure 26).

Figure 26: heavy delaminated module subjected to insulation test. No insulation failures detected.

Possible effects of delamination on module efficiency depend on several aspects, in particular when the delamination affects the active cell area.

One module with some cells variously affected by delamination has been analysed. After the execution of performance measurements on individual cells, the power degradation of each damaged cell has been calculated and then compared to the corresponding delaminated area. The results show that performance losses of single cells are proportional to their affected area (Figure 27, Figure 28 and Table 2).

This measurements, executed in 2001, evidenced that the presence of partially delaminated cells does not necessarily significantly affect the overall module efficiency; in this case the module showed no measurable degradation in power, having a maximum of 33 W (mean modules maximum power), similar to other non-delaminated panels.

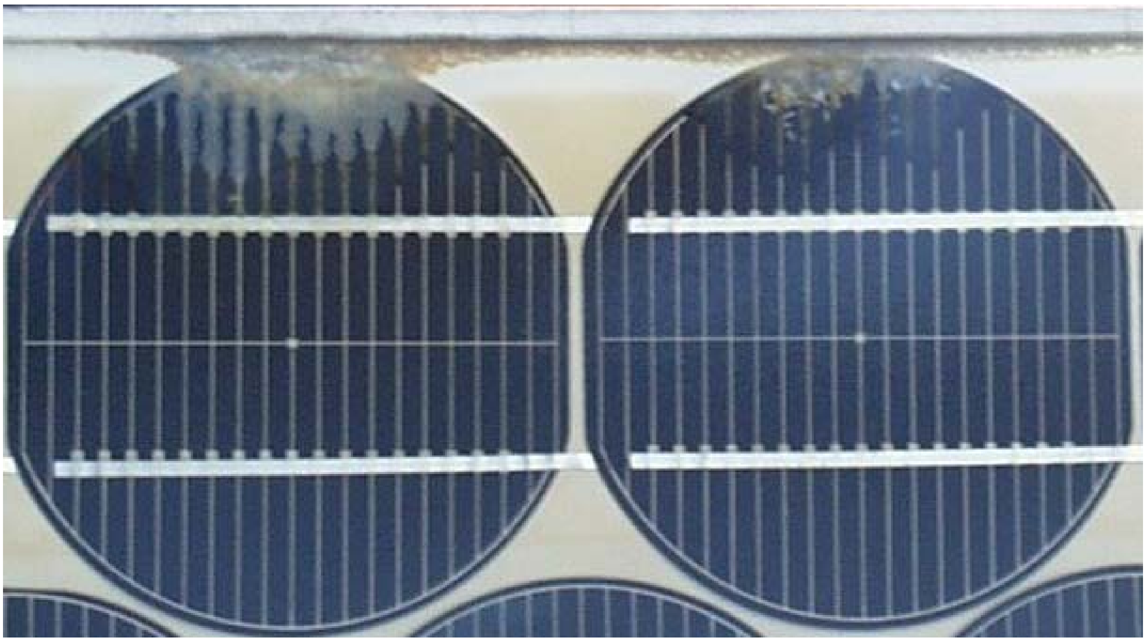


Figure 27: cell 5 (on the left) and cell 6 (on the right) differently affected by delamination in 2001.

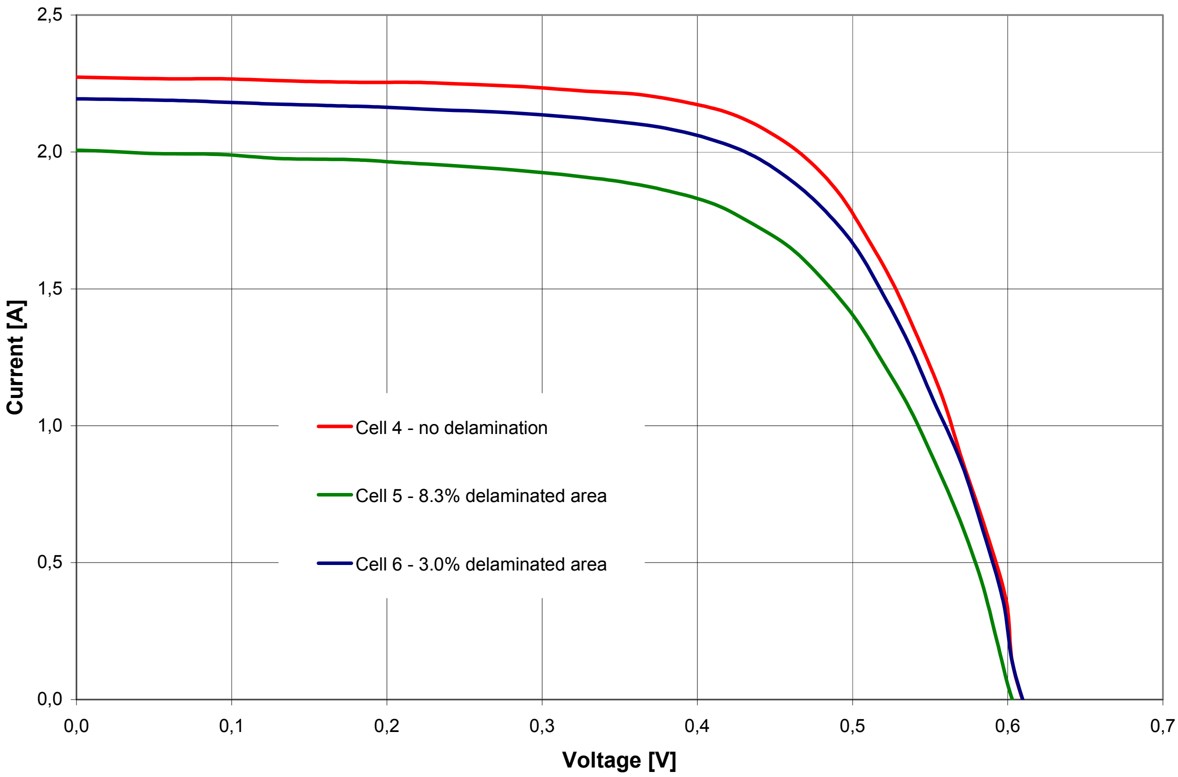


Figure 28: comparison between I-V characteristics of cells 5 and 6 (**Figure 27**) and one of a not delaminated cell.

Cell number (n)	Delaminated area (%)	Pm [W]	ΔPm (%)	Isc [A]	ΔIsc (%)
4	0.0	0.93	-	2.27	-
5	3.0	0.87	-6.5	2.20	-3.4
6	8.3	0.76	-18.3	2.00	-11.7

Table 2: cells performance degradation compared to the cells corresponding area.

During two years, this module has been kept under control to follow the progressive electric degradation related to the cells deterioration. Table 3 shows the differences of the electrical parameters of four differently delaminated cells (Figure 29), detected from 2001 to 2003.

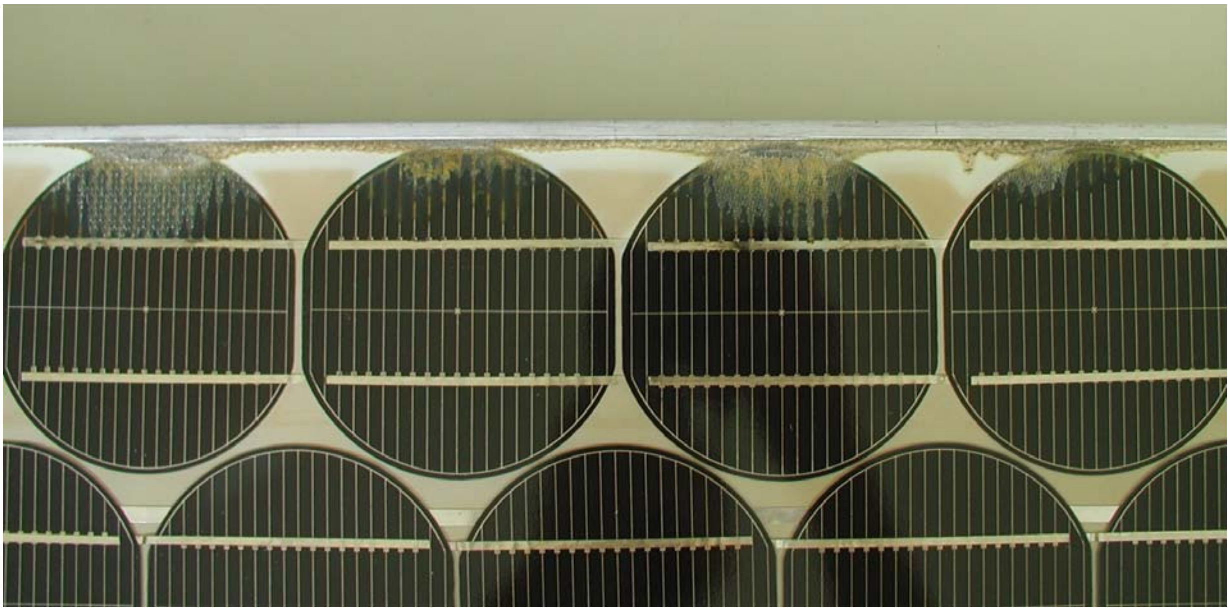


Figure 29: from left to right – cells 5, 6 (same as in **Figure 27**), 7 and 8. Different degrees of delamination detected in 2003.

Cell number	5	6	7	8	***Mean values***
Δ**Pmax**$_{2003-2001}$	-4.1%	-3.6%	-3.9%	-3.6%	*-3.8%*
Δ**Isc**$_{2003-2001}$	-2.8%	-3.8%	-3.0%	-2.4%	*-3.0%*
Δ**Voc**$_{2003-2001}$	1.8%	1.8%	0.7%	1.0%	*1.3%*
Δ**FF**$_{2003-2001}$	-2.5%	-2.2%	-1.0%	-1.1%	*-1.7%*

Table 3: I-V characteristics evolution of 4 differently delaminated cells (**Figure 29**).

With respect to the data obtained in 2001, recent results show that the increase in the number of delaminated cells affects the overall module efficiency, but it involves different parameters. In the last three years, the overall module power degradation has been equal to -2.5%, while the power loss of the cells affected by delamination has been *-3.8%* (Table 3). 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.

	2001	**2002**	**2003**	$\Delta_{2003-2001}$
Pmax [W]	32.8	32.6	31.9	-2.5%
Isc [A]	2.20	2.20	2.19	0.0%
Voc [V]	21.1	21.0	21.0	-0.4%
FF (%)	70.9	70.5	69.4	-2.1%

Table 4: I-V characteristics evolution of the overall module.

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 does not occur.

Another example of the effects of cell delamination increase on module electrical characteristics is shown in Figure 30 and Table 5.

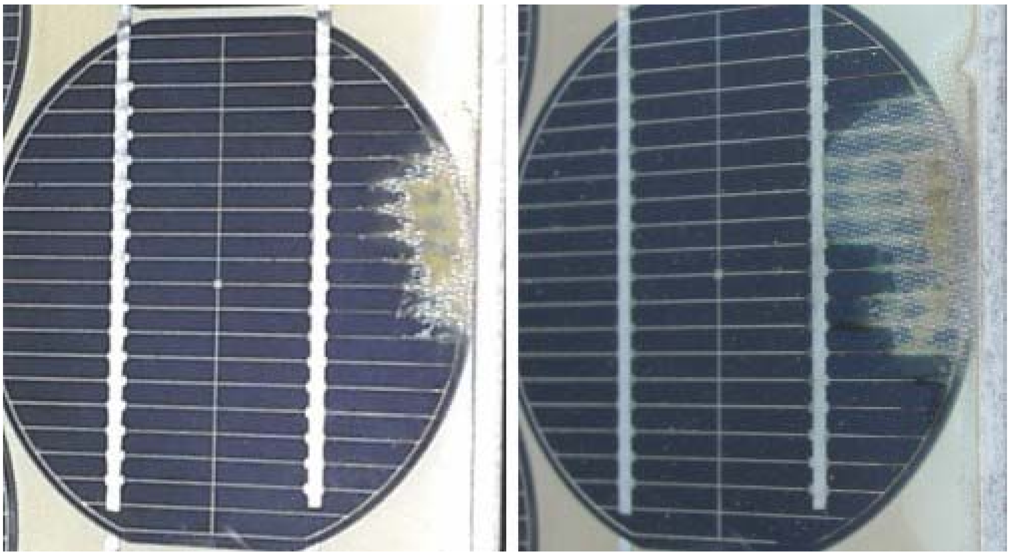


Figure 30: delamination evolution on cell surface from 2001 (left) to 2003 (right).

	2001	2002	2003	$\Delta_{2003\text{-}2001}$
Pmax [W]	32.0	31.7	31.1	-2.8%
Isc [A]	2.24	2.23	2.25	0.5%
Voc [V]	21.1	21.1	21.0	-0.6%
FF (%)	67.6	67.2	65.7	-2.8%

Table 5: I-V characteristics evolution of one module with one delaminated cell (**Figure 30**).

Particular attention has to be paid to modules where delamination affects the area of hot-spotted cells (chapter 9). 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 (Figure 31) (-20.2% and –14.8% with respect to the actual mean module power).

Figure 31: delamination on one hot-spotted cell.

8.4 Broken cells

The presence of broken cells was detected on 20% of plant modules in 1984 [8], and no influence on modules performance was reported. It is possible that all or part of them were damaged since the beginning, as cracked cells with no inactive areas were however used during the module assembling process (Annex 0).

From performance measurements executed on each module emerged that detected cracked cells do not significantly affect modules efficiency; even though their presence is sometimes verifiable by the analysis of the I-V curve shape (Figure 33). In 2003, the percentage of modules with cracked cells increased to **22%**; with new breakages corresponding to hot-spotted cells (Figure 32 and Figure 33).

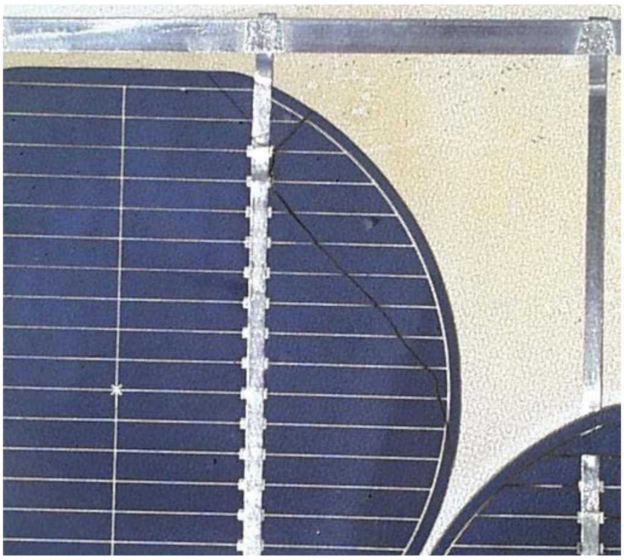


Figure 32: cracked cell which presence is visible in the module I-V curve (**Figure 33**).

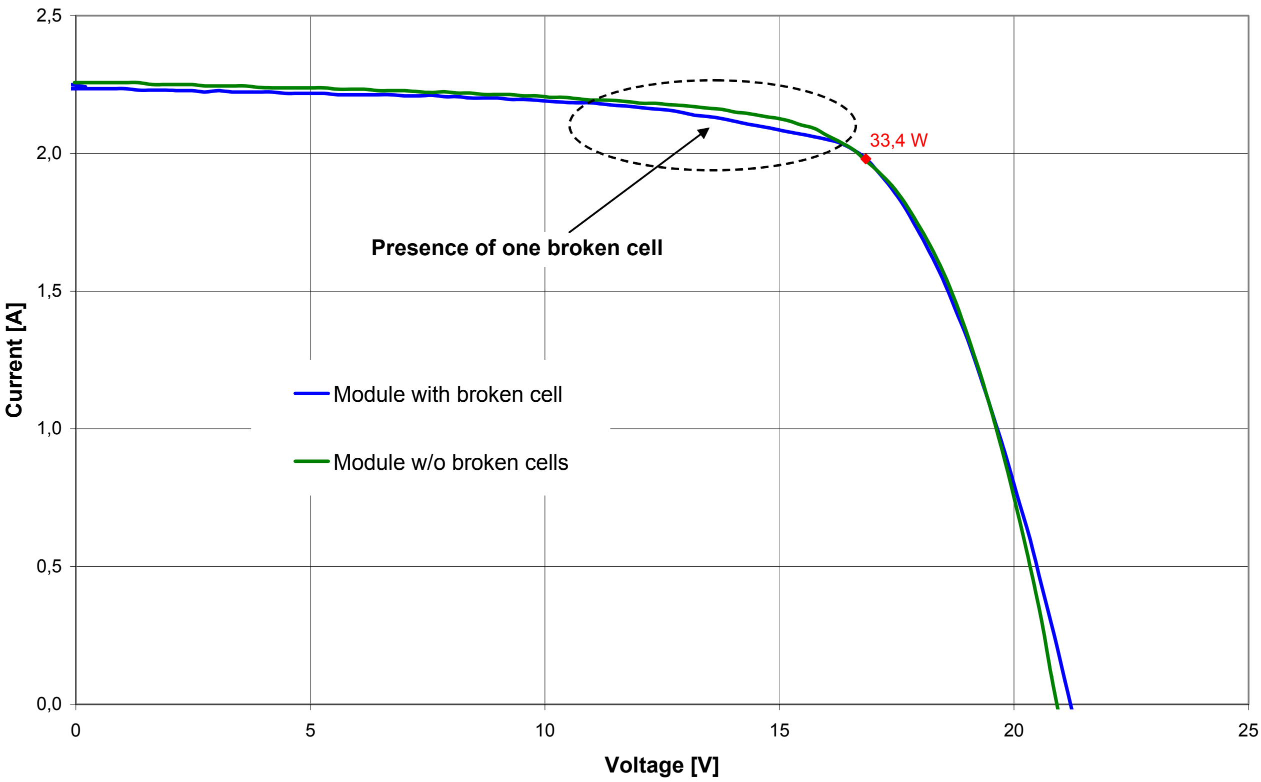


Figure 33: I-V characteristic of a module with one broken cell (**Figure 32**) compared with the one of a device having the same maximum power but no damaged cells.

8.5 Junction box

Since 1992, the junction box has found to be the principal weak point of ASI 16-2300 modules. “The principal weakness discovered in this kind of modules is situated in its terminal box. Terminals directly attached to the back of the cells, water infiltration in the terminal box, overheating of the cell next to the terminal box, unsatisfactory water proofing and poor adhesive qualities of the terminal box are the principal flaws in the kind of connection” [2].

Bad sealed junction boxes have been fixed with silicone and detached terminals replaced with cables (8.2.2, Figure 25).

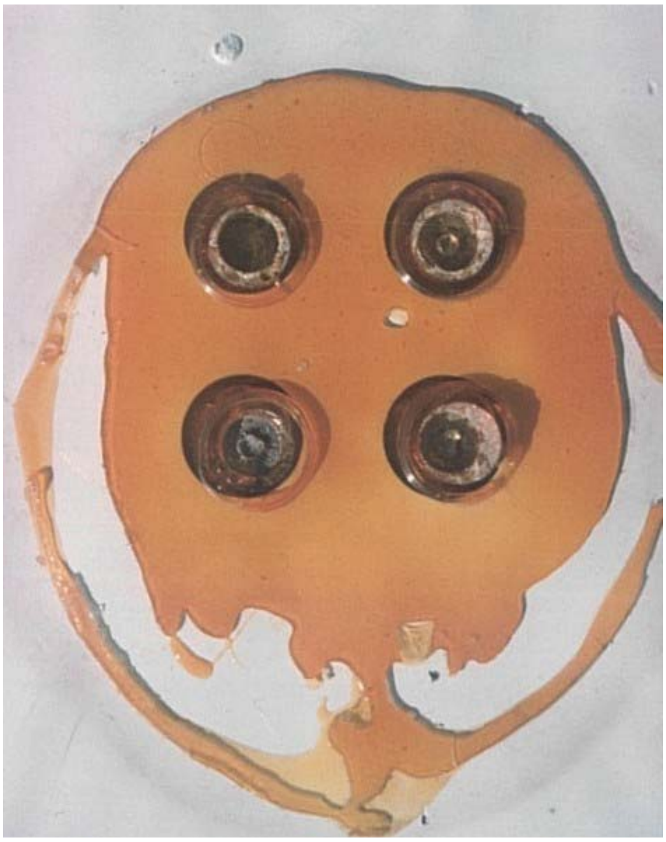


Figure 34: box and terminals detachment caused by bad seal (so bad insulation) of the junction box.

8.6 Tedlar detachment

Tedlar is a tough and durable polyvinyl fluoride film, conventionally used as PV module backskin. It serves as a barrier layer, being very weatherable and temperature resistant.

Despite these positive properties, it has disadvantages: it is hard to bond to, and it has a low puncture resistance due to its thinness.

Regarding ASI 16-2300 the tedlar detachment from the metal layer was detected in the bottom part of two modules (Figure 35) in October 2002. Since then, this phenomena has been rapidly increased (about 4 modules/month); in march 2003, 24 modules (9.5% of the overall plant) presented such a defect; at present they are 50 (**20%** of the overall plant).

Figure 35: wrinkles caused by the detachment of Tedlar backsheet from the metal foil.

Tedlar detachment has been also observed during execution of accelerated ageing tests in accordance with the International Standard IEC 61215 (Chapter 12.1).

In spite of the backskin detachment, the presence of the metal foil should avoid humidity penetration, hence delamination; on the other hand, its exposure could represents an electrical safety hazard, as the foil will be raised, by capacitive coupling, to a maximum potential above ground equal to the maximum system voltage.

9 Infra-red analysis results

In all modules of the plant, the cell located in front of the junction box (Figure 36) has always exhibited a higher temperature (~ 4°C) with respect to the rest of the module area, due to insulating effects of the junction box.

In 1985, hot-spots were not detected yet [11]. In 1996, 48 affected cells were noted and 56 in 1999 (+3.2%). In 2003, infra-red analysis of the plant detected the presence of hot-spots on 67 modules (**26%** of 252; +4.4% with respect to 1999); they are generally found on the cell in front of the junction box (Figure 36), which shows an overheating of about 10°C with respect to the rest of the module surface.

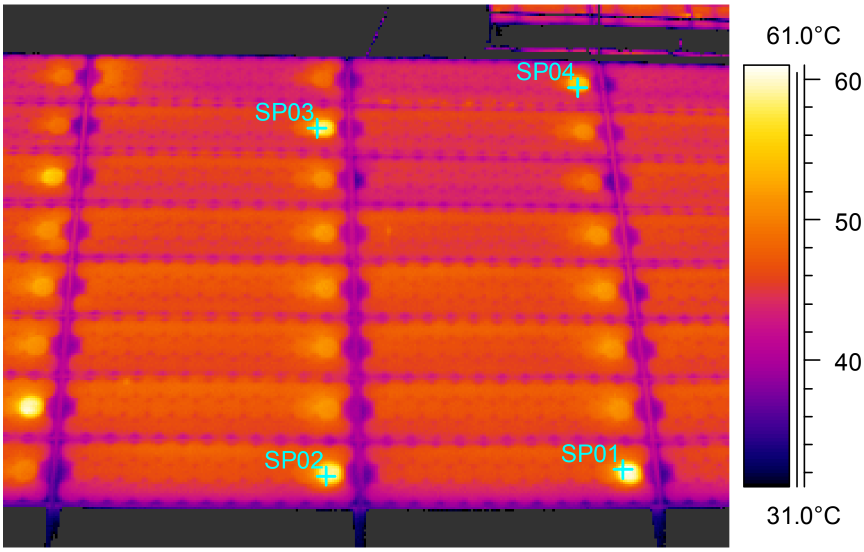


Figure 36: IR image showing higher temperatures always localized in correspondence of the junction box location. Four cells with hot-spot are also indicated (SP0x with ΔT_{cell_module} > 10°C).

Cells partially affected by delamination also present higher temperature (Figure 37). The increase of delamination on the overall cell area could lead to hot-spot formation.

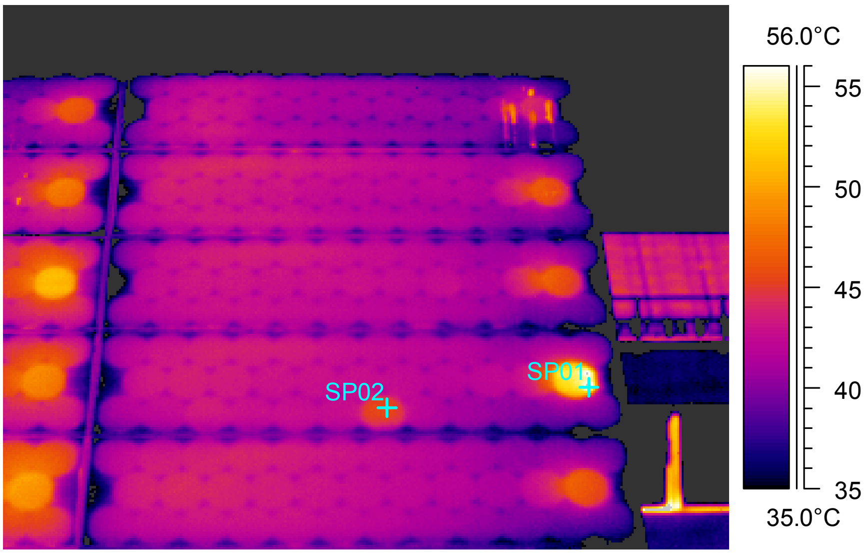


Figure 37: IR image showing one cell with hot-spot (SP01) and one area with higher temperature (SP02) corresponding to a partially delaminated cell.

This gradual increase of number of hot-spots has to be monitored closely, as modules with hot-spots show the highest power degradation; the worst affected module of the plant (Figure 38), whose maximum power is equal to 25.8 W (-22.0% with respect to the actual mean module power), has a hot-spot.

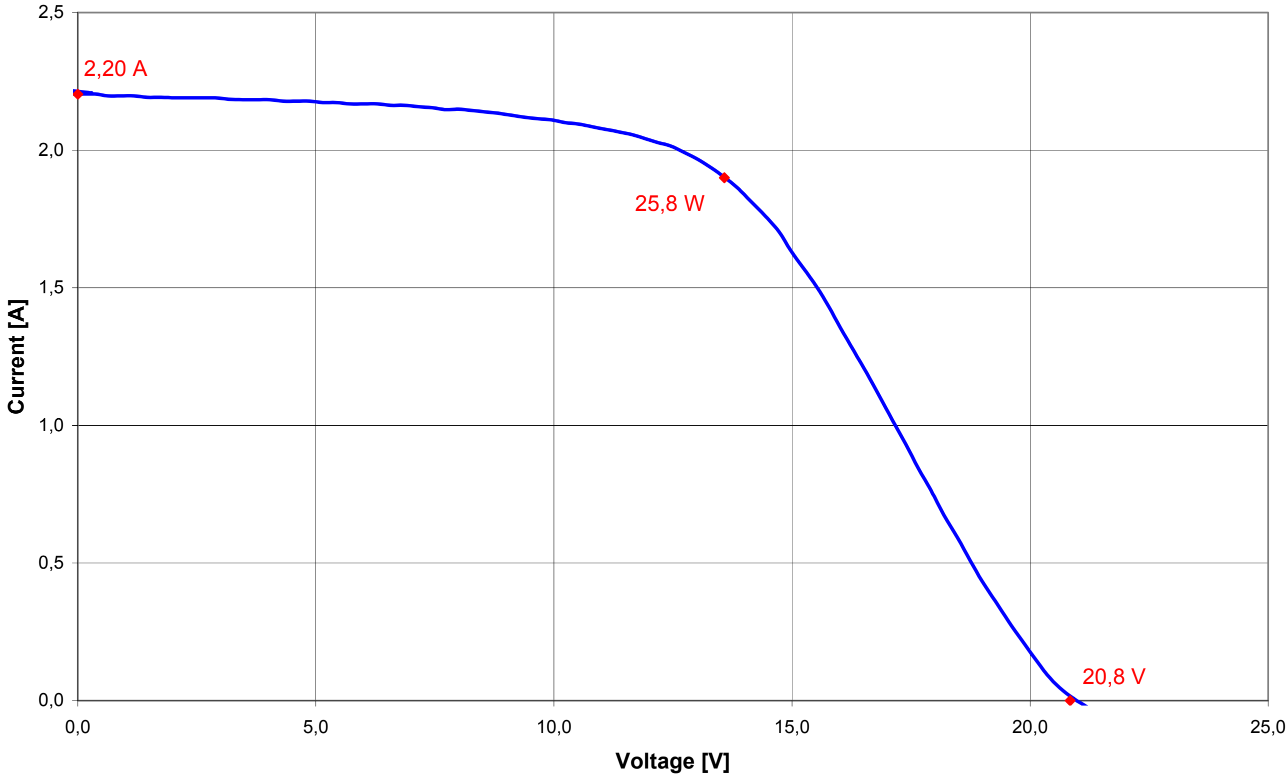


Figure 38: I-V characteristic of the most degraded module of the plant, which has a hot-spot.

10 Performance measurements results

10.1 Outdoor measurements

In 1983, the outdoor performance measurements of the 24 strings of the plant were performed, giving a total power output, after Standard Test Conditions (STC) correction and comparison with indoor measurements of a batch of modules, equal to 9.8 kW [12]. Having no initial strings measurements or measured maximum power value of each module, it has not been possible to state if the ~10% difference from the nominal power existed since the beginning, or it is attributable to module degradation and/or wiring losses.

In January 2002, measurement of the 12 strings was performed. The sum of the power output of all strings, after correction at STC, was equal to 8.33 kW. Due to the changes of the plant configuration (Chapter 3.2) a comparison between the current results and the ones obtained in 1983 was impossible. However, a rough estimate of the annual degradation rate of the module power, since 1983 has been calculated (Table 6).

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%**

Table 6: estimate of module power degradation based on outdoor string measurements performed in 1983 and 2002.

ASI 16-2300 technical specifications supplied by Arco Solar in 1982 did not indicate any warranty limit about module power. Considering that the majority of today's PV modules manufacturers guarantee the 90% of the initial declared power for 10 years and the 80% for 20 years, the **-0.2%/year power degradation** rate obtained for the ASI 16-2300 has to be considered a satisfactory result (97% of initial power after 19 years of outdoor exposure), especially considering the modules age.

I-V measurements of the two sub-fields (positive and negative) have also been performed and no differences have been detected (Figure 39). This result has been relevant to explain the anomaly detected by the analysis of daily production data (Chapter 13).

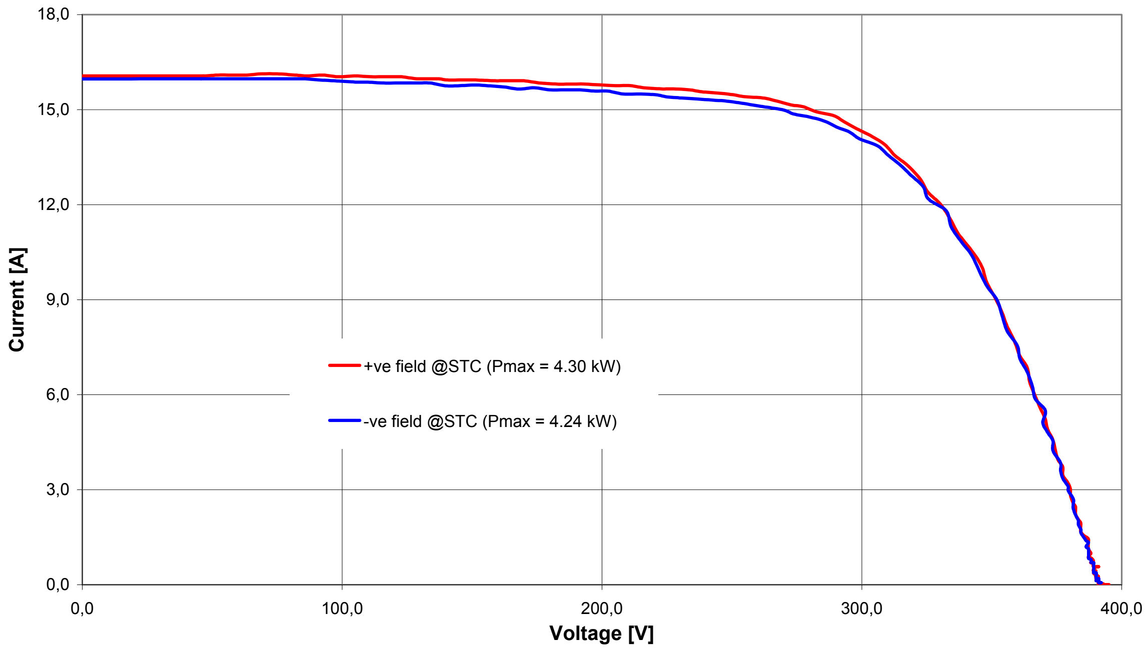


Figure 39: comparison of the 2 sub-fields I-V characteristics (after STC correction).

10.2 Indoor measurements

In March 2001, all 252 modules of the plant were measured indoor with the LEEE-TISO Sun Simulator for the first time.

Having no initial measured maximum power value for all of the modules the data have been compared to the manufacturers nominal power (37 W). Results, represented in Figure 40, show that after about twenty years, 59% of the modules exhibited a variation of less than -10% to the stated nominal power, 35% of modules exhibited a variation of between -10% and -20%, and only for the 6% of modules showed a variation loss greater than -20%. The **mean maximum power** is equal to **33.1 W**, which is in good agreement with the 32.9 W (Δ = +0.6%) obtained through the power estimation of the 12 strings outdoor measurements (Table 6).

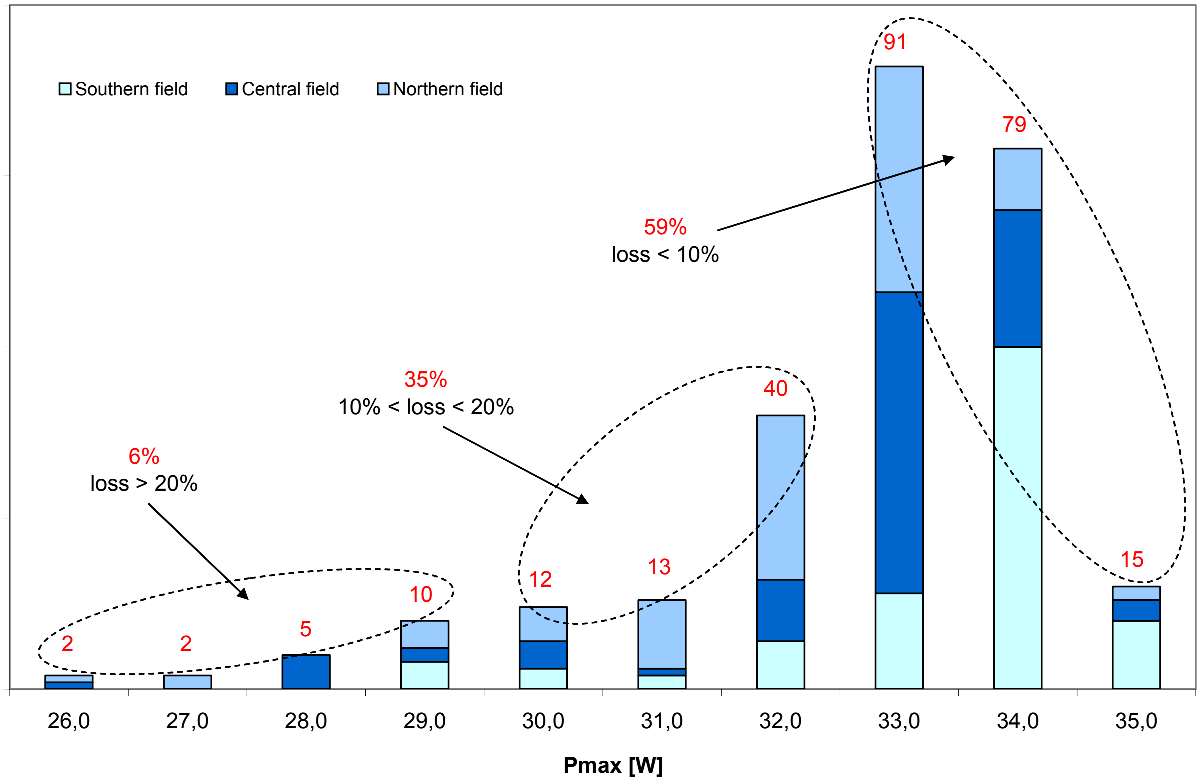


Figure 40: maximum power distribution of all plant modules. Red figures indicate the percentages of modules, while black values refer to the difference vs. nominal value (37 W).

Performance measurements on modules presenting major physical defects, like heavy delamination and hot-spots, have been periodical repeated to control the eventual progressive power degradation linked to the defects evolution. Some examples has been given in Chapter 8.3.

Since 1982, indoor performance measurements on a batch of 18 modules of the plant have been periodically executed by ESTI (except for the period between 1986 and 1996, where only one measurement was executed in 1992). Their electrical evolution during the time has been kept as general reference for all the plant modules.

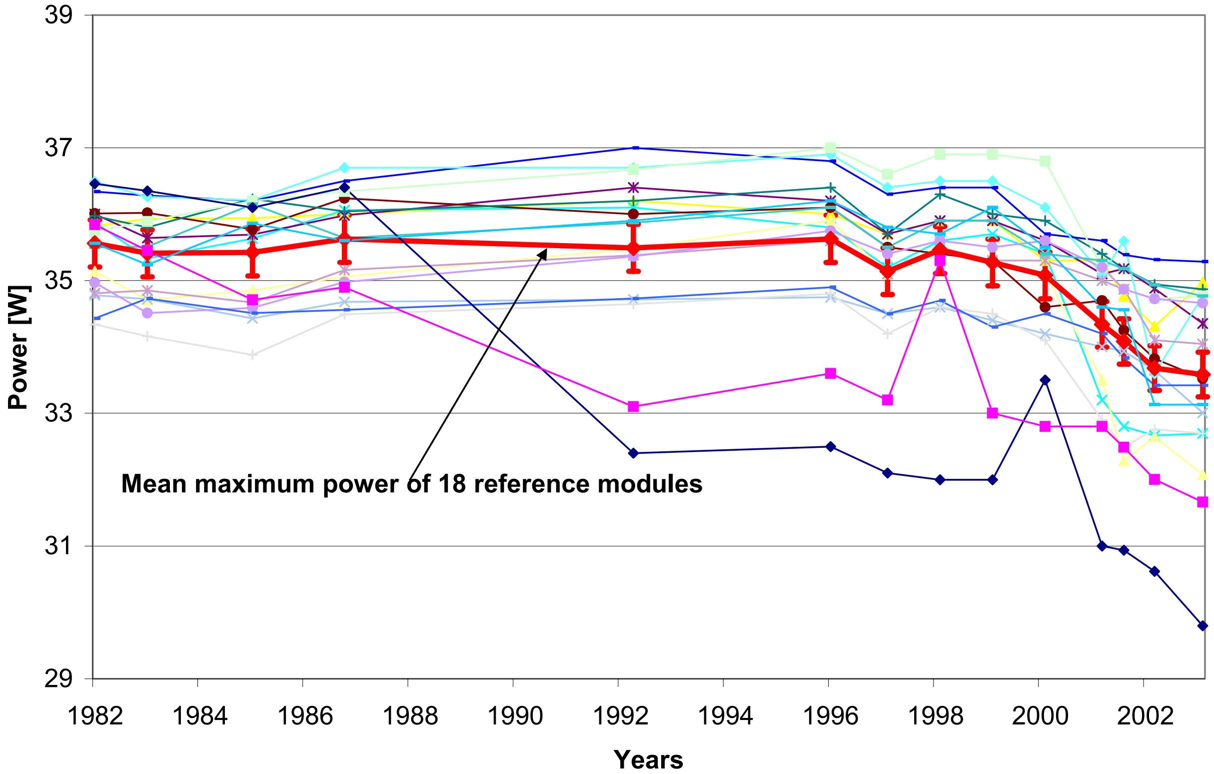


Figure 41: maximum power trends of the 18 reference modules form 1982 to 2003. The red line represents the mean measured power (without data of the two most degraded modules).

Figure 41 shows that till 1999 only 2 modules showed a noticeable power degradation ($\Delta P_{1999\text{-}1982}$: -7.8% and -12.2%) with respect to the other modules, which efficiency remained stable ($\Delta Pmean_{1999\text{-}1982}$: 0.4%). The presence of hot-spots on both the degraded modules was reported in 1996; one of them presented also delamination from frame to circuit. No detailed reports of visual inspection and infra-red analysis are available before 1996, hence it is not possible to exactly determine when these defects have appeared; however, it is reasonable to locate the hot-spots formation between 1986 and 1992, as clearly visible in the graphic.

Since 1999, the efficiency of all 18 modules has started to decrease, with different intensities, in relation with the presence of physical defects (hot-spots, broken cells and delamination).

The annual power degradation of the 18 reference devices has been calculated from 1982 (21 years) and from 1999 (4 years). The estimation has been done both considering all the 18 devices and excluding the two modules whose degradation started in 1992. Results show that the degradation has greatly accelerated since 1999 (Table 7).

	Annual power degradation 1982-2003	**Annual power degradation 1999-2003**
18 reference modules	-0.26%	**-1.20%**
16 reference modules (w/o the 2 most degraded)	-0.21%	**-1.18%**

Table 7: annual power degradation of the 10 kW plant reference modules.

11 Defects vs. efficiency

In the previous chapters the main physical defects detected on ASI 16-2300 modules and the results obtained by outdoor and indoor performance measurements have been reported.

The analysis of all these data allowed to define which defects could affect modules efficiency. It has not been possible to precisely quantify the effects of single defect on module performance, because of the presence of more than one defect in the same module, and for the lack of initial measured electrical characteristics of all devices.

Results obtained by the correlation between module efficiency and defects distribution are summarized in Table 8, where the power degradation has been calculated with reference to the nominal power declared by the manufacturer (Pn = 37W). Percentages, in *italic*, font refers to the number of modules indicated in the second row of the table. An example: 100% of the 17 modules which power differs more than 20% with respect to the nominal one show PVB yellowing and hot-spots.

ΔPmax_Pn		**<10%**	**10%<Δ<20%**	**>20%**
N° of modules		143	92	17
DEFECTS	YELLOWING OF ENCAPSULANT	*97%*	*99%*	*100%*
	DELAMINATION	*94%*	*90%*	*94%*
	HOT-SPOT	*7%*	*43%*	*100%*
	TERMINAL OXIDATION	*42%*	*52%*	*29%*

Table 8: correlation between module efficiency and defects distribution. Percentages in *italic* refers to the N° of modules in the 2nd row of the table. An example: *100%* of the 17 modules which Pmax differs more than **20%** with respect to Pn show PVB YELLOWING and HOT-SPOTS.

In general, it is possible to state:

- Yellowing of PVB encapsulant affects modules current: completely yellowed modules present higher loss in Isc with respect to the white or partially yellowed ones. The presence of additional defects avoid to precisely quantify the effects of yellowing on module power.
- Delamination: performance losses of single cells are proportional to their affected area (loss in Pmax and Isc). Module performance is not necessarily affected by delamination; it depends on the total affected area (for example, modules where delamination affects the entire area of hot-spotted cells).
- Hot-spot represents the principal cause of power degradation. It strongly affects power and lead to an increase of series resistance, as is clearly visible in Figure 42, where the I-V characteristics of two modules having the same Pmax and Isc are compared. The different shape of the curves is due to the presence of a hot-spot in one module.
- Presence of broken cells could affect module performance. The degree of cell cracking and resulting electrical isolation dictates the level of associated performance loss.
- Terminal oxidation could affect module power output, as in the case of ASI 16-2300, where it sometimes leaded to partial terminal detachment and so to a bad power transmission.

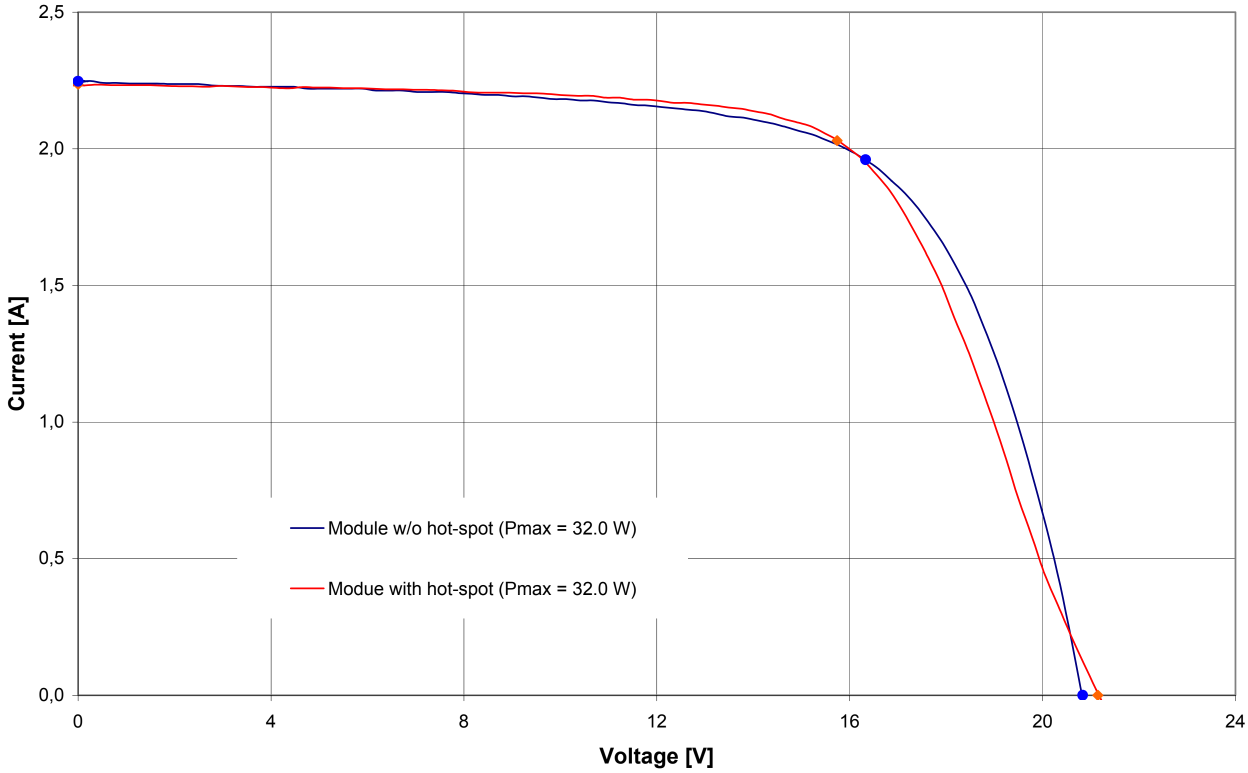


Figure 42: comparison of I-V curves of modules having the same Pmax. The different shape is due to the increase of series resistance in the module affected by a hot-spot.

In confirmation the results of a recent study conducted by Sandia and NREL [13]; module degradation observed in fielded systems is grouped into five categories that ultimately drive the performance loss and possibly failure:

- degradation of packaging materials (glass breakage, dielectric breakdown, bypass diode failure, encapsulant discoloration, backsheet cracking and/or delamination);
- loss of adhesion (delamination);
- degradation of cell/module interconnections;
- degradation caused by moisture intrusion (corrosion and increase of leakage currents);
- degradation of the semiconductor device.

12 Repeated accelerated lifetime testing - IEC 61215

In 1997, 10 modules were removed from the plant, and 8 of these were subjected to repeated sequences of accelerated lifetime tests, in accordance with the International Standard IEC 61215 (Chapter 6.6).

12.1 Tests results

Considering that the ASI 16-2300 modules were manufactured in 1981/1982, and were exposed for 15 years, their resistance to the repeated ageing tests has been remarkable.

No electrical performance degradation was observed after:

- 2 repetitions of the UVE / TC50 / HUF cycle;
- 1020 thermal cycles (TCY);
- 4000 hours of damp heat (DAH).

Regarding physical defects, damp heat test provoked a major defect, consisting in the detachment of the external layer of the tedlar backsheet from the underlying metal foil, detected on 2 modules after 1000 hours of exposure (Figure 43). Despite this major defect, both modules met the electrical performance and the electrical insulation test requirements. Very dark yellowing of module background was also detected (Figure 44).

Figure 43: Tedlar detachment in modules subjected to 4000h DAH. After the test the module was installed in the plant, and complete detachment occurred after one year of further exposure.

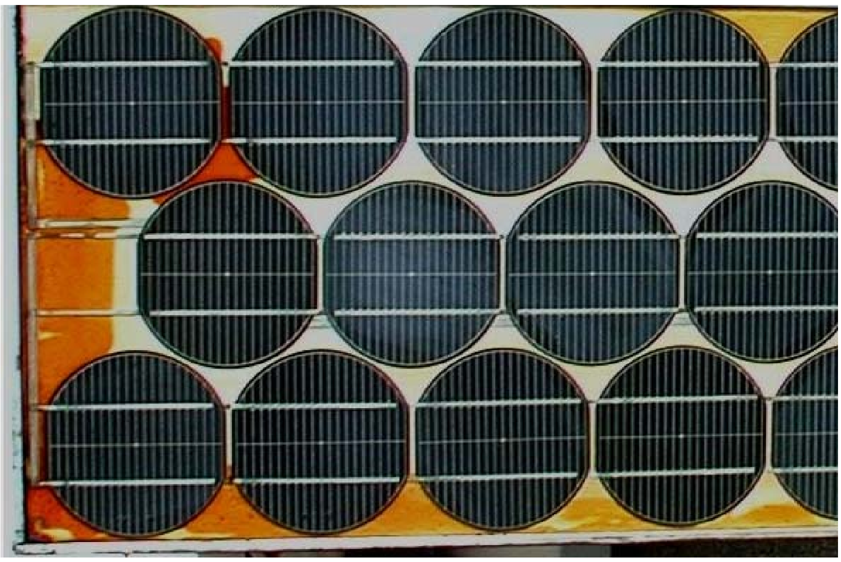


Figure 44: dark yellowing of background in module subjected to DAH.

Another major defect recorded was the partial detachment of the terminal box of one module after 650 thermal cycles.

On the basis of these results, it is reasonable to assume that the ASI 16-2300 modules could continue to provide useful electrical power for another 15 years [14].

Consideration on the tedlar backsheet detachment have been already described in Chapter 8.6.

12.2 Accelerated ageing tests in comparison with ageing in the field

Comparing module ageing under field condition and accelerated lifetime tests, the following differences have been detected:

- encapsulant delamination has been observed in about 92% of the modules exclusively aged in outdoor conditions, while it not affected devices subjected to accelerated ageing tests;
- yellowing has been detected both in natural and accelerated conditions, but the one provoked by the damp heat test, seems to affect only the background tedlar and not the PVB encapsulant;
- damp heat provoked tedlar backsheet detachment; this defect has not been observed on naturally aged modules until October 2002, when 2 modules have been found affected. Since then, this phenomena has been rapidly increased, as described in Chapter 8.6.

These observations drive to the conclusion that accelerated ageing tests do not always reproduce the same effects detected in real conditions. In particular, module delamination has been observed in several long-term field exposure tests, while typical accelerated-ageing tests have not been effective in reproducing the mechanisms responsible for this phenomena.

It is reasonable to assume that natural environment conditions coupled with long-term exposure could be more severe than standard accelerated ageing tests.

13 Plant energy production

Figure 45 shows the annual energy production of the TISO 10 kW plant since 1982. The production variations are due to the configuration changes (1989 – 1991), the works for the roof insulation (1995), the execution of several tests, and, since November 2001, to an inverter anomaly.

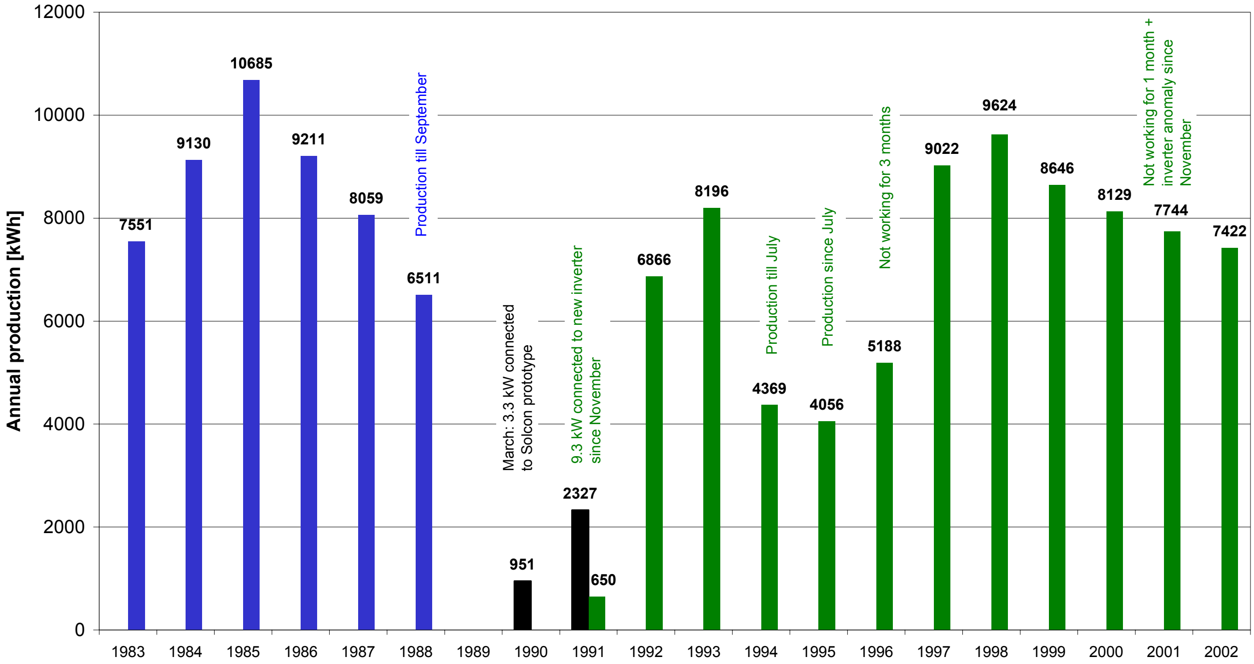


Figure 45: TISO 10 kW annual energy production.

Even if the daily data production have been recorded since the beginning, the changes of configuration, cabling and modules inclination avoid a direct comparison of energy production during all the 21 years of plant functioning.

Out of the energy production, an important index for the evaluation of the plant functioning is the Performance Ratio (PR), which indicate the effective plant performance, as it consider the insulation in the analyzed period, but it not depends on the weather conditions. It is calculated as follow:

$$PR = \frac{\frac{Eac,t}{Pn}}{\frac{Ht}{Gstc}} [-]$$

where:

Eac: AC energy production in the t period

t: analyzed period

Pn: plant nominal power

Ht: incident irradiance in the t period

Gstc: reference irradiance (1000 W/m²)

Figure 46 shows the AC and DC plant performance ratio from August 1996 up to July 2003. The plant PR shows seasonal variations due to the different working temperatures of the modules, whose production is higher in winter than summer (Voc temperature coefficient β = - 0.0739 V/°C, Pmax temperature coefficient γ = - 0.1214 W/°C [12]).

The difference between AC and DC performance ratio varies during the year; this could be attributed to a decrease of the inverter efficiency in summer (negative influence of higher temperature on power elements), and/or to the different daily insulation distribution on the plant in winter and summer.

Summarising: in summer the inverter often works for a longer period, but with a lower load, so a lower efficiency.

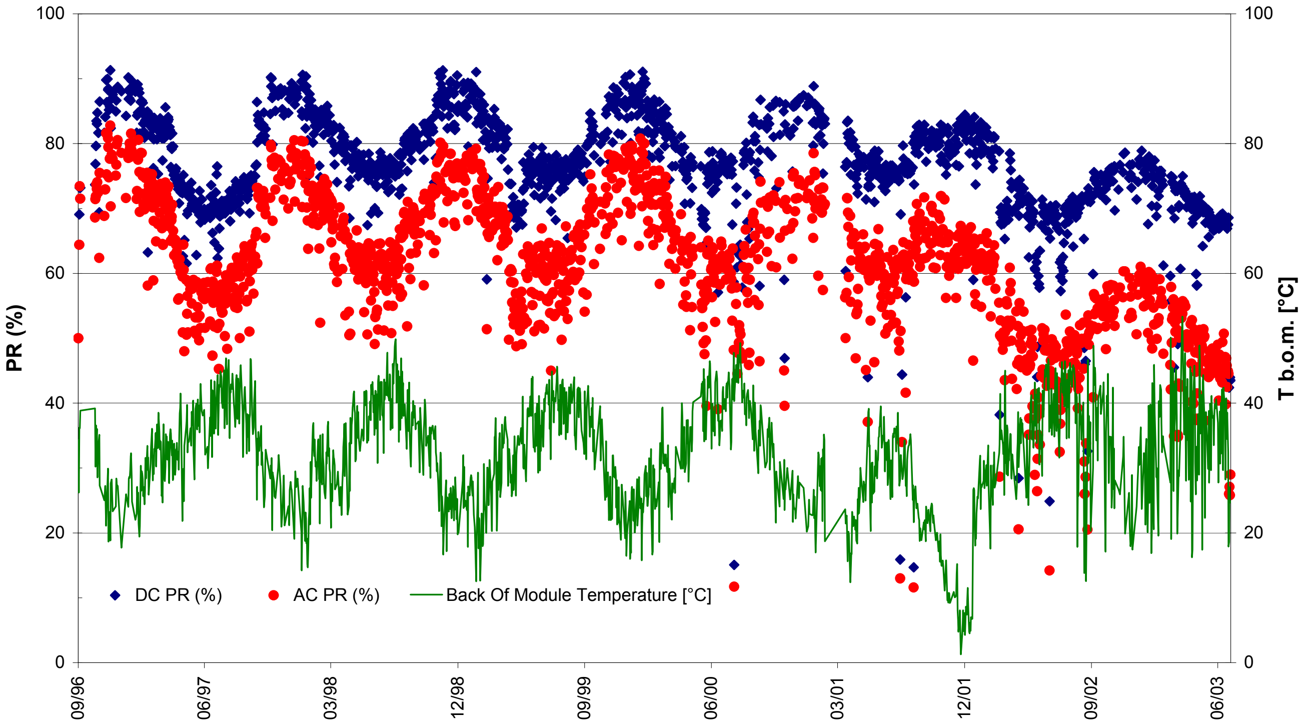


Figure 46: DC and AC Performance Ratio trend of the TISO plant since 1996.

Until November 2001, the annual PR trend have remained quite stable, then a gradual decrease started. The data acquisition system installed in June 2000, which records the production of the single strings of the system, has allowed to delimit the area of the plant affecting the total PR.

As shown in Figure 47, the anomaly concerns the negative sub-field. Analyzing the electrical behaviour of each string of the negative array, it has been detected that PR of all the 6 series started simultaneously to decrease from November 2001, which means that anomaly has been caused by faulty elements upstream the field (so not by damaged/broken modules). After several controls, the cause has been found in the inverter, presenting broken connection in the electric circuit. Nevertheless the fault has been repaired the anomaly has remained, so it has been decided to substitute the inverter (Chapter 16), also because of its lifetime (11 years vs. the mean inverter lifetime of 8-10 years).

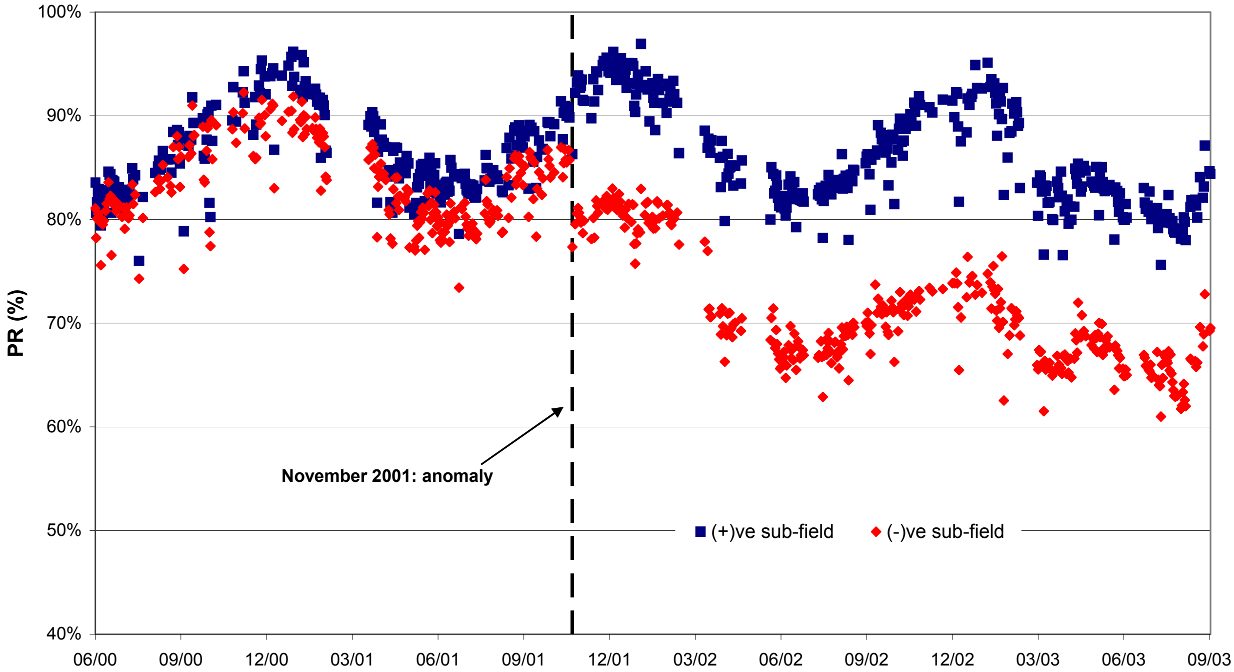


Figure 47: Performance Ratio trend of the two plant sub-fields since June 2000. Effect of the inverter anomaly on negative field behaviour.

As demonstrated above, the possibility to monitor the individual string behaviour has aided anomalies detection. Another example is given by a fault occurred in July 2002, when one string was found to be not working (Figure 48). After checking of all 21 modules, one burned cable in the connector used to wire the modules together was detected (Figure 49).

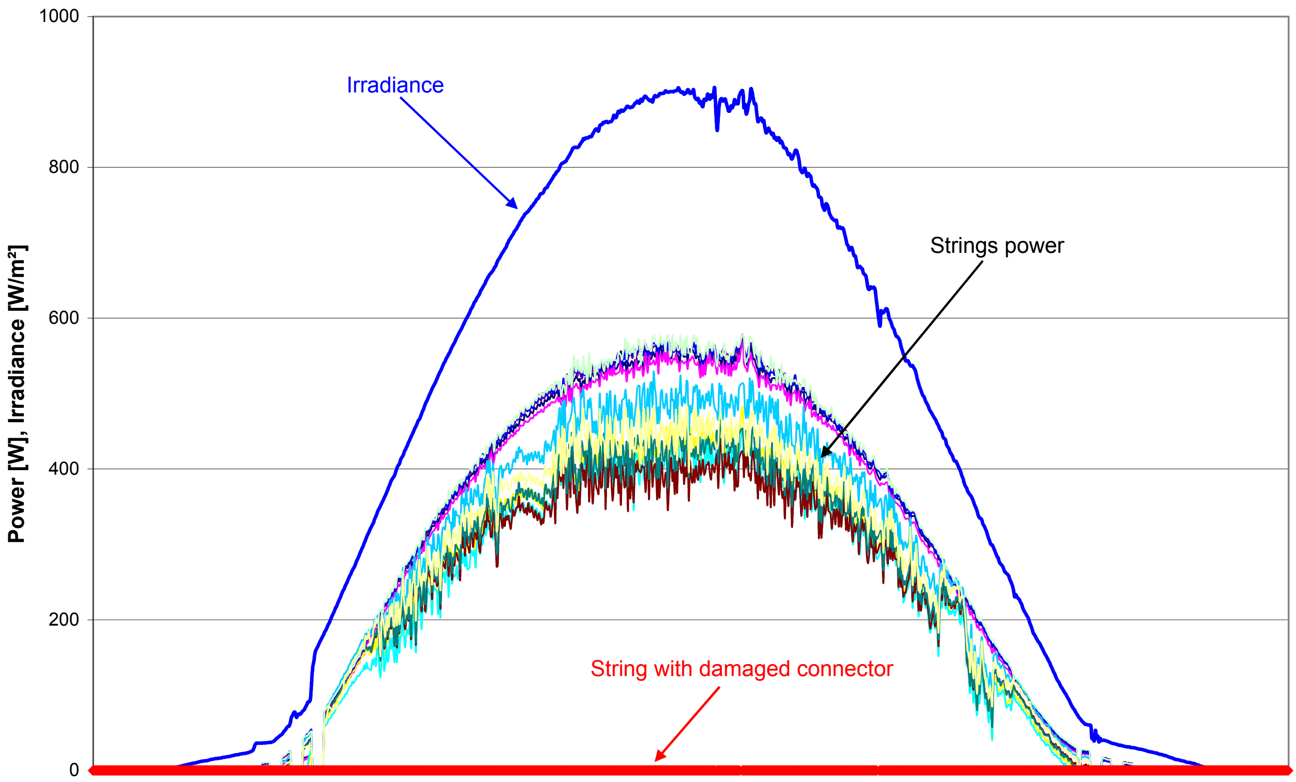


Figure 48: string fault detected by the analysis of the daily individual string's power production.

Figure 49: burned cable and damaged connector which caused string fault.

In addition to strengthen the importance of an accurate plant monitoring, this fact, together with the inverter fault, clearly shows that not only module ageing could affect the system performance, but also the deterioration of all system components.

14 Comparison between ASI 16-2300 & new module types

Every year, the LEEE-TISO carries out systematic tests, under real operating conditions, on the most important modules present on the market. Since 1999, two ASI 16-2300 modules has been inserted into these test cycles to compare the energy production of most recent modules types with the one of an “old generation”.

A part from the aspect related to the difference between real measured power and the one declared by the manufacturer, and the initial degradation occurring in new modules, the electrical behaviour in real operating conditions of recent and old crystalline silicon devices is, quite often, similar and stable. An example is given in Figure 50 where the performance ratio trends of two ASI 16-2300 (TEC51 and TEC52) and another type of sc-Si modules (ACO51 and ACO52) of test cycle 7 (2000-2001) are shown.

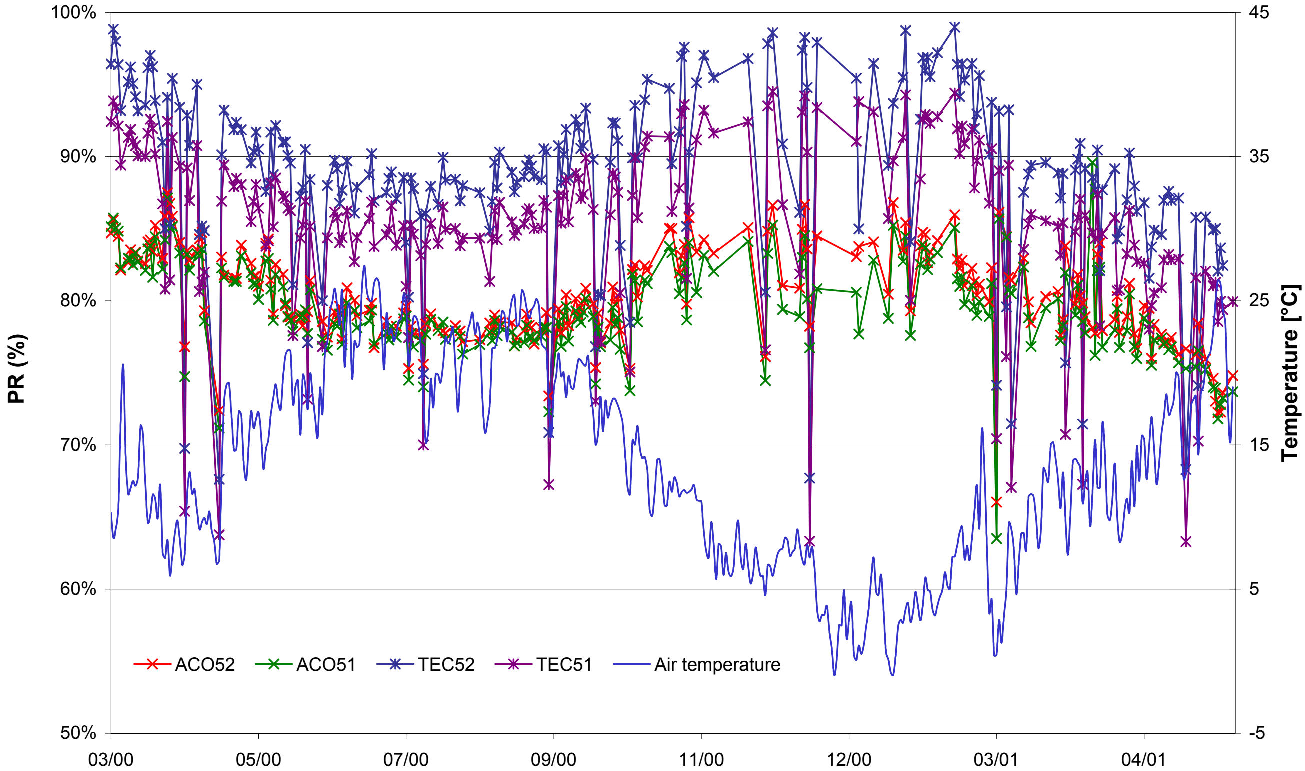


Figure 50: PR trends of two ASI 16-2300 (TEC51 and TEC52) and two “newer” sc-Si modules (ACO51 and ACO52) operating in real conditions (test cycle 7).

15 Other studies on ASI 16-2300 modules

Long-term effects of outdoor exposure on the performance and reliability of ASI 16-2300 and ASI 16-2000 were also studied by the Florida Solar Energy Center [15].

168 ASI modules (28 ASI 16-2300) were installed in the arrays of grid-connected residential PV systems at the Southeast Regional Experiment Station in Cape Canaveral, Florida, from 1980 to 1994.

Over 14 years of operation 6 modules failed, indicating a failure rate of 0.2% per year.

Performance measurements and wet and dry insulation tests were executed before and after the exposure. The modules did not show relevant power losses, but problems with insulation resistance were detected (none of the modules met the IEEE Standard 1262 recommended value).

Regarding visual inspection results, the following defects were detected:

- tearing of the back surface tedlar on 59 modules (~35%)
- yellowing of PVB encapsulant in varying degree in most of the modules
- internal corrosion: 30% of cells showed brown corrosion of metal grid contacts.

The above mentioned defects have not indicated any effect on modules performance.

These results confirm the good reliability of ASI modules, despite the presence of several visual defects. Moreover, it is important to evidence that the warm, humid and ocean-salt environment did not have any additional effect on modules performance with respect to the temperate central Europe climate.

16 New TISO 3 x 3kW plant configuration

As already described in previous chapters, the gradual decrease of negative sub-field energy production started in November 2001 has been attributed to an inverter anomaly.

At present, the company which produced the ECOPOWER 15 kW does not deal with inverter anymore, so an eventual repair would be impossible due to the lack of a service and spare parts. This fact, together with the age of the inverter (11 years) lead to the decision of substituting the inverter unit.

As the plant is physically divided in three fields, it has been decided to split the power into three phases (one for each field). In this way an eventual fault of one field will not prevent the rest of the plant from functioning.

The inverters are installed outdoor for practical reasons, so the choice of the inverter type has also been influenced by this aspect.

New plant configuration (Figure 51):

- 3 fields (~3.2 kW each)
- 4 series of 24 modules for each field
- 1 inverter for each field

Inverter characteristics (additional information in Annex 0):

- Sunny Boy 2500 (Figure 52)
- Input voltage range (Umpp): 250-550 Vdc
- Max input current (Impp): 11.2 A
- Max output power (Pac max): 2.5 kW
- Max efficiency: 94%

Data acquisition system – recorded data:

- Current of each string measured by means of a Current Transducer
- Voltage measure of each field: +Udc - -Udc by means of a voltage divider and an isolation amplifier
  +Udc – ground by means of a voltage divider.
- AC energy production measured by means of a simple single-phase energy meter
- Temperature of each string recorded as before

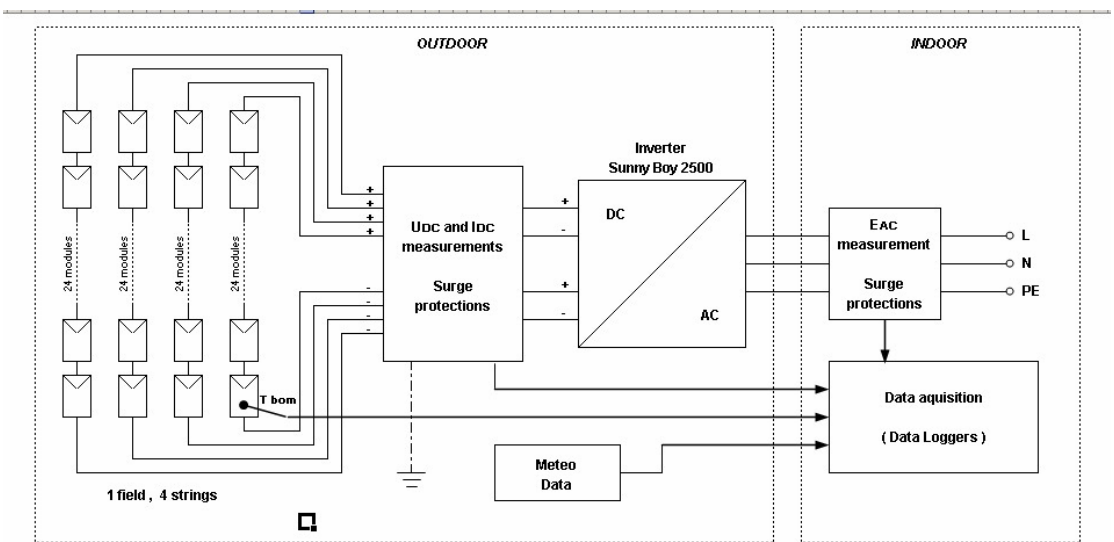


Figure 51: wiring diagram of the new 3 x 3 kW plant configuration (only one field represented).

Figure 52: Sunny Boy 2500 inverter connected to one field of the TISO plant.

17 The inverter unit

As described in chapter, the configuration changes which the TISO 10 kW plant was subjected during its 21 years of functioning were due to the breakage, so the substitution, of the inverter unit.

The present ECOPOWER® 15 kW inverter will be soon substituted because of the fault detected in November 2001. During 9 years of operation (1992-2001) it only had an initial fault due to a bad insulation of a DC electrical part.

In a grid-connected PV plant the inverter represents an expensive and complex key component; the majority of system failures involved the inverters [16].

Many of the problems that exist with inverters are known; they include design problems, manufacturing flaws and poor management practices. Although PV inverters are the most mature of any Distributed Energy Resources (wind, fuel cells, micro turbines) inverter, a Mean Time to First Failure (MTFF) equal to 5 years is unacceptable. Low inverter reliability contributes to unreliable fielded systems and a loss of confidence in renewable technology.

At present the research is focusing its efforts to develop a “next generation” inverter that has 10-year MTTF, better performance and lower cost [17].

18 Conclusions

After 21 years the Arco Solar ASI 16-2300 modules of the 10 kW TISO plant are still working in a satisfactory manner. This conclusion has been attained by the analysis of plant energy production data and by the results of indoor and outdoor performance measurements.

Results from the indoor performance measurements executed on each module of the plant showed that

- 59% of the modules exhibited a decrease lower than -10% to the stated nominal power
- 35% of modules exhibited a decrease between -10% and -20%
- only the 6% of modules showed a decrease greater than -20%.
- the mean maximum power is equal to 33.1 W.

Considering that the majority of today's PV modules manufacturers guarantee the 90% of the initial declared power for 10 years and the 80% for 20 years, the -0.2%/year power degradation rate estimated for the ASI 16-2300 (Chapter 10.1) has to be considered a very good result for modules manufactured more than 20 years ago.

Results of periodical indoor performance measurements executed on 18 reference modules showed that power degradation has greatly accelerated since 1999:

- annual power degradation 1982-2003 = - 0.2%
- annual power degradation 1999-2003 = - 1.2%

This result could appear improbable if related to the modules appearance. Many types of defects were detected during intensive visual inspection of all plant modules:

	$\%_{2003}$ **of plant modules**:
▪ yellowing of encapsulant	98%
▪ browning of cell electrical grid	93%
▪ terminals oxidation probably caused by the bad sealing of the junction box	45%
▪ terminals detachment when wiring caused by above mentioned oxidation	n.a.
▪ encapsulant delamination	92%
▪ broken cells	22%
▪ tedlar backsheet detachment	20%
▪ junction box detachement.	n.a.

The correlation between modules electrical characteristics and visual defects allowed to determine which of the detected physical anomalies affect modules performance:

- yellowing of PVB encapsulant affects modules current: completely yellowed modules present higher loss in Isc with respect to the white or partially yellowed ones.
- delamination: performance losses of single cells are proportional to their affected area. Module performance is not necessarily affected by delamination; it depends on the total affected area.
- presence of broken cells could affect module performance and it depends on the crack position.
- terminal oxidation could affect module power output, leading to partial terminal detachment and so to bad electrical transmission.

Particular attention has to be paid to the presence of hot-spots, physical defect not detectable to the naked eye. The infra-red analysis of the plant identified the presence of hot-spots on 26% of the plant; they are always localized on the cell in front of the junction box. Hot-spot represents the principal cause of power degradation; modules with hot-spots show the highest performance losses. As cells partially affected by delamination also exhibit higher temperature, the increase of delamination on the overall cell area could lead to hot-spot formation.

Results of repeated accelerated lifetime tests (International Standard IEC 61215) executed on a batch of 8 modules of the plant already outdoor exposed for 15 years, enabled to reasonably assume that the ASI 16-2300 modules could continue to provide useful electrical power for another 15 years at least. As for ageing under field condition, also in this case the presence of physical defects like dark yellowing of background tedlar and tedlar backsheet detachment did not seriously affect modules performance.

The comparison of module ageing under field condition and accelerated lifetime tests leads to the conclusion that accelerated ageing tests do not always reproduce the same effects detected in real conditions. It is reasonable to assume that natural environment conditions coupled with long-term exposure could be more severe than standard accelerated ageing tests.

As well as the analysis of failure mechanisms affecting the modules, an important aspect to consider in the plant management, is the maintenance of other system components (Balance-Of-System - BOS); in particular, in a grid-connected PV system the inverter represents an expensive and complex key component. The configuration changes which the TISO 10 kW plant was subjected during its 21 years of functioning were due to the breakage, so the substitution, of the inverter unit.

The study of the 10 kW TISO plant enabled to verify the good reliability of Arco Solar ASI 16-2300 modules. Although these modules are not manufactured anymore, the fact that after 21 years of outdoor exposure they are still working in a very satisfactory manner (97% of initial power and 6 modules not working anymore) contributes to strengthen the credibility of photovoltaic technology as alternative energy resource. The perspective to produce commercial modules with lifetimes of 30 years or more is so realizable, trying to avoid the degradation mechanisms which could compromise modules efficiency and lifetime (in particular encapsulant delamination and hot-spot formation).

In parallel with the “PV module” aspect, the research for developing more efficient and durable inverters is of great importance to reach a better reliability of the overall PV system and cost reductions.

19 References

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20 Publications

2000:

- G. Travaglini, N. Cereghetti, D. Chianese, S. Rezzonico; 16th European PVSEC; Glasgow (GB), May 2000 – “Behaviour of m-Si plant approaching its 20-year design life”
- A. Realini, E. Burà, D. Chianese, S. Rezzonico, G. Travaglini; Swiss National Photovoltaic Symposium 2000; Neuchâtel (CH), November 2000 – “Determination of the Mean Time Before Failure of a 20-year old PV plant”

2001:

- A. Realini, E. Burà, D. Chianese, S. Rezzonico, G. Travaglini; 16th Photovoltaic Symposium; Staffelstein (D), March 2001 – “Determination of the Mean Time Before Failure of a 20-year old PV plant”
- A. Realini, E. Burà, N. Cereghetti, D. Chianese, S. Rezzonico; 17th European PVSEC; Monaco (D), October 2001 – “Study of a 20-year old PV plant (MTBF project)”

2002:

- A. Realini, E. Burà, N.Cereghetti, D. Chianese, G. Friesen, S. Rezzonico; PV in Europe; Rome (I); October 2002 – “TISO 10 kW plant: the oldest grid-connected PV system in Europe”
- A. Realini, E. Burà, N. Cereghetti, D. Chianese, G. Friesen, S. Rezzonico; Swiss National Photovoltaic Symposium 2002; Lugano-Trevano (CH); May 2002 – “1982-2002: state of the 1st grid-connected PV plant in Europe”
- A. Realini, E. Burà, N. Cereghetti, D. Chianese, S. Rezzonico; EUROSUN 2002; Bologna (I); June 2002 – “The oldest grid-connected PV plant in Europe: study and first results”

2003:

- D. Chianese, A. Bernasconi, E. Burà, N. Cereghetti, G. Friesen, A. Realini, S. Rezzonico; 3rd World Conference on Photovoltaic Energy Conversion; Osaka (J); May 2003 – “Analysis of weathered c-Si PV modules”

21 Acknowledgements

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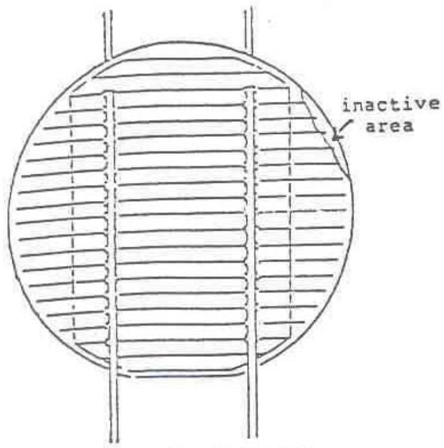
Annexes

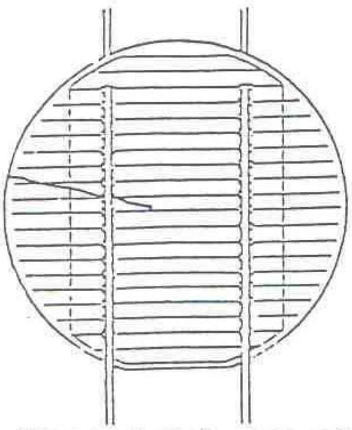
Criteria for the evaluation of damaged cells (by Arco Solar)



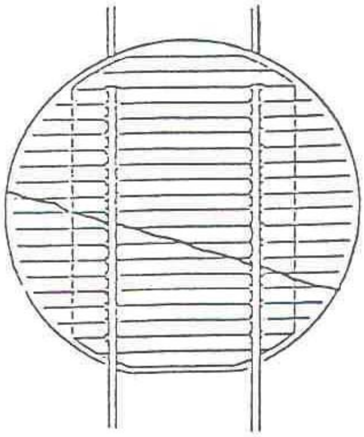
KRITERIEN FUER DIE BEURTEILUNG
VON ARCO-SOLARGENERATOREN

Alle auf dieser Seite dargestellten Zellendefekte haben keinen Einfluss auf die Ausgangsleistung des Panels. Panels mit diesen "Schönheitsfehlern" werden von ARCO-Solar mit voller Garantie verkauft. Ein Rückgaberecht besteht nicht.

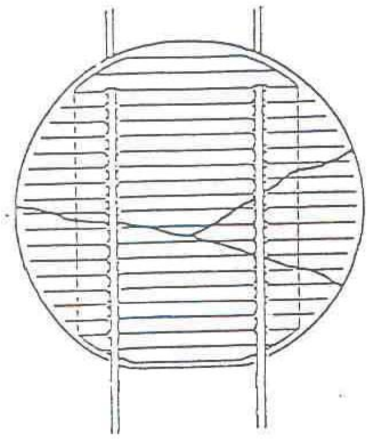
Crack confined to ear.
Less than 1 % inactive area.



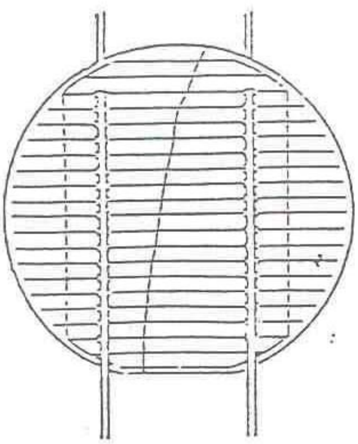
Terminated crack. Runs under interconnect. Propagation will not create inactive area.



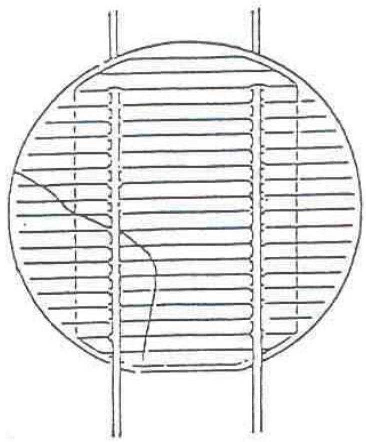
Crack runs under interconnects. No inactive area. Interconnect not damaged.



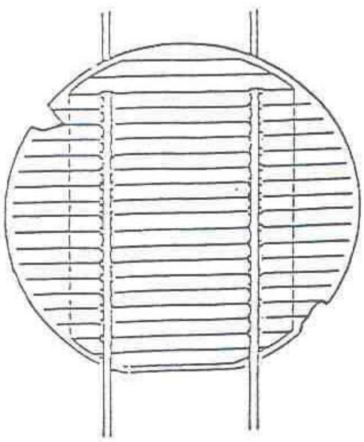
Three point crack. No inactive area.



Crack across full diameter. No inactive area.

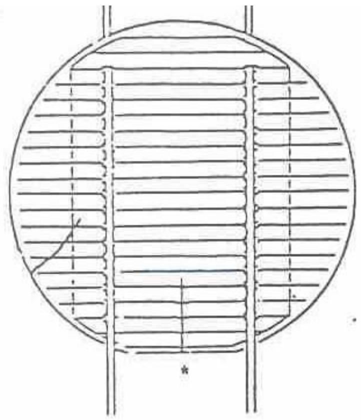


Crack runs under interconnect. No inactive area. Interconnect not damaged.



Chips.

According to Arco Solar, cells defects showed above did not affect module performance, so modules with such a cells were sold, fully guaranteed, and returning was not included.

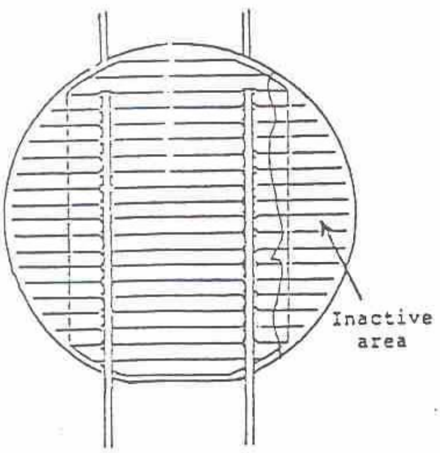


Alle diese Zellendefekte beeinträchtigen die Ausgangsleistung bzw. die Langzeit-Stabilität der Panelleistung.

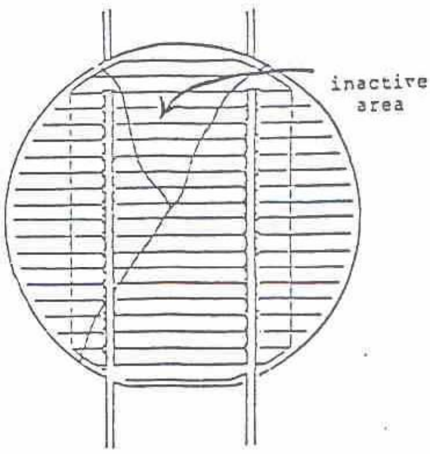
Panels mit solchen Fehlern werden von der Qualitätssicherung von ARCO-Solar zurückbehalten.

Short terminated radial crack. Could propogate such that high percentage of inactive area created. High probability of propagation.

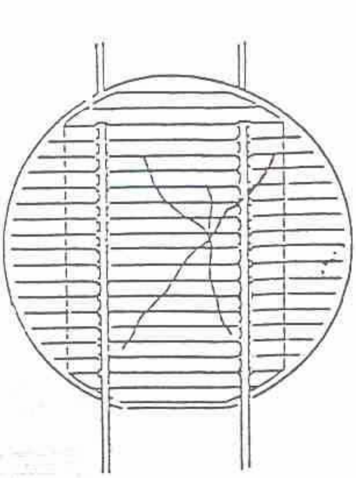
*Crack in this area acceptable. Low probability of failure.



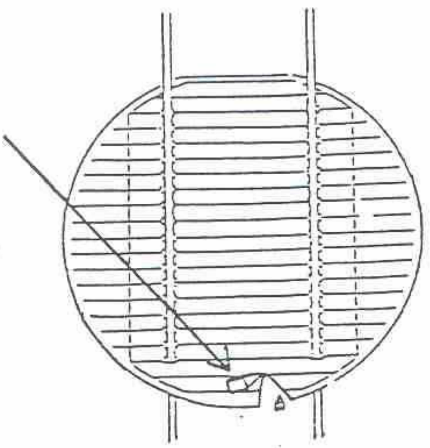
Crack confined to ear.
Greater than 15% inactive area.



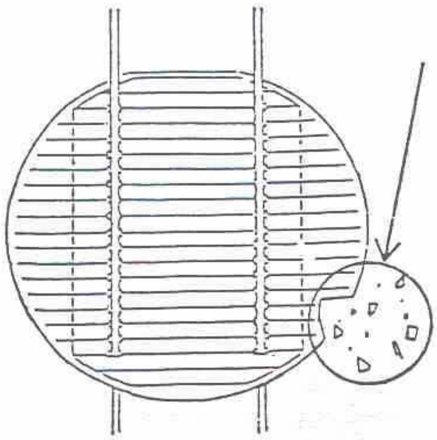
Three point crack.
Greater than 15% inactive area.



Caused by point impact.



Chip on top of cell > 2mm. any one direction.



Cell pieces > 1/16" over area greater than one square inch.

According to Arco Solar, cells defects showed above affected modules performance and stability. Modules with these defects were not sold.

Sunny Boy 2500 technical data

Input Values (240V)		
Recommended max PV Power	***P****PV*	2800 to 3000 Wp STC*
Max DC Power	***P****DC, max*	2500 Wp PTC**
Max DC Voltage	***V****DC, max*	600 Vdc
PV Voltage range, MPP	***V****PV*	250V to 550V
Max input current	***I****PV, max*	10.5 A
DC Voltage ripple	***V****PP*	< 10%
DC Disconnectors		Optional external DC Disconnect/Breaker
Pole confusion protection		Short Circuit diode
Ground fault protection	***I****Dif*	> 1000 mA
Output Values (240V)		
Max AC Power	***P****AC*	2500 W
Nominal AC Power	***P****AC*	2200 W
Total Harmonic Distortion	***THD****IAC*	< 4% (With KVgrid < 2% and PAC > 0.5 PACnom)
Operating Range, Grid Voltage	***V****AC*	211 V to 264 V
Operating Range, Grid Frequency	***f****AC*	59.3 Hz - 60.5 Hz
Phase Shift (Ref. Fundamental)	***cos****(phi)*	0°
Output Protection		
Islanding Protection		VAC; fAC in accordance with UL 1741
Ground Fault Protection		IDIF; In accordance with UL 1741
AC Disconnect		External AC Breaker
Short Circuit Protection		Current Controlled
Overvoltage Classification		III
Testing voltage (50 Hz)		2.88 kV (1s)
Testing voltage for surge		4 kV (serial interface 6 kV) (1.2/50 us)
Efficiency		
Peak Efficiency		94.10 % (Rebate Efficiency)
Euro - ETA Efficiency		93.20 % (Nominal Efficiency)
Power Consumption		
Internal consumption in operation		< 7 W
Internal consumption at night		0.25 W
European Standards		
EMC		EN 50081,T.1 & EN 50082,T.1
Grid Interference		EN 61000-3-2
Grid Monitoring		DIN VDE 126
Low-Voltage regulation		EN 50178
CE Conformity		EN 60146, Teil 1-1
Size and Weight		
Width		434 mm
Height		295 mm
Depth		214 mm
Weight		ca. 30 kg
Ambient Conditions		
Ambient Temperature Range		-13ºF to +140ºF or -25ºC to +60ºC
Relative Humidity Level		0 to 100%

Publications

- “Behaviour of m-Si plant approaching its 20-year design life”
- “Study of a 20-year old PV plant (MTBF project)”
- “The oldest grid-connected PV plant in Europe: study and first results”
- “TISO 10 kW plant: the oldest grid-connected PV system in Europe”
- “Analysis of weathered c-Si PV modules”