PV MODULE AND SYSTEM PERFORMANCE

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Hangzhou, 06 November 2012

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TÜV Rheinland Group

- Experience from PV module qualification since 1996
- Team of 150 engineers and technicians worldwide (partly > 25 PV experience)
- Research and development with focus on module qualification (characterization and life time assessment)
- Active participation in national and international standardization committees
- Global PV Network with locations in Cologne, Arizona, Shanghai, Taipei and Yokohama

Outline

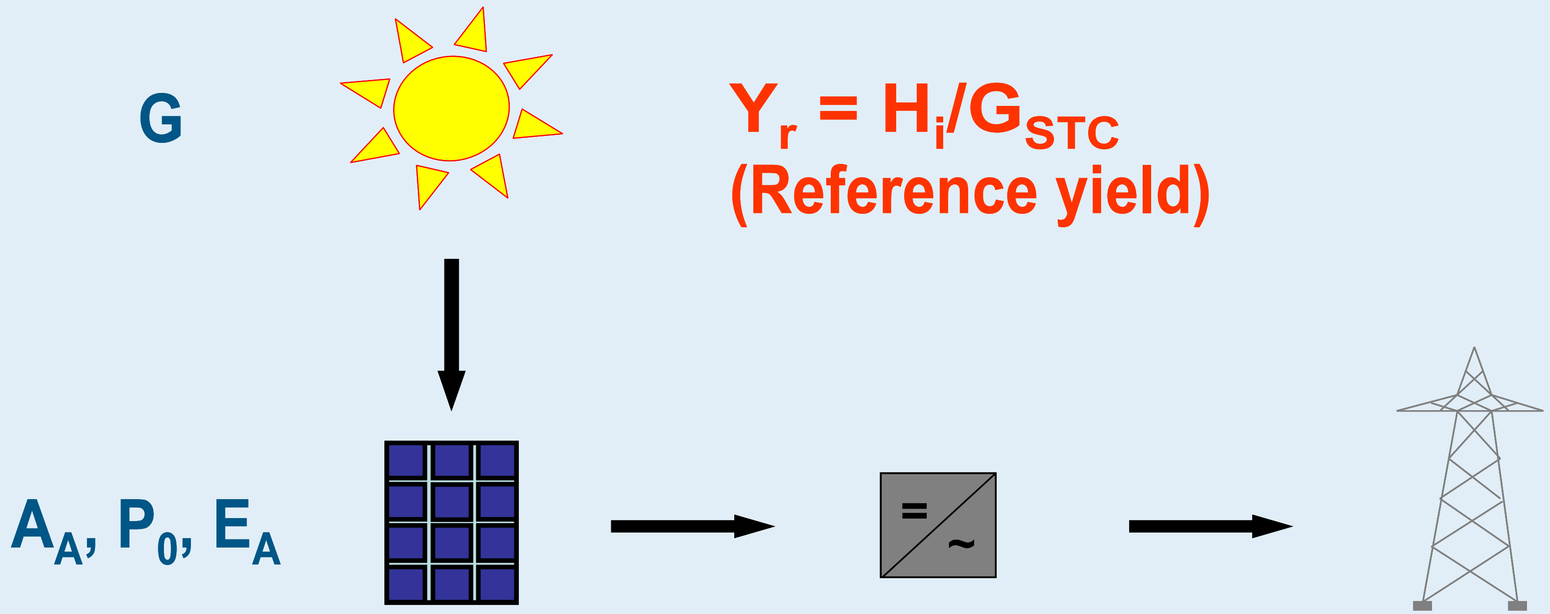
- **Introduction**
- **PV system performance analysis**
- **PV system energy yield prediction**
- **PV module reliability**
- **Statistics of laboratory testing**
- **Extended laboratory testing**
- **Conclusions**

Introduction

Reliable operation of PV modules and systems

Performance, energy yield and lifetime……

PV System Performance Analysis



$Y_r = H_i/G_{STC}$
(Reference yield)

$Y_A = E_A/P_0$
(Array yield)

$Y_f = E_{PV}/P_0$
(Final yield)

$L_c = Y_r - Y_A$ Capture losses
$L_s = Y_A - Y_f$ System losses
$PR = Y_f/Y_r$ Performance ratio

$\eta_A = E_A/H_i \cdot A_A$ Array efficiency
$\eta_s = E_{PV}/H_i \cdot A_A$ Global efficiency
$Y_f + L_c + L_s = H_i/G_{STC}$

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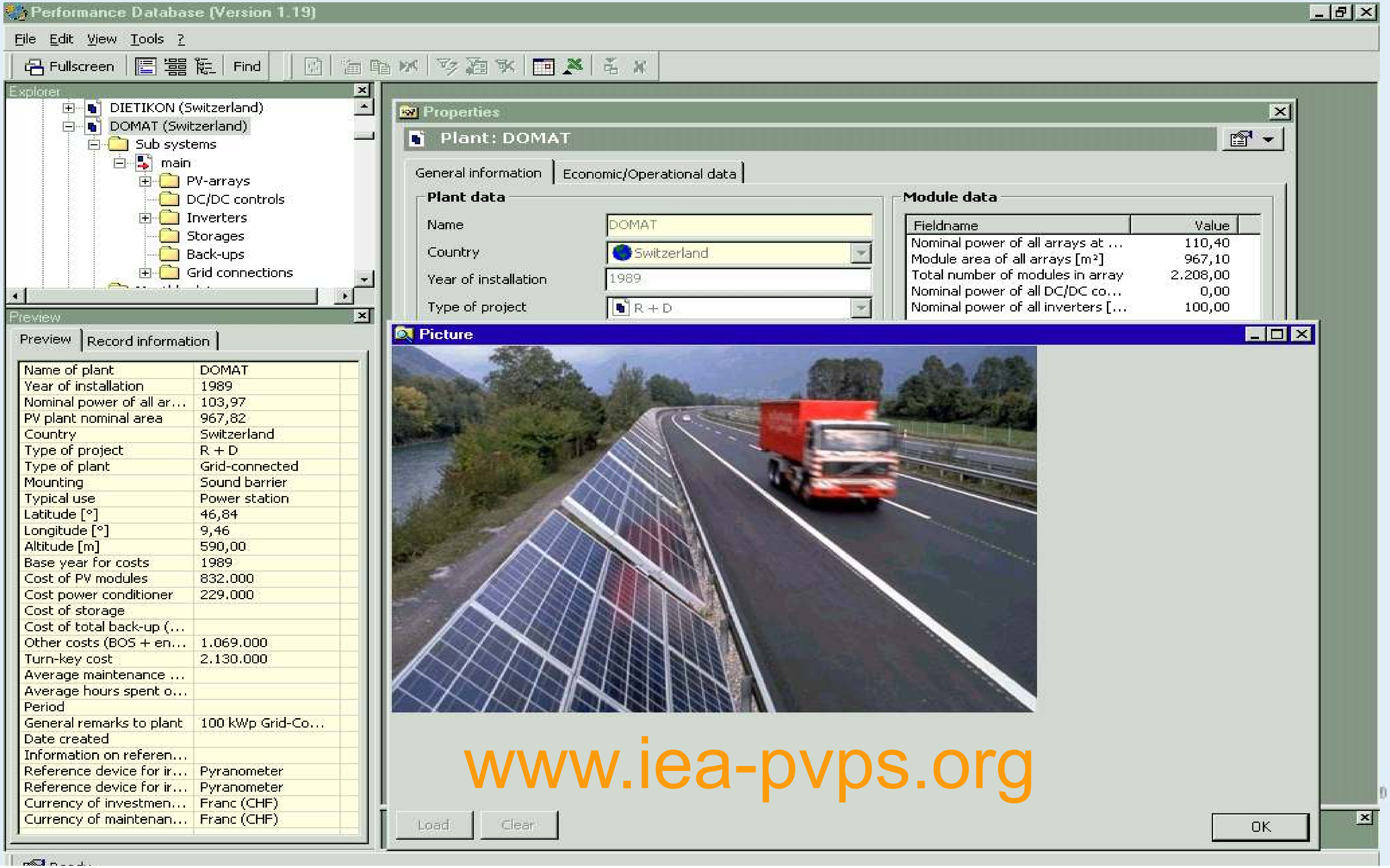
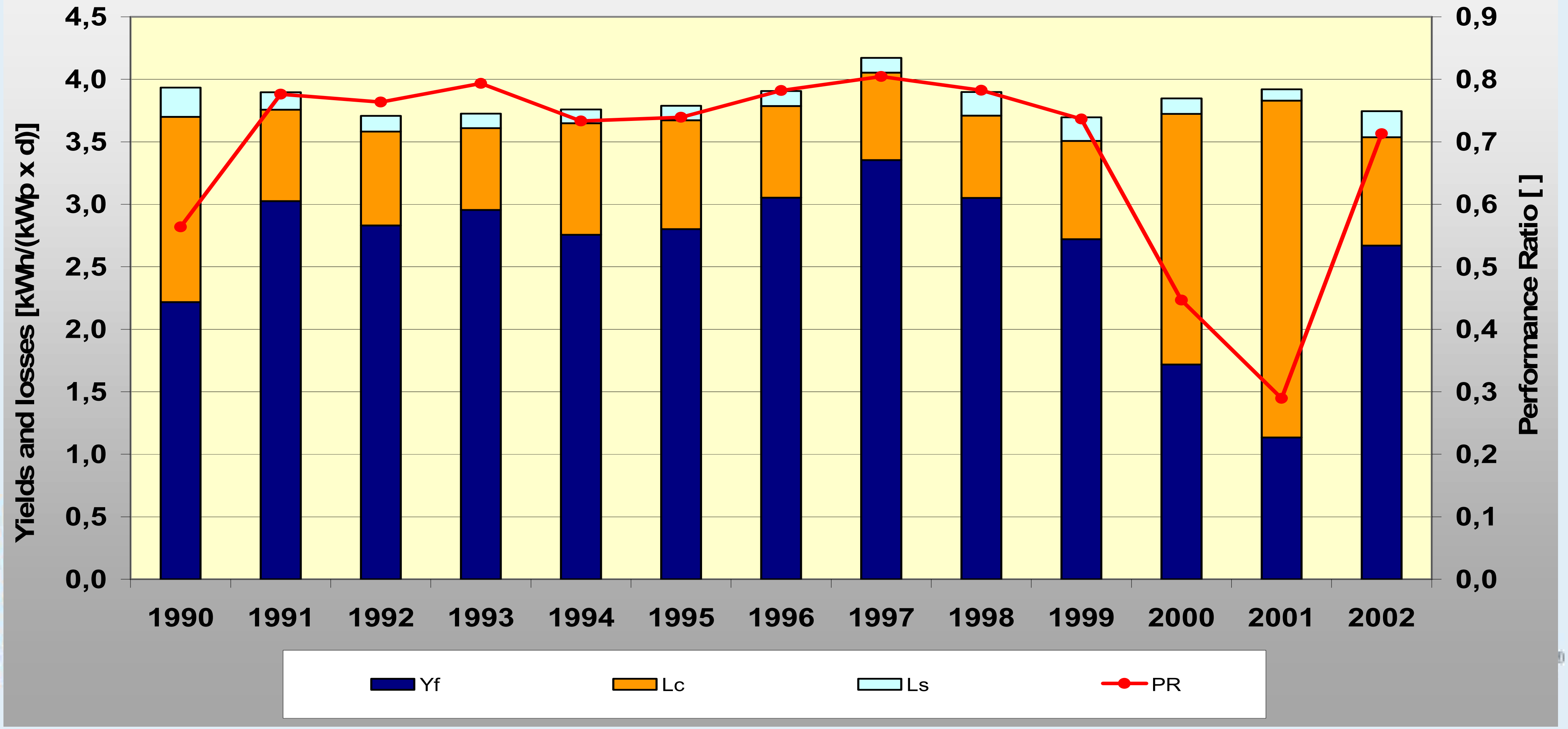
PV Performance Database



www.iea-pvps.org

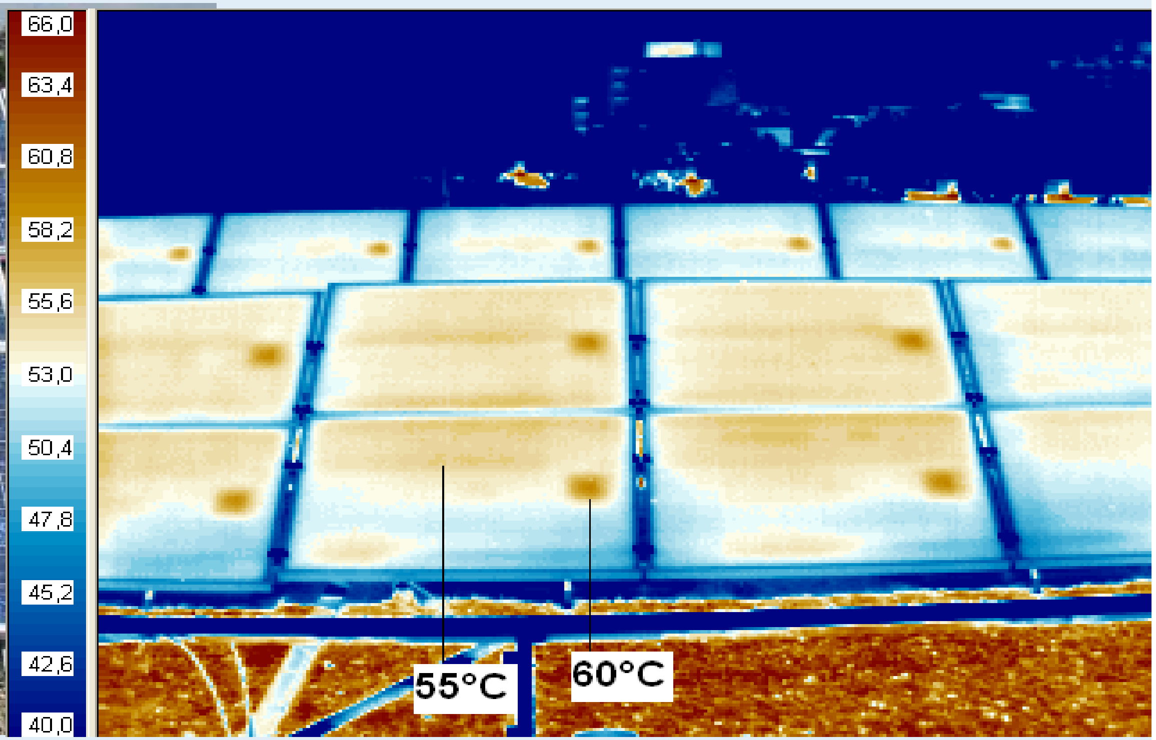
PV System Performance Analysis

104 kWp PV Sound Barrier in CHE: PR = 0.68



PV System Analysis

Temperature effect on energy yield



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Freestanding, roof mounted PV system, 30° tilt
IR image (right) with Tbom= 55° C for Germany

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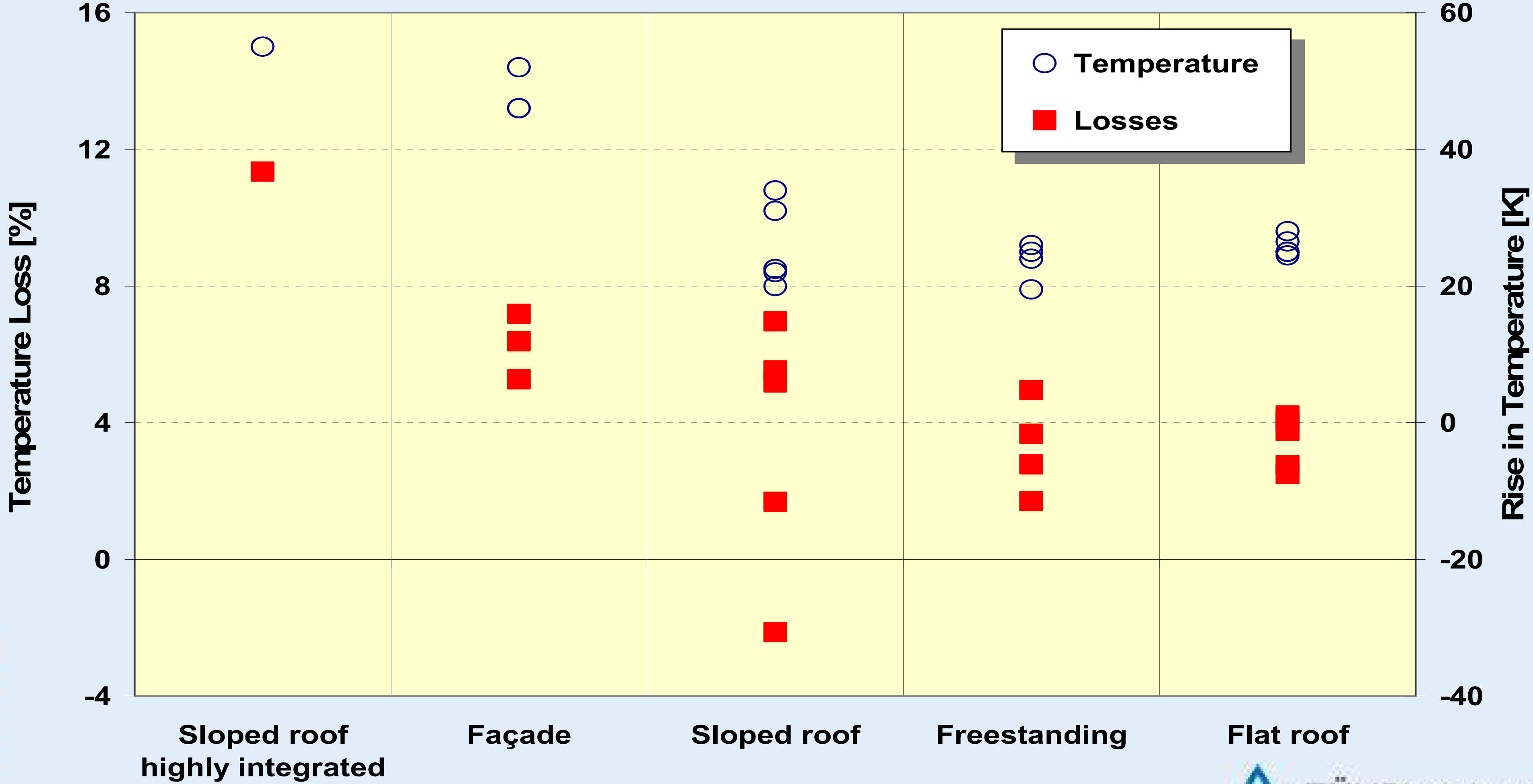
PV System Analysis

Temperature effect on energy yield



Temperature effect depends on type of mounting.

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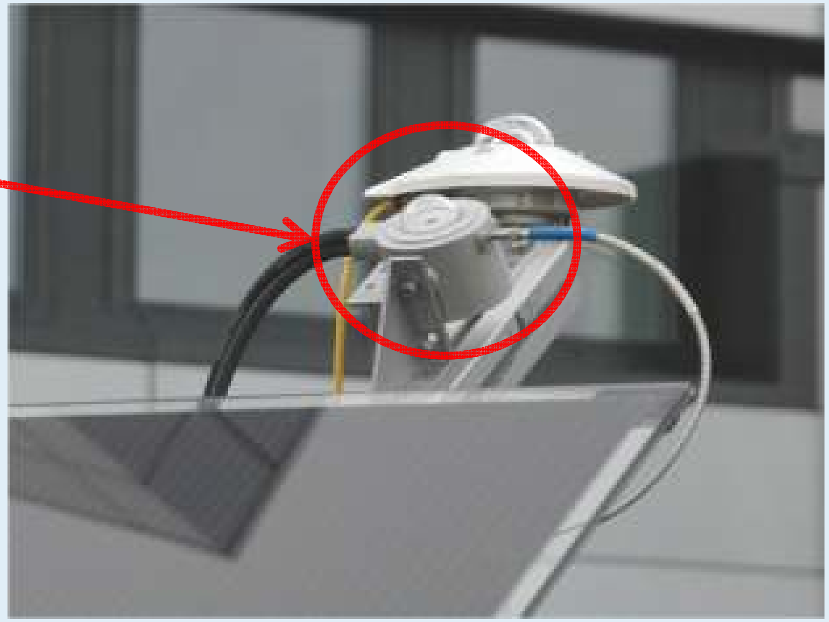
Prediction of Actual Long-Term Yield
Spectral effects on energy yield



Outdoor spectrometer measurements: 300nm – 1600nm

In module plane, 35° tilted facing south (direction influences result)

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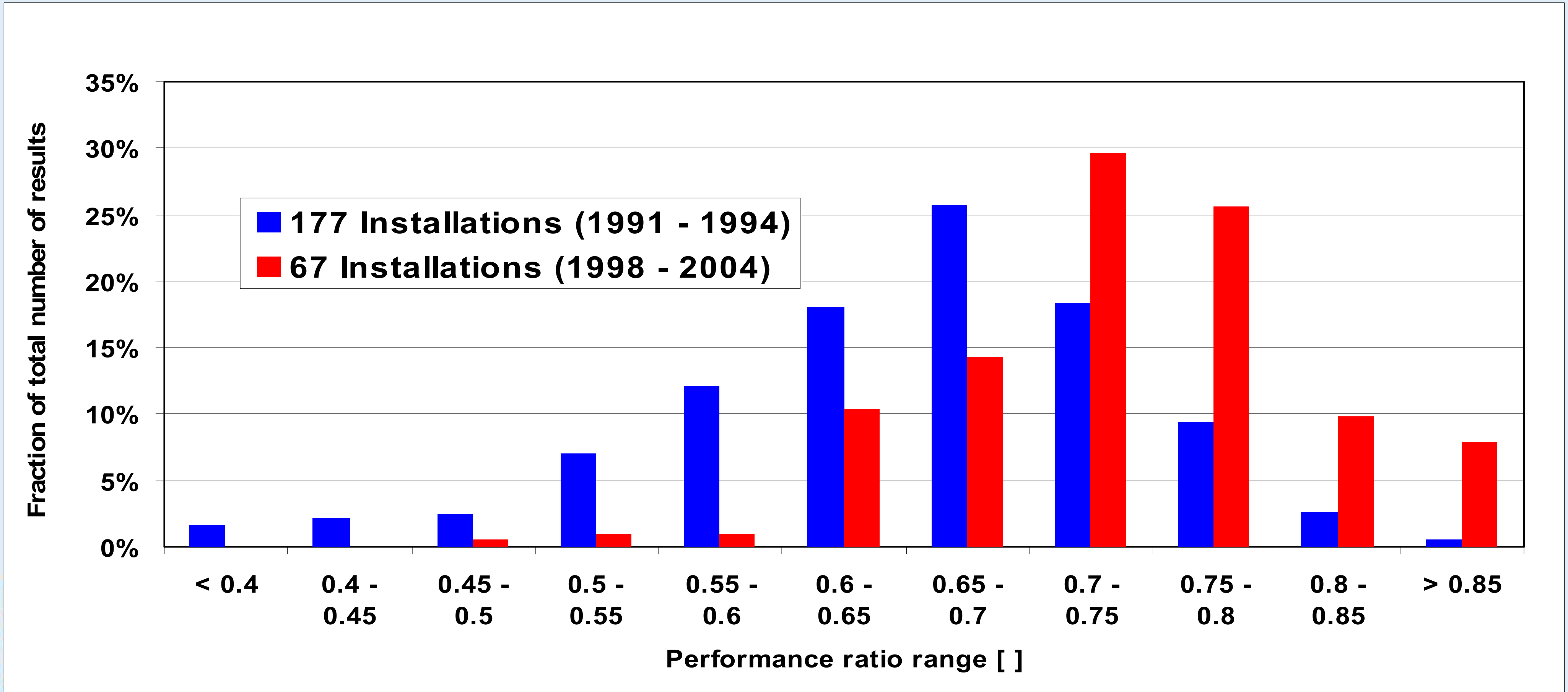
PV System Performance Analysis

Germany: 1991 - 2005



Before 1995: **PR = 0.65**; after 1995: **PR = 0.74**

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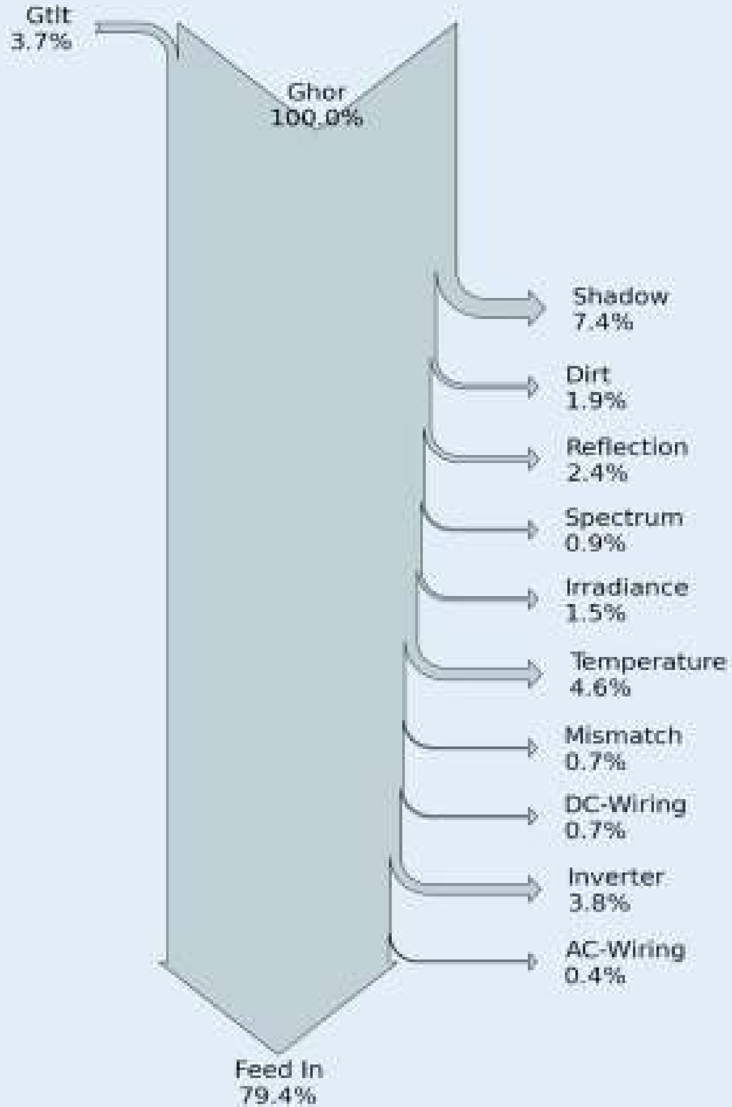
Prediction of Performance Ratio (PR)



Reise et. al. reported on the accuracy of Performance Ratio prediction at earlier EU PVSECs

Reise et. al. at the 27th EU PVSEC, Frankfurt, September 2012.

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Prediction of Actual Long-Term Yield

Uncertainties Related to Yield Prediction

• Irradiation resource (horizontal)	3% to 5%
• Direct/diffuse ratio and conversion model	2% to 3%
• Shading (+ inverter behaviour)	1% to 4%
• Soiling	1% to 3%
• Reflection	0% to 2%
• Spectrum	0% to 2%
• Real vs. rated power	0% to 5%
• Irradiance level dependency	1% to 2%
• Temperature dependency	0% to 2%
• Mismatch	0% to 1%
• DC + AC cabling	0% to 1%
• Inverter	0% to 2%
• Transformer	0% to 1%
• System degradation	0% to 5%
	5% to 10%

Reise et. al.

at the 27th EU PVSEC, Frankfurt, September 2012.

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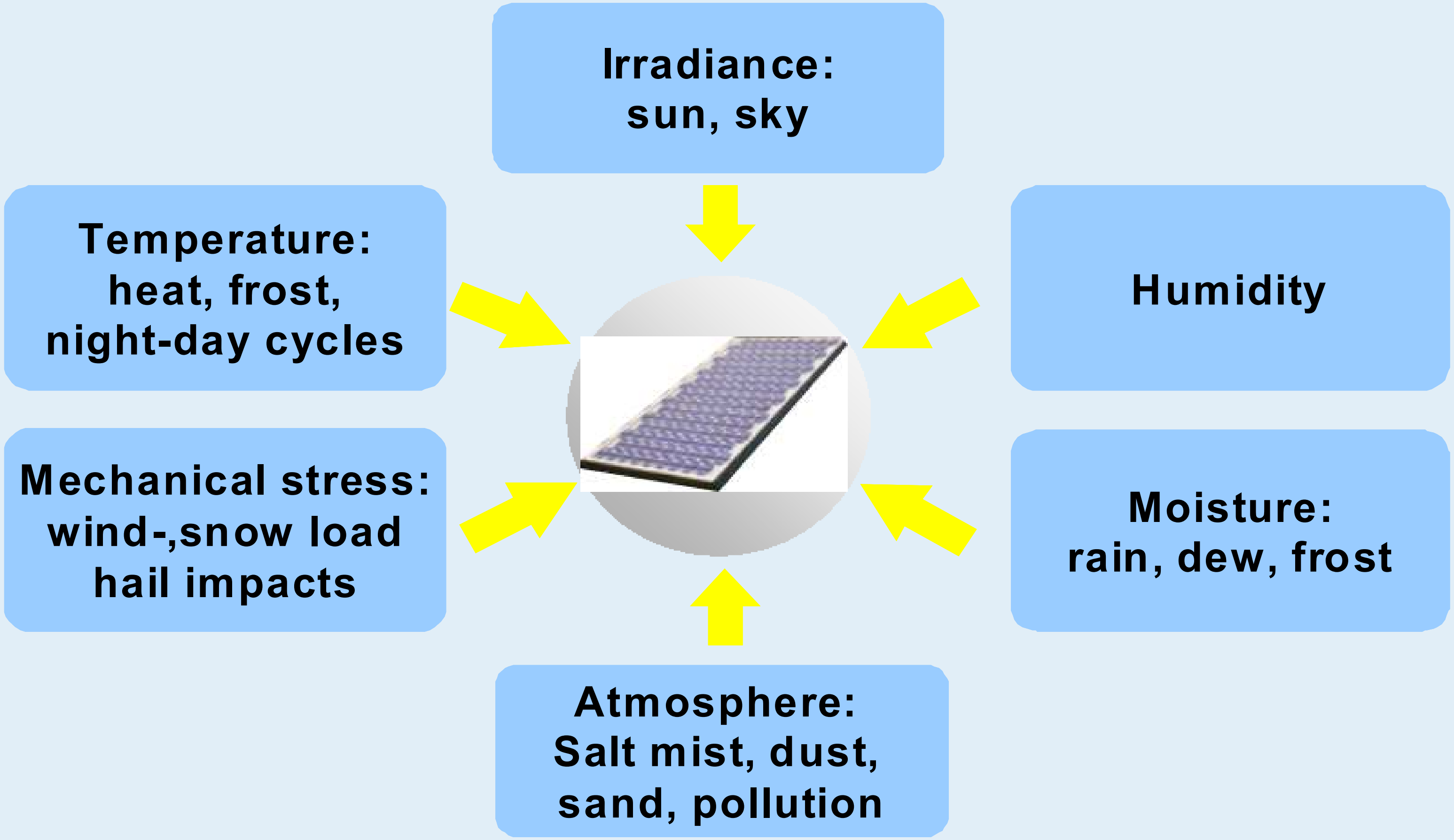
PV Module Reliability



PV modules are complex products that combine materials of different physical and chemical properties.

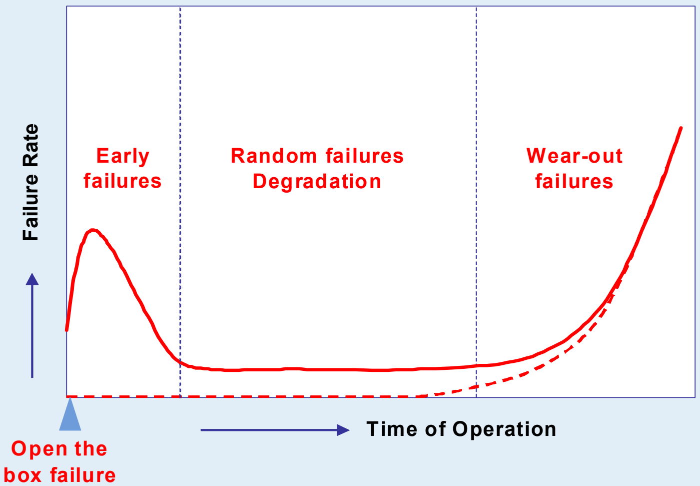
PV Module
Reliability Testing

- **IEC test standards for product qualification** of PV modules as a minimum requirement to undertake reliability testing.
- The primary goal of IEC testing is to identify the initial short-term reliability issues in the field.
- **Extended IEC testing** is typically applied to reveal weaknesses in the construction

IEC 61215:
c-Si PV modules

IEC 61646:
Thin-film PV modules

IEC 62108:
CPV modules



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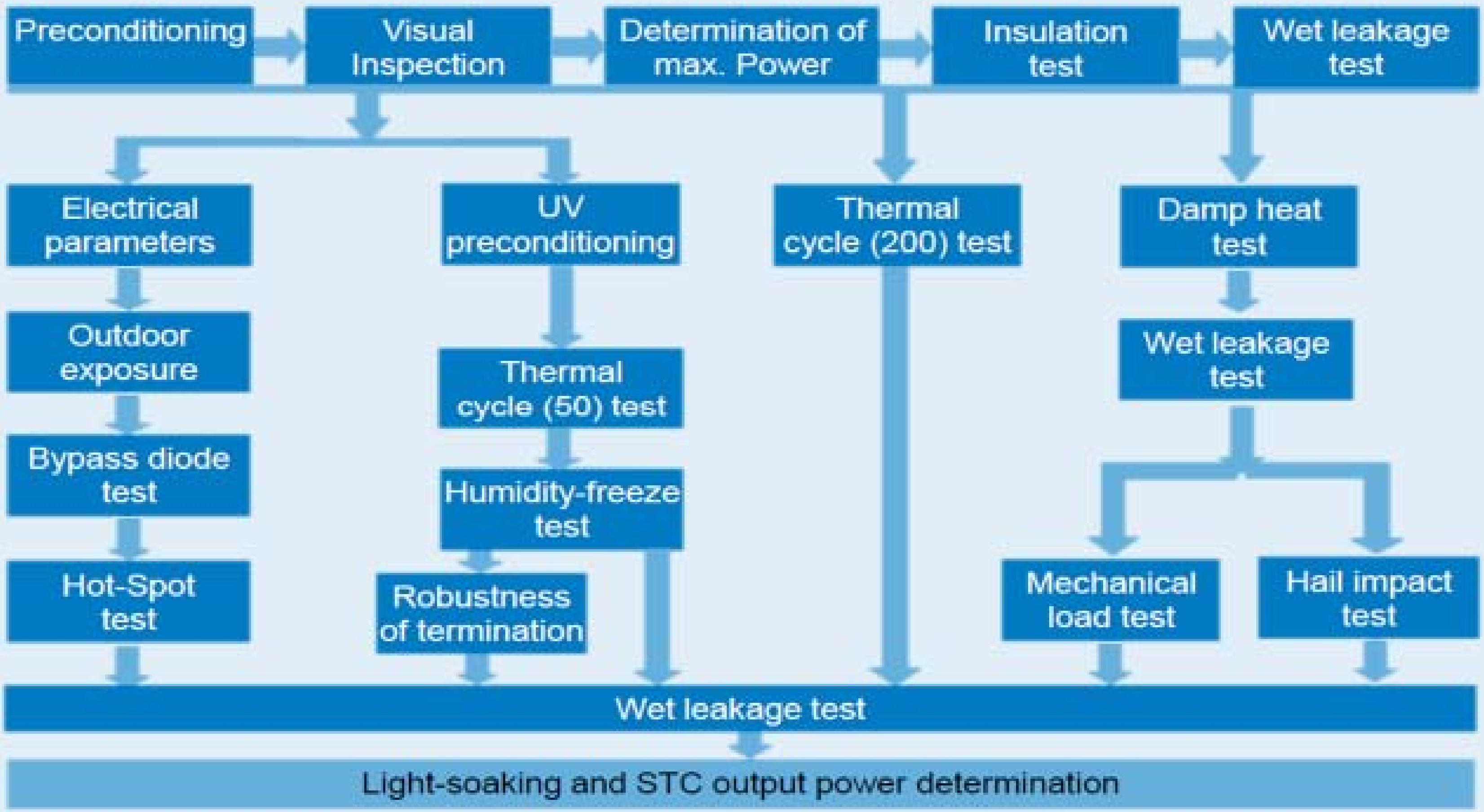
IEC standards

Type approval of PV modules according to IEC 61215 and IEC 61646



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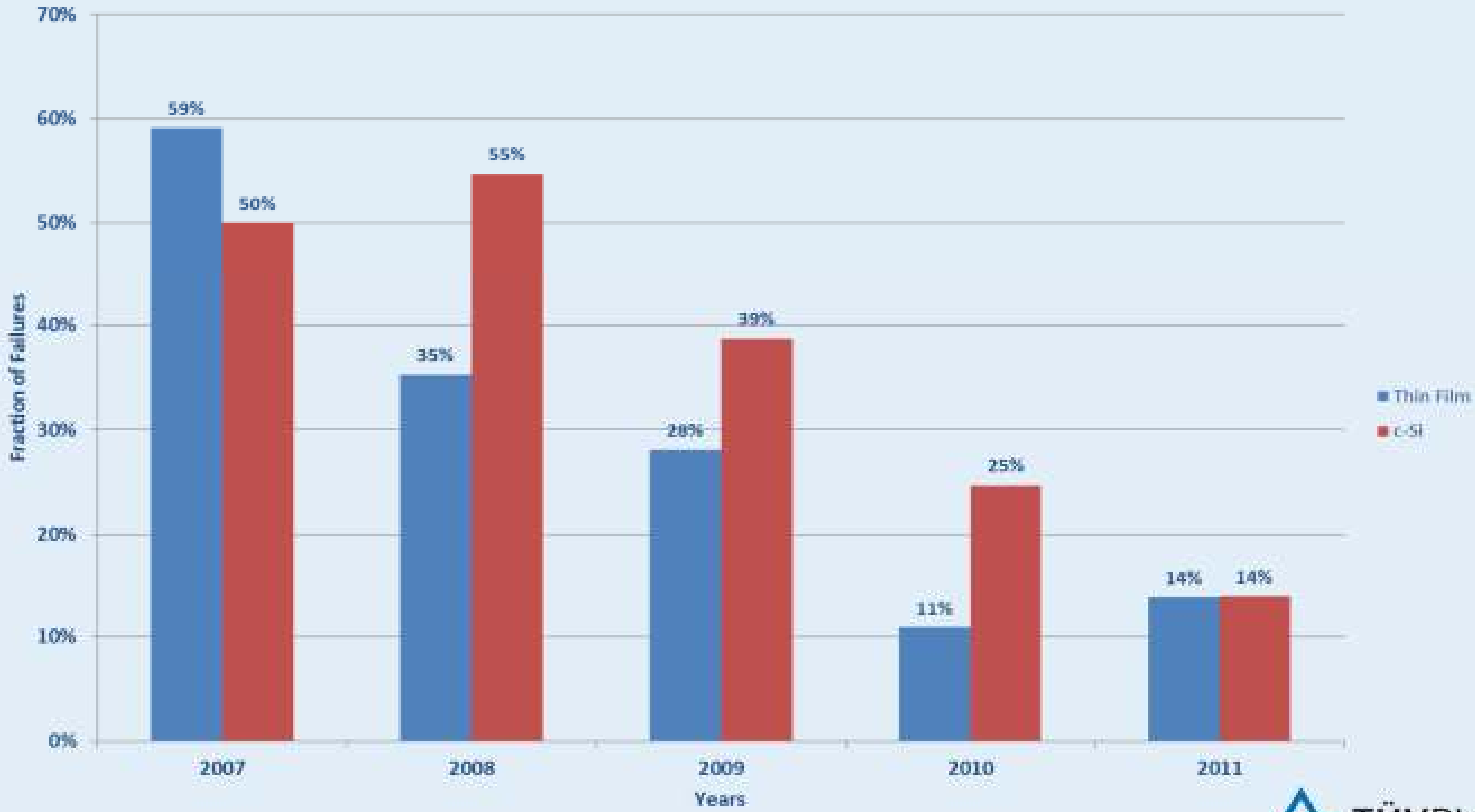
IEC Qualification Testing
Monitoring of degradation

Degradation parameter	Test method / procedure
Visual changes (Yellowing, soiling, corrosion etc.)	Visual inspection
Deterioration of max. power	Max. power characterisation at STC (5% threshold in IEC 61215)
Insulation resistance	Dry insulation test Wet insulation test
Internal series resistance	I-V measurement at 3 irradiances and constant module temperature
Microcracks in cells, interruptions of electrical interconnection circuit	Electroluminescence (EL) record $I_{TEST} = I_{SC,STC}$

IEC Qualification Testing

Failure rates c-Si and TF modules (2007 - 2011)



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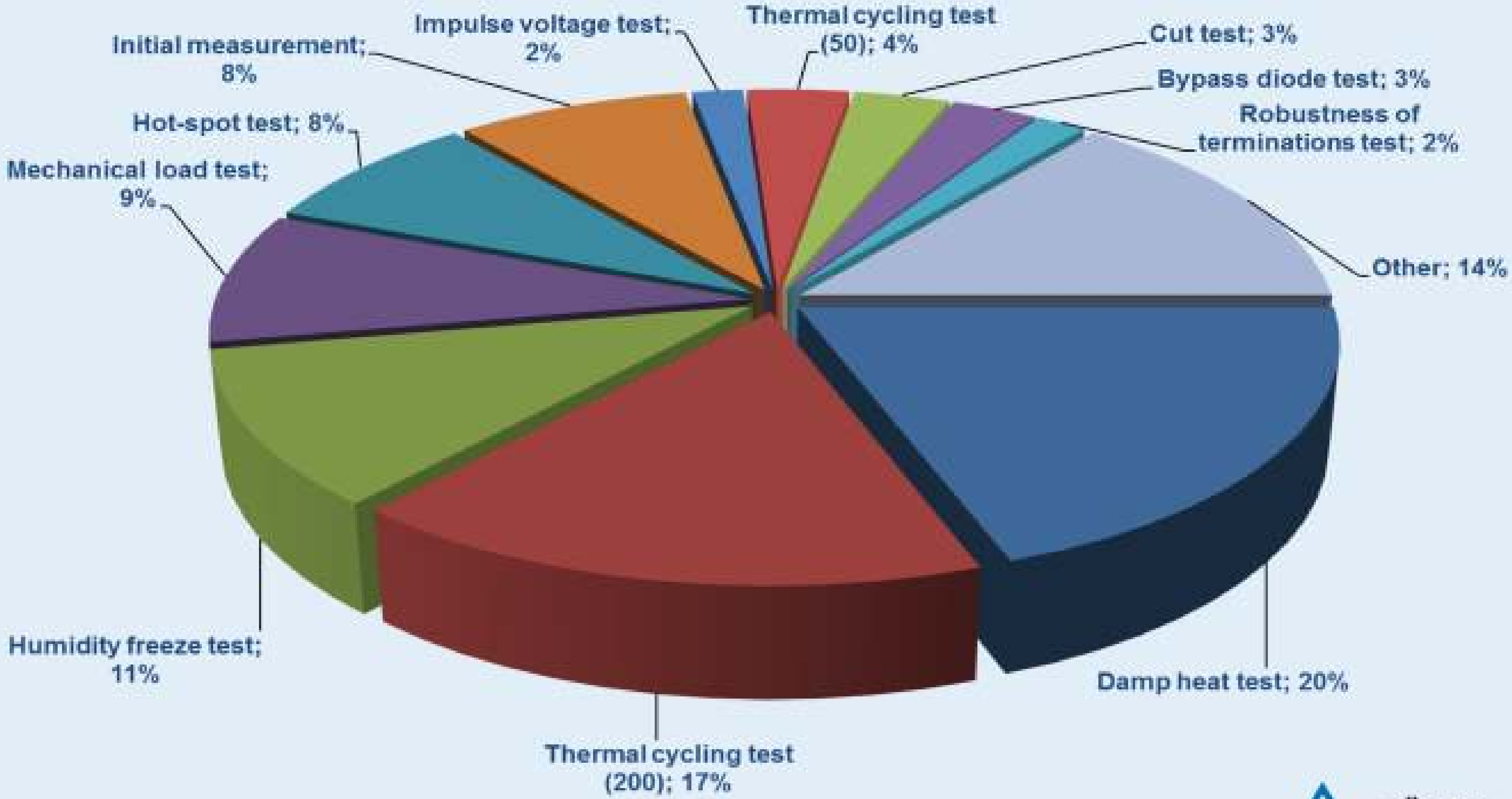
IEC Qualification Testing

Failure rates c-Si modules (2007 - 2011)



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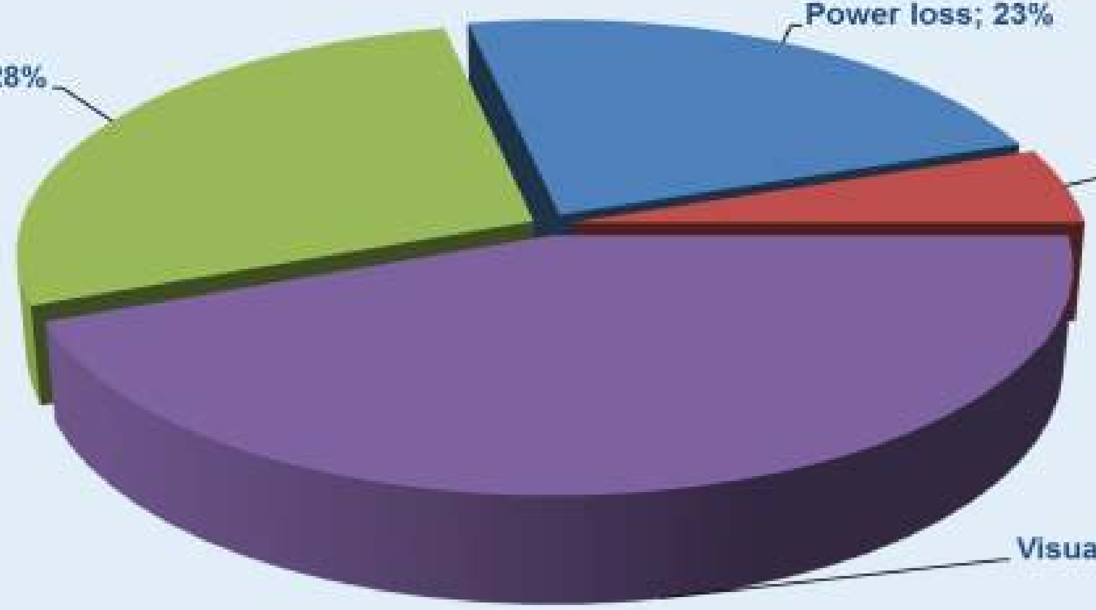
IEC Qualification Testing

Failure rates c-Si modules (2007 - 2011)



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Critical Tests for c-Si

- **Damp Heat Test (DH)**
  - 1000 h, 85° C, 85% RH
- **DH is a stress test for the quality of the used encapsulant (moisture protection)**
- **Failure cause:**
  - Delamination due to processing, contamination, material properties
  - Back sheet adhesion loss (lamination problems)
  - Corrosion

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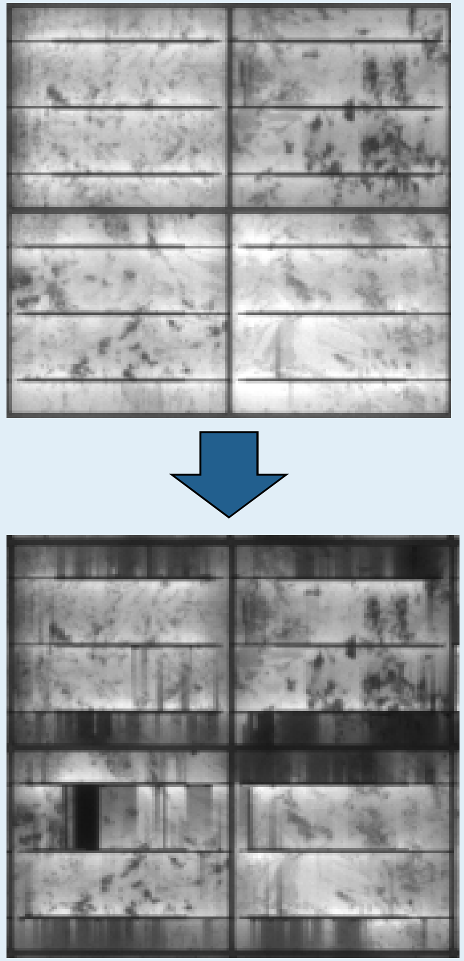
Critical Tests for c-Si

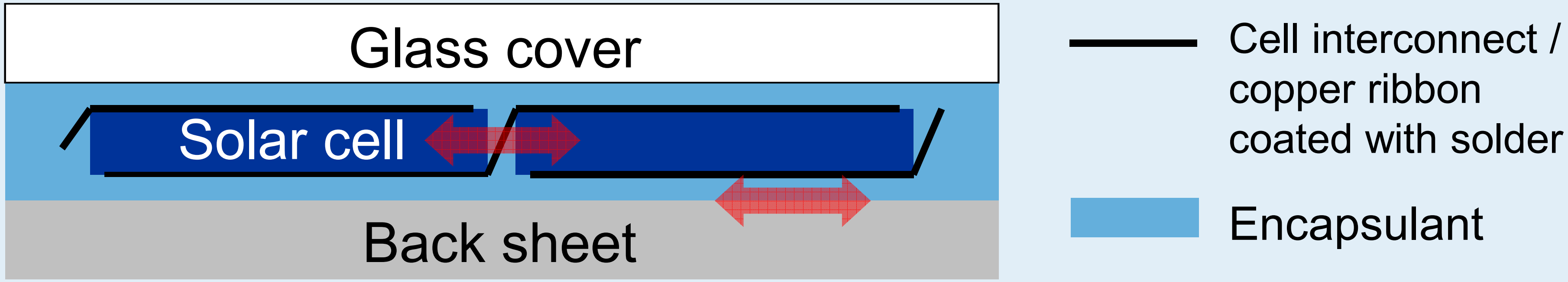
- **Thermal Cycling Test (TCT)**
  - 200 cycles, -40° C to +85° C
- **TCT is a stress test for cell connectors due to different thermal coefficients of glass, Si wafer and copper**
- **Failure cause:**
  - Thermo-mechanical stress



Laboratory Testing

Failure mechanism: Thermo-mechanical induced stress

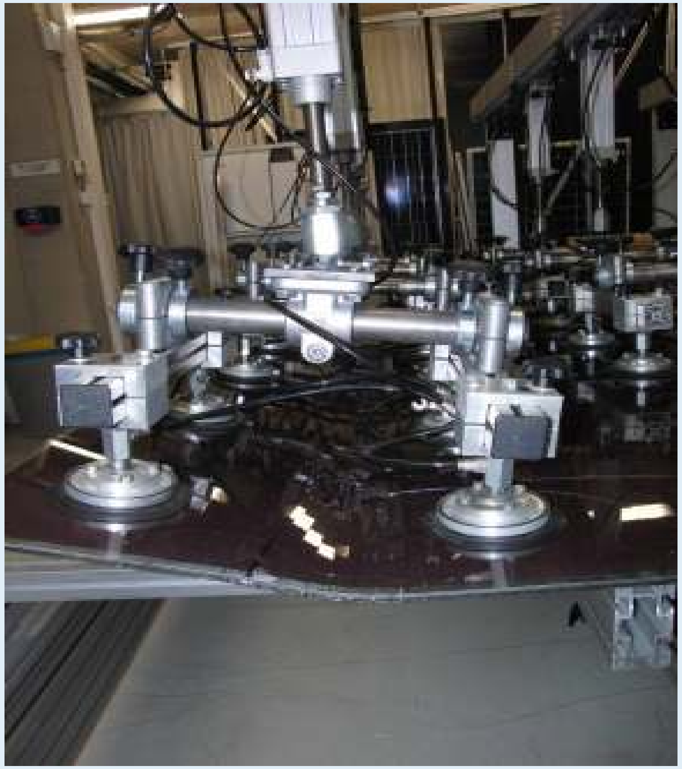
- PV modules combine materials with different coefficients of thermal expansion (glass cover, polymeric encapsulation, solar cells, polymeric back sheet, metal parts of internal wiring)
- Degradation processes may occur originating from thermo-mechanically induced stresses to interconnects (cyclic movement of cells) of loss of adhesion strength at interfaces [1]



[1] S. Dietrich: Mechanical and Thermo-Mechanical Assessment of Encapsulated Solar Cells by Finite-Element-Simulation, SPIE Optics+Photonics, 2010

Critical Tests for TF

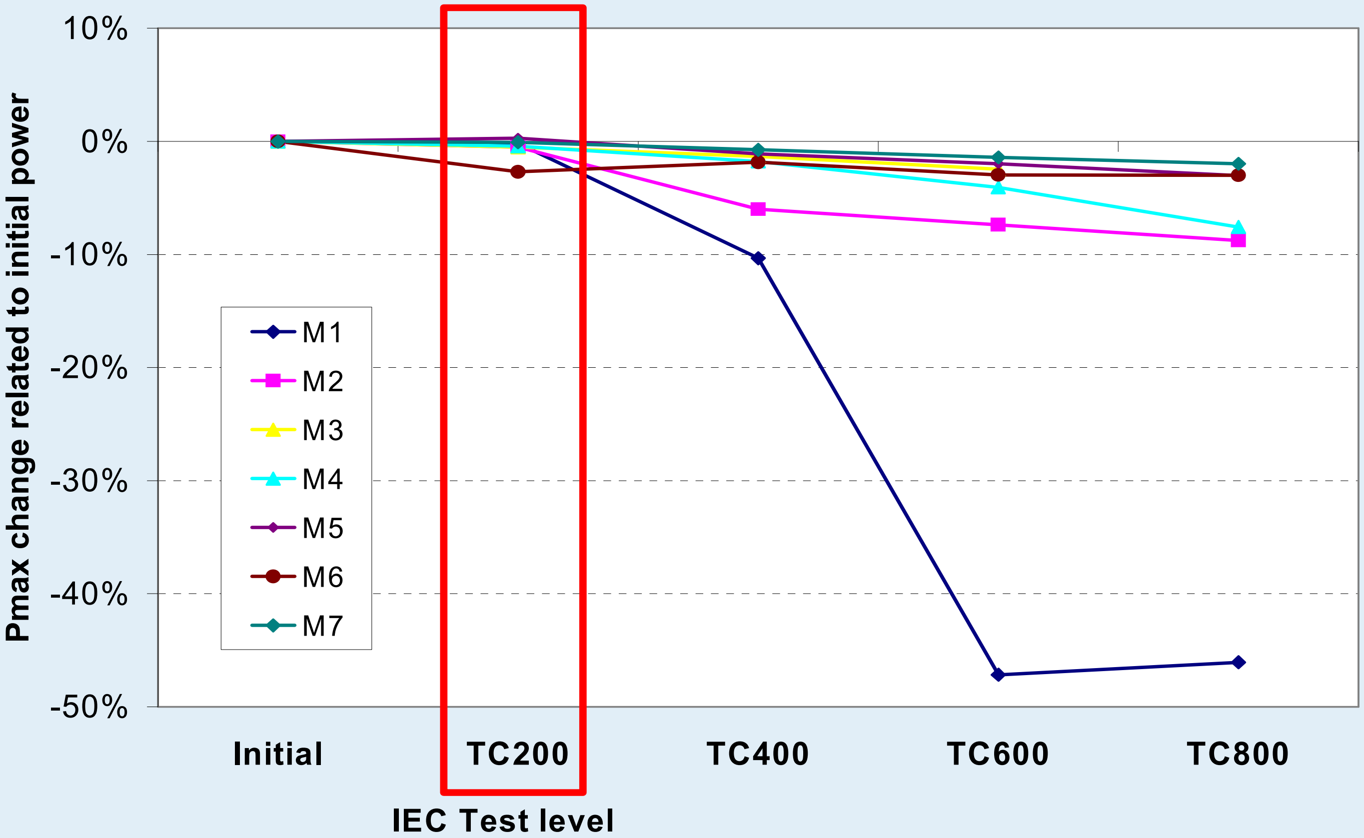
- **Mechanical Load Test (ML)**
  - Uniform load of 2400 Pa, applied for 1 hour to front and back surfaces in turn
- **ML is a stress test for the mechanical quality of modules (frame, glass, laminate) in combination with mounting system**
- **Failure cause:**
  - High wind and snow loads



Laboratory Testing

Extended Thermal Cycling Test

7 crystalline silicon PV modules with intermittent diagnostic measurements after 200, 400, 600 and 800 cycles



Results:

All modules fulfill IEC 61215 test requirements (TC200)

Three modules still fulfill IEC 61215 test requirements after TC800

Increased power degradation starting from TC400

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Conclusions (1)

- Quality of PV system performance has been increasing during the past years. Optimized grid-connected PV systems obtain mean annual PR values higher than 0.80.
- Improved PV system quality is due to:

  - more precise rated module power, less tolerances

  - improved inverter efficiencies

  - higher system availability
- PV system monitoring and fault are significantly increasing energy yields and reliability of PV systems.

Conclusions (2)

- Prediction of Actual Long Term Yield is (still) rather uncertain
- Comparison to operational data leads to refined and validated models
- Detailed investigations may improve also single calculation steps
- Even 15 minute average values of in-plane irradiation and AC power output contain valuable information
- Despite of the overall uncertainty, validated models for single calculation steps allow for a reliable optimization of some design parameters.

Conclusions (3)

- Failure rates of IEC qualification testing tend to decrease over the past years due to advanced/advancing technologies and improved quality control (both c-Si and TF)
- **Most frequent test failures and causes of module failures are:**
  - *DH, TCT (200), HF, ML, HS (for crystalline modules)*
  - *DH, ML, RC, HS (for thin film modules)*
- Most test failures are due to problems in module processing and quality control issues.
- Most frequent failures causes of IEC qualification are: soldering problems, lamination problems and glueing materials for c-Si.

Conclusions (4)

- PV modules are complex products and are subject to fabrication and material-related tolerances:
  - Degradation processes and long-term reliability are complex and may not be uniform for modules of the same construction and type;
  - For laboratory tests also variations in test conditions need to be considered.
- IEC test levels are normally not sufficient to find out weaknesses in the module construction. For c-Si modules enhanced degradation will appear beyond 2000 hours test duration for Damp Heat Test and beyond 400 cycles for Thermal Cycling Test.
- More sophisticated non-destructive diagnostic tools are needed to better monitor degradation processes on module and materials level.

Thank You for Your Attention!

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IEC Qualification Testing
Pass criteria for TF modules

After completion of all test sequences, the following pass criteria have to be fulfilled:

•Final STC output power after stabilization (e.g., light-soaking) at least 90% of the minimum rated power : (0.9 x ($P_{manufacturer}$ – tolerance))

•Minimum requirements for the electric insulation (dry and wet) fulfilled:

- **R_{iso} > 40 MΩ / A [m²] (A = module area)**

•No major visual defects detected

Critical Tests for c-Si

- **Humidity Freeze Test (HF)**
  - 10 cycles, -40° C to +85° C, 85% RH
- **HF is stress test for cell connectors due to different thermal coefficients of glass Si and copper**
- **Failure cause:**
  - Thermo-mechanical stress

Critical Tests for c-Si

- **Mechanical Load Test (ML)**
  - Uniform loads of 2400 Pa, applied for 1 hour to front and back surfaces in turn
- **ML is a stress test for the mechanical quality of modules (frame, glass, laminate) in combination with mounting system**
- **Failure cause:**
  - High wind and snow loads

Critical Tests for c-Si

- **Hot Spot Test (HS)**
  - Shading of one cell of the module
- **HS is a stress test for cell quality**
- **Failure cause:**
  - Different cell qualities
  - Local defects, shunts in wafer
  - Shunts due to soldering problems

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Critical Tests for TF

- **Hot Spot Test (HS)**
  - Shading of cells of the module
- **HS is a stress test for cell quality**
- **Failure cause:**
  - Different cell qualities
  - Local defects, shunts
  - HS may lead to overheating of material and glass breakage

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