Failure modes and degradation rates from field-aged crystalline silicon modules

Tony Sample

European Commission, DG JRC, Institute for Energy, Ispra, Italy

This presentation does not contain any proprietary or confidential information.

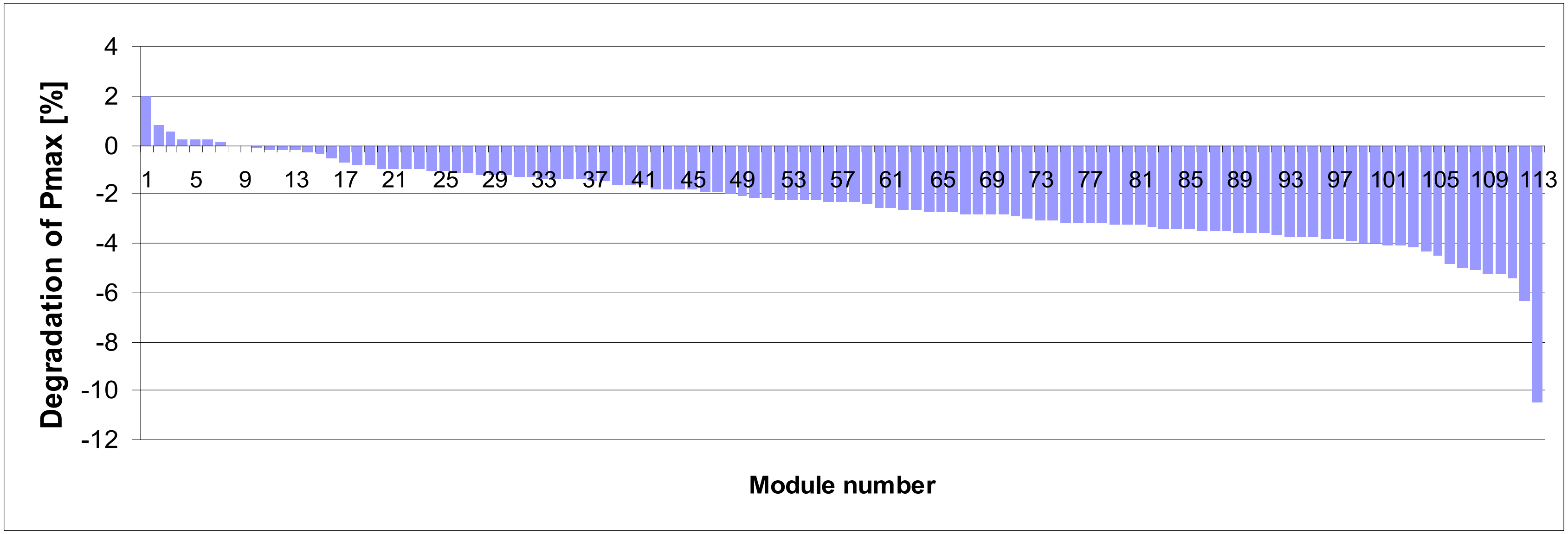
What we would like to know

- The **Degradation Mechanisms.**
  - One such source is the initial photon degradation related to a physical process in the solar cell itself, **short term**.
  - Other sources are related to **long term** weathering and degradation of the module package.
- The **Degradation Rates**. In order to understand the effect and relevance of each of these mechanisms on the total energy production of a PV module or array over its life time.
- The **Life Expectancy**. With this Life expectancy and knowledge of the degradation rates we can define the total energy output per lifetime of a PV module or array.

Examples of Initial Degradation

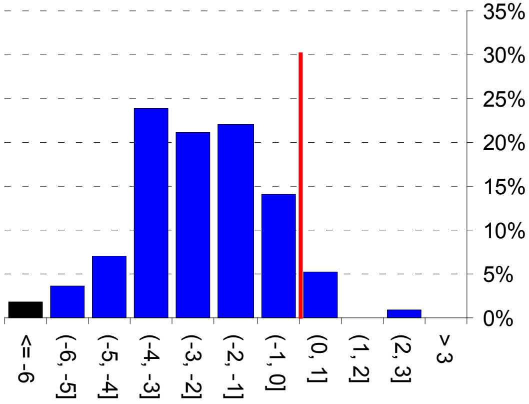
- During an IEC 61215 test procedure there is the requirement to perform a outdoor exposure (OE) test of 60kWh solar irradiance in short circuit conditions.
- At the JRC ESTI laboratory 113 modules types have been subjected to this test.
- Degradations observed range from zero to -6.3% with a correlation between the P_{max} degradation and the I_{sc} degradation.
- The average degradation observed is **2.4%** with deviation of ± 1.7%.

Degradation in OE Test



Summary of the degradation in P_{max} after the Outdoor Exposure Test for 113 module types tested at JRC Ispra.

histogram



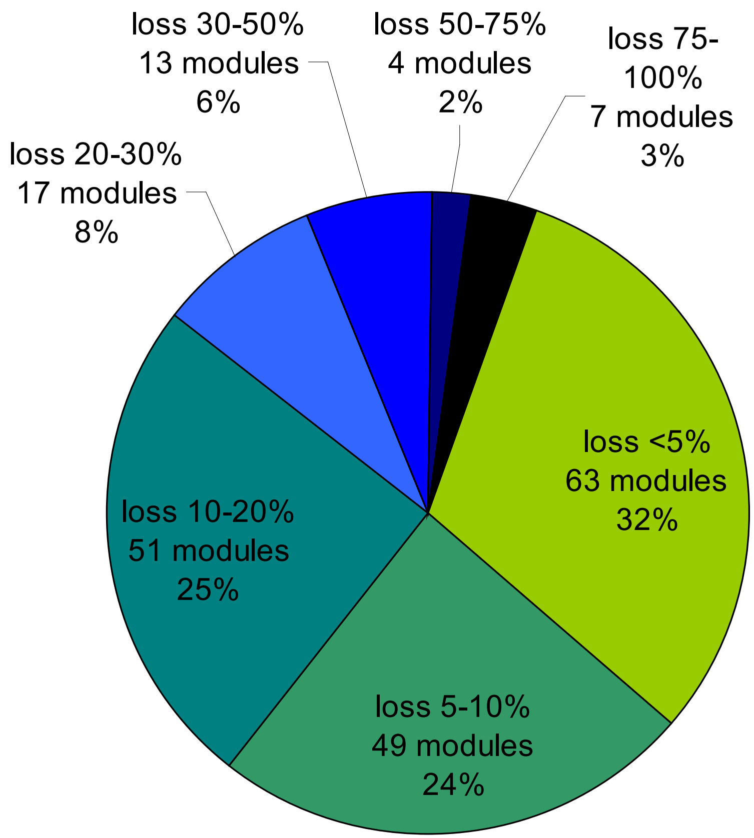
The ESTI Outdoor Test Field, Operating Since 1982

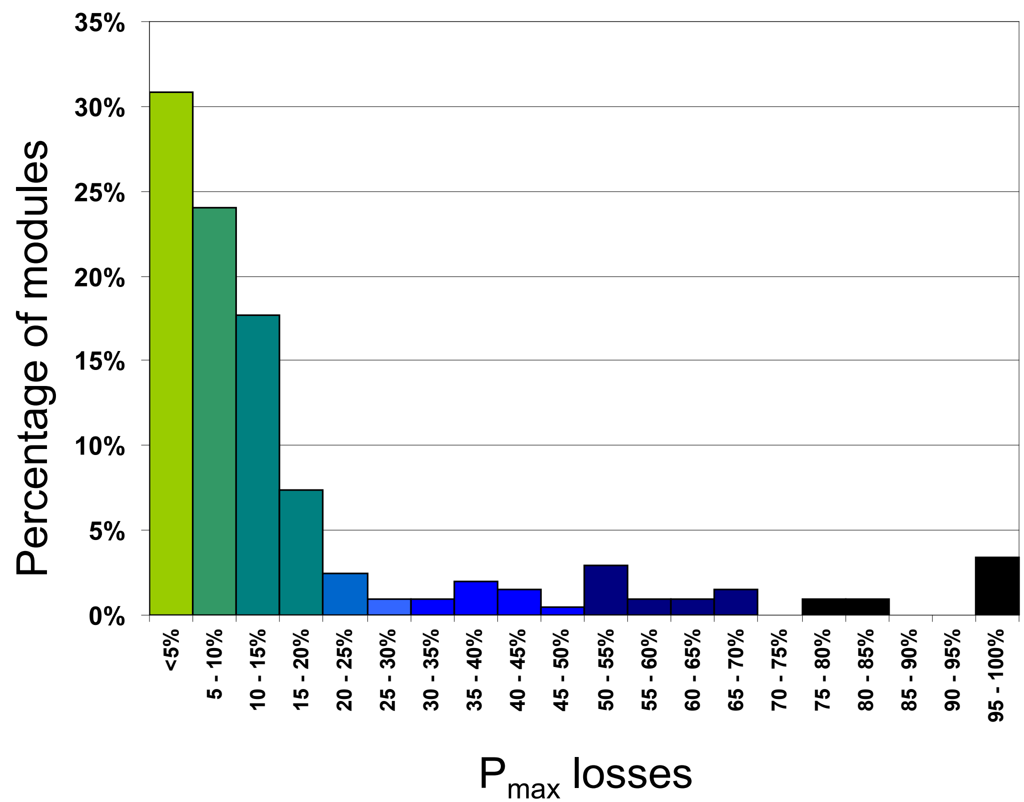
Long-term outdoor exposure

Long-term (18 - 24 years) outdoor exposure
Location: Ispra - moderate subtropical (-10º..+35º, >90% RH)

No of modules		204
No of producers		20
No of module types		53
Cell type	Mono	123
	Poly	81
Encapsulant	PVB	59
	Silicone	40
	EVA	101
	Other (unknown)	4
Substrate / Backsheet	Glass	68
	Tedlar, Tedlar/Aluminium/Tedlar	62
	Tedlar/Aluminium/Polyester	8
	Polyester/Aluminium	20
	Silicone	20
	Others, polyethylene, "plastic" Unknown	26

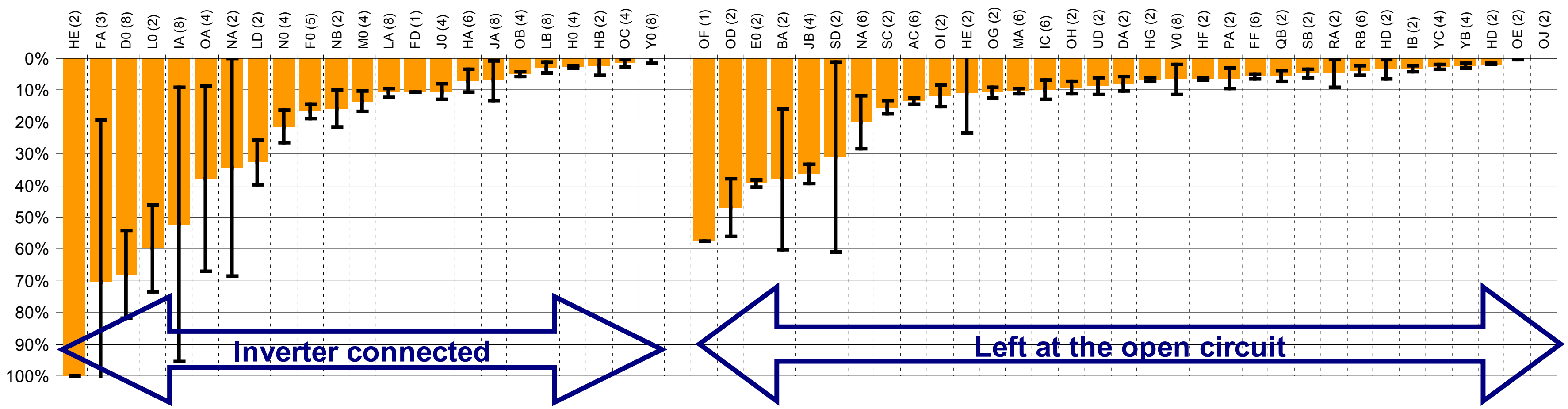
P_{max} losses from all 204 modules





Effect of electrical condition

Relative P_{max} losses of modules series grouped by module's test conditions

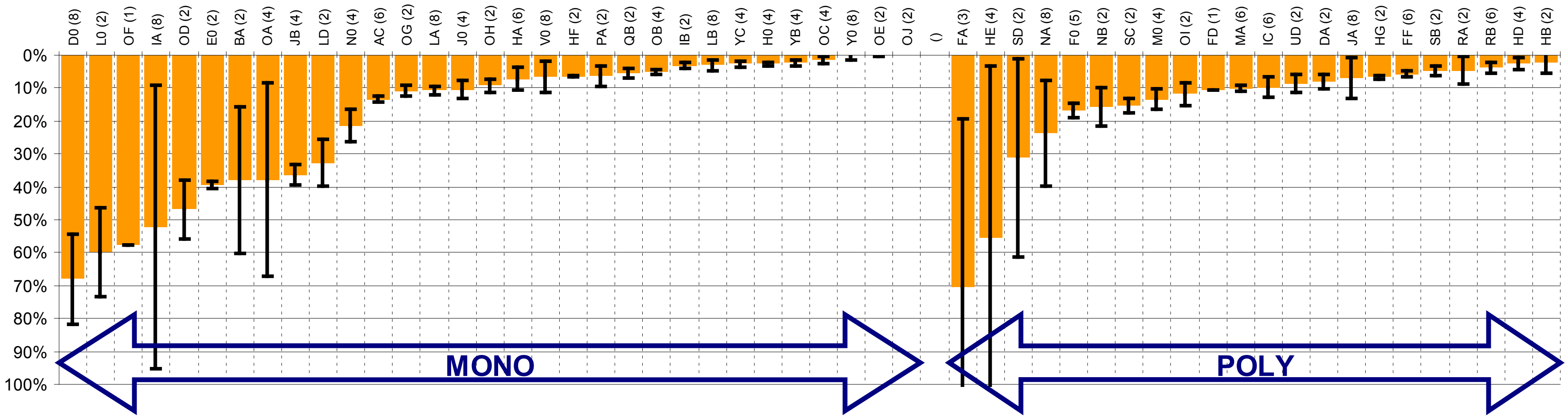


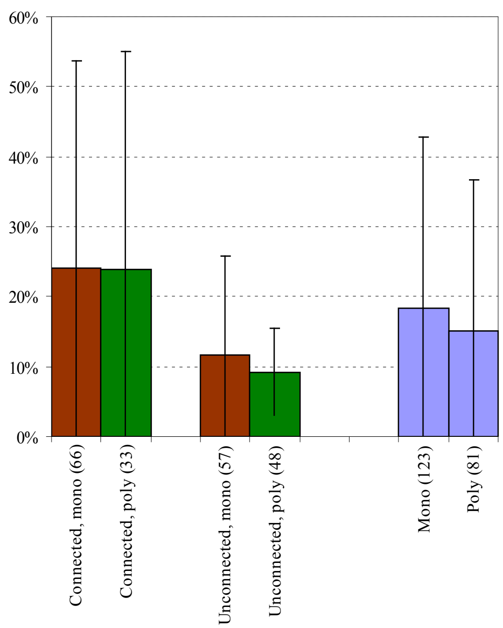
A statistical difference between modules initially connected to the inverter (charger) which exhibited approximately twice the average degradation in comparison to modules left in open circuit.

All of the modules (7) which exhibited total circuit breakage were connected to the inverter.

Impact of cell type

Relative P_{max} losses of modules series grouped by cell technology

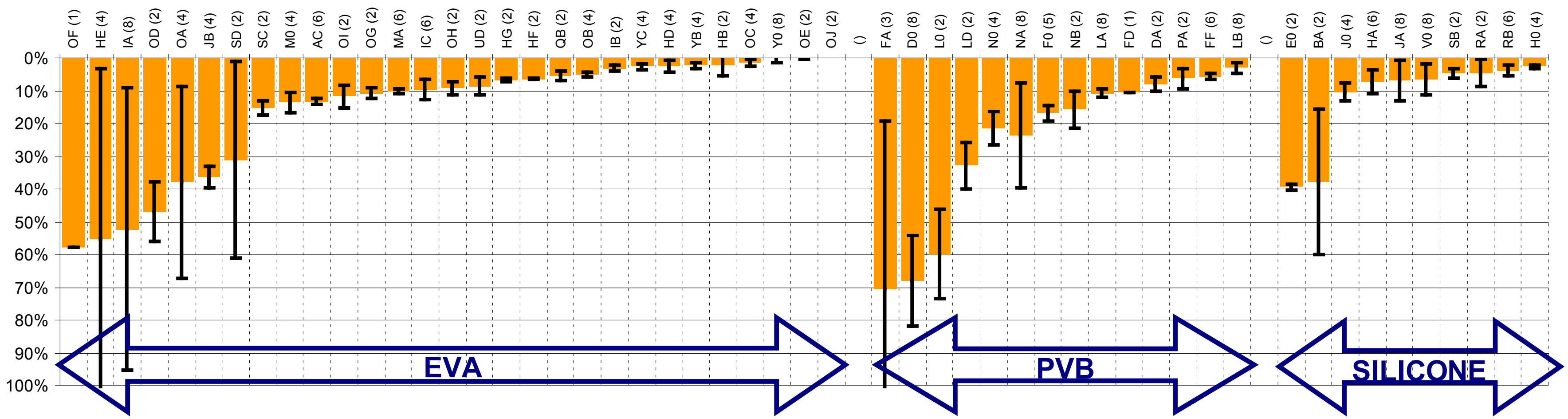


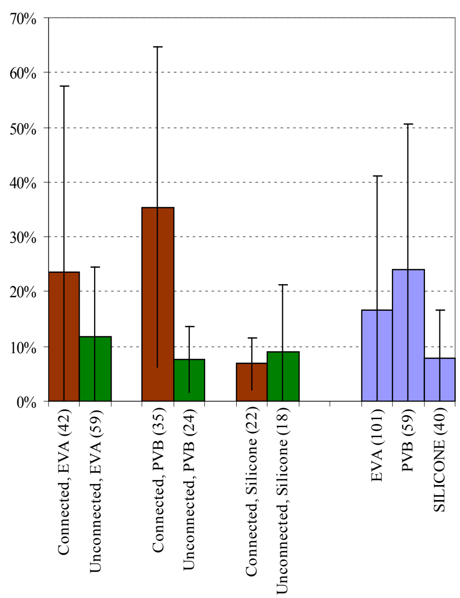


No statistical difference between modules incorporating monocrystalline or polycrystalline cells

Impact of the type of encapsulant

Relative P_{max} losses of modules series grouped by encapsulant

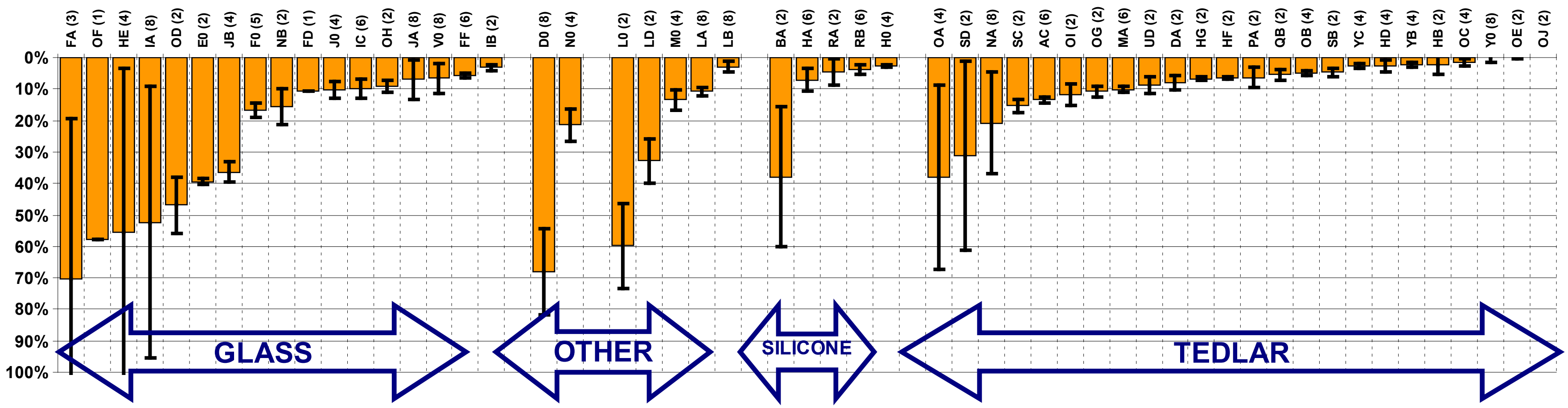


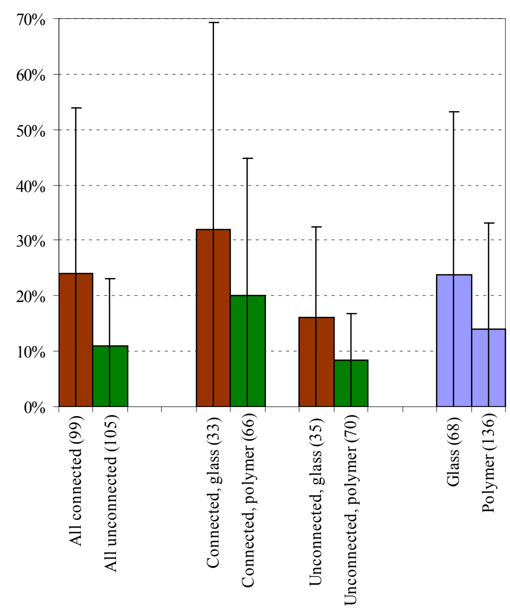


Modules incorporating silicone encapsulation generally exhibited lower degradation

Impact of the substrate

P_{max} losses of modules series grouped by back sheet

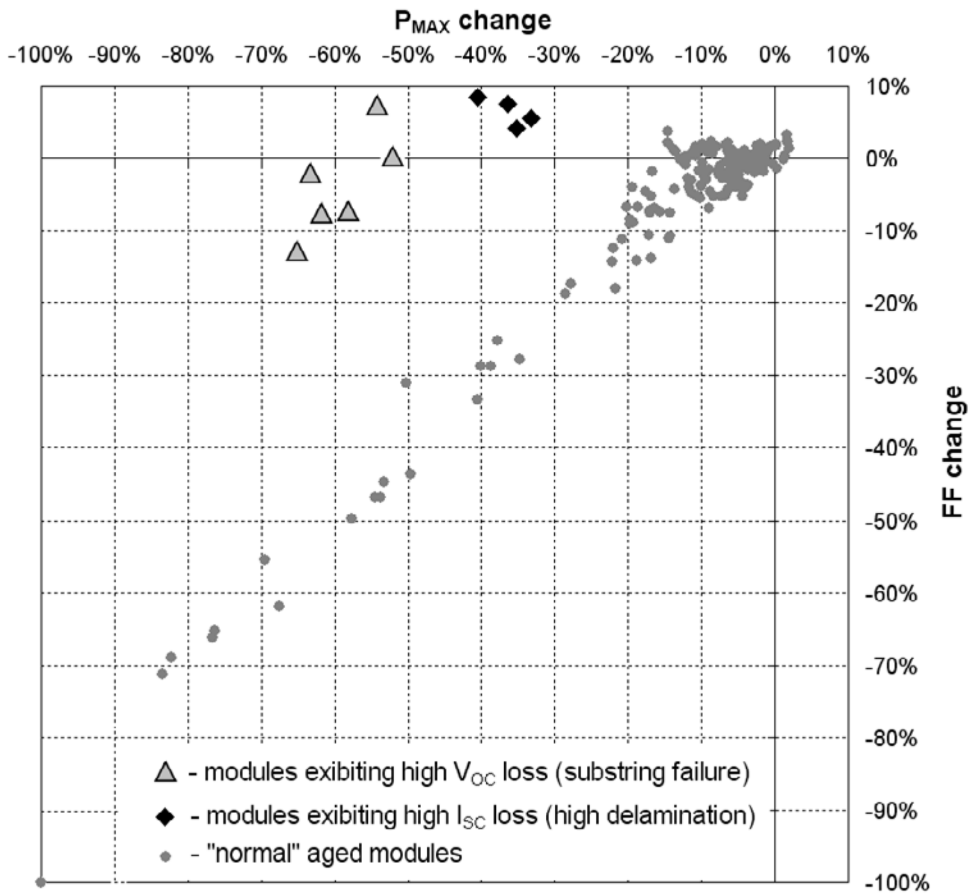




Glass-glass modules generally exhibited a greater degradation than glass-polymer construction

Correlation of P_{max} and FF

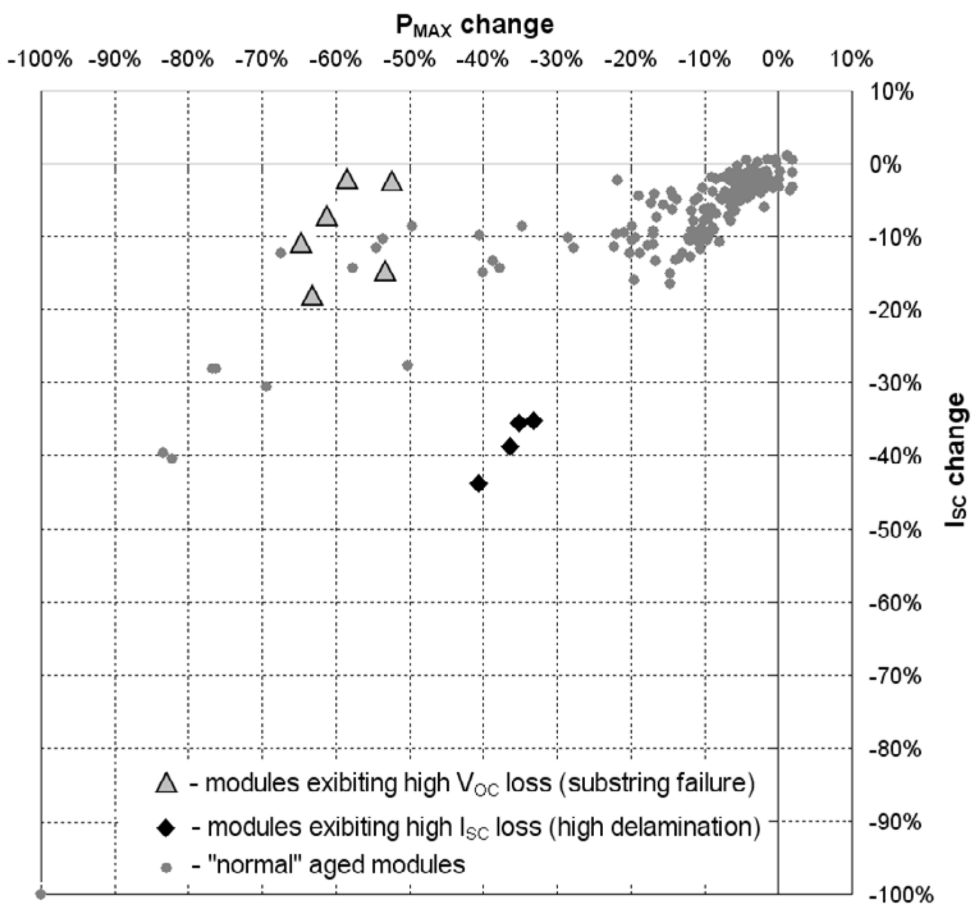
The scatter plot of the dependence of the P_{MAX} losses on the FF losses



Generally high P_{max} losses (>20%) are attributed to FF losses (series resistance increase)

Correlation of P_{max} and I_{sc}

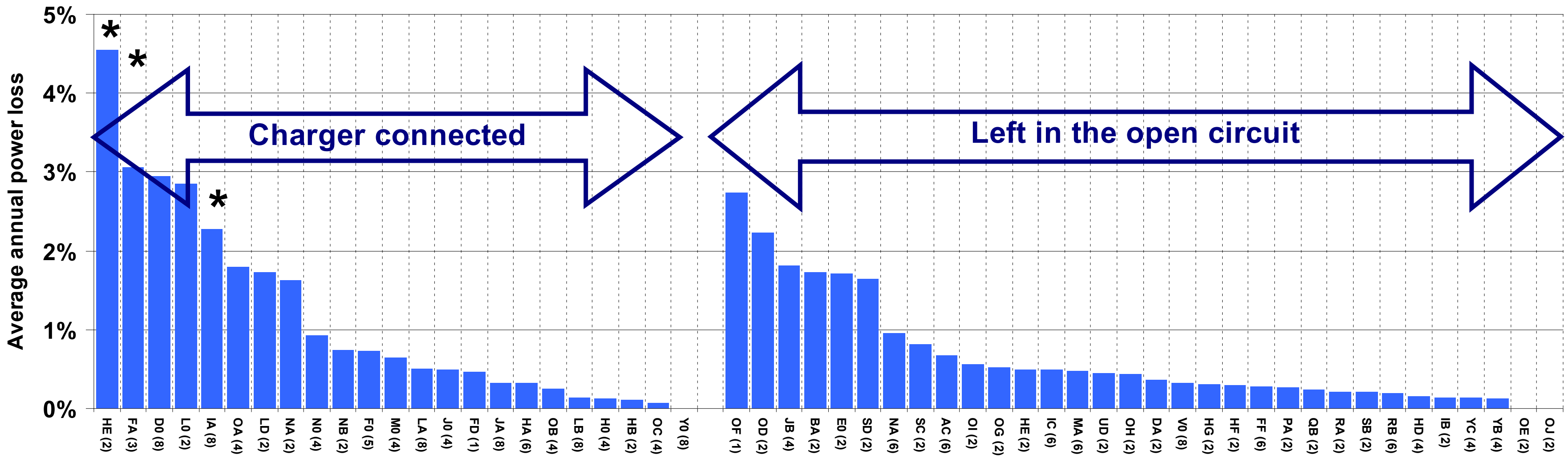
The scatter plot of the dependence of the P_{MAX} losses on the I_{SC} losses



Moderate P_{max} losses (<20%) can be attributed to I_{sc} losses (optical properties degradation)

-Changes in optical transmittance (glass or encapsulant)
-Delamination
-Light induced boron-doped silicon degradation

Annual degradation rates



* Average including total failures

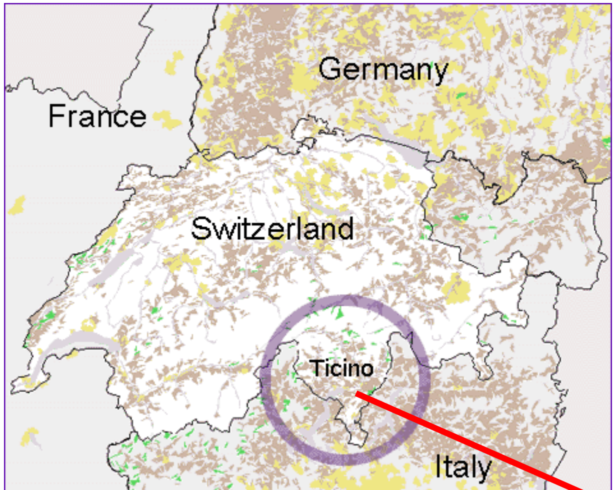
The average annual degradation for all of the connected modules **1%** (0.8% excluding total failures)

The average annual degradation for all of the modules left in open circuit **0.6%**

Field exposed modules summary

- No statistical difference between mono or polycrystalline cells
- Glass-glass modules generally exhibited a greater degradation than glass-polymer construction
- Modules incorporating silicone encapsulation generally exhibited lower degradation
- Generally high P_{max} losses (>20%) are attributed to FF losses (series resistance increase)
- Moderate P_{max} losses (<20%) can be attributed to I_{sc} losses (optical properties degradation)
- A statistical difference between modules initially connected to the inverter (charger) which exhibited approximately twice the average degradation in comparison to modules left in open circuit.
- The average annual degradation for all of the connected modules **1%** (0.8% excluding total failures)

10 kW PV plant study



252
(12 strings of 21 panels each)

Arco Solar

ASI 16-2300 modules

35 m-Si cells, PVB encapsulant, Tedlar/Al/Tedlar backsheet

Plant configuration

Arco Solar, ASI 16-2300 m-Si Module power @STC: 37Wp

Construction

Monocrystalline cells, PVB Encapsulant, Tedlar/Aluminium/Tedlar backsheet

Initial Configuration 1982

288 Modules (24 strings of 12) (nominal 10.66 kWp)
200V operation (Abacus 10kW inverter)
Tilt array 65º

Present Configuration since 1992

252 Modules (12 strings of 21) (nominal 9.32 kWp)
± 350 V operation (Ecopower 15kW inverter)
Tilt array 55º

1982: Initial aim

- To study technical and safety problems of a PV plant connected to the grid

2000-2003:

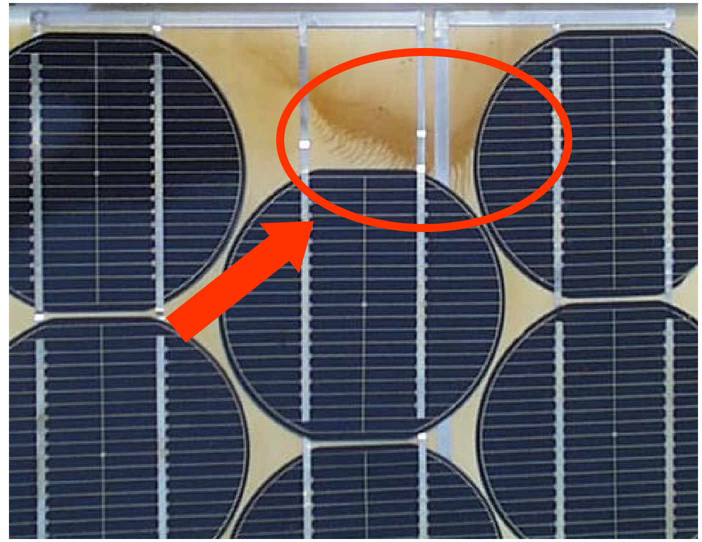
- Plant aging
- Investigation of physical degradation mechanisms
- Field reliability/accelerated lifetime tests (CEI/IEC 61215) correlation

Investigation of the 10kW PV Plant

- Detailed visual inspection
- InfraRed analysis
- Indoor IV measurements
  - reference modules
  - all modules
- Repeated CEI/IEC 61215 Damp heat and Thermal Cycling

Visual inspection

Visual defects: yellowing

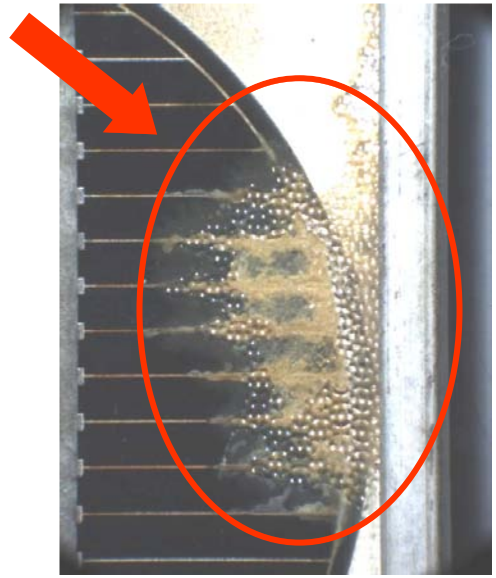


- 98% of modules (2003)
  (~50% in 1985)
- 78% exhibiting complete coverage of module
  (63% dark yellowing)
- Darker spots
- Practically no influence on encapsulant transparency
  (same spectral response for white and yellow modules)

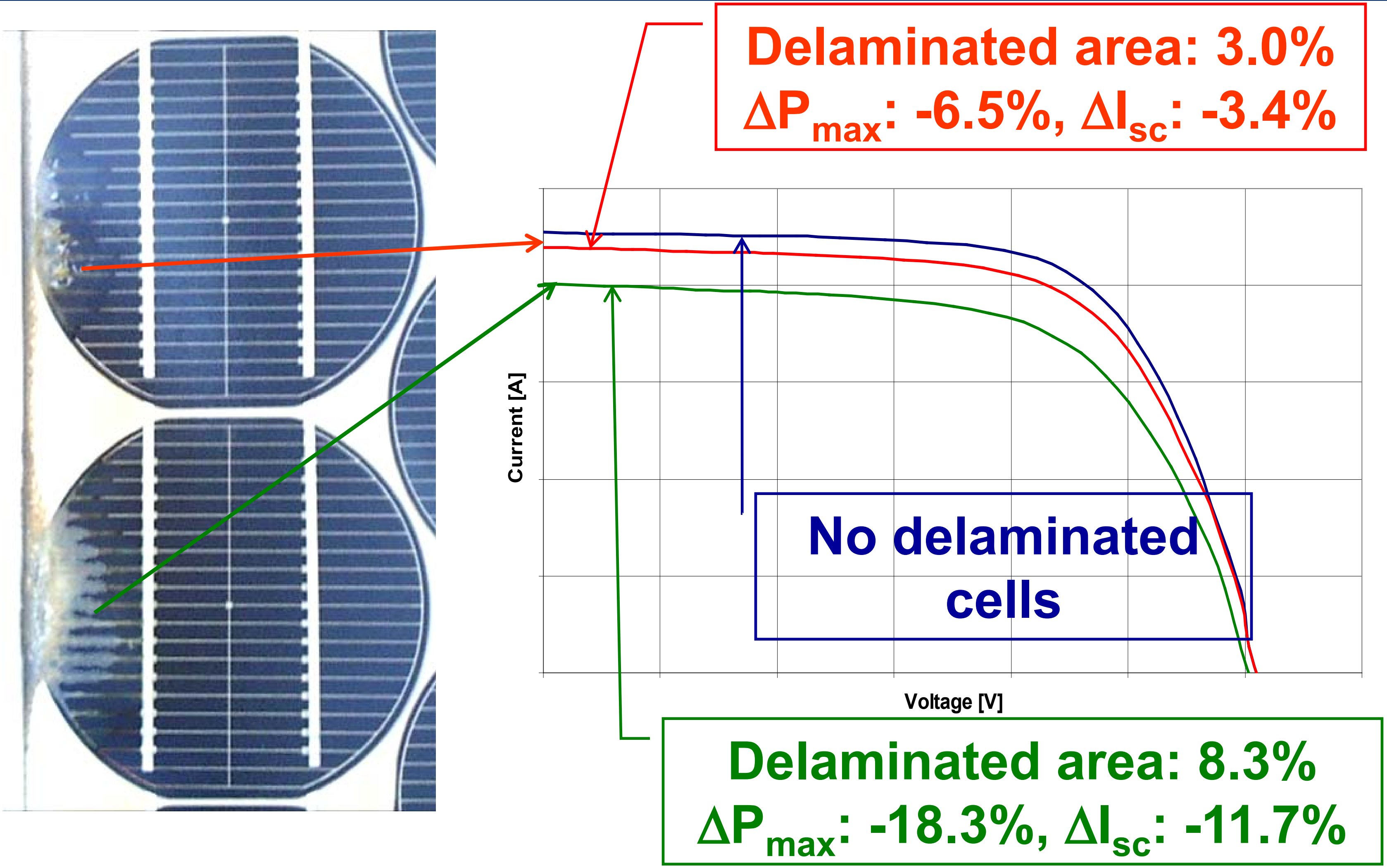
Visual inspection

Visual defects: delamination

- 92% of modules (74% in 1996)
- 27% major defect according to IEC 61215
- No effects on modules insulation (dry & wet insulation tests)
- Effects on modules performance (delamination in front of cells) (cumulative total delaminated area)



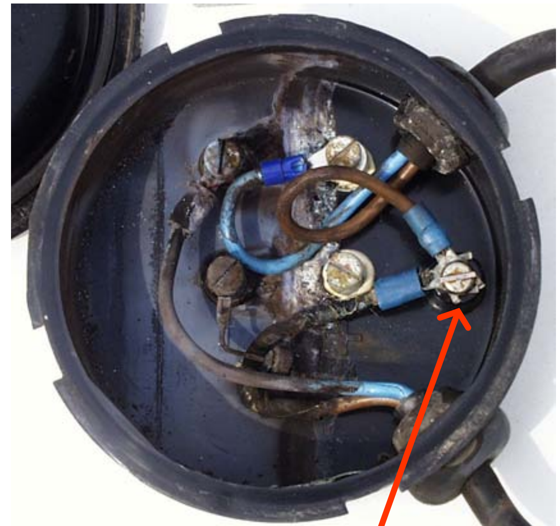
Effect of delaminated areas



No great effect on module performance

Additional Visual defects:

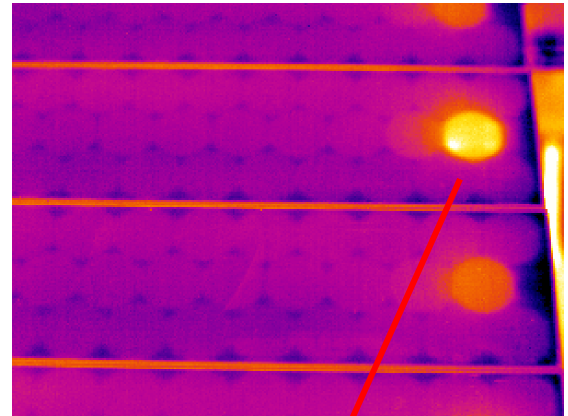
- Sealant infiltration
  76% of modules
- Cracked cells
  15% of modules
- Browning (oxidation) of gridlines
- Poor Junction box seal to backsheet tedlar
  risk of detachment; bad insulation
- Terminal oxidation
  problems when wiring

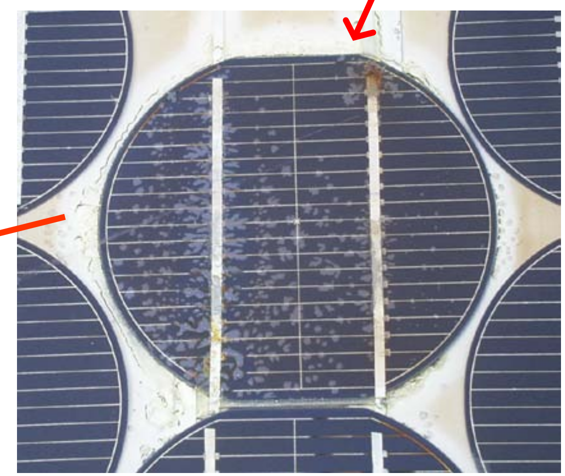


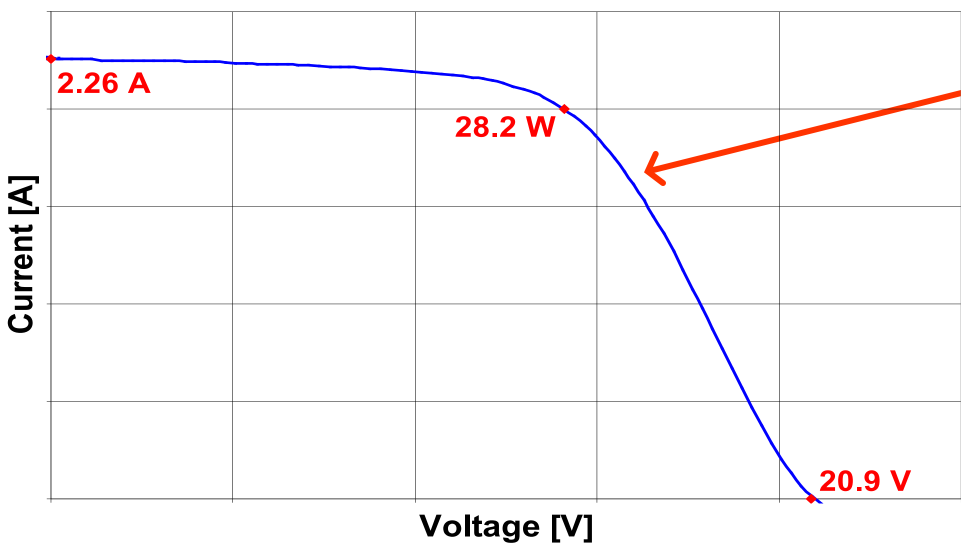
Infrared Analysis

- Noticeable Hot-spots: 24% of modules
  (22% in 1999)
  (Not just the effect of the junction box)

- Most degraded modules
  worst P_{max}: -29% vs P_n







P_{max}: -24% vs P_n
(-15% vs average actual P_{max})

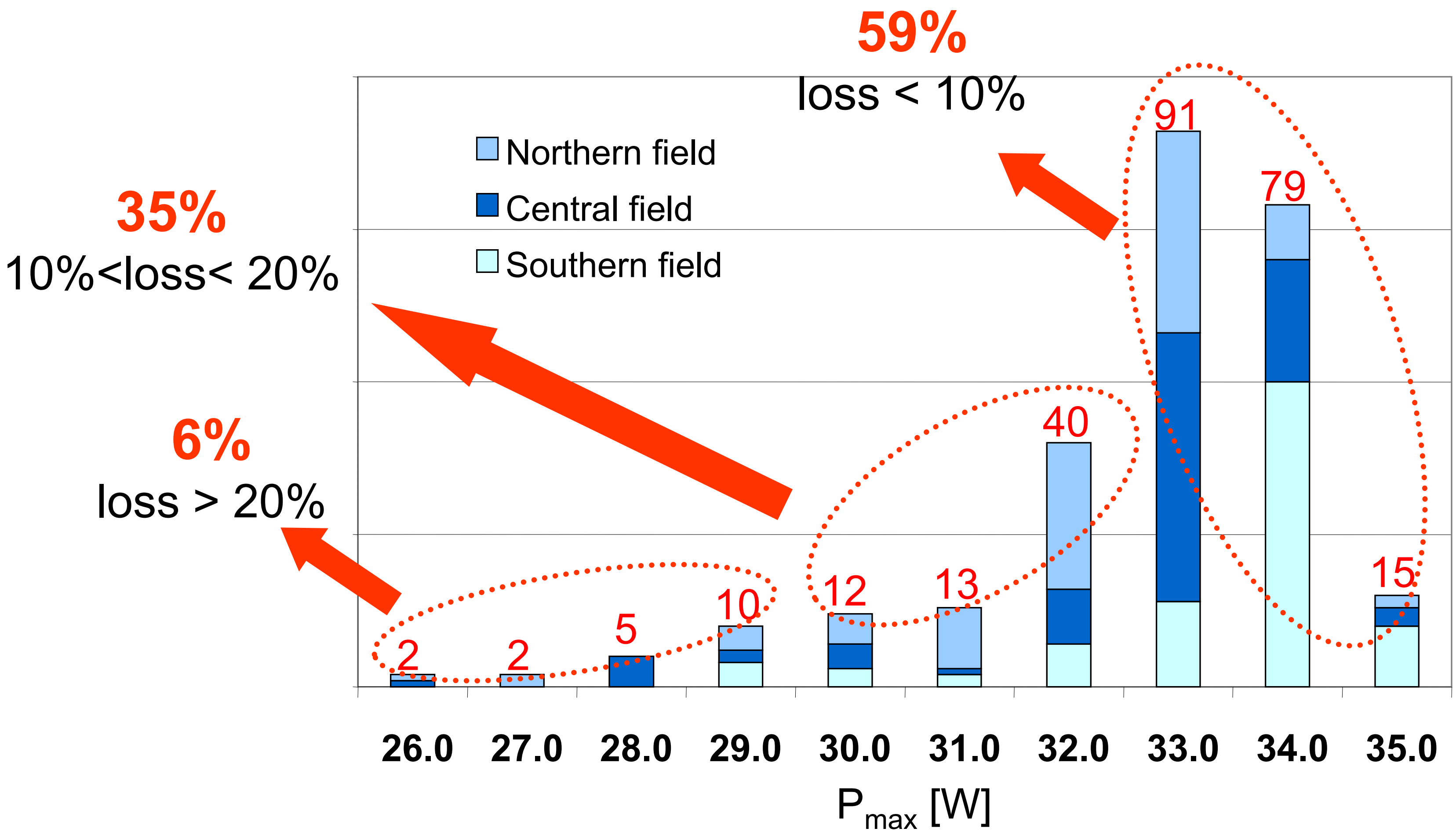
Indoor IV measurements

- **18 modules reference modules**
  ESTI laboratory IV measurements - since 1982

- **13 stable modules**
  power loss: -1.7% vs 1982 mean P_{max}

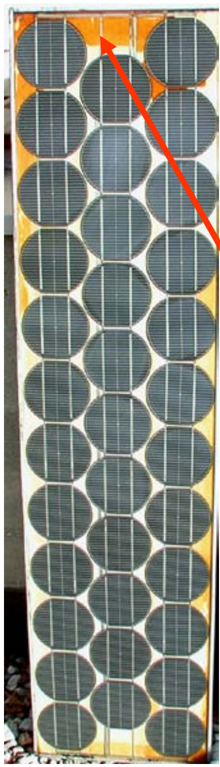
- **5 degraded modules**
  power loss: **-9.1%** vs 1982 mean P_{max}
  (2 hot-spot, 1 damaged cell)

IV measurement of the whole plant



Original Nominal Module power @STC: 37Wp

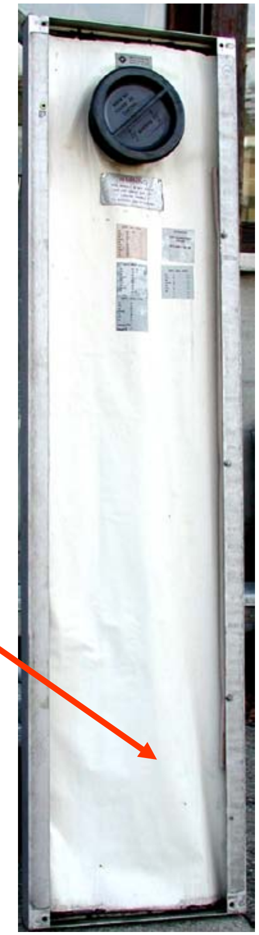
Testing of 20 year old modules



- 1220 Thermal Cycles:
  no major defects
  no measurable power losses

- 6000 hours Damp Heat:
  dark yellowing
  detachment of tedlar backsheet
  (not observed outside)
  no measurable power losses

Observed delamination outdoor, not reproduced through indoor tests



Conclusions for the 10kW TISO Plant

- **Good 20-year old technology**
- Not good looking, but perfectly functioning plant
- Hot-spots
- Delamination
- Remarkable modules resistance of old modules to repeated indoor Damp Heat and Thermal Cycling
- Good expectation for at least 30 year lifetime?

Currently at 29 years and still working well!

EUROPEAN COMMISSION JRC

Examples of Degradation rates

Institute for Energy

Detailed analytical data of the progressive degradation of PV modules is not readily available.

Realini et. al. For a crystalline silicon array, with Arco Solar ASI 16-2300 modules. Indicates an average weighted degradation of 5.2%. Over the 19 years of operation or **0.3% per annum** including initial degradation.

Reis et. al. For a crystalline array, with Arco Solar M-75 modules. The array was installed in 1990 and indicates a degradation of 4.39% in 11 years or **0.4% per annum** including initial degradation.

Osterwald et al. Stated rates of between **0.5 and 0.8% per annum** (shorter term experiments which linked to total UV dose to degradation in I_{sc})

Granata et al. Concluded that only one of the eight arrays studied showed true power degradation beyond experimental error at **1.4 0.8% per annum**

"Comparison of PV module performance before and after 11-years of field Exposure" AM Reis, et al . Proceedings of the 29th IEEE PVSEC, New Orleans, USA, 2002; 1432–1435.

"Degradation analysis of weathered crystalline-silicon PV modules" C.R. Osterwald, et al Proceedings of the 29th IEEE PVSEC, New Orleans, USA, 2002; 1432–1435.

"Long-term performance and reliability assessment of 8 PV arrays at Sandia National Laboratories" J.E. Granata, et al. Proceedings of the 34th IEEE PVSEC, Philadelphia, USA, 2009; 1486–1491.

Summary: Degradation Mechanisms

Short Term Losses: have been shown to be in the order of **2.4%** ± 1.7%.

Long Term Losses: have been shown to in the order of 0.2% per annum up to 1% per annum.

May be skewed data towards low degradation rates, due to the types of systems studied

The effect on **Energy Life** can result in losses in the order of ~5% up to ~8% based on a 20 year operation.

Over the module lifetime this is dominated by the long term losses.

Acknowledgments

The ESTI laboratories module qualification team past and present

Artur Skoczek, Mike Field and Ewan Dunlop

Antonella Realini (LEEE-TISO)

The work was partially funded by the PERFORMANCE project of the European Commission under contract number SES-019718 within FP6.