QUALITY ASSURANCE AND BANKABILITY OF PV POWER PLANTS

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Head of Group PV Power Plants

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Head of Team Data Analysis and Modelling

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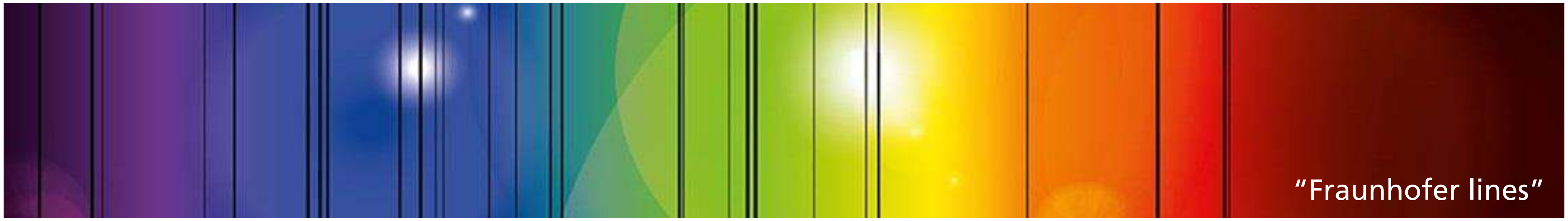
The Fraunhofer-Gesellschaft
Largest Organization for Applied Research in Europe

- 72 institutes and research units with total staff of ca. 25,000
- More than €2.3 billion annual research budget, of which around €2 billion is generated through contract research
  - Roughly 70 percent of contract research is generated on behalf of industry and publicly funded research projects.
  - Roughly 30 percent is contributed by the German federal and state governments in the form of base funding.
- International cooperation throughout the world



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At a Glance

Institute Directors:
Prof. Dr. Hans-Martin Henning
Dr. Andreas Bett

Staff:	ca. 1200
Budget 2017:	€89.2 million
Established:	1981

Photovoltaics

Solar Thermal Technology

Building Energy Technology

Hydrogen Technologies

Energy System Technology

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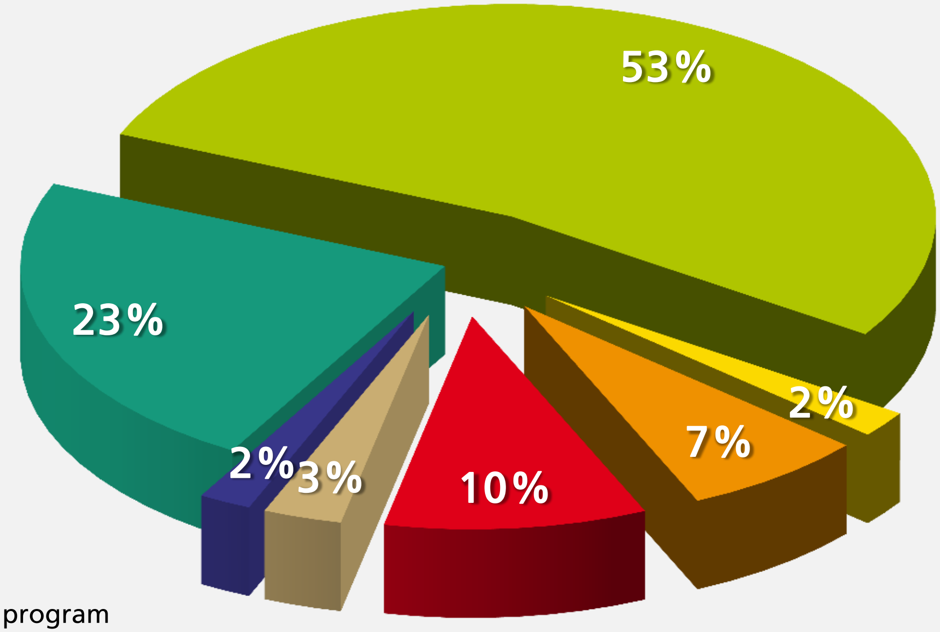
Revenue Structure, Operation 2017

Operation:	€75.4 million
Investment:**	€14.0 million
Total:	€89.2 million

- Industry
- Fed. Gov.
- State Gov. (BW/NRW)
- European Union
- Other
- Special Programs, FhG
- Basic Funding*



* 90% federal and 10% state (BW) funds
** without building investment and economic program

Status: March 2018

Department „Analysis PV Modules and Power Plants“

Fields of Work

Boris Farnung

Photovoltaic Power Plants

Performance optimi-zation and quality assurance from planning to the ongoing operation.

Module Calibration

Comprehensive and precise calibration and performance testing of PV modules.

Frank Neuberger

Klaus Kiefer
Head of Department

Staff of 90 scientists, engineers, technicians, students

Daniel Philipp

Service Life and Failure Analysis

Detection of damage mechanisms in PV modules, quality and reliability tests.

Forecasting of Solar Irradiance and Power

Development of forecast models for the reliable predic-tion in different time and spacial scales.

Elke Lorenz

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OVERVIEW BANKABILITY – TOPIC 1

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Head of Group PV Power Plants

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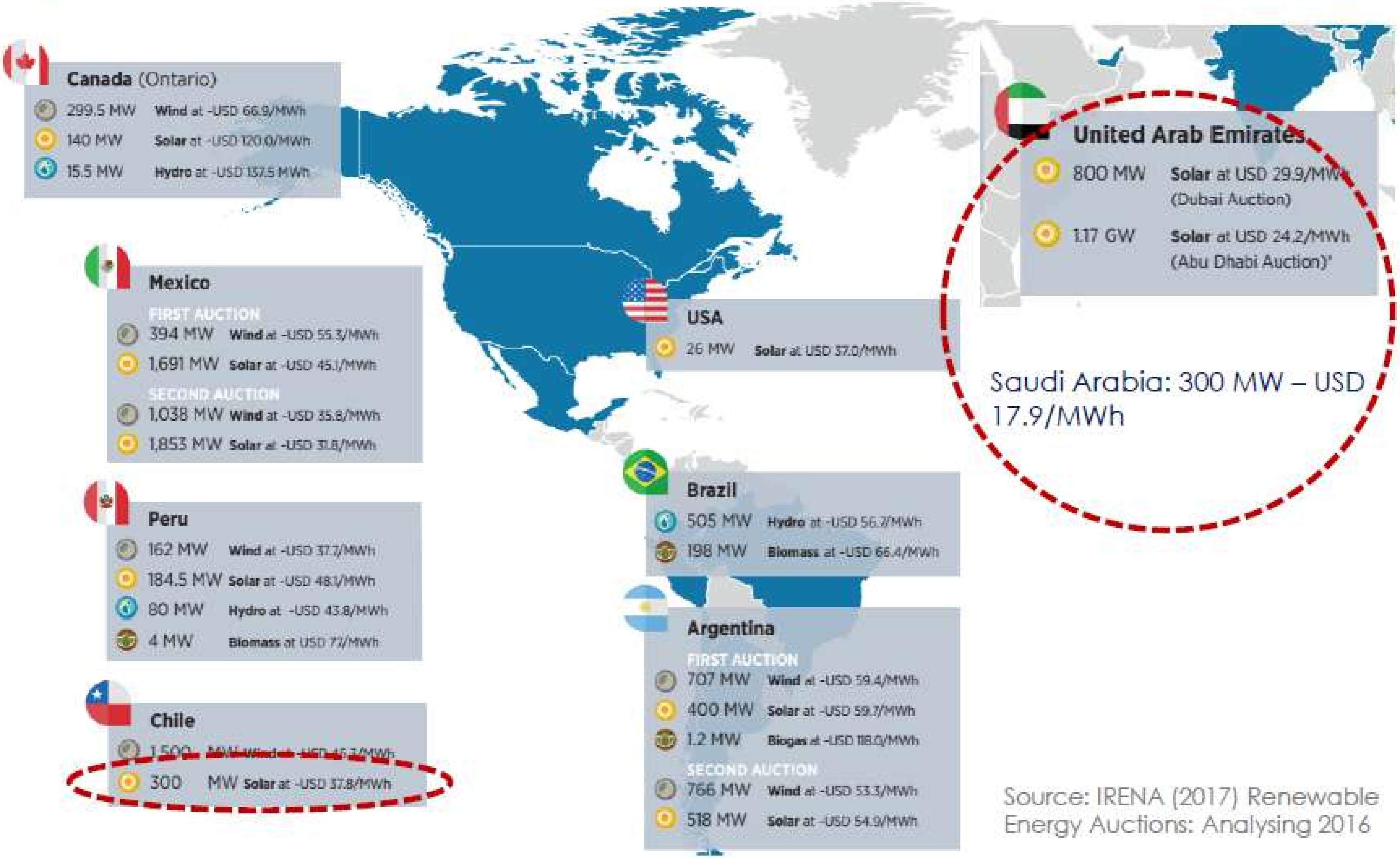
Solar Industry
Market dynamics

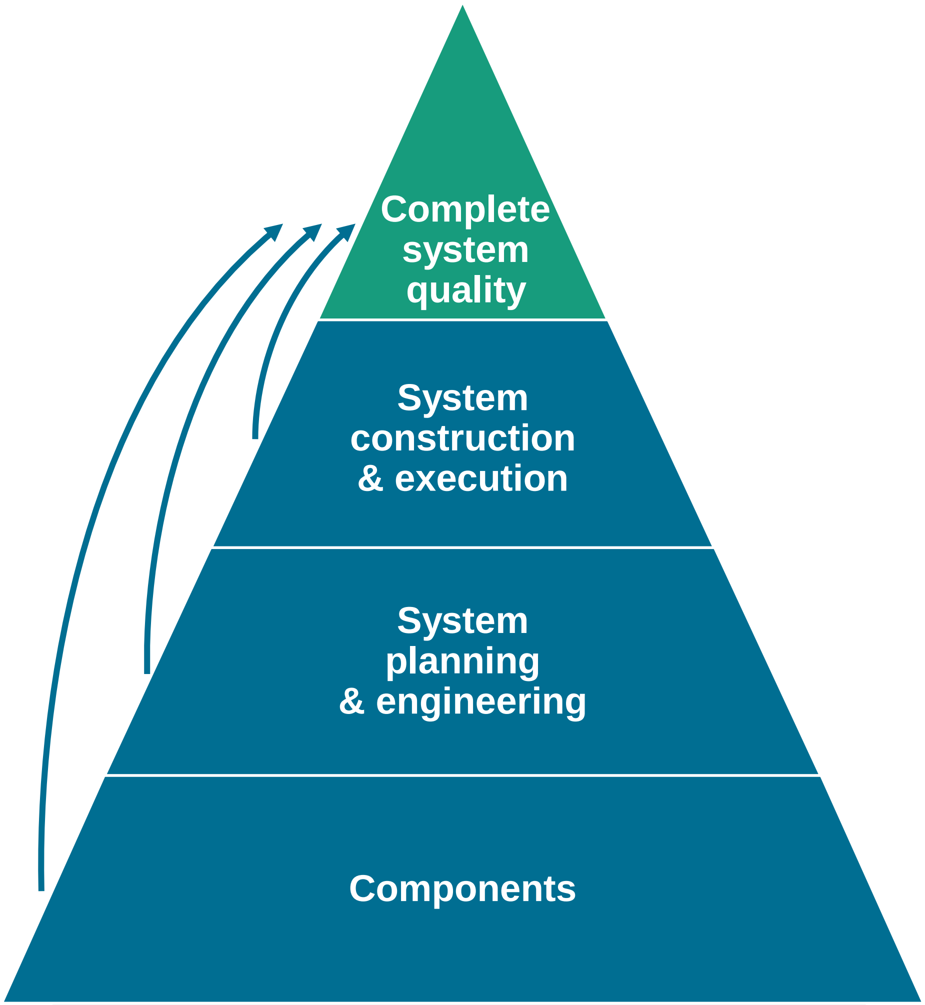
- Transitioning from government subsidies to market based asset financing
- Ambitioned Country Targets: 5.4 additional GW in Mexico by end of 2019
- In most auctions around the world, quality is a minor evaluation criteria
- Record PV Prices in Auctions

Record PV prices – what will be delivered?



Change in marked situation
Effects on PV investments

- Increased uncertainty
- Higher perceived risk
- Redefinition of bankability criteria
- Higher expectations on **overall system quality**



Technical bankability
Requirements of stakeholders

Understanding of quality for different stakeholder translated to technical language:

- Bank: wants only get their money back
- EPC, System operator: high performance ratio and low maintenance
- Investor: expects maximum yield, low risk

Leads to the following technical requirements for components and system

- High efficient and reliable
- Long-term stable with minimum degradation
- State-of-the-art design

Challenges for technical bankability
Technical requirements from a lenders perspective

- Extract of requirements from Deutsche Bank

Ensuring the debt service capabilty requires special attention during the first two years

1. a provisional acceptance test (PAT) at comissioning of a project.
2. a final acceptance test (FAT) after about two years of operation.
3. partners who are able and willing to fulfil any warranty claims during the first two years at least. Or:
4. an insurance solution making this procedure redundant.

Third party QA required on system level

Felix Holz, Deutsche Bank: Quality requirements from a lenders/investors point of view, 40th IEEE, Denver

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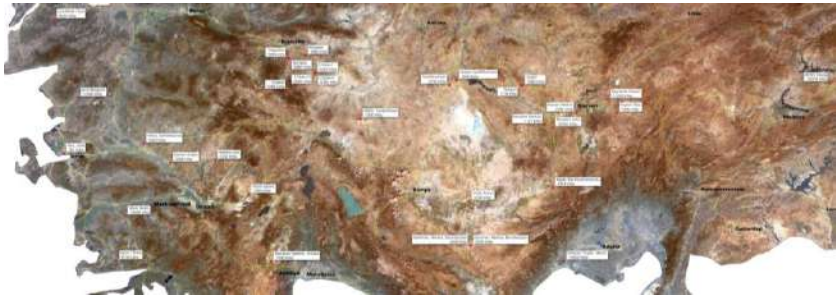
What we are talking about?
Multi MW Power Plants

Power Plant in China

Utility scale Power Plant (100+X MWp)

hunderes to thousands of inverters

several millions of modules



Portfolio in Turkey

Portfolio with more than 100 MWp

more than 30 individual Power Plants

different geografic location and conditions

Rooftop in Germany

Challenging interface between mounting structure and roof membrane

Very Individual conditions (e.g. shading)

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LCOE and Performance Ratio

Levelized Costs of Energy

LCOE : ———

Performance Ratio

PR : ———

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Levelized costs of energy and quality

$$LCOE = \frac{\text{cost of produced electric energy}}{\text{produced electric energy}} = \frac{I_0 + C_0 \sum_{t=1}^{n} \frac{(1+i)^t}{(1+r)^t}}{R_P \, \eta_{STC} \cdot E_y \sum_{t=1}^{n} \frac{(1+d)^t}{(1+r)^t}}$$

quality sensitive

LCOE	Levelized cost of energy
I_0	initial investment for power plant
C_0	annual operation & maintenance cost
n	service life
i	annual inflation rate
r	annual discount rate
R_P	initial Performance Ratio of power plant
η_{STC}	initial module efficiency (STC)
E_Y	yearly sum of energy irradiated on module plane
d	annual degradation rate

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Quality Assurance for utility scale PV plants

DEVELOPMENT
- solar resource assessment
- site analysis
- environmental stress assessment
- design review and optimization
- feasibility studies

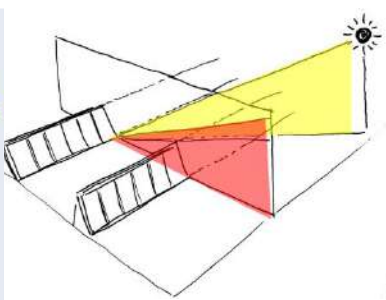
ENGINEERING
- yield assessment
- component bench-marking:
  - module power and energy rating
  - inverter testing

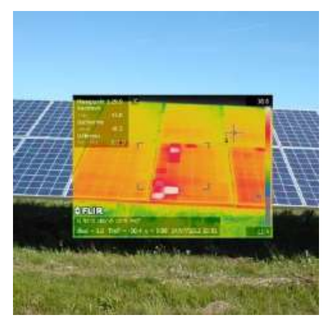
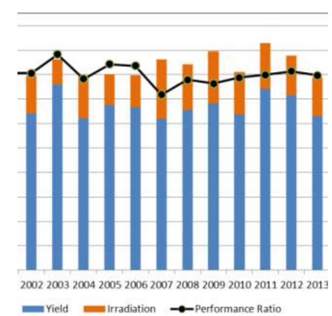
PROCUREMENT
- representative module sampling and checks:
  - performance
  - reliability
  - workmanship

COMMISSIONING
- final power plant test:
  - visual inspection and thermography imaging
  - module power measurements
  - initial performance verification
- final acceptance report

OPERATION
- continuous long-term performance reporting
- failure analysis and reporting
- optimization and re-powering
- warranty check

- technical and financial due dilligence*
- comprehensive PV plant certification*

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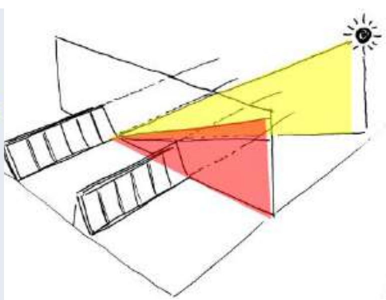

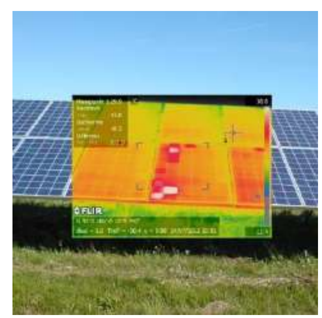

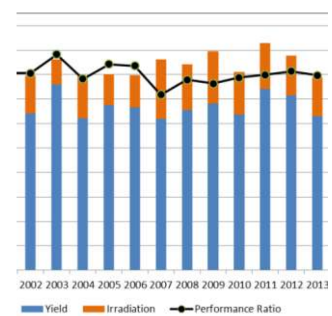

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Quality Assurance for utility scale PV plants
Yield assessment as basis for the financial assessment

- independent, accurate simulation
- detailed documentation with validated results
- Uncertainty statement

Calculation step	Uncertainty*	Value	Unit	Gain/Loss**	PR***
Irradiation global horizontal	5.0%	1550	kWh/m²		
Irradiation on tilted surface	2.5%	1821	kWh/m²	17.5%	100.0%
Shading					
External Shading	0.5%	1803	kWh/m²	-1.0%	99.0%
Internal Shading	2.0%	1765	kWh/m²	-2.1%	96.9%
Soiling	1.0%	1739	kWh/m²	-1.5%	95.5%
Reflection losses	0.5%	1695	kWh/m²	-2.5%	93.1%
Deviation from STC operation of modules					
Spectral losses	1.0%	1661	kWh/kWp	-2.0%	91.2%
Irradiation-dependent losses	1.0%	1682	kWh/kWp	1.3%	92.4%
Temperature-dependent losses	1.0%	1634	kWh/kWp	-2.9%	89.7%
Interconnection losses (mismatch)	0.5%	1602	kWh/kWp	-2.0%	88.0%
Cabling losses	0.5%	1579	kWh/kWp	-1.4%	86.7%
Inverter losses	1.5%	1538	kWh/kWp	-2.6%	84.5%
Power limitation of inverter	0.5%	1538	kWh/kWp	0.0%	84.5%
Transformer	0.0%	1538	kWh/kWp	0.0%	84.5%
Total	**6.5%**	**1538**	**kWh/kWp**		**84.5%**

* Uncertainties are related to single standard deviation
** Gain/Los : energetic Gain / Loss according to the step of calculation of the simulation
*** PR: Performance Ratio

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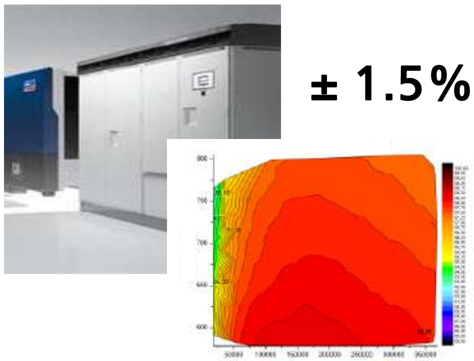
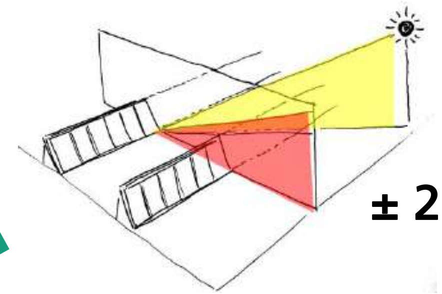
Quality measures for utility scale PV Plants

Input data for yield prediction and typical uncertainties

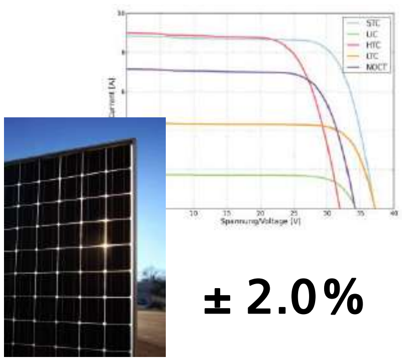
±5%



± 1.5%

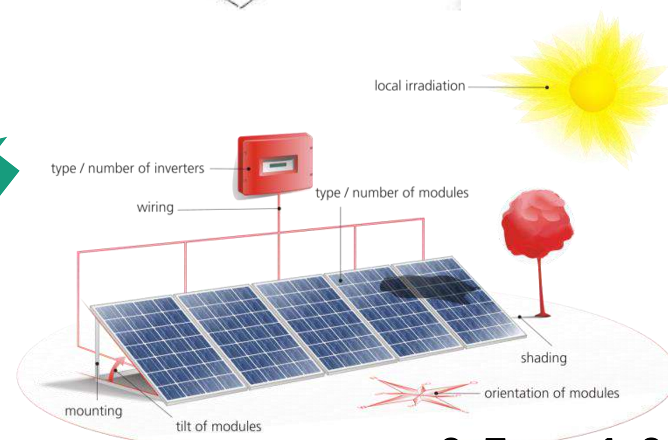


± 2.0%



± 2.0%

± 2.0%



± 0.5 to 1.0%

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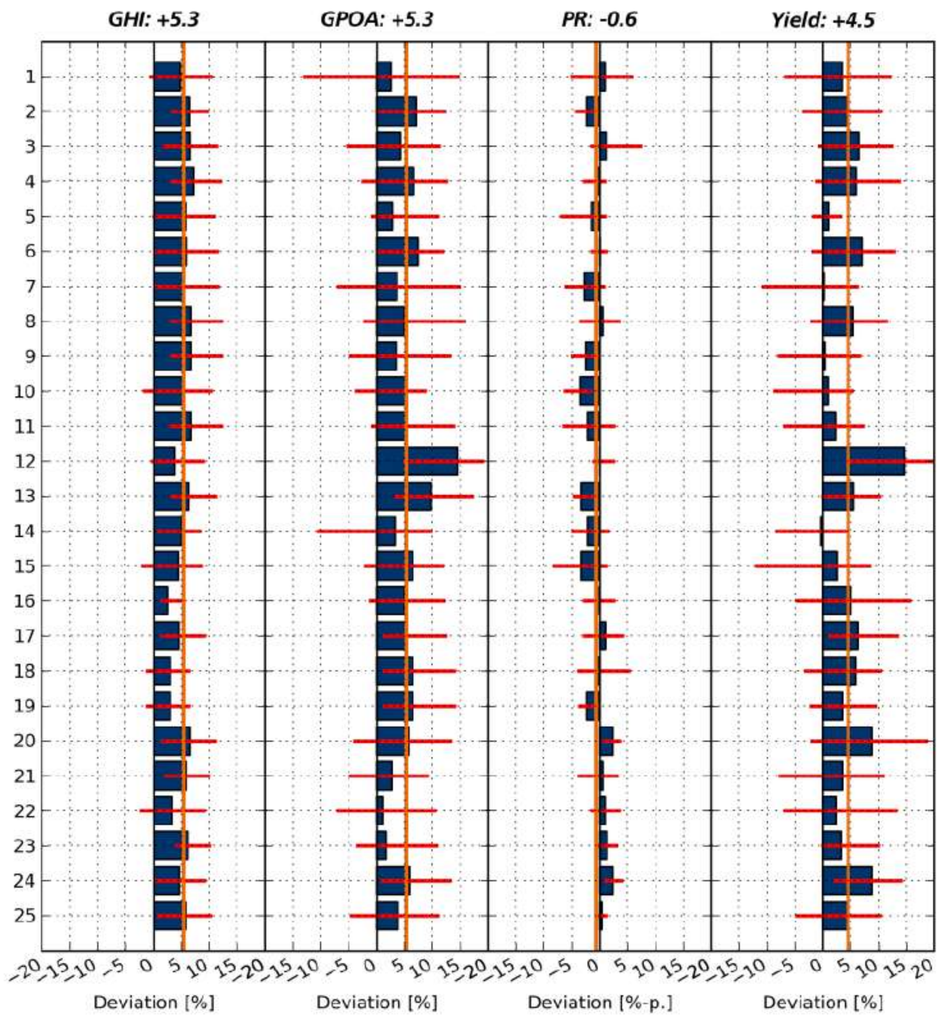
Quality Assurance for utility scale PV Plants
Measured compared to predicted PR and yield

Basis

- 25 PV Plants with 5 years highly accurate data

Result

- On average very good agreement of measured and predicted PR
- Irradiation and yield remarkably higher than predicted



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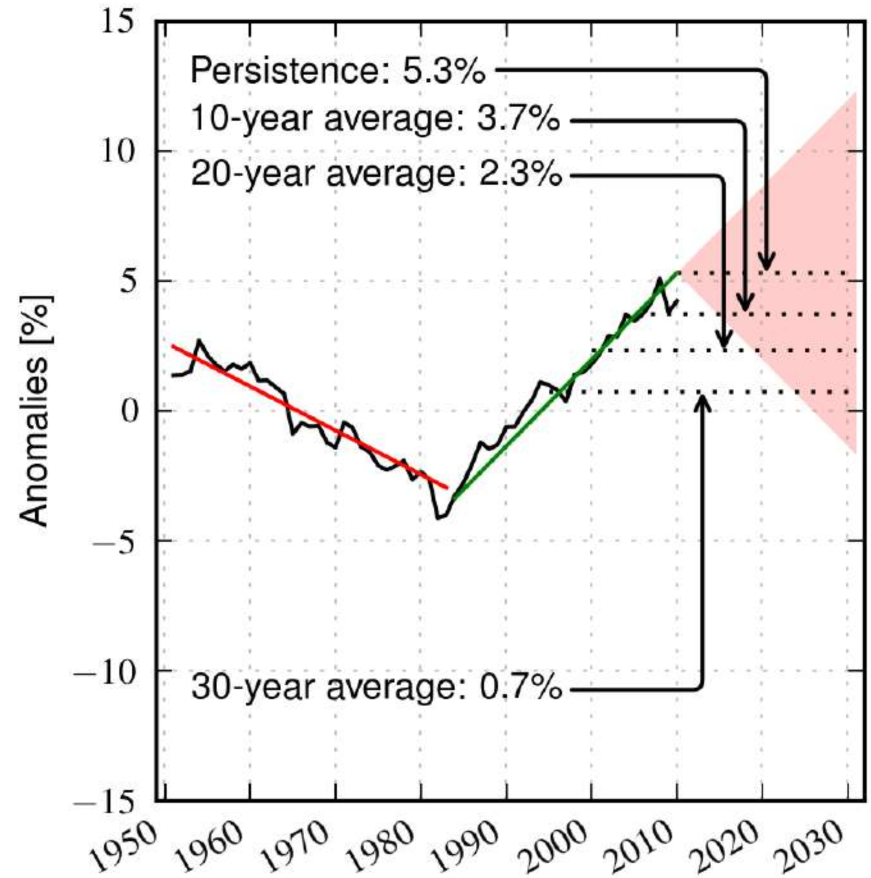
Quality Assurance for utility scale PV Plants

Input data for yield prediction and uncertainties

- Solar irradiation in Germany today about 5% above long-term average
- Use of “old“ irradiation data underestimates the potential
- Comparable variation in different regions of the world



Müller et. all: Rethinking solar resource assessments in the con-text of global dimming and brightening. Solar Energy 99 (2014)

Quality Assurance for utility scale PV Plants
Input data for yield prediction and uncertainties

- High uncertainty from irradiation data
- Dimming and brightening has a remarkable impact on the predicted yield
- High influence depending on the time period used

Observed tendencies in surface solar radiation

	1950s-1980s	1980s-2000	after 2000
USA	-6	5	8
Europe	-3	2	3
China/Mongolia	-7	3	-4
Japan	-5	8	0
India	-3	-8	-10

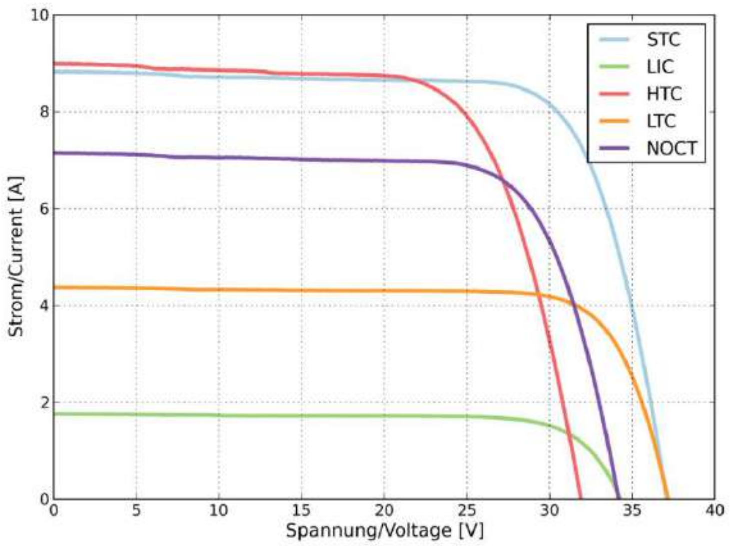
M. Wild et al.: From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. Science 308 (2005)

➡ Source and time period of irradiation data holds a high risk and must be assessed and selected carefully for accurate yield assessments

Quality Assurance for utility scale PV Plants

Power Rating in accordance to IEC 61853

- Power Rating characterizes the module at different irradiance and temperature conditions
- The data is basis for
  - accurate yield assessment
  - reliable re-calculation of on-site data to STC
  - Verification of the PV plant performance as a whole



Press Release: http://www.ise.fraunhofer.de/en/press-and-media/press-releases/presseinformationen-2013/energy-rating-of-pv-modules-improves-certainty-for-investors

Laboratory testing
irradiance dependence

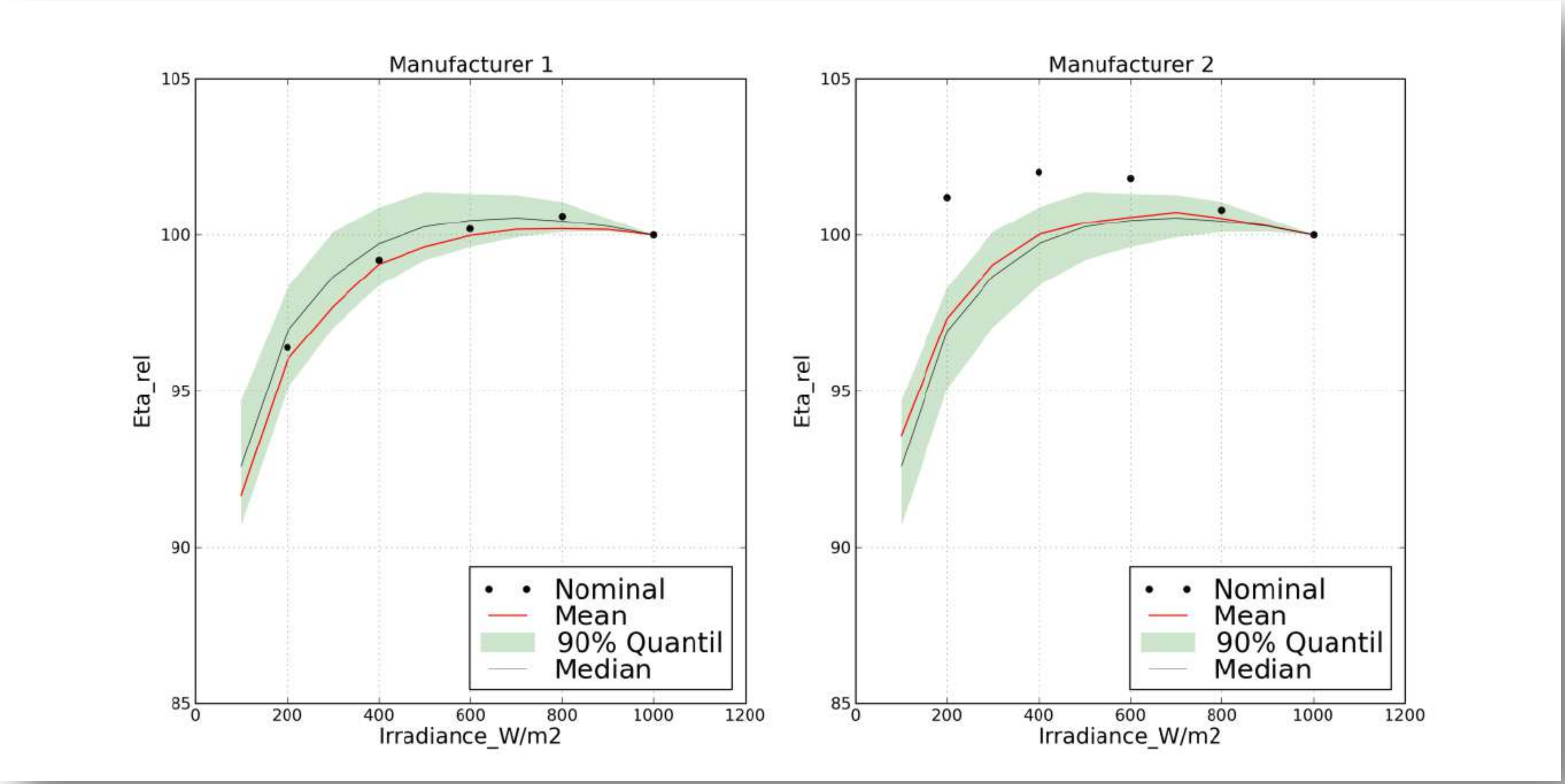


Fig: comparison on manufacturer and laboratory results for irradiance dependence of poly-Si modules

➔ *high uncertainty on data sheet and manufacturer data*

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PV Module Energy Rating

Calculated yield losses based on different irradiance dependence characteristics (Poly-Si-Module):

Percentile	5	50	95
DE Nord	-3,2%	-2,2%	-1,0%
DE Süd	-2,9%	-1,9%	-0,8%
TR Mersin	-1,6%	-1,0%	-0,2%

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Quality measures for utility scale PV Plants
Temperature coefficient

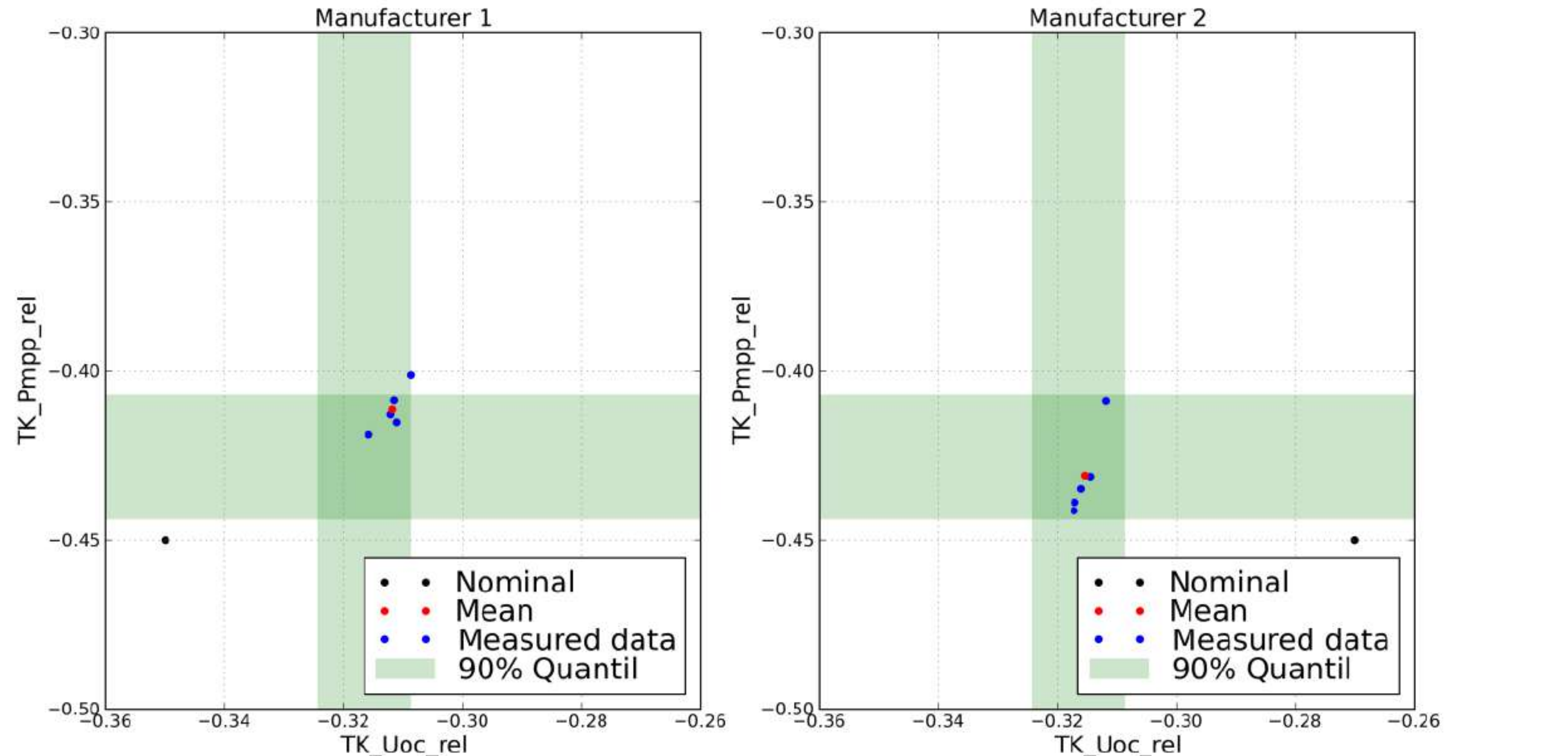

Fig: comparison on manufacturer and laboratory results for temperature dependence of poly-Si modules

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TR Mersin	-7,6%	-7,1%	-6,6%

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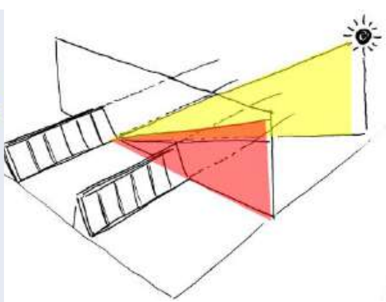
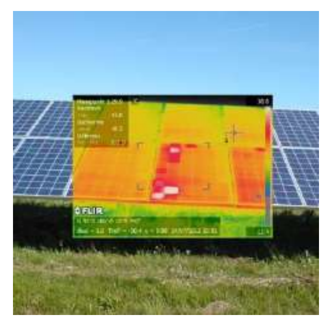
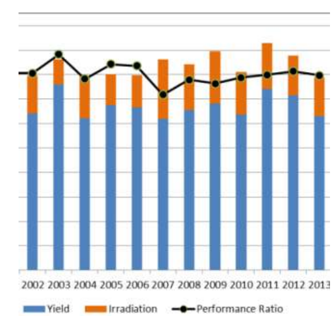
- comprehensive PV plant certification*







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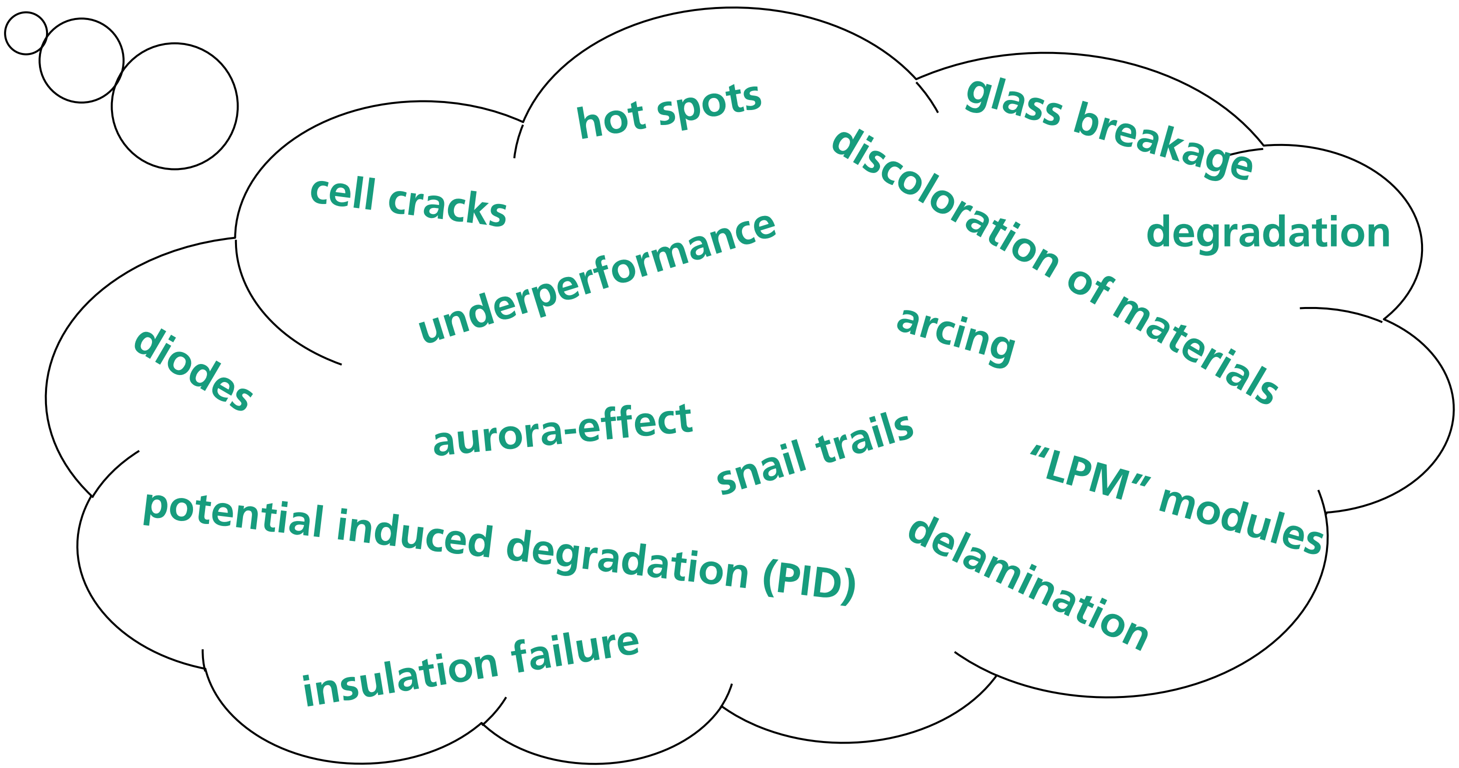
Quality Assurance on Component Level
experiences from the field

Known failure mechanisms



➢ Goal of quality assurance: prevent known failures

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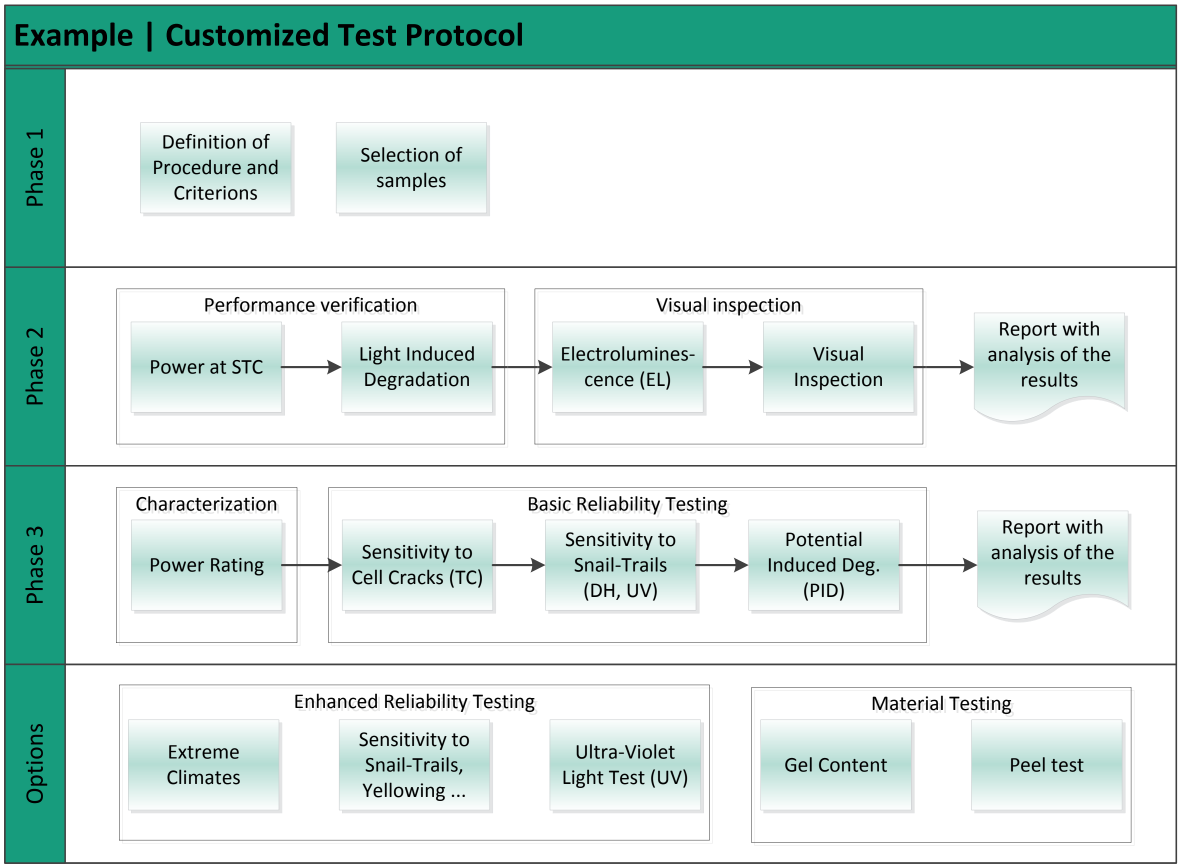
Quality Assurance on Component Level
A customized Test Protocol



Definitions

Performance und Workmanship

Power Rating und Reliability

Enhanced Testing

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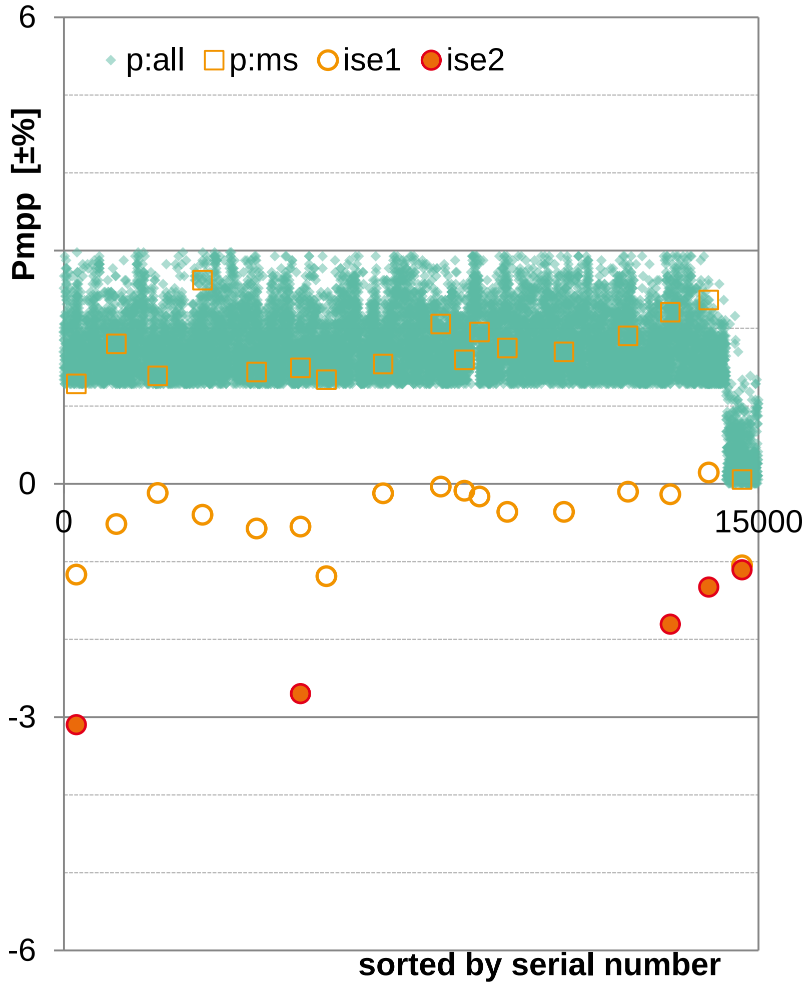
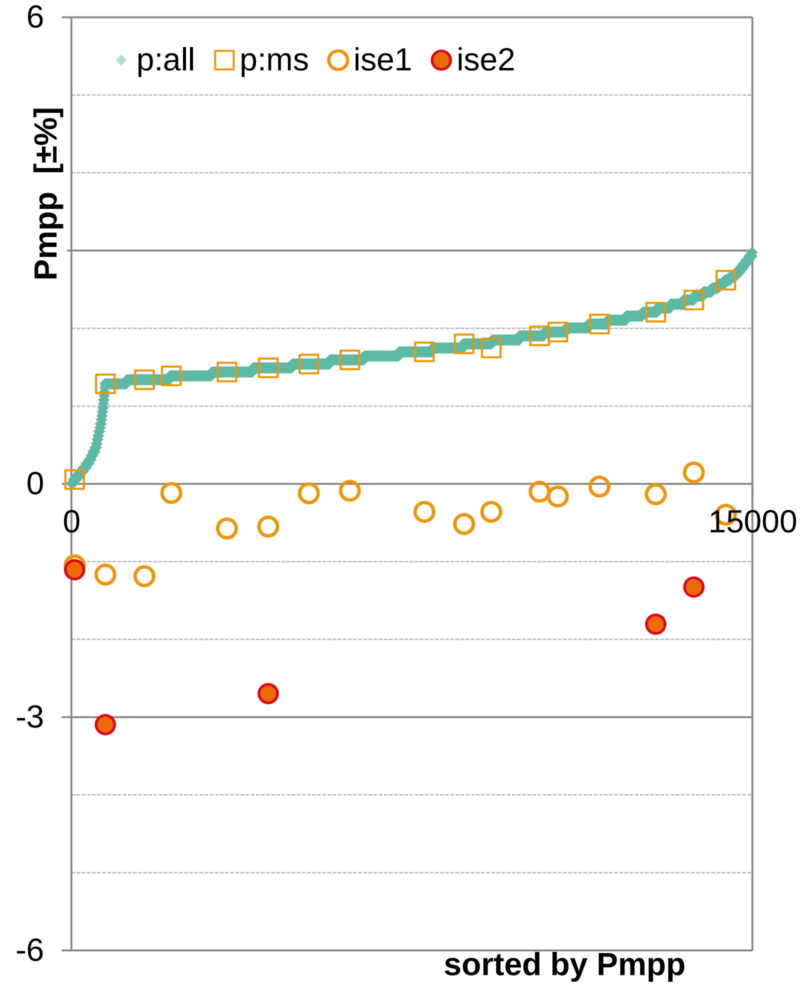
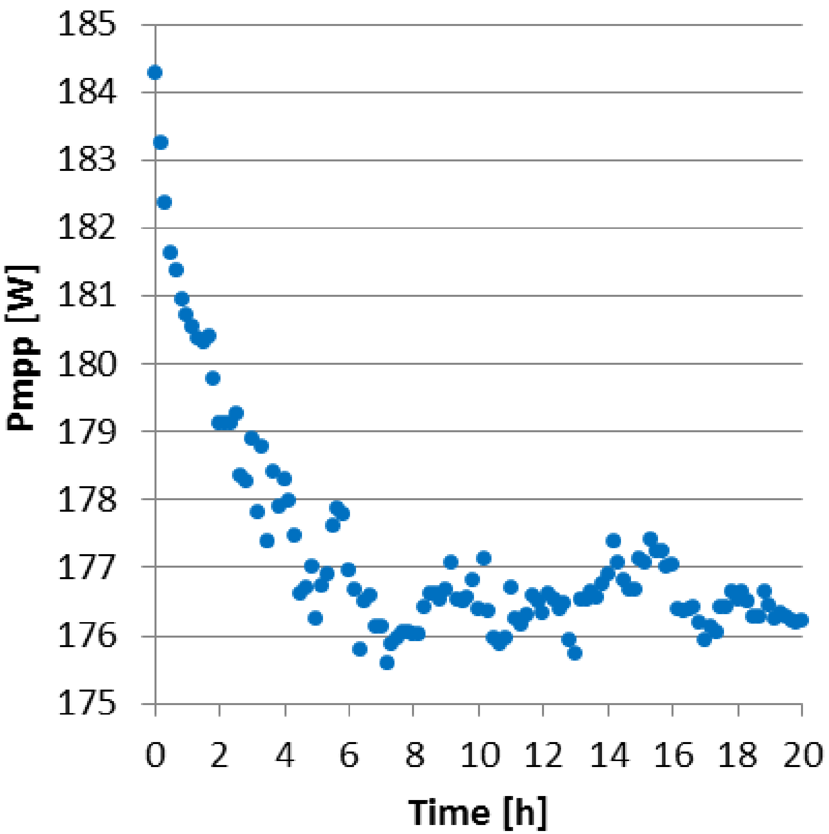
Quality Assurance on Component Level
module performance verification





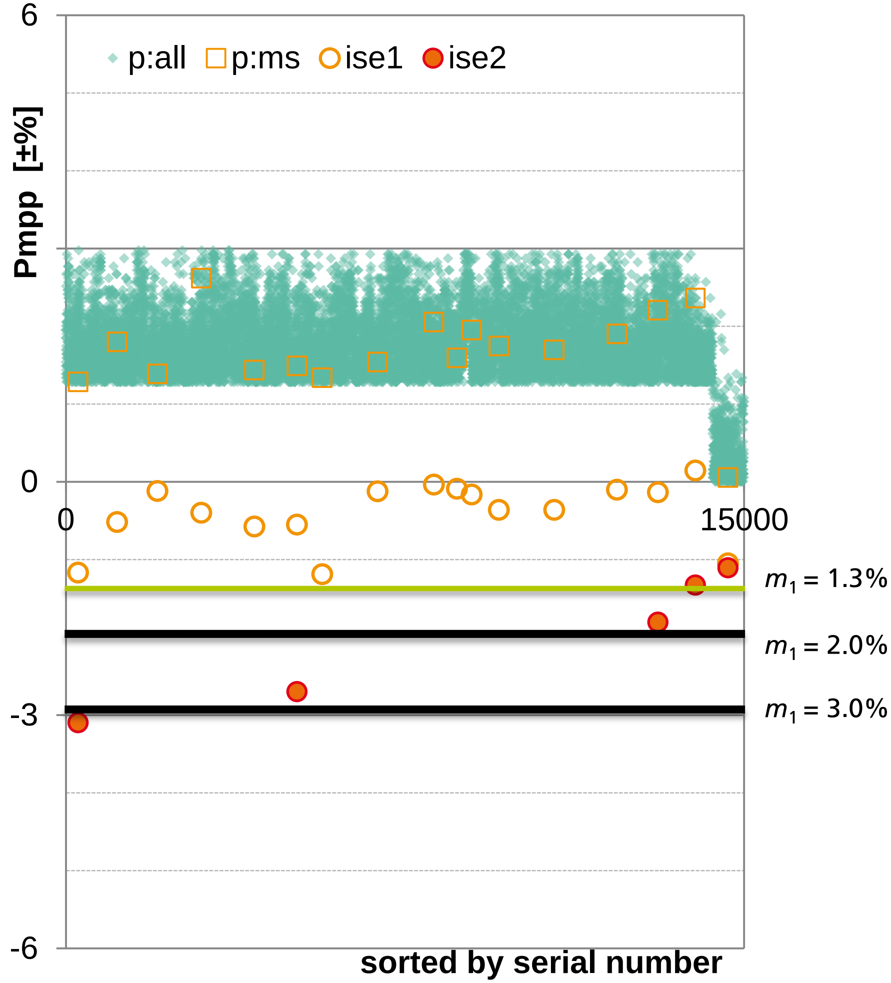
Quality Assurance on Component Level
Stability / Light Induced Degradation



above: Continuous solar simulator for light soaking of PV modules

Left: Power of a poly-Si module, measured in-situ during initial degradation

Quality Assurance on Component Level
module performance verification



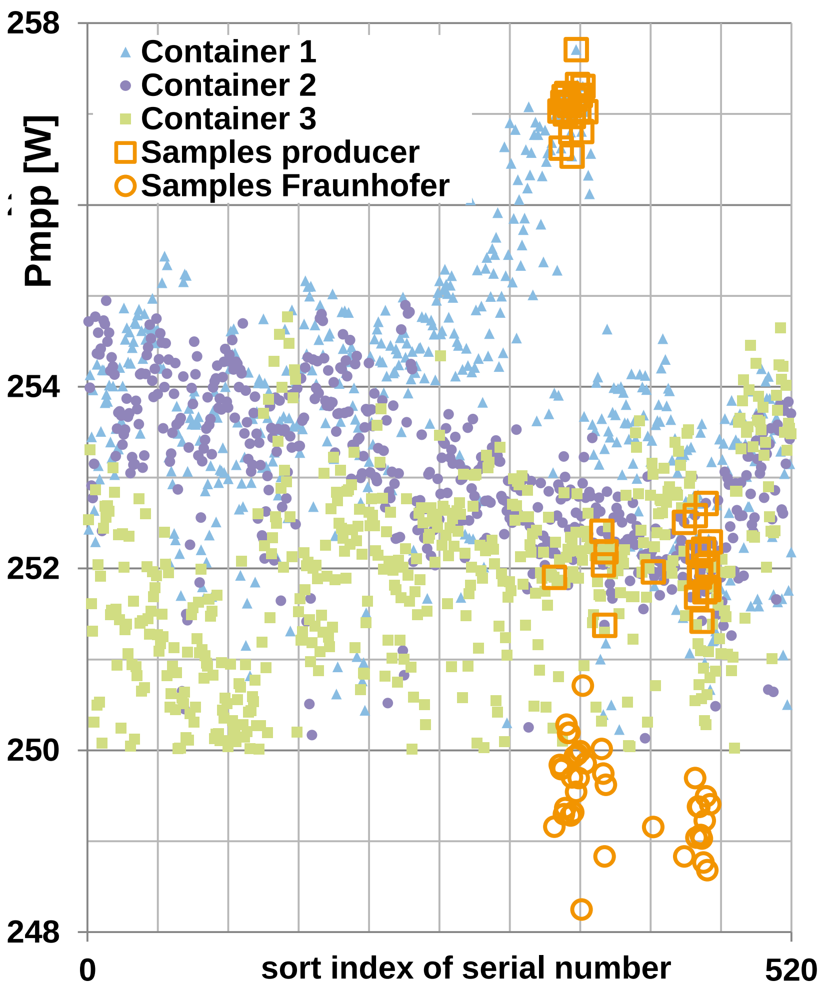
Important

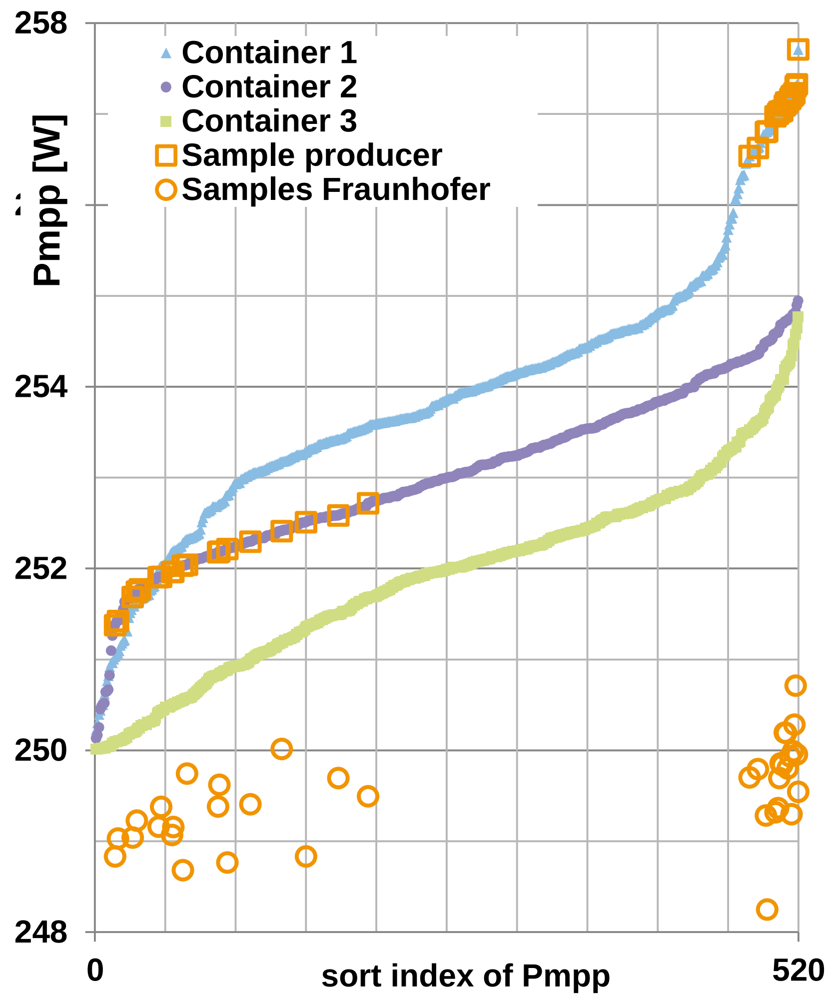
- After stabilization procedure all modes shall be within the power rating of the name plate (P_{max}(NP)) including stated measurement uncertainty m_1.[1]
- "Each percentage point increase in measurement precision corresponds to a monetary value" and "Maximum measurement precision is not just an academic exercise, rather it greatly helps gain the confidence of investors".[2]

[1] IEC 61215-1:2016

[2] https://www.ise.fraunhofer.de/en/press-media/press-releases/2017/callab-pv-modules-increases-measurement-precision-to-a-record-1-point-3-percent.html

Quality Assurance on Component Level
Module performance verification





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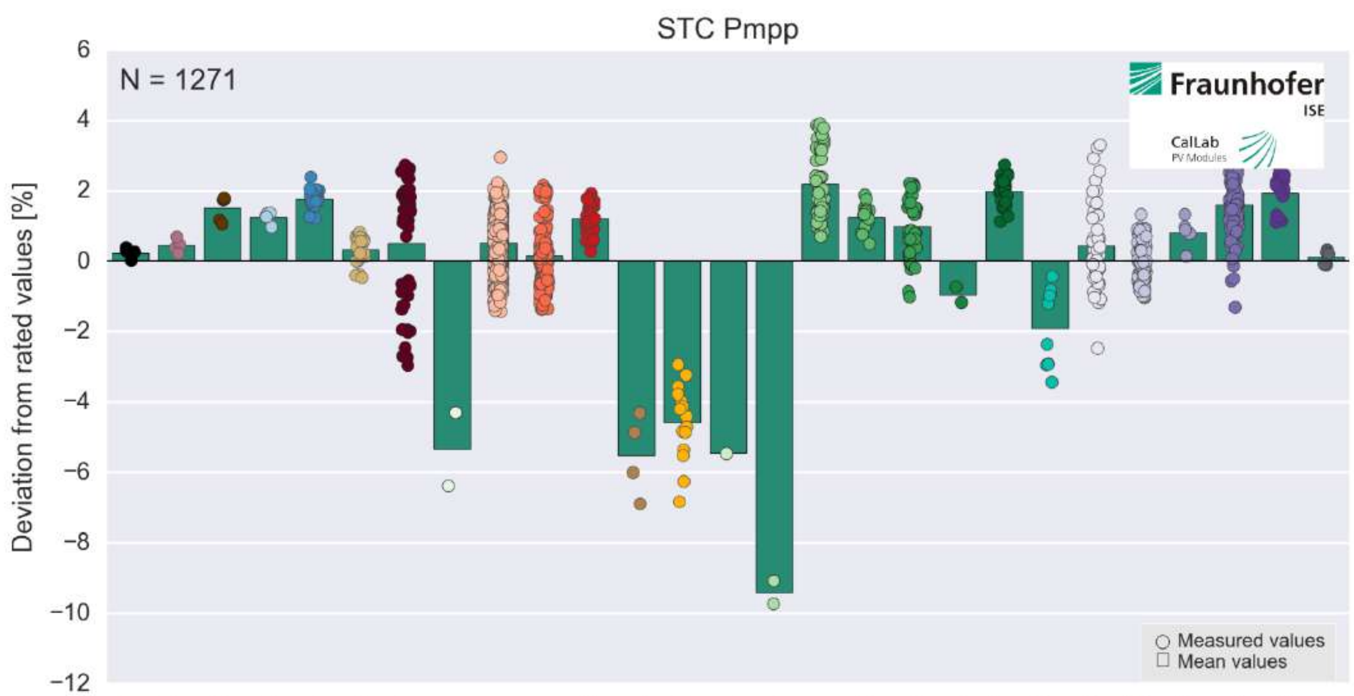
Quality Assurance on Component Level

Example: STC (initial) – Deviation from rated power



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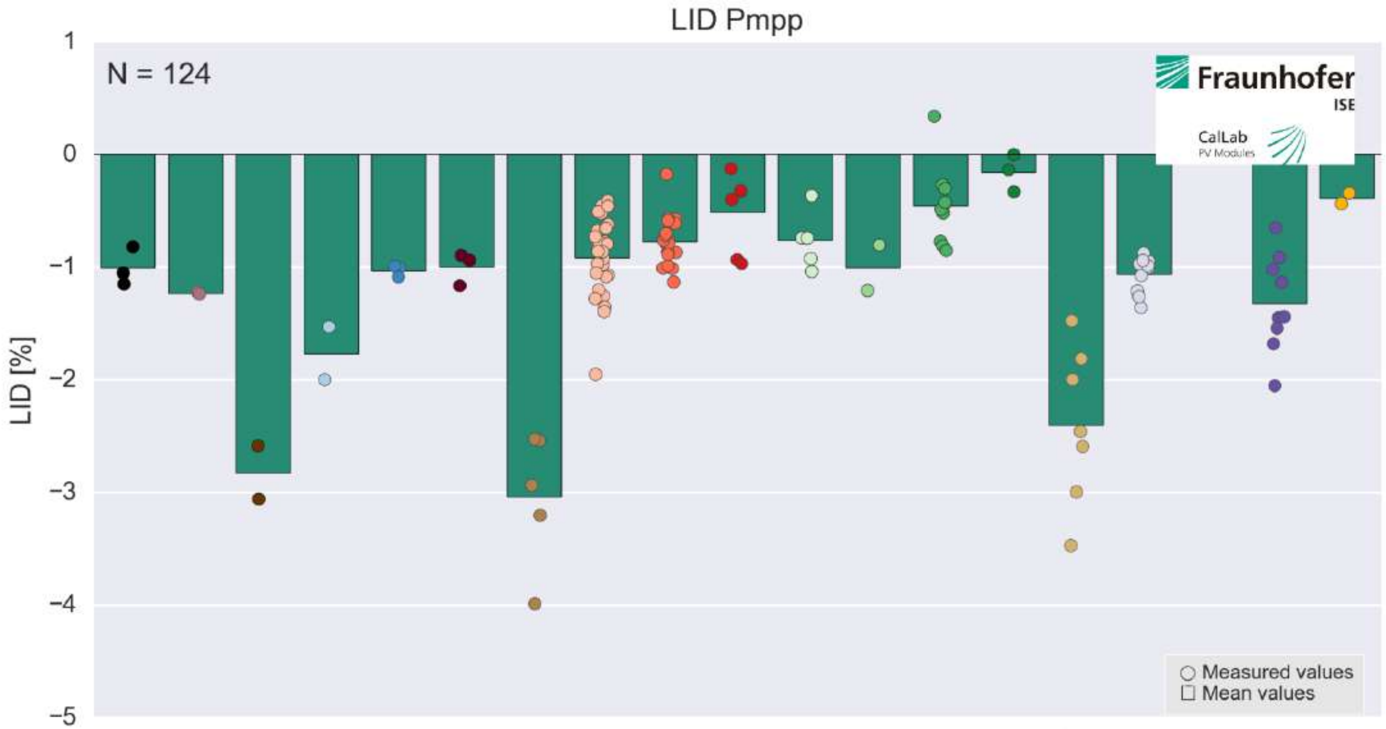
Quality Assurance on Component Level

Example: post-LID – Deviation from rated power



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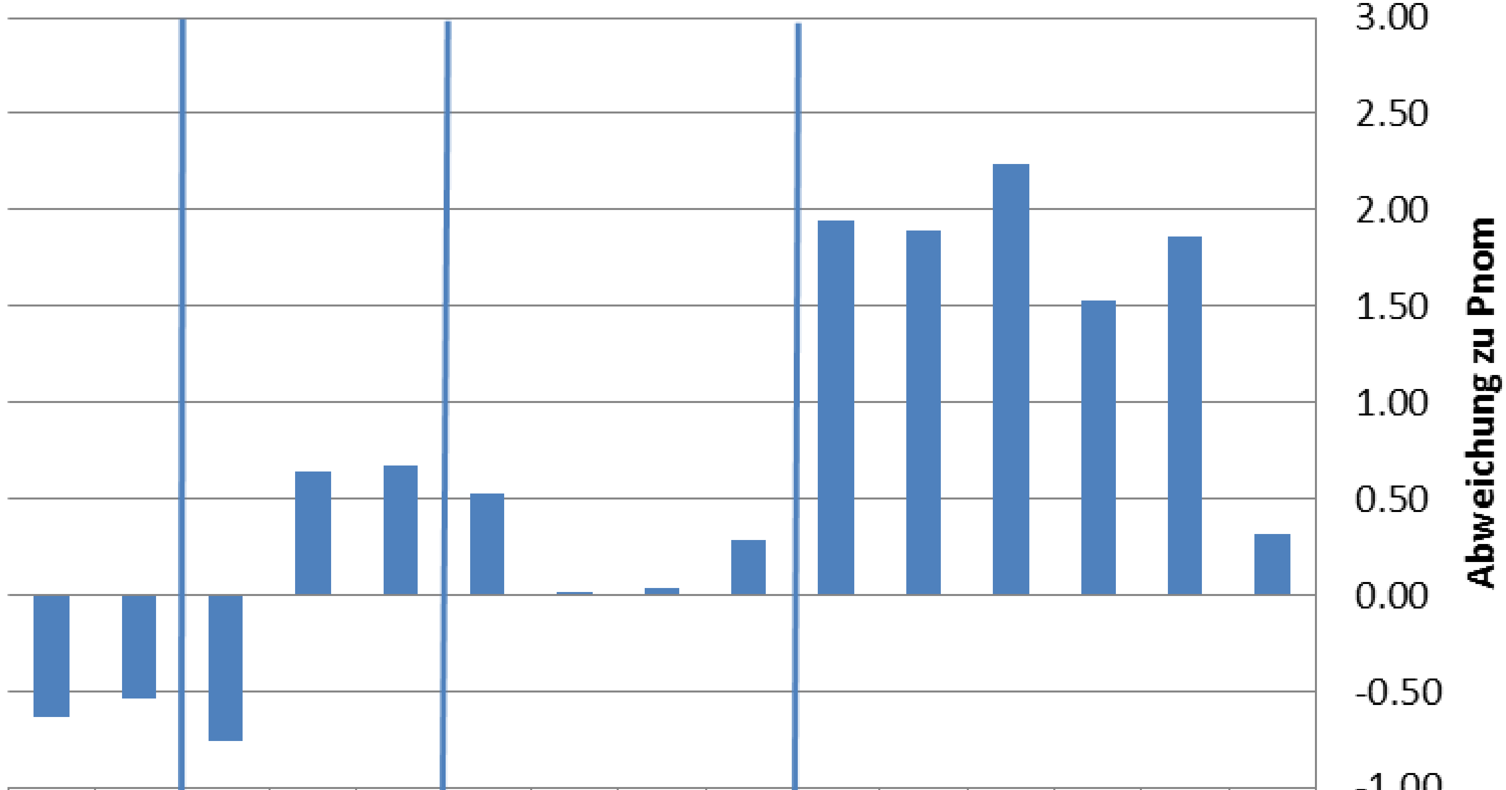
Quality Assurance on Component Level
Data for one manufacturer from one customer



	2010	2010	2011	2011	2011	2012	2012	2012	2012	2013	2013	2013	2013	2013	2013
Pmpp	-0.63	-0.54	-0.76	0.65	0.67	0.52	0.01	0.03	0.28	1.95	1.89	2.24	1.53	1.86	0.32

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Quality Assurance on Component Level
Basic Reliability testing

Efficient tests to evaluate important basic reliability characteristics

- Test duration shall not be long
- Fast and expressive results
- Targeting important failure mechanisms

Cell cracks
Yellowing
Humidity ingress
PID

Quality Assurance on Component Level
Visual Inspection beyond the standard

Module components for validation:

- Frame
- Junction Box
- Cable, Connectors
- Front and Back View
- Backsheet
- Interconnections
- Cells
- Glas

Example: Junction Boxes in different Module Types

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Quality Assurance on Component Level
Visual Inspection

Back view / Backsheet		nothing remarkable
Connection	Number and width of busbars on cells	3 pc., about 1.5 mm wide
	Processing of string between cells	Strings between cells not folded; thermal deviation can cause tensile strength on ribbon
	Quality of placing of ribbon on grid	little misalignment on some cells
	Quality of solder connection	soldering points not always clean
	Quality / Processing / Width of collecting bus bars	Collecting bus bars on side of junction box / upper side insulated insufficiently from ribbon; about 5 mm wide
Cells	Distance between the cells horzontal / vertical	about 2-3 mm / about 2-3 mm
	Adjustment	distances are not very uniform
Glass		structured, no AR-coating; marginal rest of silicone

Junction box of two different module types

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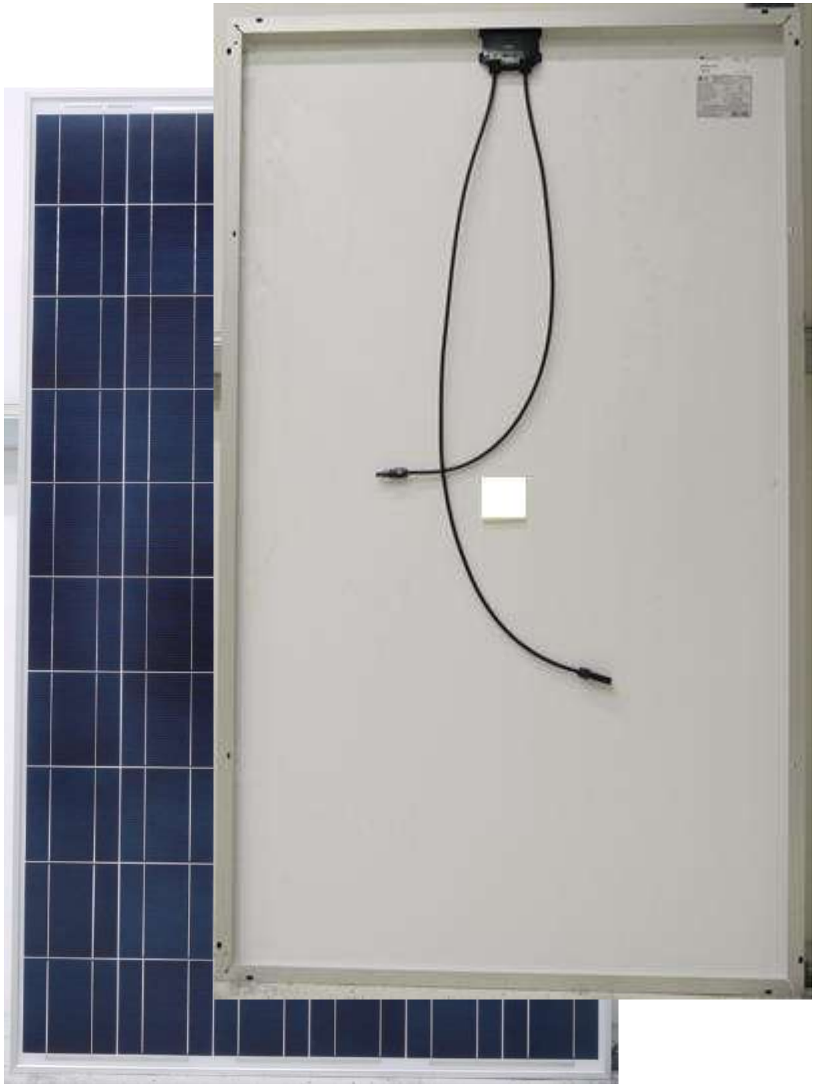
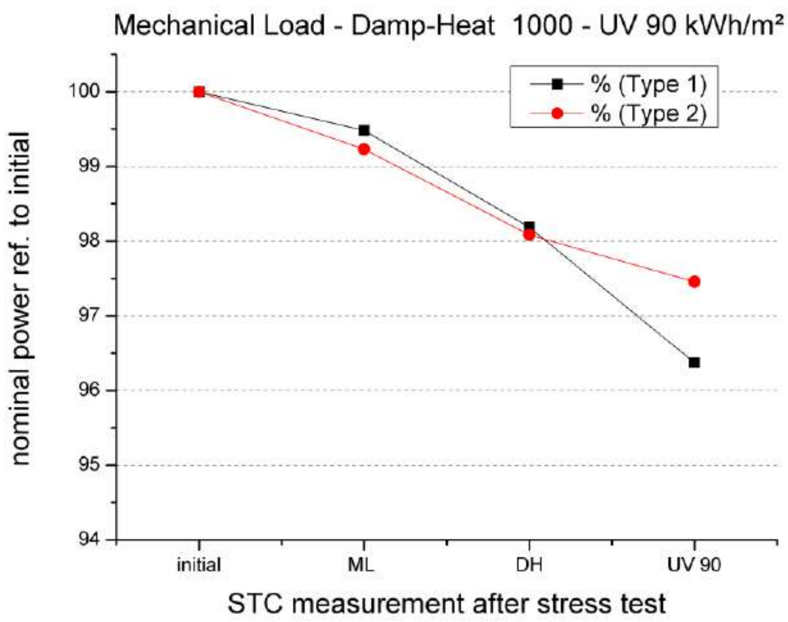
Quality Assurance on Component Level
Visual Inspection

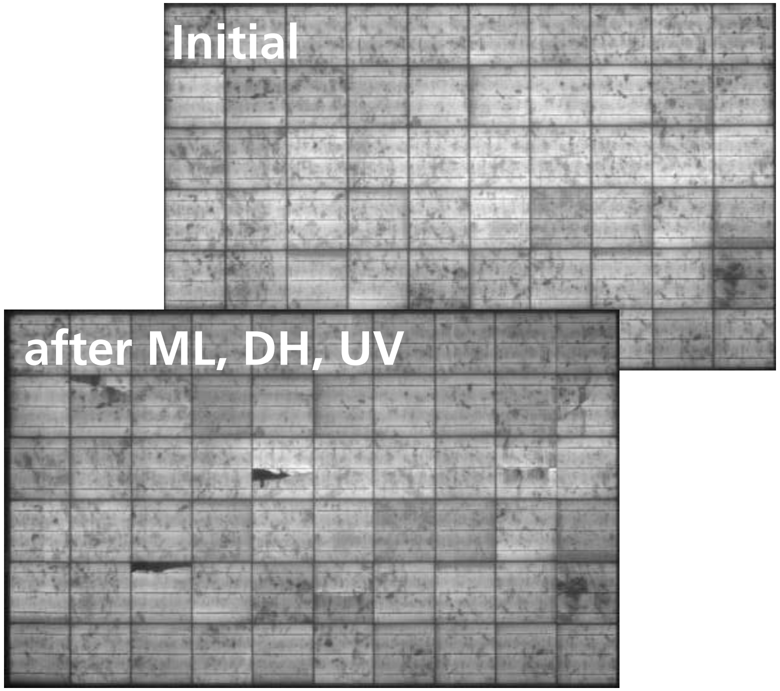
Evaluated components		
Frame	Width	46 mm
	Connection on corners	nut inserted
	Comment / qualitative evaluation	edges grinded poorly, no exact cutting; continuously glued with silicone
Junction Box	Quality of Bonding on module	continuously glued with silicone
	Clearance	OK
	Number / Type of bypass diodes	3 pcs.; not identifiable
	Connection type of bypass diodes and connection bus bars	bypass diodes continuously soldered, soldering connection not clean
	Sealing of cover	OK
Length of Cable		about 1000 mm
Type of Connector		similar to MC 4



Quality Assurance on Component Level
Basic Reliability testing

- Basic Reliability Testing
  - Type 1 and 2 show similar power loss, both meet defined criteria



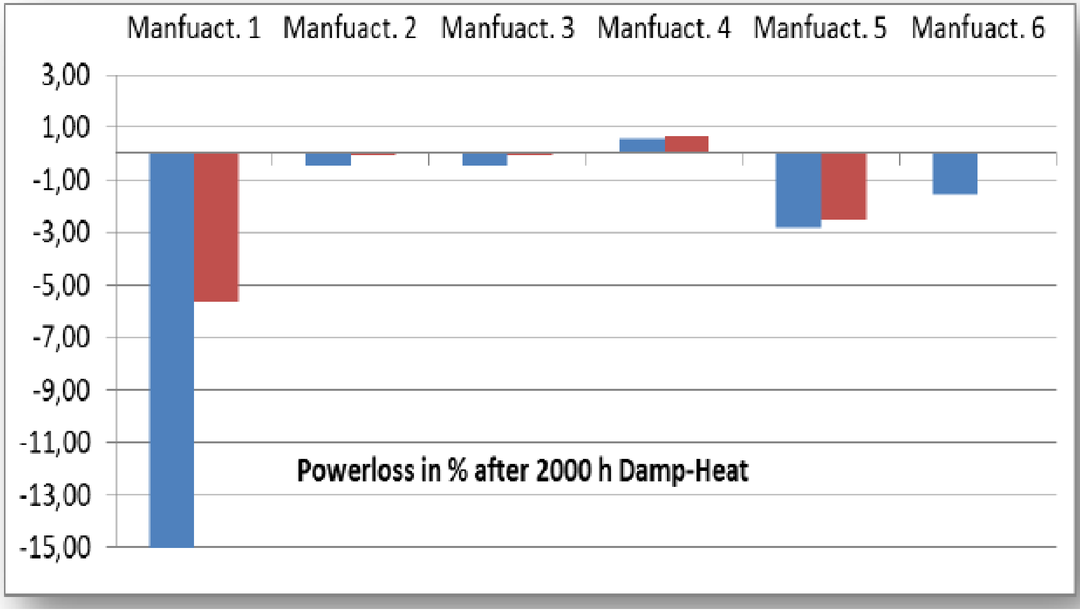


EL images initial (1) and after test procedure (2) for type 1

PV Module Testing
Humidity Ingress

Example: Sensitivity to hydrolysis, corrosion (humidity ingress)

- Benchmarking through enhanced climatic stress testing
- Power loss in % after 2000 hours Damp-Heat conditions (85°C/ 85 % RH.)

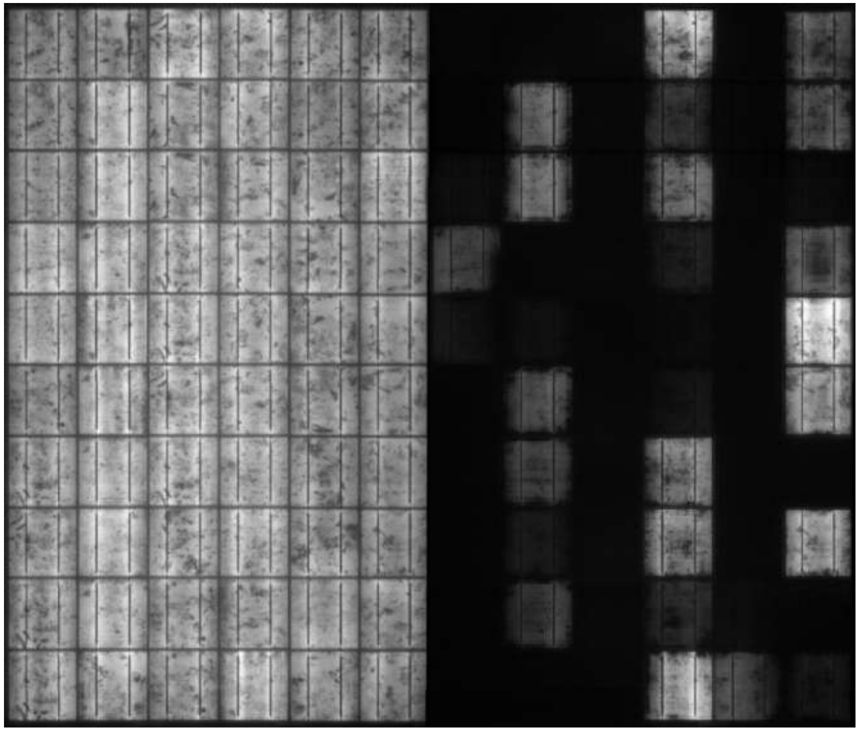


Easy to handle & calculable time and cost

Phase 3
Basic Reliability Characterization

PID Testing according to the current IEC Draft:

- 1000 V
- 60 ° C
- 85 % r.H.
- 96 h
- $P \geq 0{,}95\ P_{ini}$



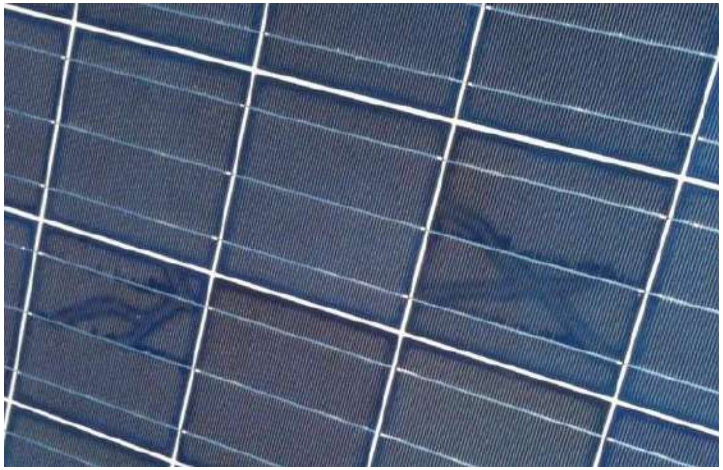
EL image before and after PID test of an example module

Quality Assurance on Component Level
Extended Stress Cycles to reduce other Specific Risks

Example:

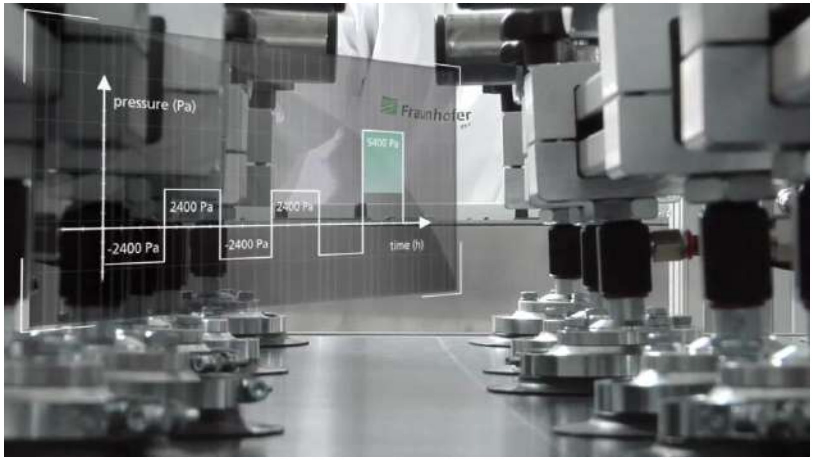
- Forms of 'Snail-Tracks'
- Forms of Yellowing
- Forms of Adhesion loss (Delamination)

Risk can be reduced due to extended **UV test** in combination with other stress tests



Quality Assurance on Component Level
Tests for Extreme Climates

- High Snow-Load at low Temperature
- Extended Hail Test (Standard: 25 mm Ø → 35 mm Ø, 45 mm Ø
- Salt Mist Corrosion Test
- Sand Abrasion



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Quality Assurance on Component Level
Gel content

- Analysis and calculation of the percentage of gel content in EVA of a PV module
- Testing facility: Soxhlet-extraction
- Influence on module durability (adhesion, chemical degradation)
- Recommended gel content is 80-90%

Quality Assurance on Component Level
Peel test

- Measurement of peel strength with a tensile testing machine
- Analysis of the encapsulant adhesion
- Procedure:
  - Strip width / length 10 mm / 300 mm
  - constant peel speed (13 mm/sec)
  - angle of approximately 90°
  - force measurement

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Reliable, time- and cost-efficient module testing
Summary

- Should cover STC power, yield-relevant characteristics as well as module design and reliability related questions

- provides profound information of performance and quality within few days
- increased efficiency for reliability testing
- shows deviation to state-of-the-art
- detects the most common failure mechanisms

Minimizes the risk of failures during operaton

Quality Assurance for utility scale PV plants

DEVELOPMENT
- solar resource assessment
- site analysis
- environmental stress assessment
- design review and optimization
- feasibility studies

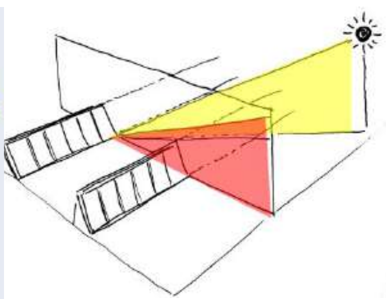
ENGINEERING
- yield assessment
- component bench-marking:
  - module power and energy rating
  - inverter testing

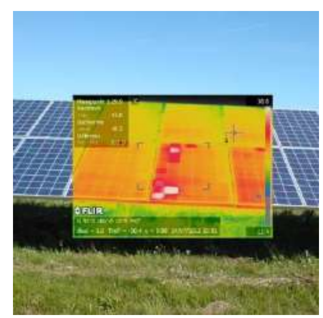
PROCUREMENT
- representative module sampling and checks:
  - performance
  - reliability
  - workmanship

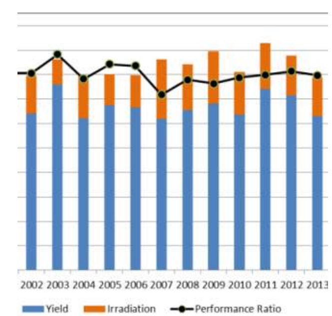
COMMISSIONING
- final power plant test:
  - visual inspection and thermography imaging
  - module power measurements
  - initial performance verification
- final acceptance report

OPERATION
- continuous long-term performance reporting
- failure analysis and reporting
- optimization and re-powering
- warranty check

- technical and financial due dilligence*
- comprehensive PV plant certification*







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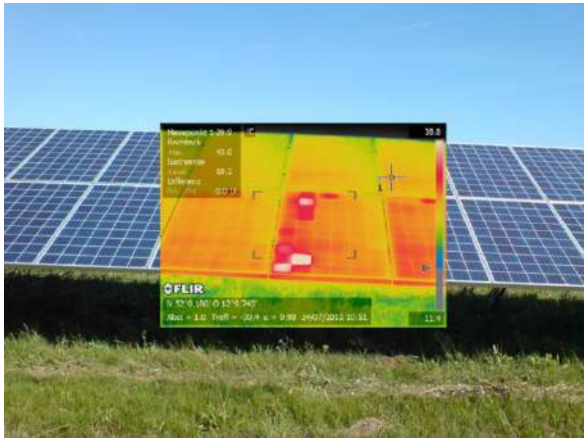
System Inspection and Testing
Main Steps

- Visual inspection of the PV plant
- Infrared images of modules and electrical connections
- Measurement of the solar generator to verify module power
- Short-term performance check of the PV plant



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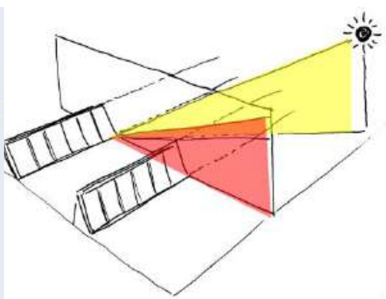

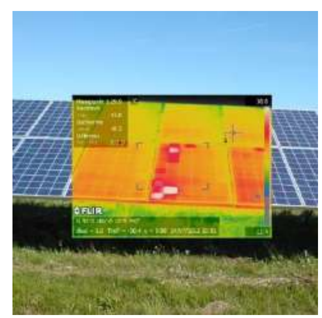

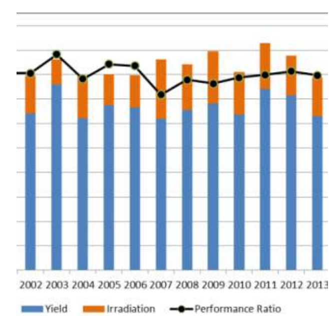

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Long-term experience
PV plant in Germany with 20 years service time

installed Power: 4,88 kWp

Construction: 1993

Location: Klausdorf, Germany

Orientation: -10° (South)

Tilt: 45 °

Long-term experience
PV plant in Germany with 20 years service time

Irradiation

1060 kWh/m² (± 13 %)

Yield

810 kWh/kWp (± 13 %)

Performance Ratio

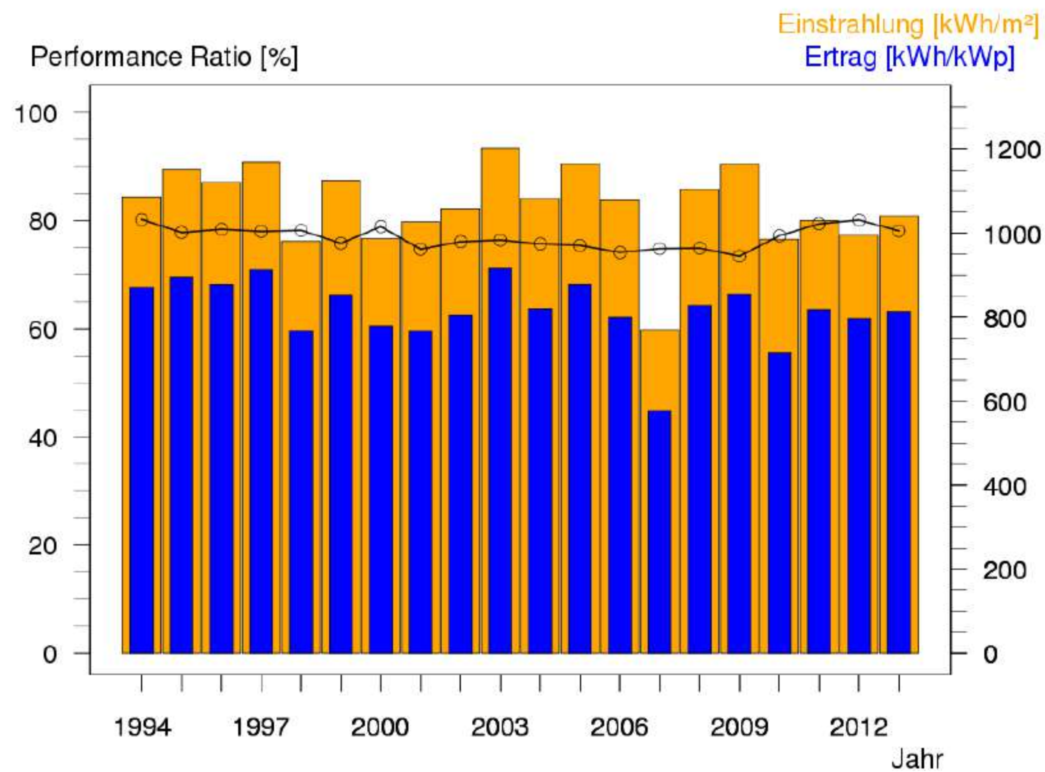
77 % (± 2,7 %)

Replacements:

2001: measurement equipment

2009: Inverter

2007: data availability 75 %



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Long-term experience
PV plant in Germany with 15 years service time

Installed power: 50 kWp

Construction: 1999

Location: Karlsruhe, Germany

Orientation: +10° (South)

Tilt: 30°

Long-term experience
PV plant in Germany with 15 years service time

Irradiation

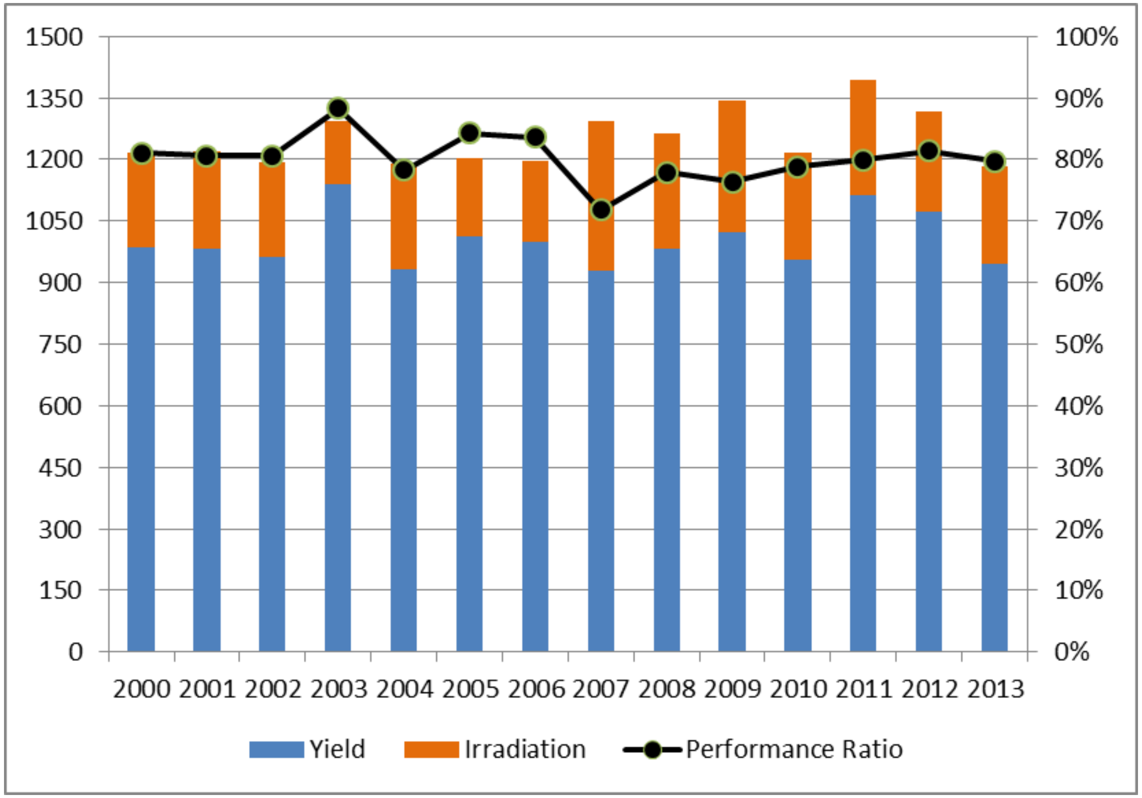
1250 kWh/m² (+/-5,1 %)

Yield

1000 kWh/kWp (+/- 6,3 %)

Performance Ratio

80 % (+/- 4,6 %)



Replacements:

2007: mesurement equipment

2013: Inverters

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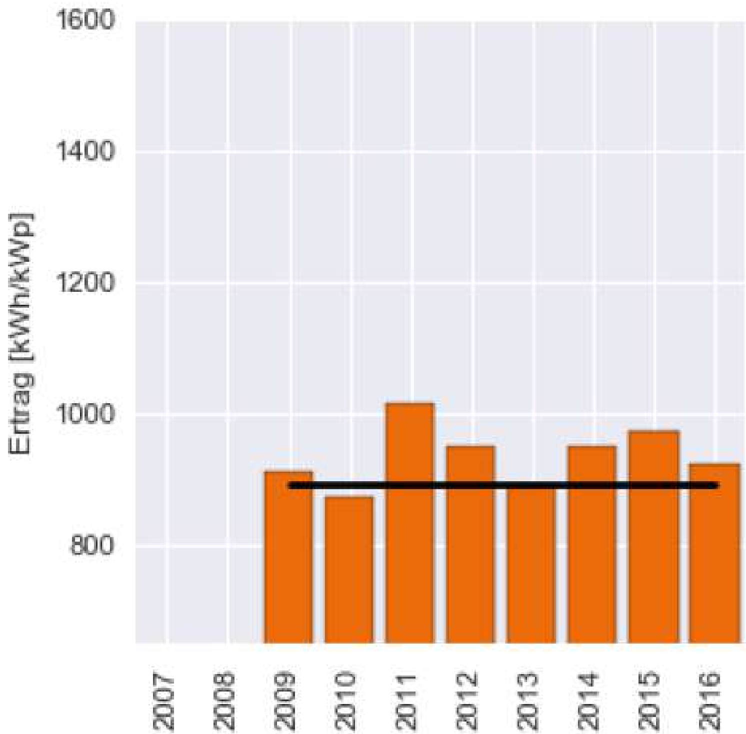
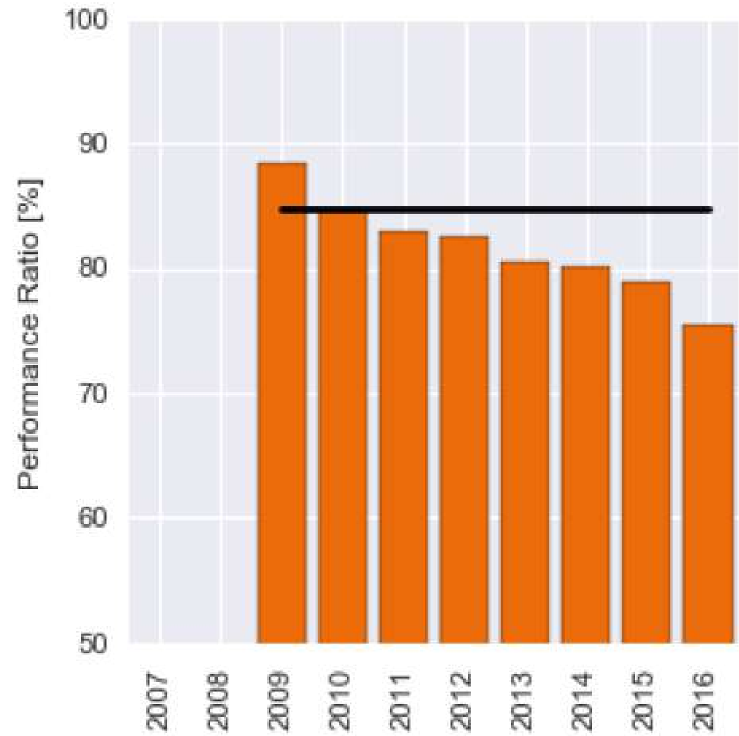
PR-Trends

Example 1: Power Plant in Germany

- DC-Power: 826.0 kWp
- Inverter: central
- Modules: c-Si





2009: PR 88.4 2016: PR 75,5

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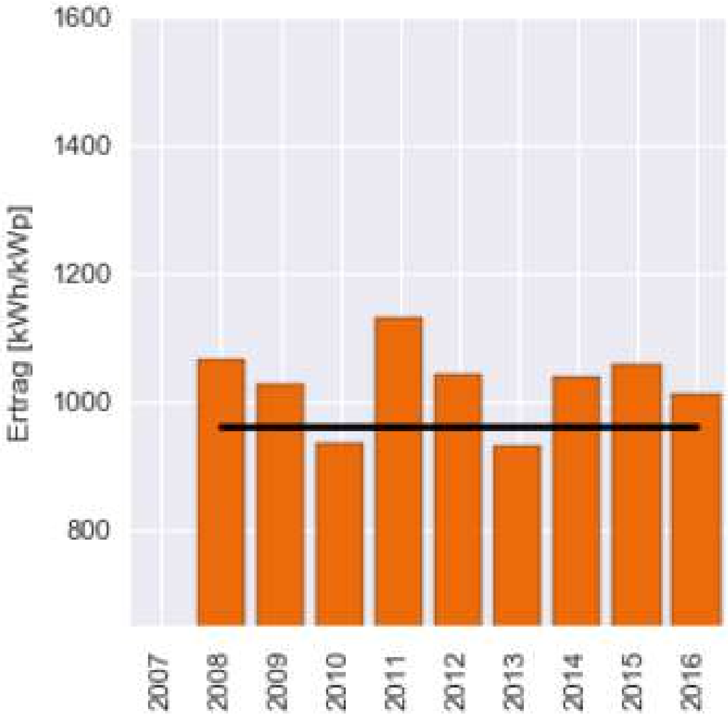
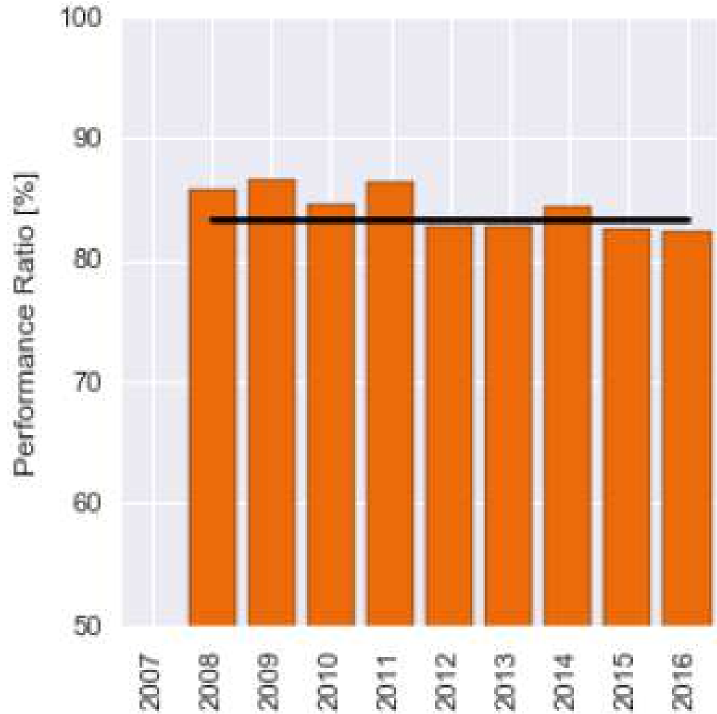
PR-Trends
Example 2: Power Plant in Germany

- DC-Power: 1044.8 kWp
- Inverter: central
- Modules: c-Si



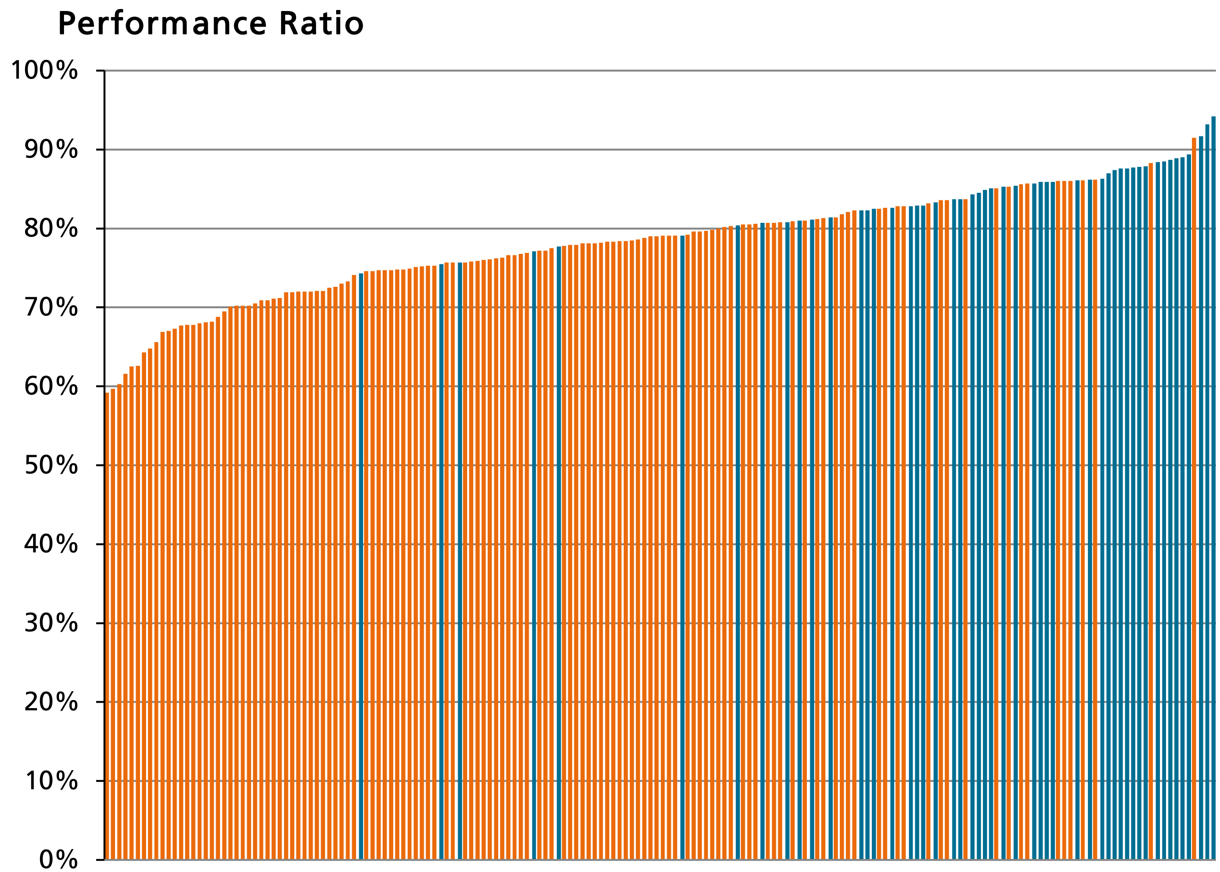


Peformance Ratio of PV Plants

Benchmarking for 2016 in Germany

Measured performance ratios for 250 PV plants

blue bars represent new plants with basic initial quality assurance and continuous O&M.



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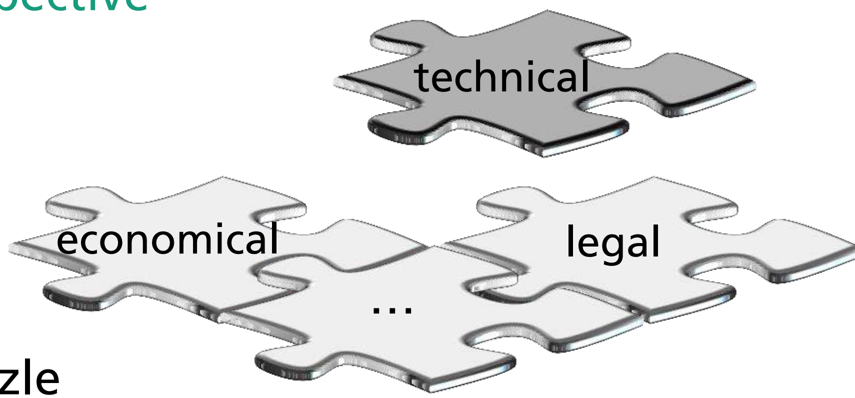
Technical bankability is …

… attractiveness of a project from the perspective of the financing institutions

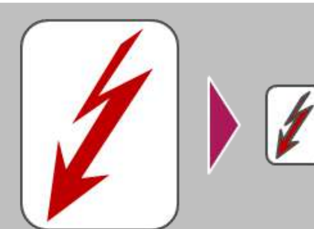


- Quality assurance is one part of the puzzle
- Different financiers have different technical requirements and evaluation criteria for projects
- no general guarantee for a bankable product or project, decision lies solely by the bank/investor

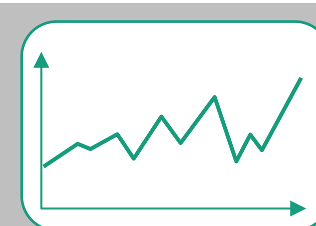
Trustworthy quality to benefit key stakeholders in the PV plant market

Quality is a core factor of technical bankability

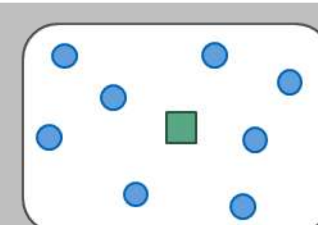
Reduce technical risk



Ensure performance and thus financial returns

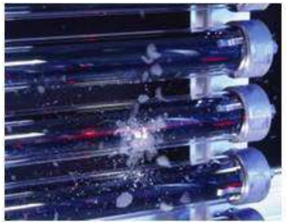
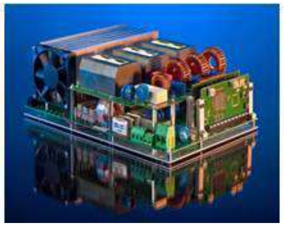
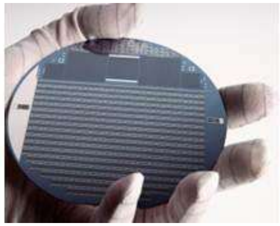


Achieve differentiation in the competitive market



Thank you for your Attention!

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YIELD AND PERFORMANCE RISK ANALYSIS

Part I

Boris Farnung, Björn Müller
Fraunhofer Institute for Solar Energy Systems ISE

Workshop "Quality Assurance and Bankability of PV Power Plants"
Mexico City, Thursday, 15.11.2018

www.ise.fraunhofer.de

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AGENDA

- Introduction to the topic
- Part I
  - Solar resources
  - Losses and gains of a PV system
- Part II
  - Uncertainty calculation and P-values
  - Region specific technical challenges for PV projects in Mexico

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What are the questions?

What are the questions?

- What is the energy yield for the projected lifetime?
- What is the risk that this yield estimation is wrong?

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- The solar resource
- Calculation steps of a yield assessment
- Calculation model examples and open questions
- What is the uncertainty?

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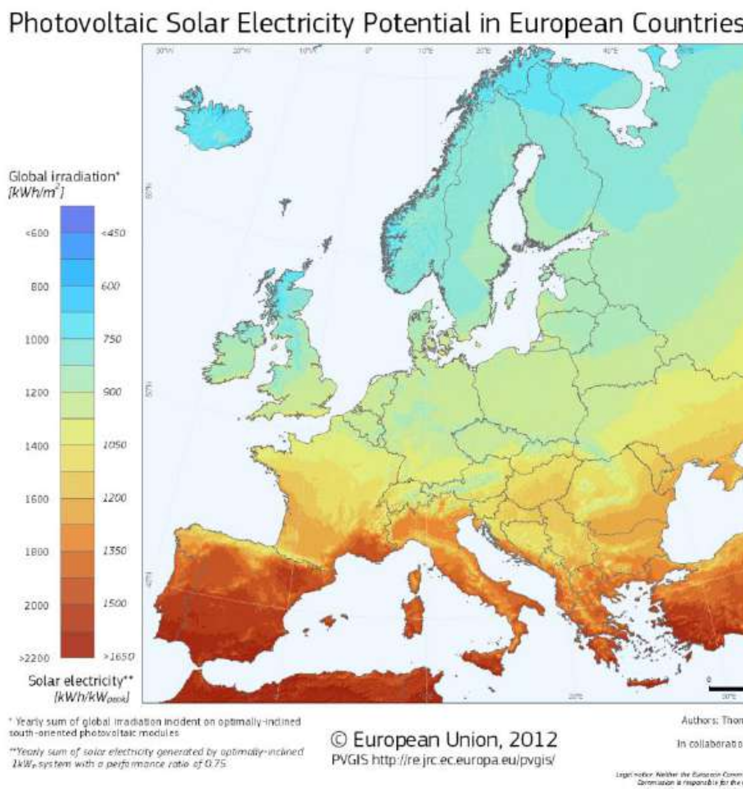
The solar resource
Data is available from various sources



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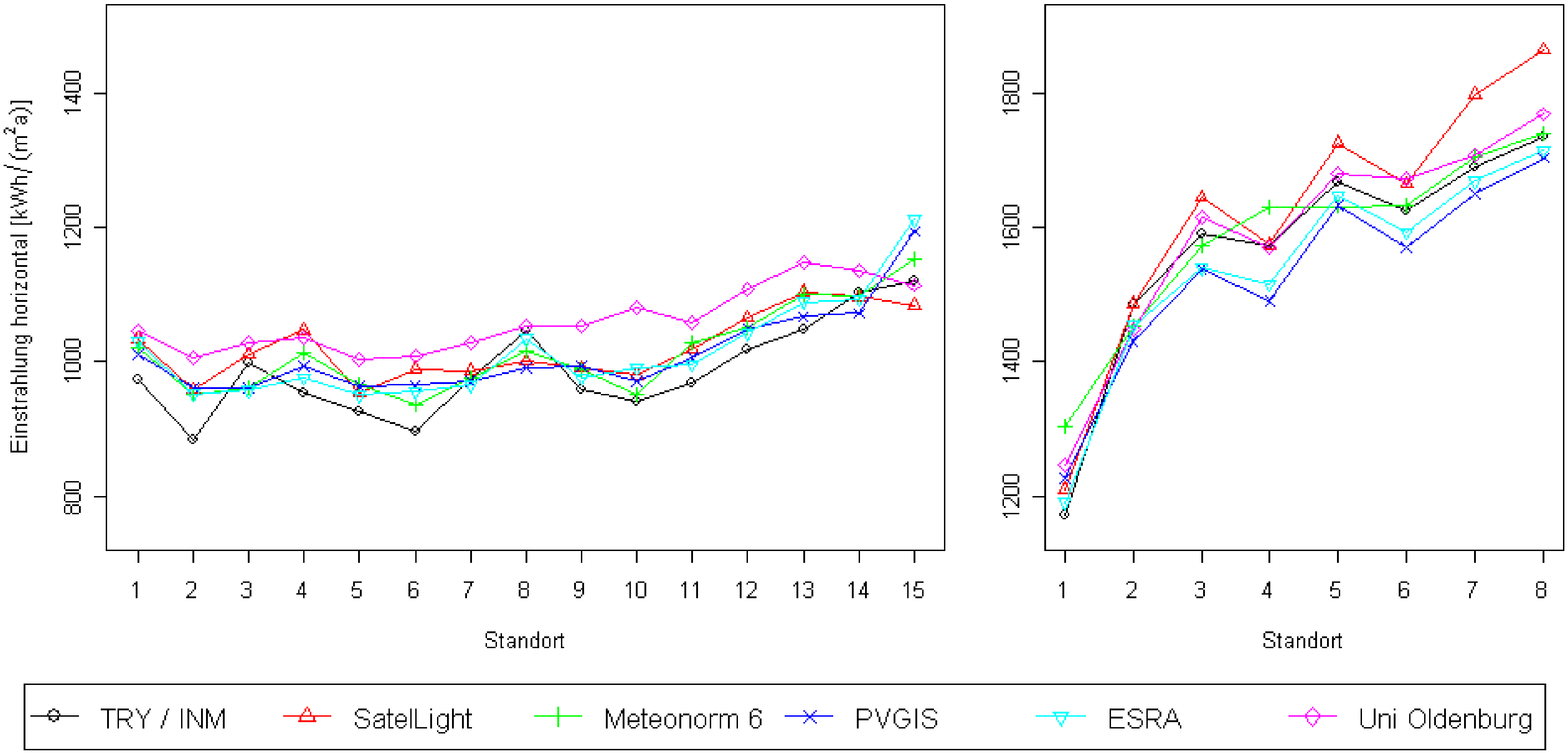
The solar resource
Data is available from various sources

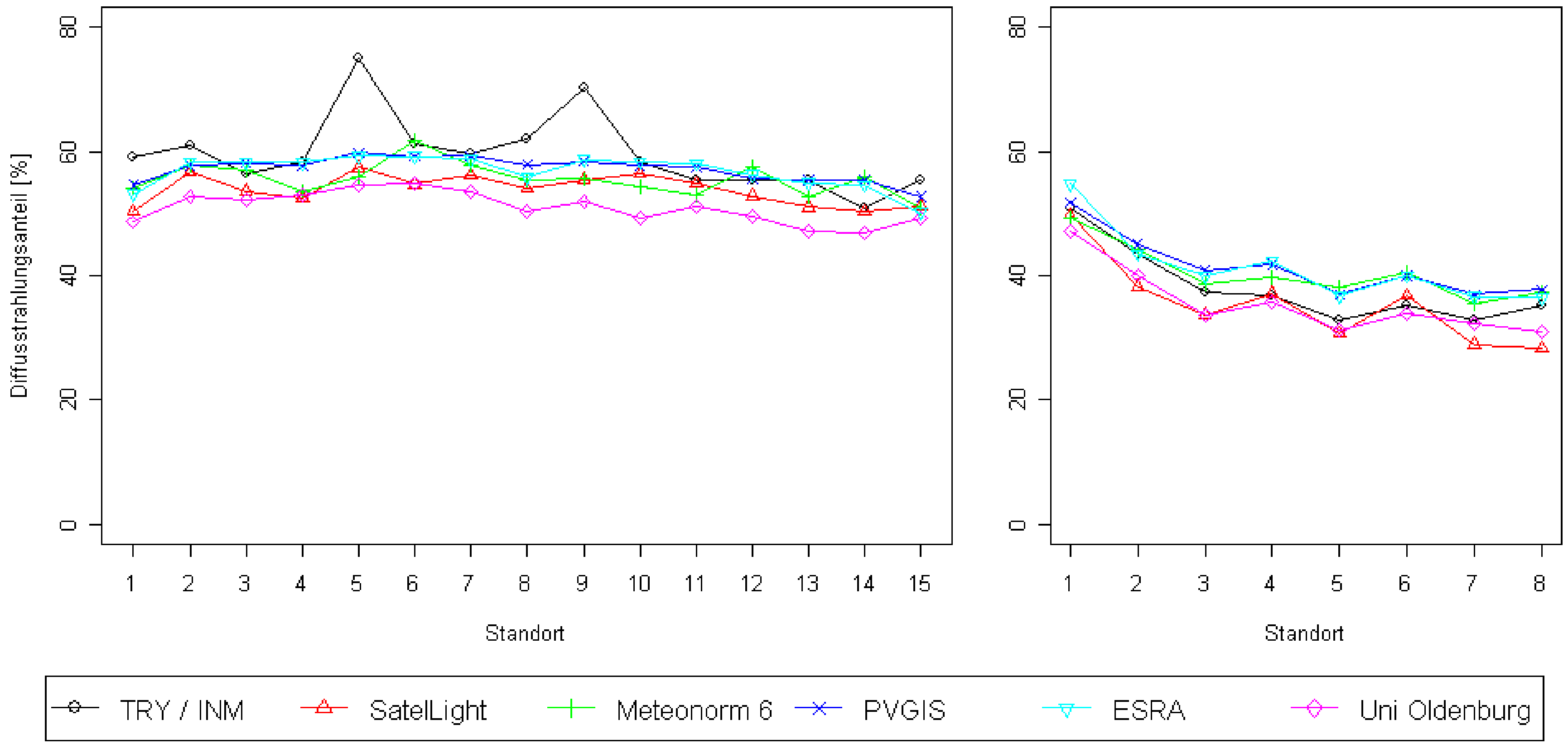
- https://globalsolaratlas.info
- www.solargis.com
- https://maps.nrel.gov/nsrdb-viewer
- www.meteonorm.com
- https://irena.masdar.ac.ae/gallery/#gallery
- …
- …

The solar resource
Irradiation differ with different sources



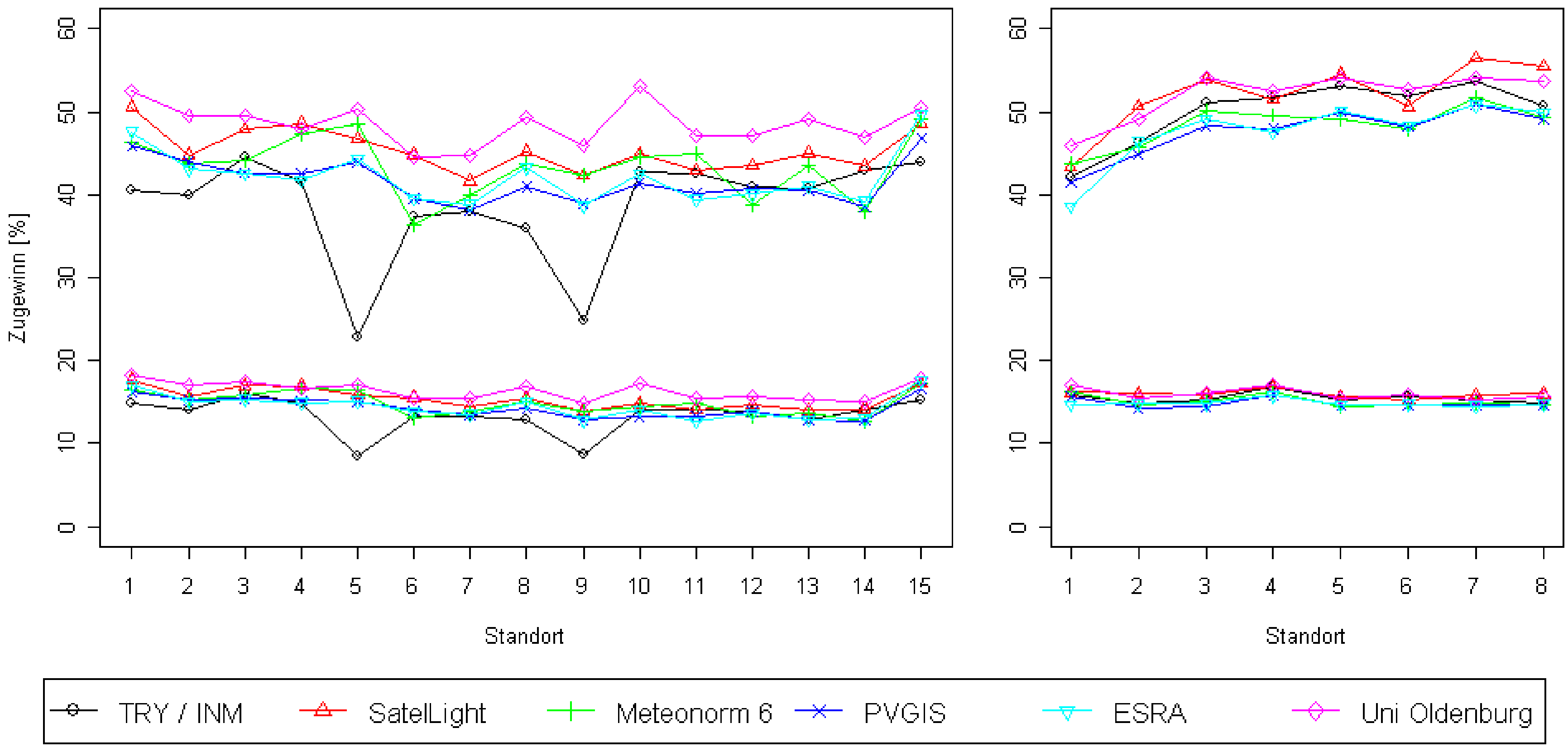
The solar resource

Diffuse fraction differs with different sources



The solar resource

Gains by tilting or tracking differ with different sources



The solar resource
Satellite data

- Example: Comparison of 13 different data sources against high quality ground measurements from 18 stations in Europe (P. Ineichen)
- Best data source: SolarGIS
- Average mean bias deviation (MBD) of global horizontal irradiance (GHI) is -0.3%, standard deviation (SD) 2.4%

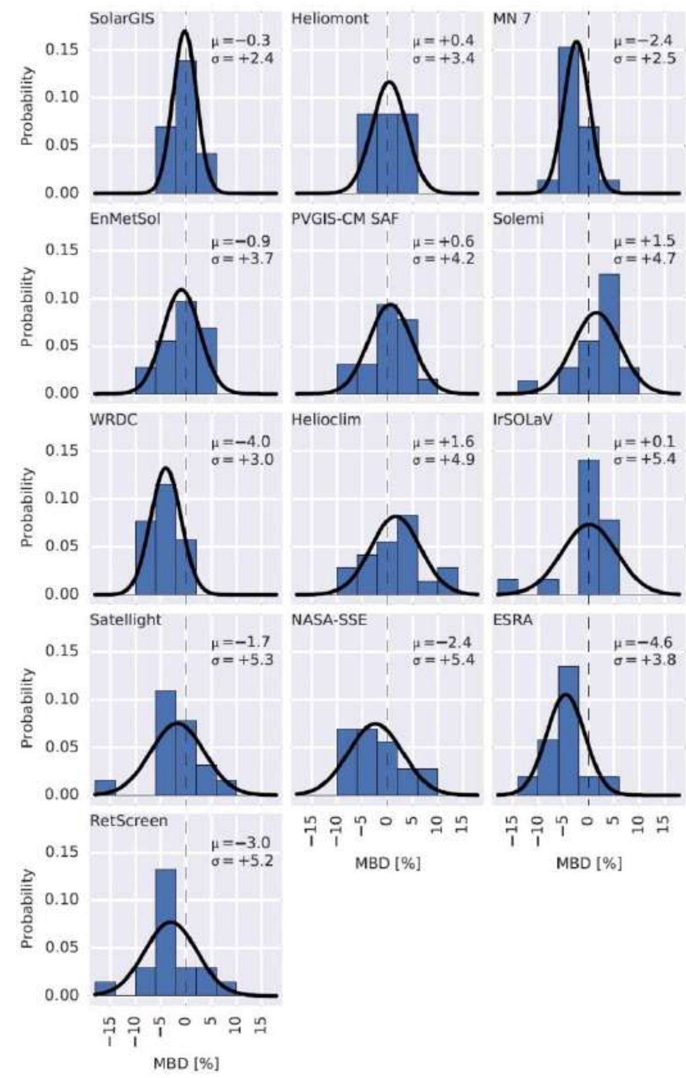
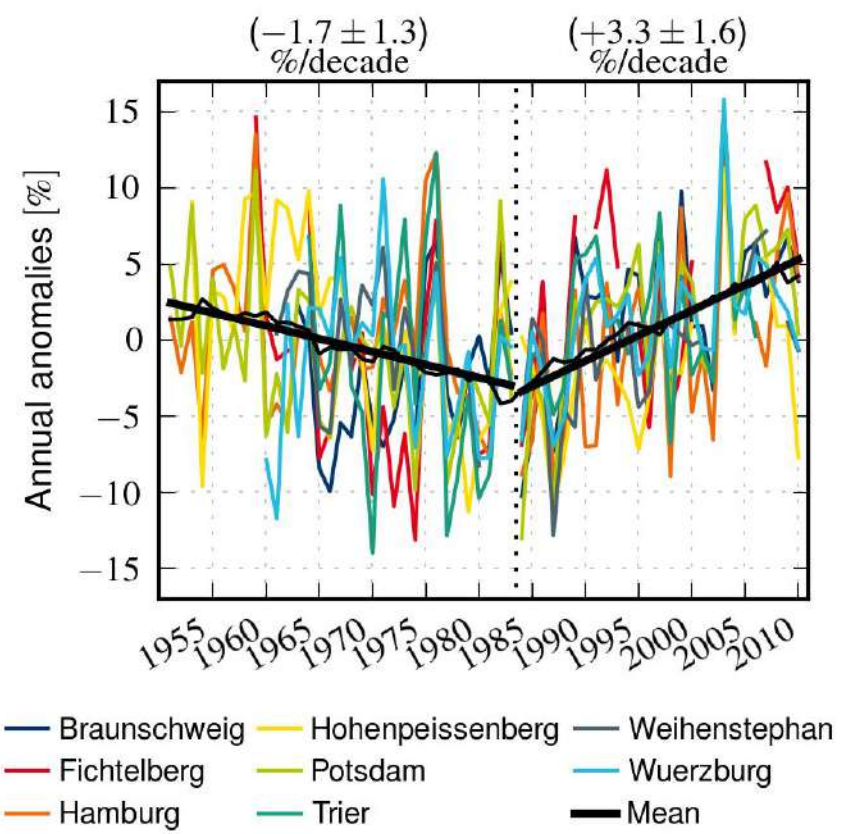


Figure based on data from:

Ineichen P. Long term satellite hourly, daily and monthly global, beam and diffuse irradiance validation. Interannual variability analysis; 2013.

The solar resource
Dimming and brightening trends

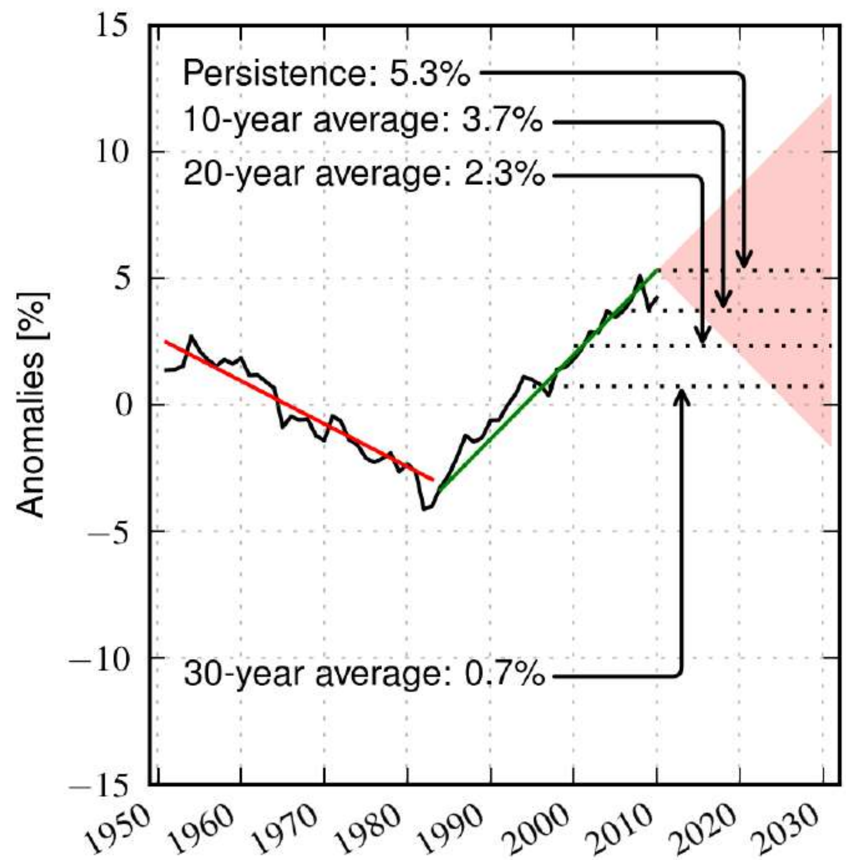
- Solar radiation is not stable over time, but shows long-term trends
- This phenomenon is known as "global dimming and brightening"
- Can be observed in most regions of the world but with different magnitude



Müller B, Wild M, Driesse A, and Behrens K, "Rethinking solar resource assessments in the context of global dimming and brightening," *Solar Energy*, vol. 99, pp. 272–282, 2014.

The solar resource
Dimming and brightening trends

- In the presence of trends, choosing the optimal reference time period is important
- Most recent 10 years are a good compromise to reduce the influence of single years, but to get a good estimate of current irradiance conditions
- Current difference in Germany between 10 and 30 year period is 3% and about 5% for GPOA



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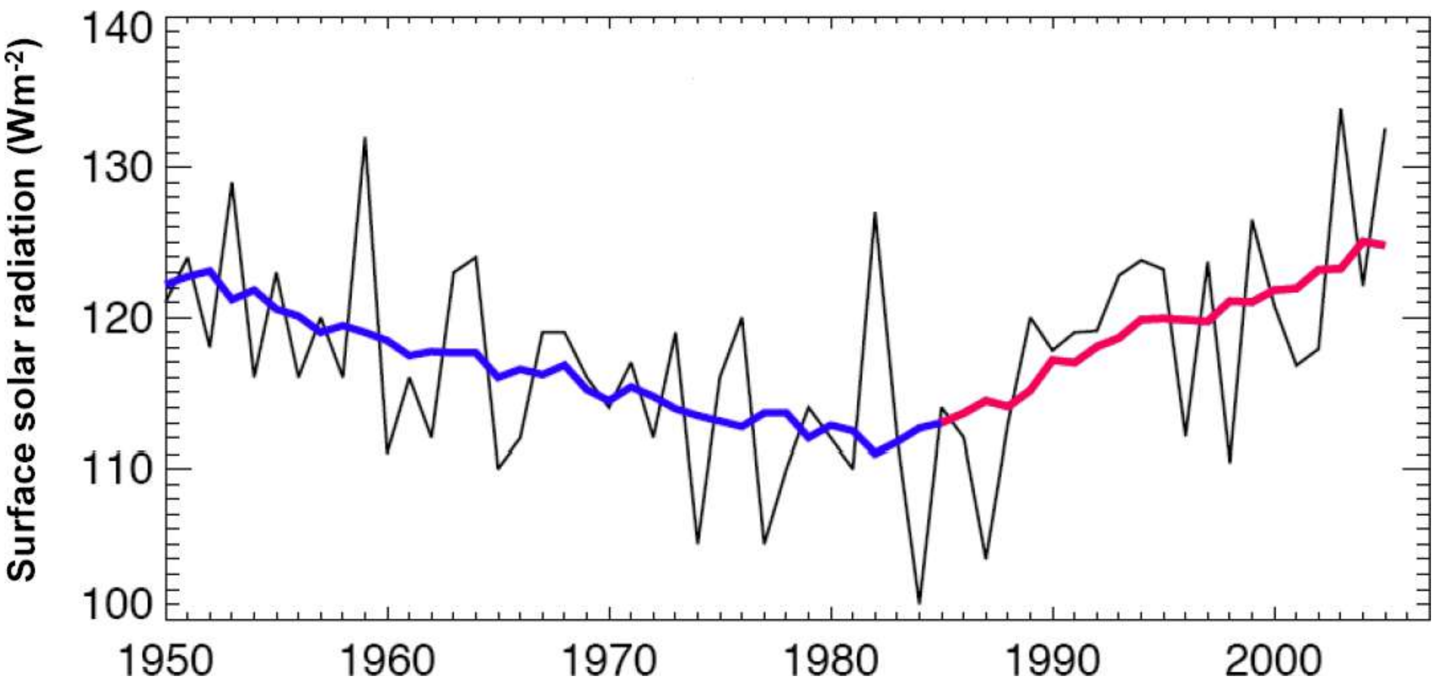
The solar resource
Example: Potsdam (Germany)

Global horizontal solar irradiation in Potsdam, Germany 1950 – 2005



M. Wild et al.: From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. Science 308 (2005)

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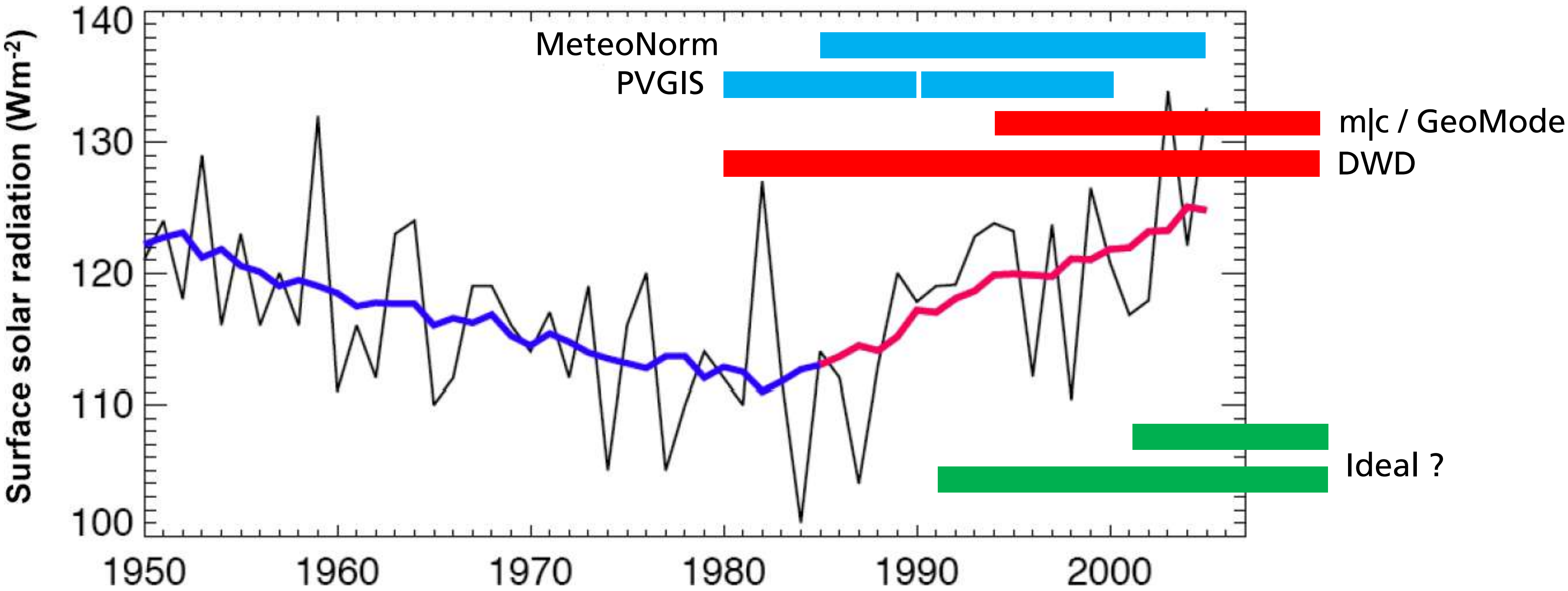

M. Wild et al.: From dimming to brightening: Decadal changes in solar radiation at the Earth's surface. Science 308 (2005)

The solar resource
Summary

- High quality (satellite derived) irradiance data sources are available nowadays
  - However: local validation and experience is needed!
- Data from different sources should be used to avoid errors and to detect regions / locations with higher uncertainties
- Long-term trends should be assessed and taken into account for solar resource assessments
- Uncertainties are higher for tracking systems, systems with different orientations or higher tilt angle

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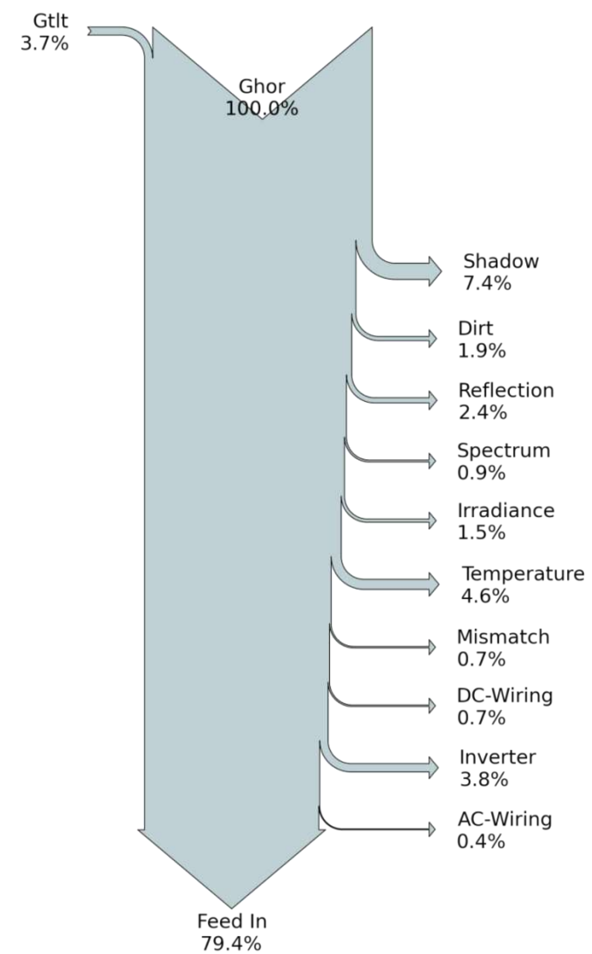
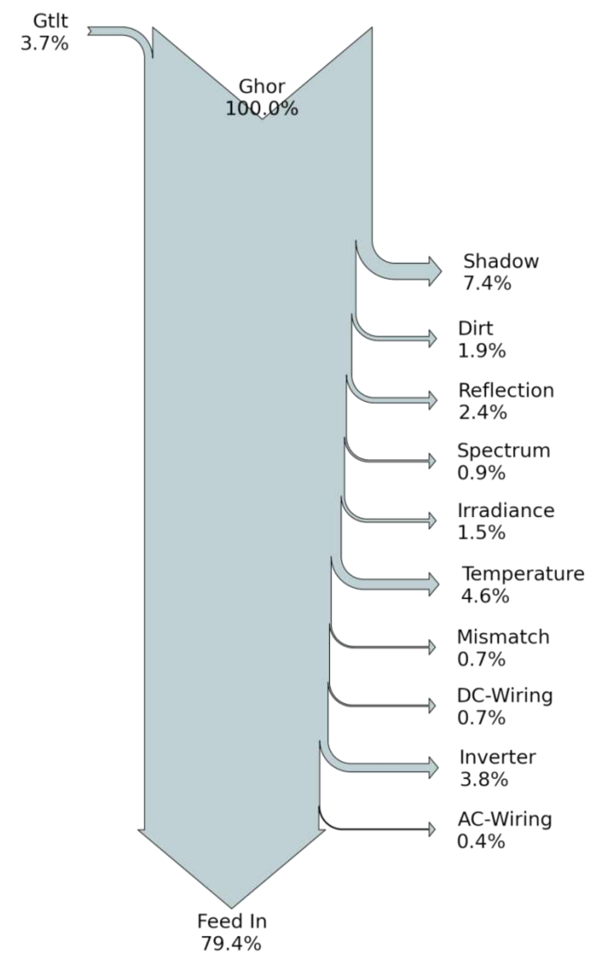
Calculation steps of a yield assessment



Calculation steps of a yield assessment

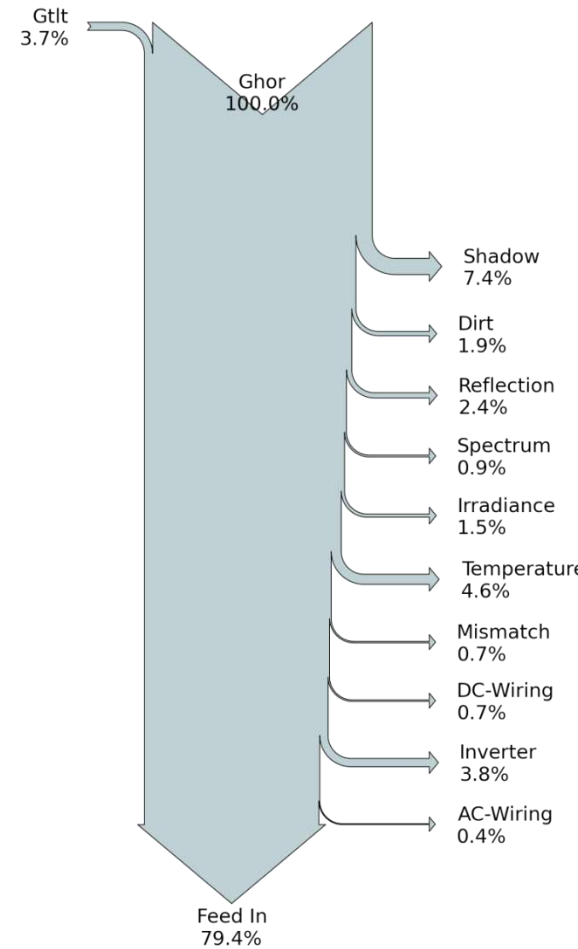
Energy Rating (ER)

-
-
-
-
-
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
-
-
-
-
-



Calculation steps of a yield assessment
Performance Ratio (PR)

-
-
-
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
-



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Calculation steps of a yield assessment
Typical initial yield

- Horizontal irradiation (history)
-
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
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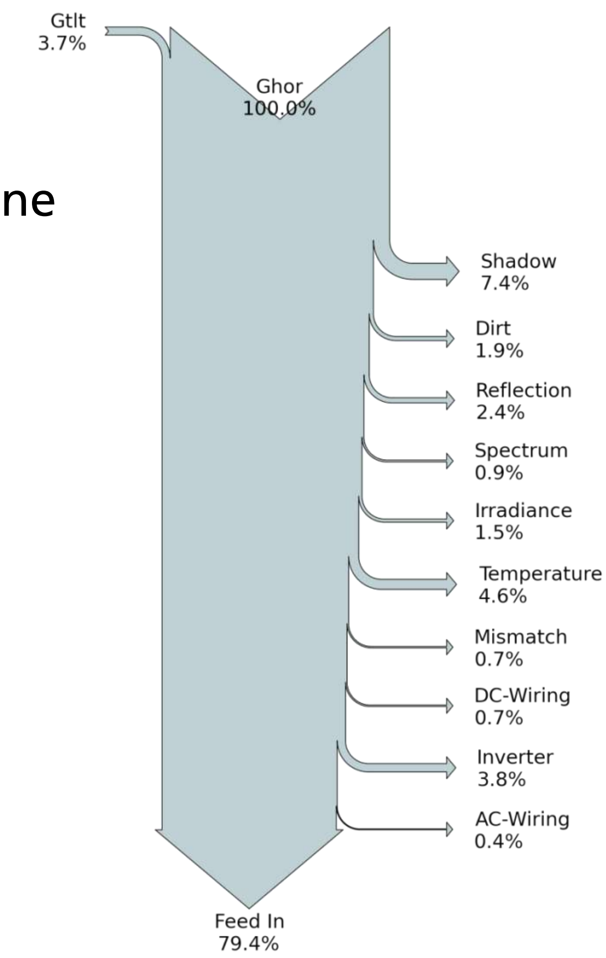
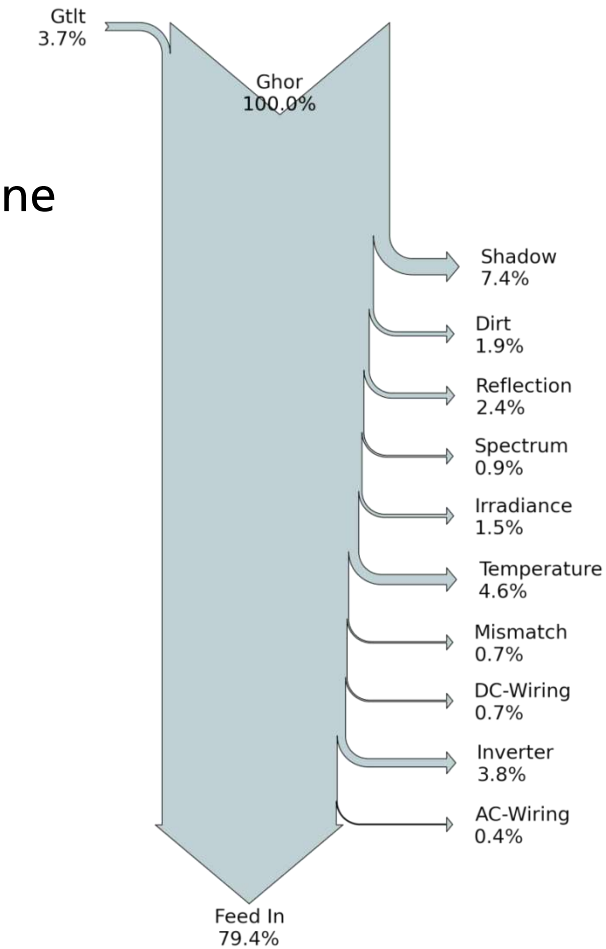
- Transformer losses
-



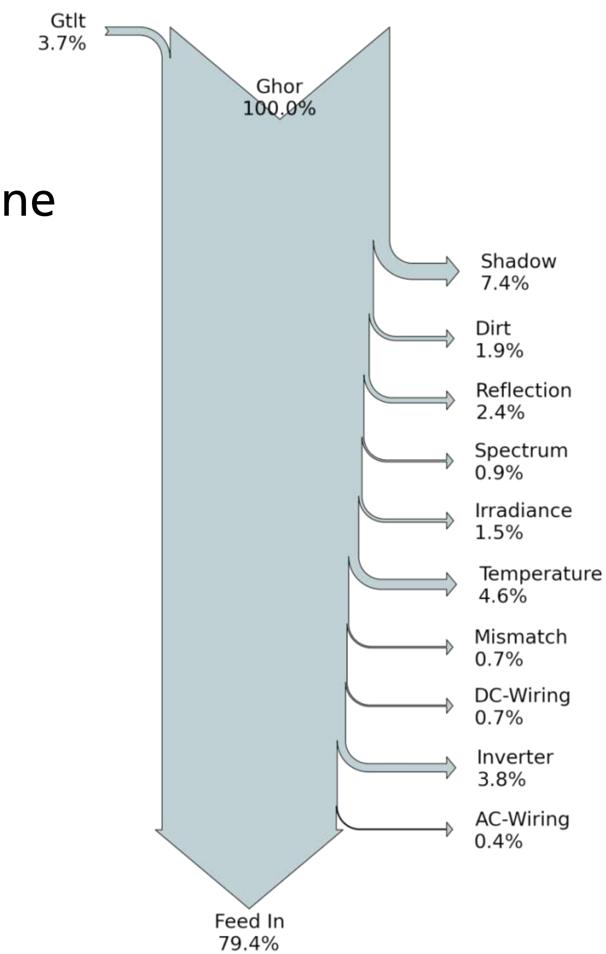
Calculation steps of a yield assessment
Long term yield

- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



Calculation steps of a yield assessment
Actual long term yield

- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
- Product specifications vs. actual properties
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



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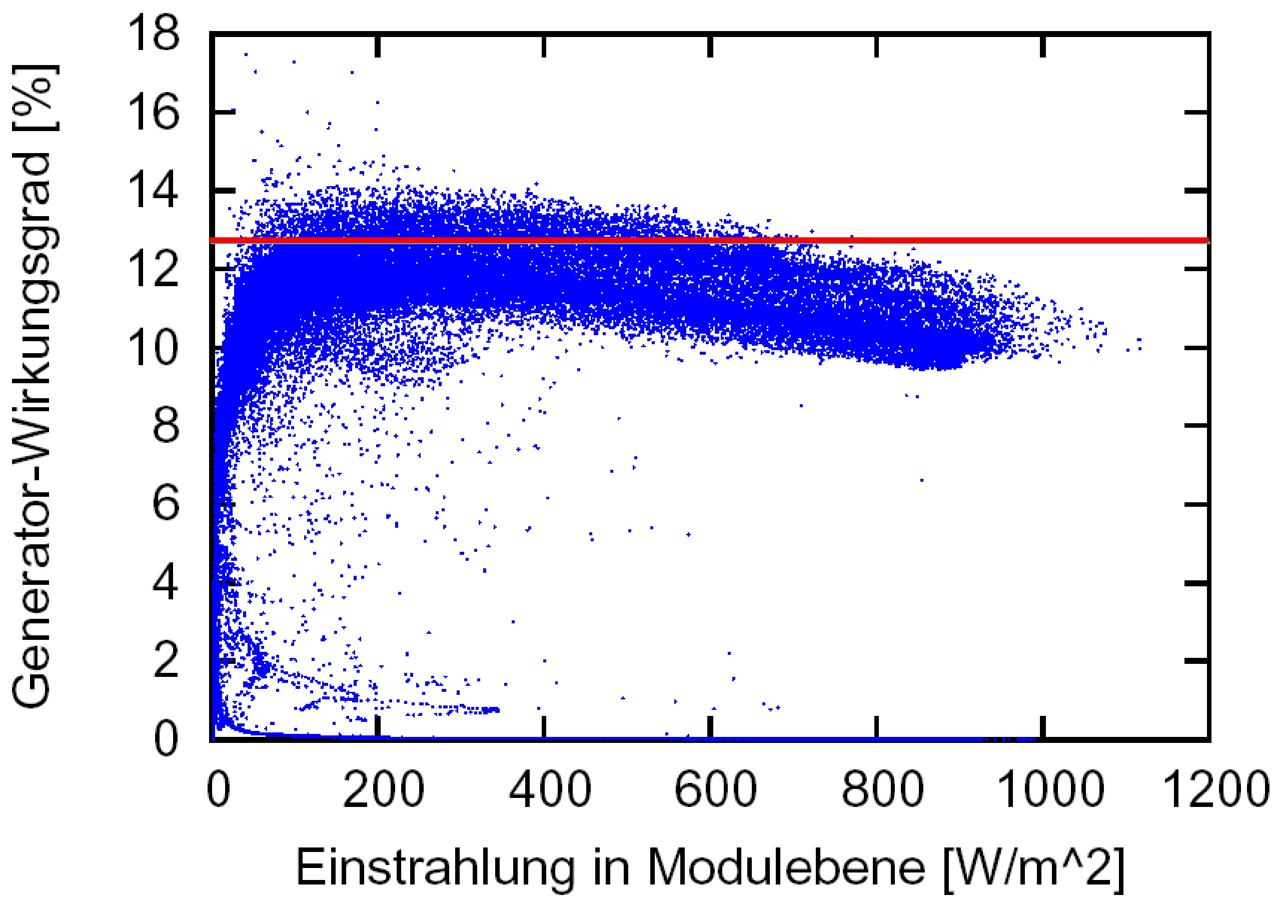
Calculation model examples
All year efficiency of PV modules



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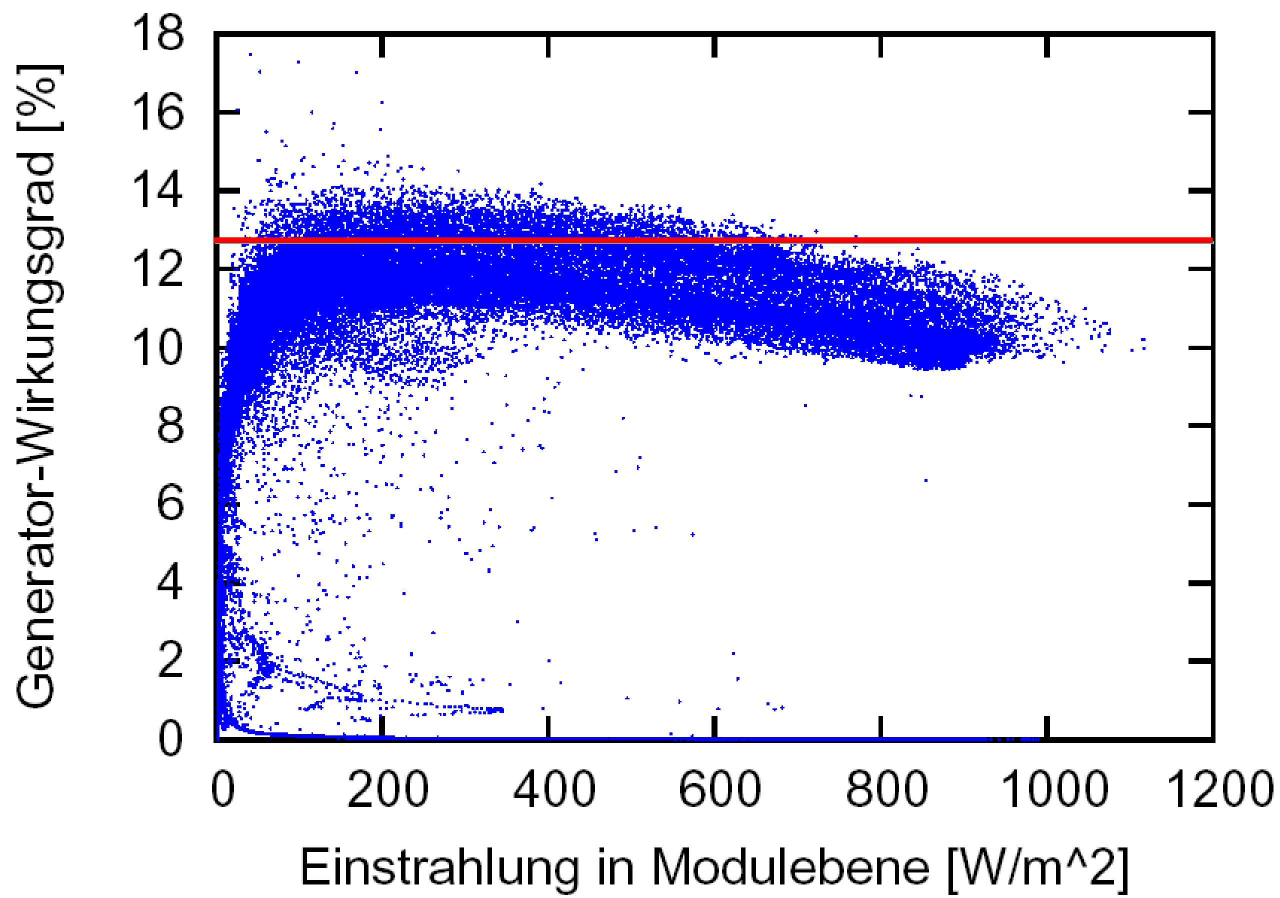
Calculation model examples
All year efficiency of PV modules

Calculation model:

- Simple and robust
- Suitable for different cell technologies
- Parameter to be derived from data sheets



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Calculation model examples
The Heydenreich module model

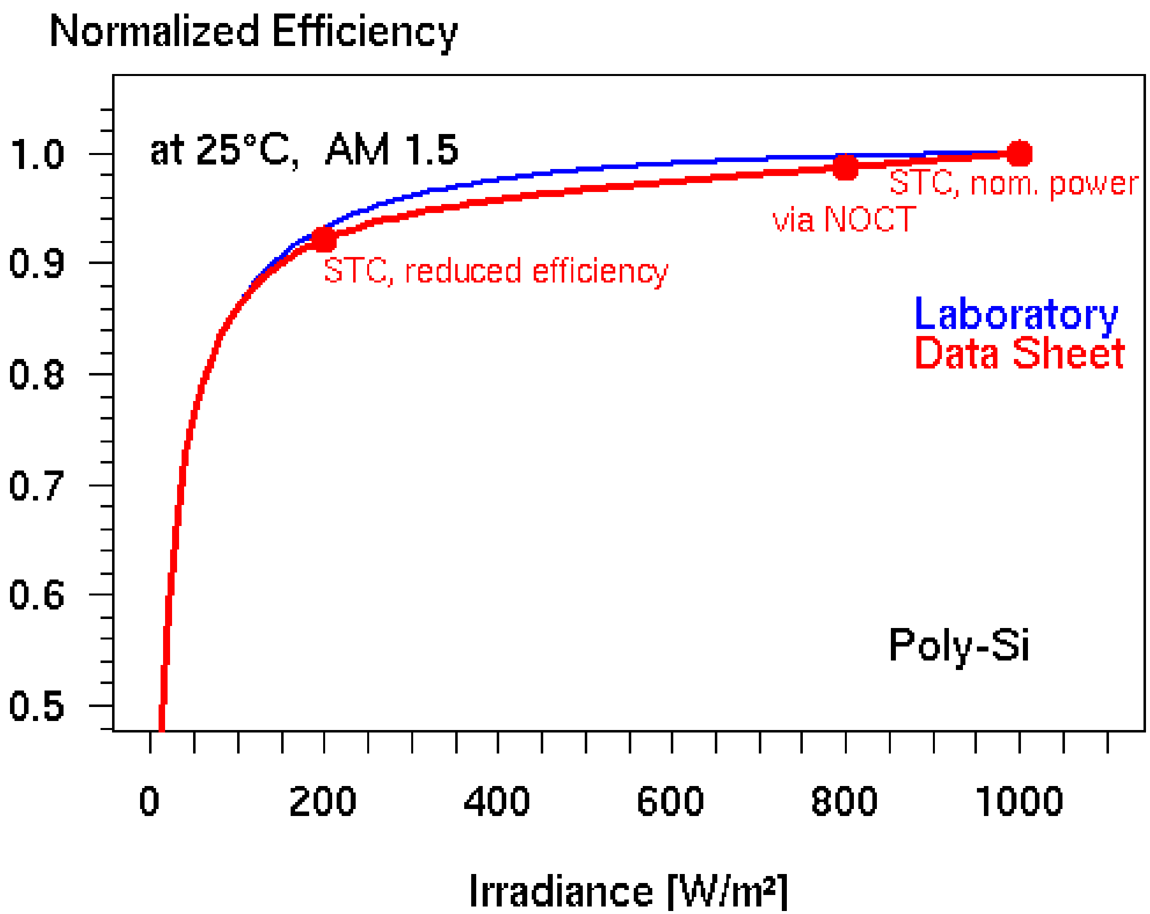
$$\eta_{25} = a\,G + b\,\ln(G + 1) + c\,[\ln^2(G + e) / (G + 1) - 1]$$

$$\eta = \eta_{25}\,[1 + \gamma\,(T - 25\,°C)]$$

$$P = \eta\,G\,A$$

- Determination of parameters a, b und c requires power values at 25°C and three different irradiance levels
- γ is found in the module data sheet

Calculation model examples
The Heydenreich module model



EN 50380 requires:

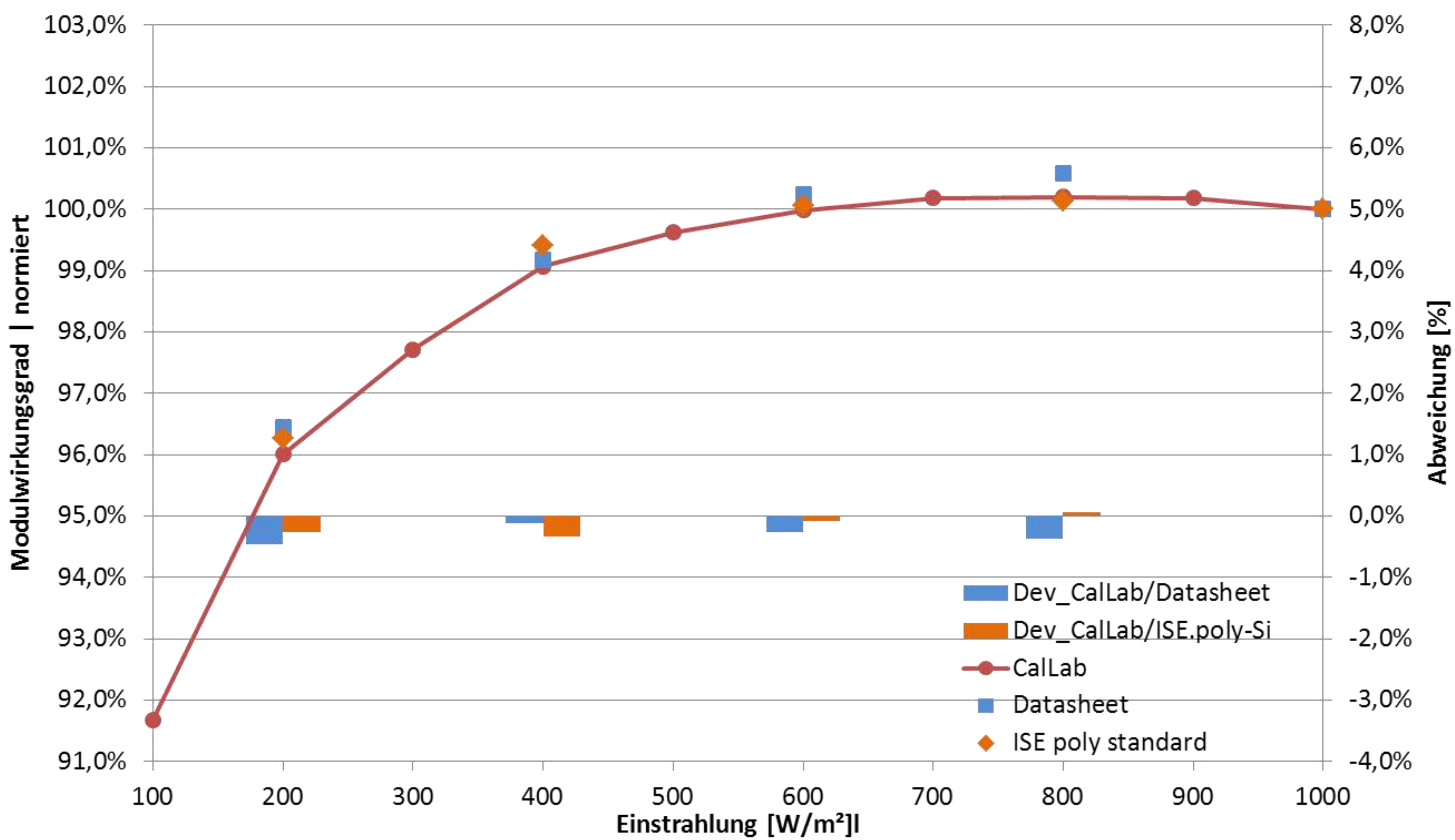
- P @ STC
- ΔP @ 200 W/m²
- P @ NOCT

Calculation model examples
The Heydenreich module model

How to derive the parameters?

- Data sheet
- Compenent libriries with commercial software
- Standard values specific for given cell technologies
- Detailed manufacturer‘s data with assured universal validity
- Laboratory measurements specific to a project

Calculation model examples
The Heydenreich module model



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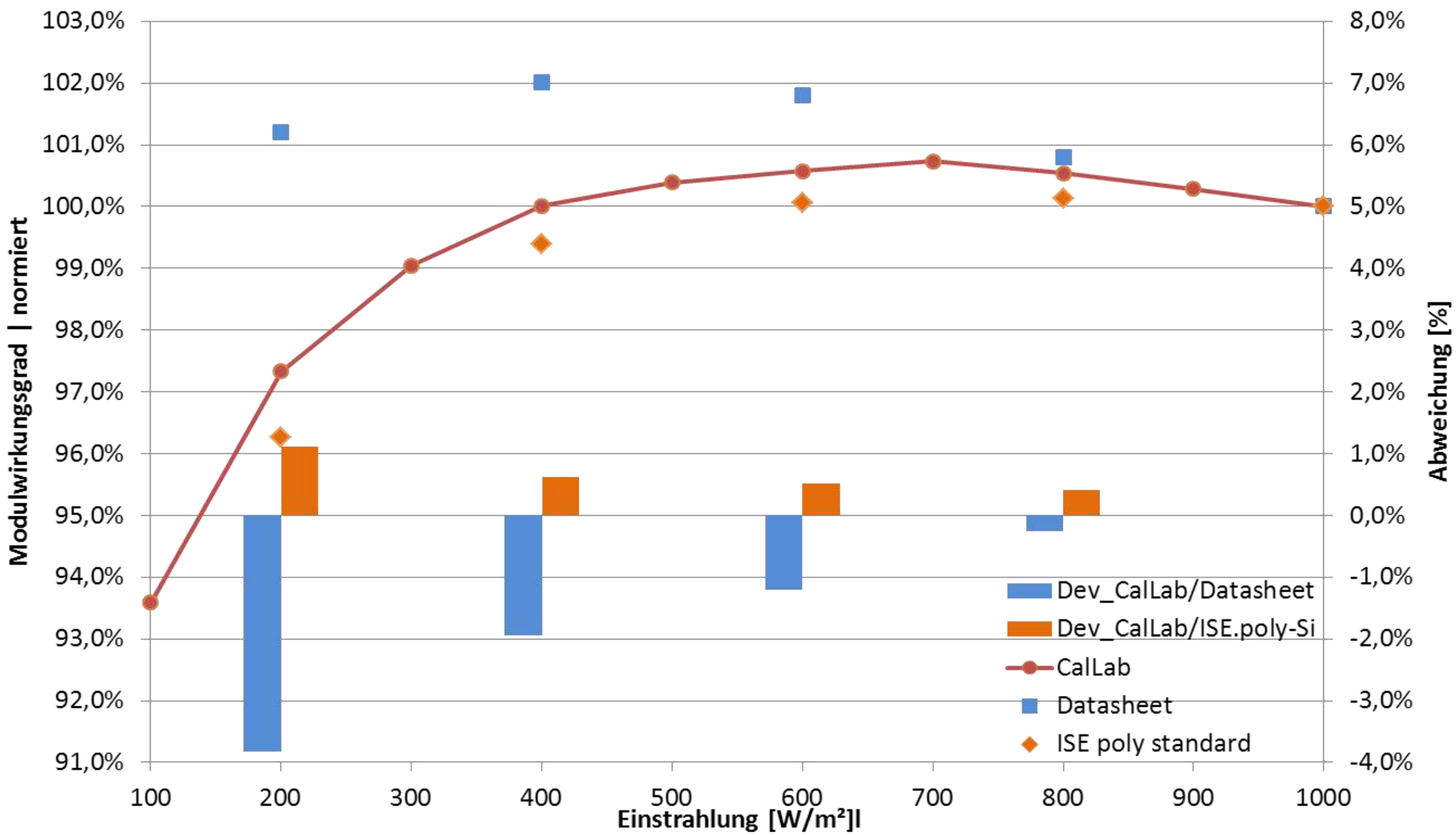
Calculation model examples
The Heydenreich module model



Calculation model examples
The Heydenreich module model

Again, how to derive the parameters?

- Data sheet
- Compenent libriries with commercial software
- Standard values specific for given cell technologies
- Detailed manufacturer's data with assured universal validity
- Laboratory measurements specific to a project

Calculation model examples and open questions
just to be mentioned here…

- Soiling & snow
- Spectral gains or losses
- Horizon / object / internal shading
- Row-to-row shading vs. maximized use of area
- Inverter: efficiency = f (power, voltage, temperature, …)
- Inverter: power / current / voltage limitations of a given device
- Average vs. peak values
- …
- …

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Conclusions…

- Independent yield estimations are an requirement
- Do not rely on a single yield estimation
- Do not rely on a single software tool
- It should be checked onsite, if the PV system is built as assumed!

- PV power plant operation is well understood and reproducible
- You (or your consultant) need to build up local / regional experience

- Uncertainties will remain

What are the questions?

- What is the energy yield for the projected lifetime?
- What is the risk that this yield estimation is wrong?

- The solar resource
- Calculation steps of a yield assessment
- Calculation model examples and open questions
- What is the uncertainty?

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End of Part I

YIELD AND PERFORMANCE RISK ANALYSIS

Part II

Boris Farnung, Björn Müller
Fraunhofer Institute for Solar Energy Systems ISE

Workshop “Quality Assurance and Bankability of PV Power Plants”
Mexico City, Thursday, 15.11.2018

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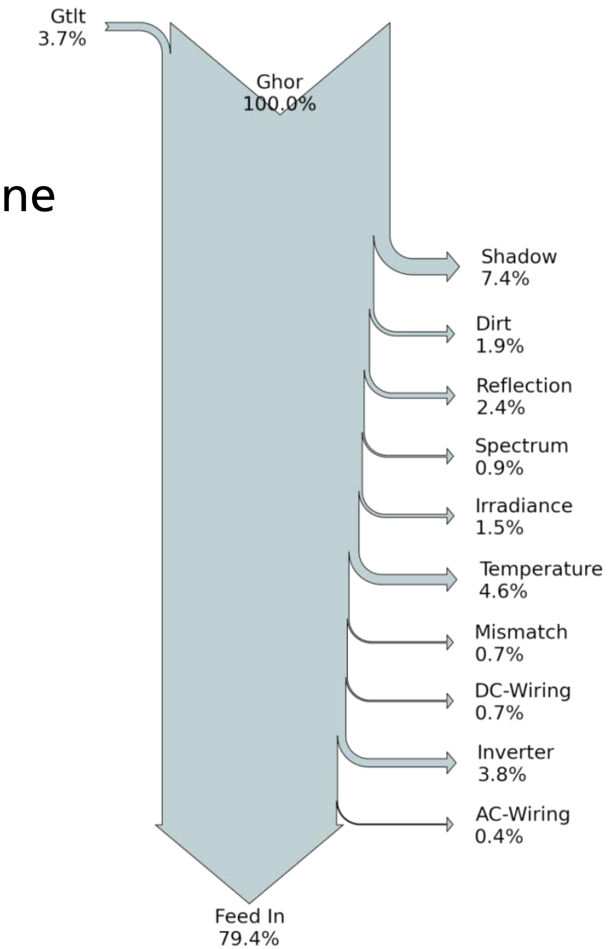
AGENDA

- Introduction to the topic
- Part I
  - Solar resources
  - Losses and gains of a PV system
- Part II
  - Uncertainty calculation and P-values
  - Region specific technical challenges for PV projects in Mexico

Uncertainty calculation and P-values

Modelling steps

- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
- Product specifications vs. actual properties
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



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Uncertainty calculation and P-values

Energy Rating (ER)

Reflection losses	0% to 2%
Spectral effects	0% to 2%
Dependency on irradiance level	1% to 2%
Dependency on temperature	0% to 2%

Uncertainty calculation and P-values

Performance Ratio (PR)

Partial shading (& inverter behavior)	1% to 4%
Soiling losses	1% to 3%
Reflection losses	0% to 2%
Spectral effects	0% to 2%
Dependency on irradiance level	1% to 2%
Dependency on temperature	0% to 2%
Mismatch losses	0% to 1%
DC + AC cable losses	0% to 1%
Inverter efficiency and limitations	0% to 2%
Transformer losses	0% to 1%

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Uncertainty calculation and P-values

Typical initial yield

Horizontal irradiation (history)	3% to 5%
Diffuse fraction & conversion into module plane	2% to 3%
Partial shading (& inverter behavior)	1% to 4%
Soiling losses	1% to 3%
Reflection losses	0% to 2%
Spectral effects	0% to 2%
Dependency on irradiance level	1% to 2%
Dependency on temperature	0% to 2%
Mismatch losses	0% to 1%
DC + AC cable losses	0% to 1%
Inverter efficiency and limitations	0% to 2%
Transformer losses	0% to 1%

Uncertainty calculation and P-values

Long term yield

Horizontal irradiation (history)	3% to 5%
Horizontal irradiation (future)	1% to 3%
Diffuse fraction & conversion into module plane	2% to 3%
Partial shading (& inverter behavior)	1% to 4%
Soiling losses	1% to 3%
Reflection losses	0% to 2%
Spectral effects	0% to 2%
Dependency on irradiance level	1% to 2%
Dependency on temperature	0% to 2%
Mismatch losses	0% to 1%
DC + AC cable losses	0% to 1%
Inverter efficiency and limitations	0% to 2%
Transformer losses	0% to 1%
System degradation	0% to 5%

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Uncertainty calculation and P-values

Actual long term yield

Horizontal irradiation (history)	3% to 5%
Horizontal irradiation (future)	1% to 3%
Diffuse fraction & conversion into module plane	2% to 3%
Partial shading (& inverter behavior)	1% to 4%
Soiling losses	1% to 3%
Reflection losses	0% to 2%
Spectral effects	0% to 2%
Product specifications vs. actual properties	0% to 5%
Dependency on irradiance level	1% to 2%
Dependency on temperature	0% to 2%
Mismatch losses	0% to 1%
DC + AC cable losses	0% to 1%
Inverter efficiency and limitations	0% to 2%
Transformer losses	0% to 1%
System degradation	0% to 5%

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Uncertainty calculation and P-values
Uncertainty propagation: state of the art

- Uncertainty propagation
  - Uncertainties of individual modelling steps are assumed to be normally distributed, independent and not correlated
  - Propagation of uncertainties to final yield by calculating the root of the sum of squares of the individual uncertainties

- Probability of exceedance values (P-values) are used to express information on the uncertainty distribution of the Predicted Yield.
  - Pxx is the value that is exceeded with the probability of xx%
  - E.g. P90 of the Predicted Yield = 1000 kWh/kWp -> 1000 kWh/kWp is the Predicted Yield that is exceeded with a probability of 90%.
  - Pxx values can be calculated based on the quantile of a normal distribution.

Uncertainty calculation and P-values
Uncertainty propagation: state of the art

- Advantages
  - Easy to use
  - Result of a yield prediction usually consist of just three numbers: predicted yield, P90 and degradation rate

- Disadvantages
  - Uncertainty distributions must be normal
  - No uncertainty of degradation rate covered
  - No inter-annual variability covered
  - Normal distribution is an oversimplification for the uncertainty of some modelling steps (e.g. soling 1 ± 2 % losses)

Uncertainty calculation and P-values

Uncertainty propagation: state of the art

Calculation step	Uncertainty*	Value	Unit	Gain/Loss**	PR***
Irradiation global horizontal	5.0%	1550	kWh/m²		
Irradiation on tilted surface	2.5%	1821	kWh/m²	17.5%	100.0%
Shading					
External Shading	0.5%	1803	kWh/m²	-1.0%	99.0%
Internal Shading	2.0%	1765	kWh/m²	-2.1%	96.9%
Soiling	1.0%	1739	kWh/m²	-1.5%	95.5%
Reflection losses	0.5%	1695	kWh/m²	-2.5%	93.1%
Deviation from STC operation of modules					
Spectral losses	1.0%	1661	kWh/kWp	-2.0%	91.2%
Irradiation-dependent losses	1.0%	1682	kWh/kWp	1.3%	92.4%
Temperature-dependent losses	1.0%	1634	kWh/kWp	-2.9%	89.7%
Interconnection losses (mismatch)	0.5%	1602	kWh/kWp	-2.0%	88.0%
Cabling losses	0.5%	1579	kWh/kWp	-1.4%	86.7%
Inverter losses	1.5%	1538	kWh/kWp	-2.6%	84.5%
Power limitation of inverter	0.5%	1538	kWh/kWp	0.0%	84.5%
Transformer	0.0%	1538	kWh/kWp	0.0%	84.5%
Total	**6.5%**	**1538**	**kWh/kWp**		**84.5%**

* Uncertainties are related to single standard deviation

** Gain/Los : energetic Gain / Loss according to the step of calculation of the simulation

Long-term trends

Pure losses!

Degradation and Availability ?

It is physically not meaningfull to asume gains from modelling steps as shading or soiling!

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Uncertainty calculation and P-values
Monte Carlo Simulation

- Why Monte Carlo?
  - To consider the possibly asymmetric uncertainties of all simulation steps
  - Because it’s (quite) easy to implement

- Advantages
  - Easy to use non-normal uncertainty distributions
  - Consideration of uncertainties in individual years due to inter-annual variation
  - Results can be directly used for further calculations e.g. financial models

Uncertainty calculation and P-values

Monte Carlo Simulation: from normal to asymmetric

Calculation step	Symmetric (assuming normal distributions for all parameters)		Asymmetric (individually selecting normal and triangular distributions)			
	Parameter		Distribution	Parameter		
	μ	σ	Normal	μ	σ	
			Triangular	a	b	c
	%	%		%	%	%
Solar ressource potential in the reference period						
GPOA	11.4	2.5	normal	11.4	2.5	
Yield in the reference period						
Horizon shading	0	0.5	triangular	-1.0	0	0
Row-shading	-1.0	2.0	triangular	-5.0	0	-1.0
Soiling	-0.5	0.5	triangular	-1.5	0	-0.5
Reflection	-3.1	0.5	triangular	-4.1	-2.6	-3.1
STC power	0	2.0	normal	0	2.0	
Spectrum	-1.0	0.5	normal	-1.0	0.5	
Irradiation level	-3.9	1.9	normal	-3.9	1.9	
Temperature	-2.4	1.0	normal	-2.4	1.0	
Mismatch	-0.8	0.5	triangular	-1.8	0	-0.8
DC cabling	-1.5	0.5	triangular	-2.5	-1.0	-1.5
Inverter	-2.7	1.5	triangular	-5.7	0	-2.7
Power limitation	0	0.5	triangular	-1.0	0	0
Transformer	-1.0	0.5	triangular	-2.0	-0.5	-1.0
Yield in the prediction period						
System behavior	-0.6	0.5	triangular	-1.6	0	-0.6
Solar irradiation	0	0.3	normal	0	0.3	
Annual variation	0	4.9	normal	0	4.9	

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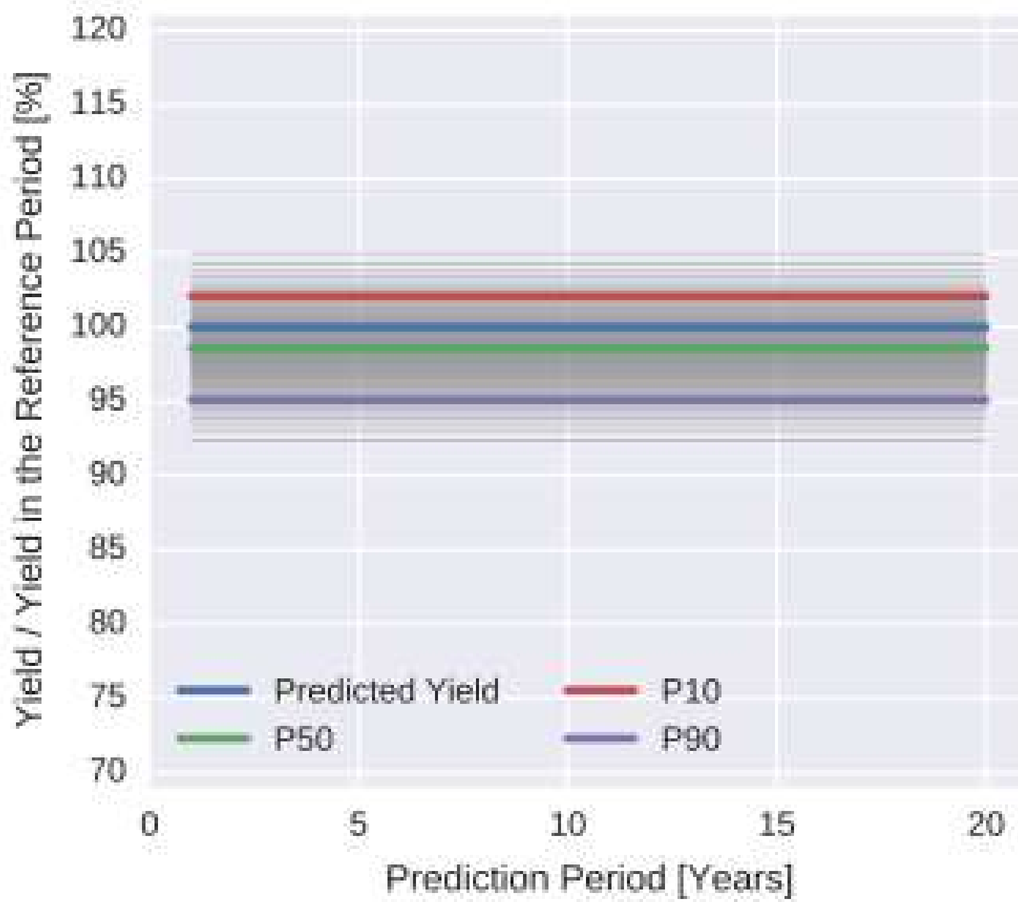
Uncertainty calculation and P-values
Monte Carlo Simulation

Prediction without long-term changes



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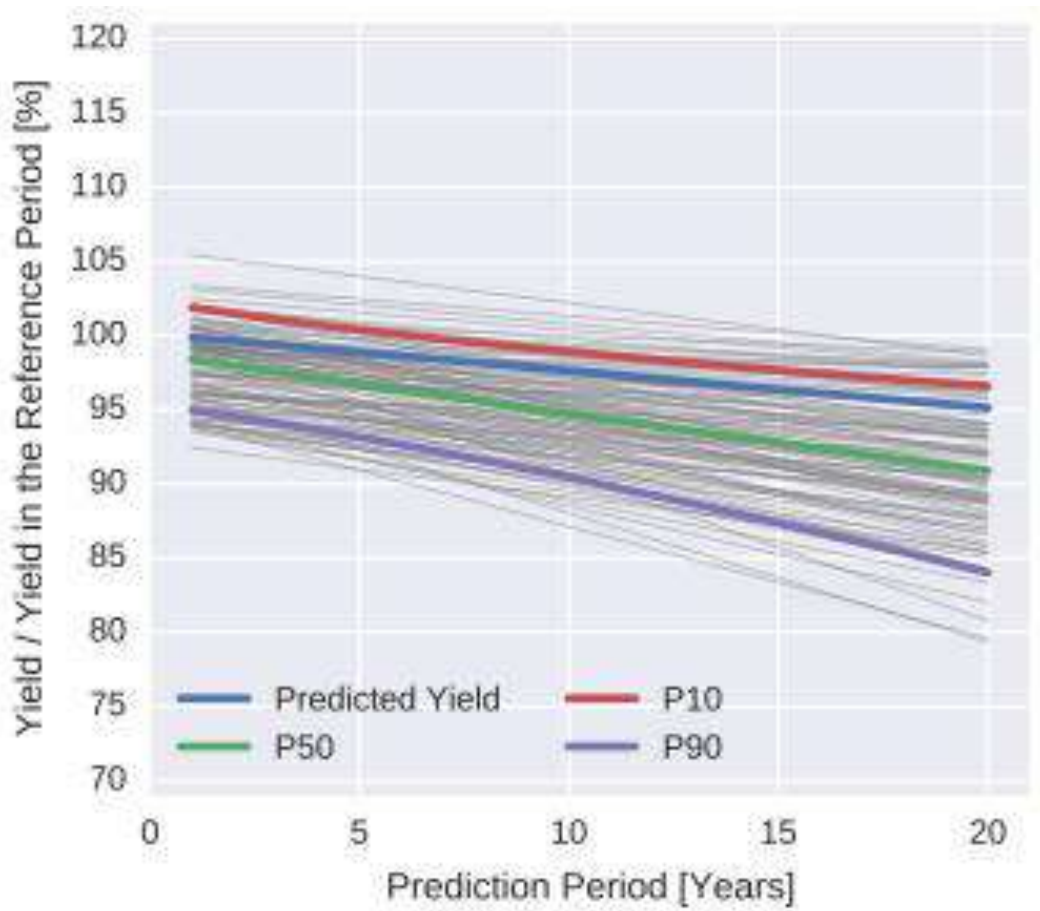
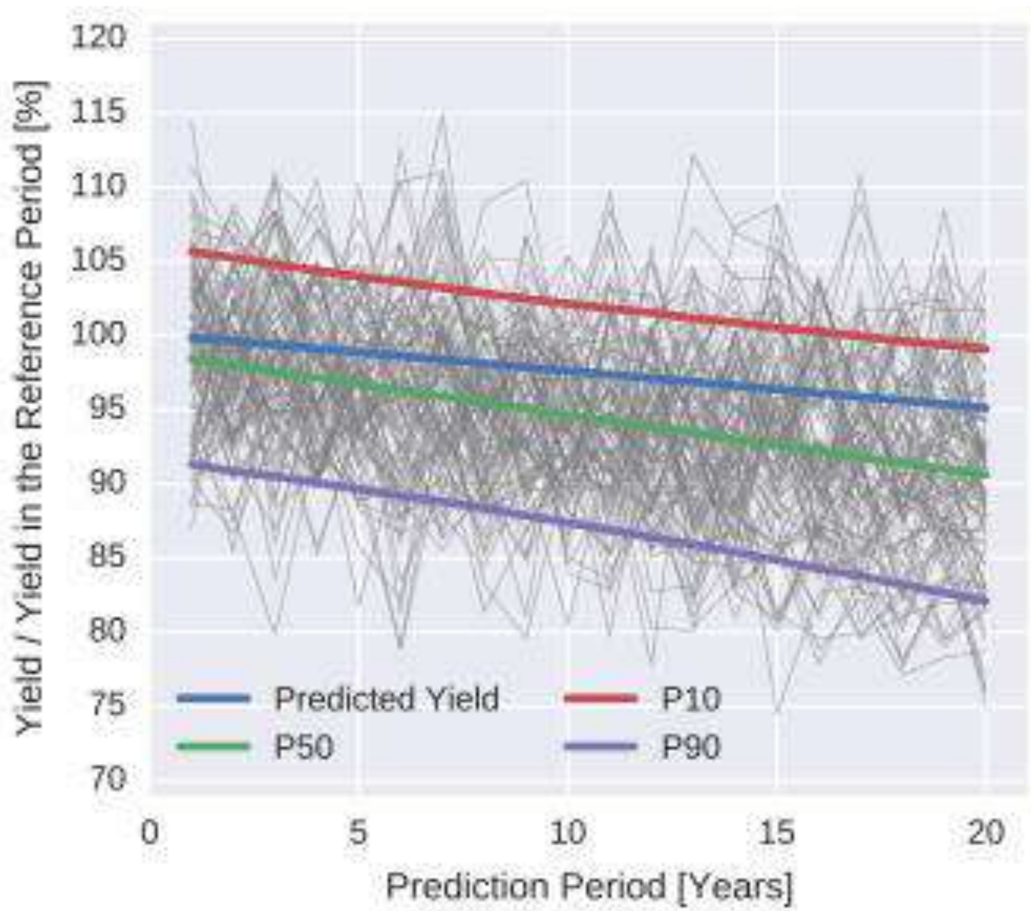
Uncertainty calculation and P-values
Monte Carlo Simulation

Prediction with long-term changes



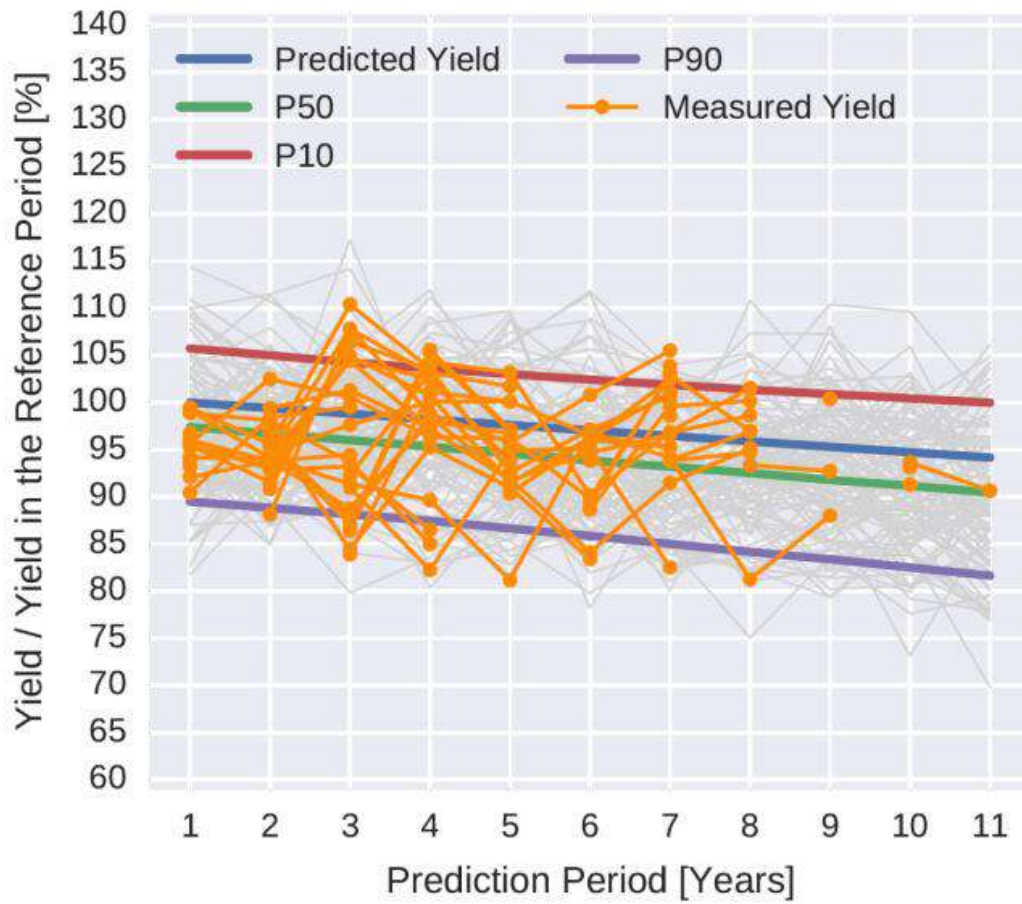
Uncertainty calculation and P-values
Monte Carlo Simulation

Prediction with inter-annual variations



Uncertainty calculation and P-values
Monte Carlo Simulation vs. Real Life (26 systems)

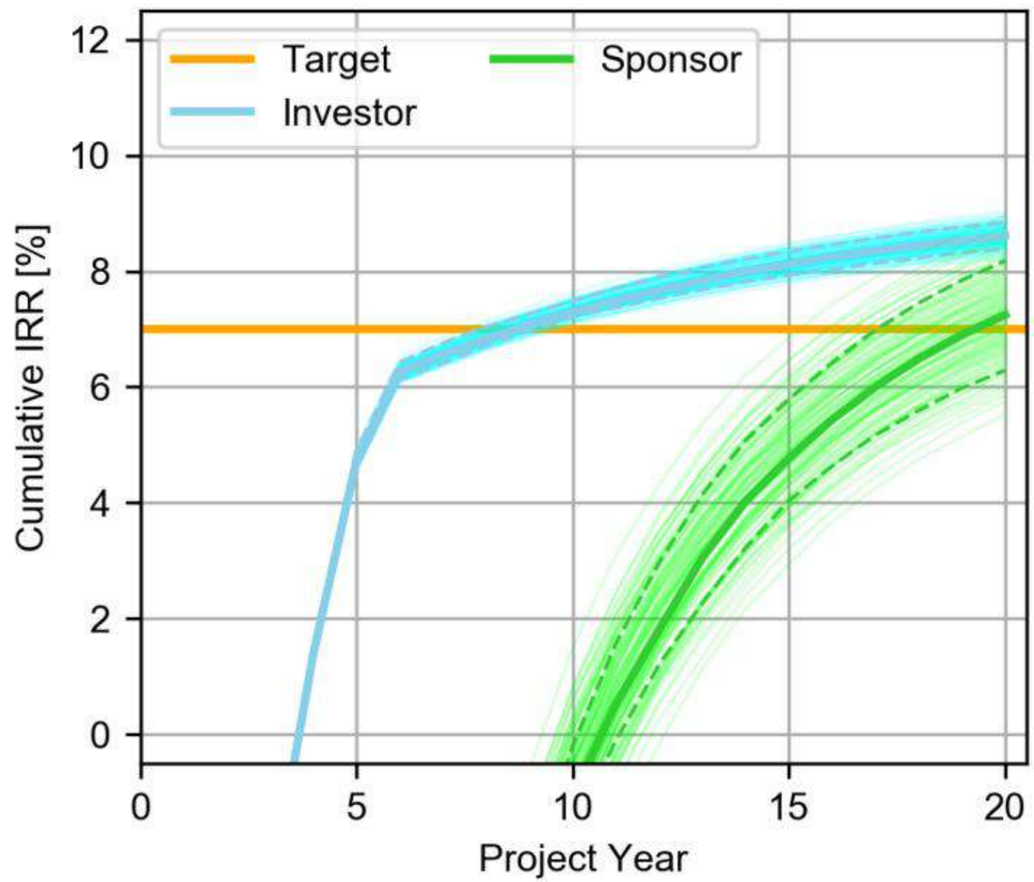
Comparison with measured yields



Uncertainty calculation and P-values

Example: Annual yields as input for financial model

Uncertainties of after tax internal rates of return for an "All Equity Partnership Flip" model in the US



Source:

B. Müller, B. Xu-Sigurdson, P.Bostock, B. Farnung , "The Influence of Interannual Variation and Long-term Effects of PV Energy Yields on Financial Models", 7th WCPEC, Hawaii, 2018

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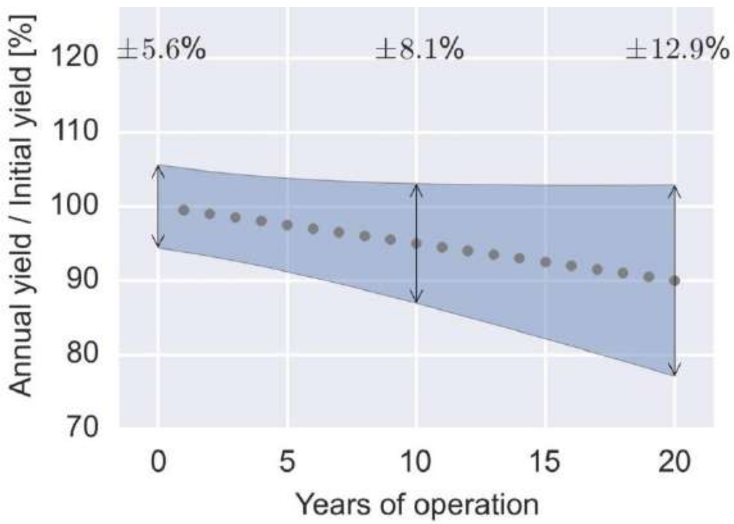
Uncertainty calculation and P-values
Reducing uncertainty and financial risk

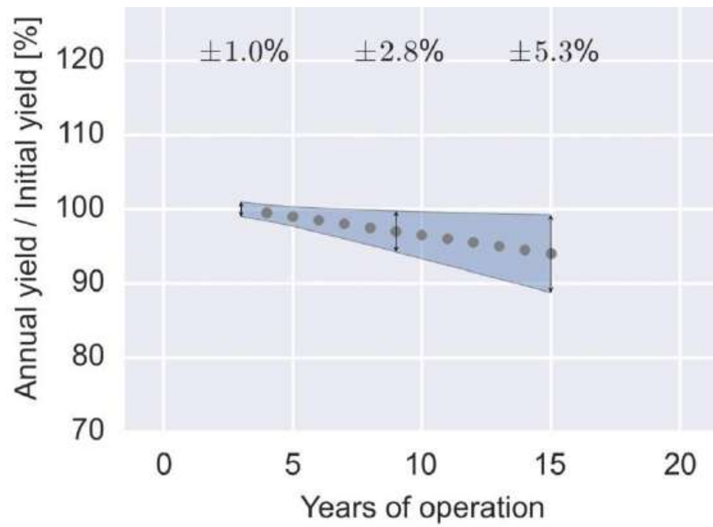
- Uncertainty and risk can be lowered by
  - PV plant portfolio
  - Adjusted investment period
  - Laboratory and on-site testing

B.Müller et al. „Investment risks of utility-scale PV: Opportunities and limitations of risk mitigation strategies toreduce uncertainties of energy yield predictions“, *42. IEEE PV Specialists Conference, New Orleans (2015)*

20-year prediction for individual plant



Portfolio and adjusted investment period



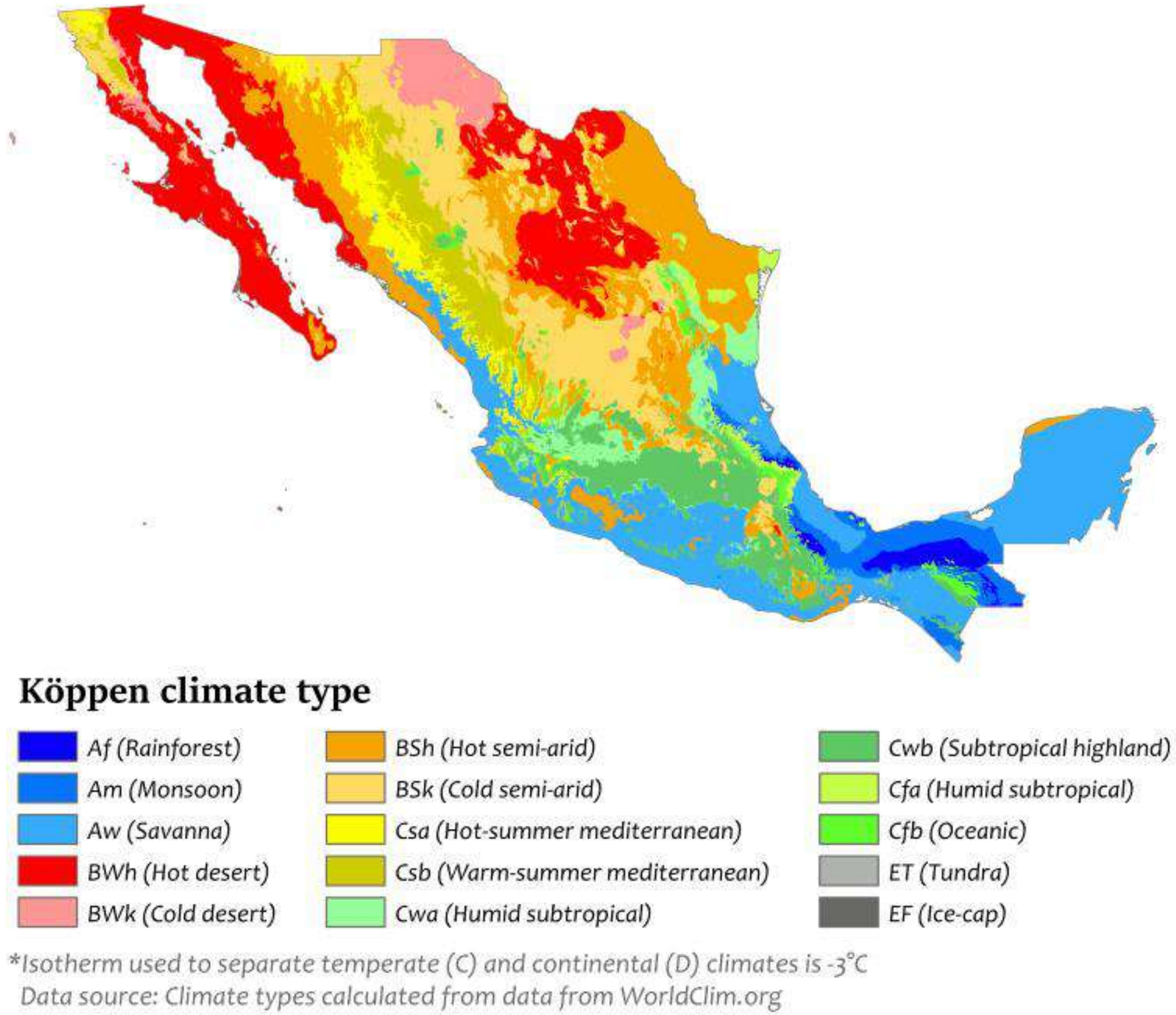
Uncertainty calculation and P-values
Summary and Conclusion

- Uncertainties of lifetime energy yield predictions for PV systems are quite well understood
- Monte Carlo based uncertainty estimation
  - is able to reflect “real” (measured) deviations between prediction and measurement
  - can consider asymmetric uncertainty distributions e.g. for degradation rates
  - can be directly used as input for financial models
- Uncertainties can be reduced with
  - shorter project lifetimes and
  - for portfolios of systems

Region specific technical challenges
High Solar resource and PV power potential

Region specific technical challenges

Many different climate zones



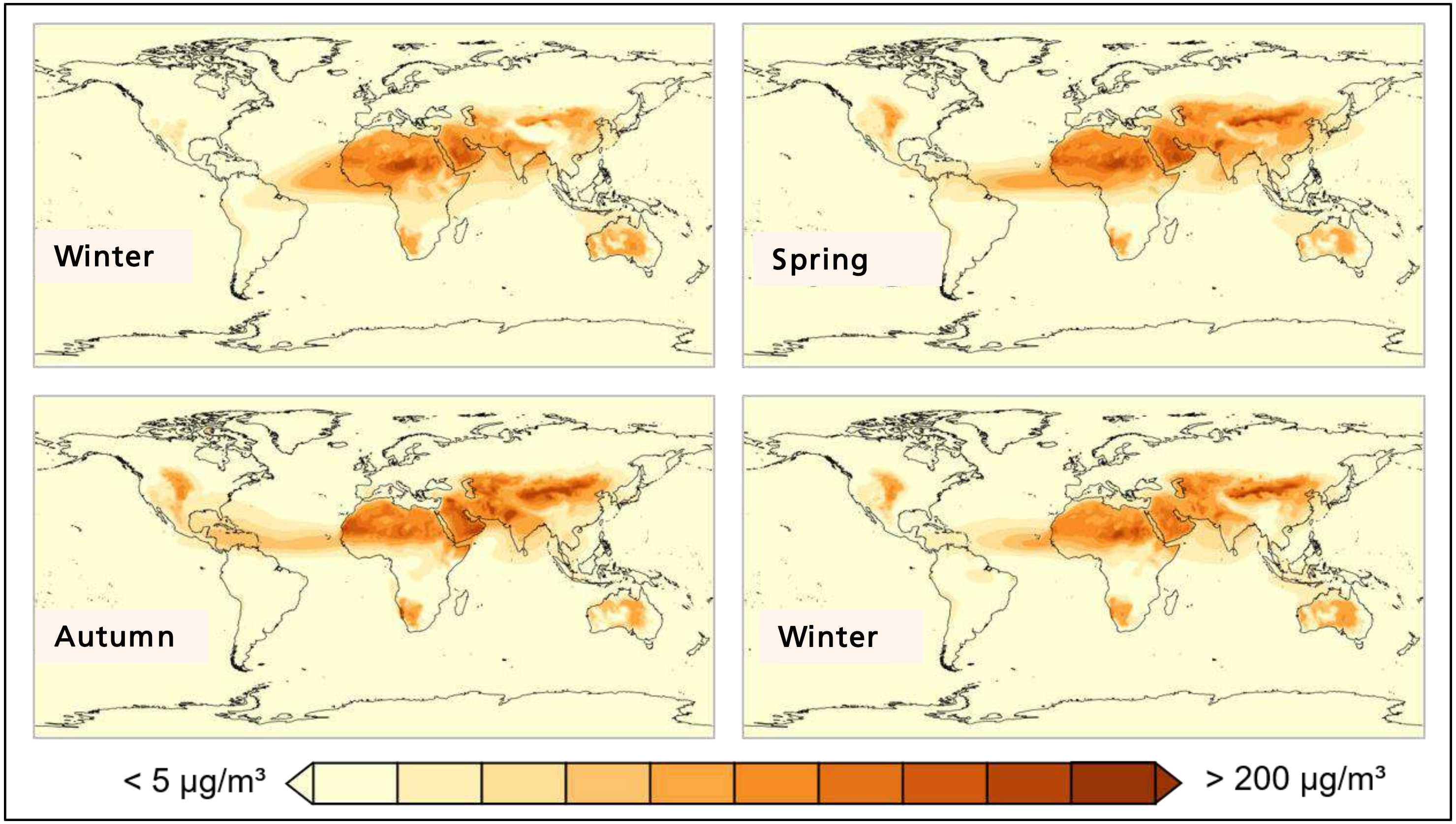
Source: Köppen-Geiger/Wikipedia for Mexico

Region specific technical challenges
PV systems planed everywhere

Fuente: Elaborado por GIZ con información de CENACE y SENER

Source: Köppen-Geiger/Wikipedia for Mexico

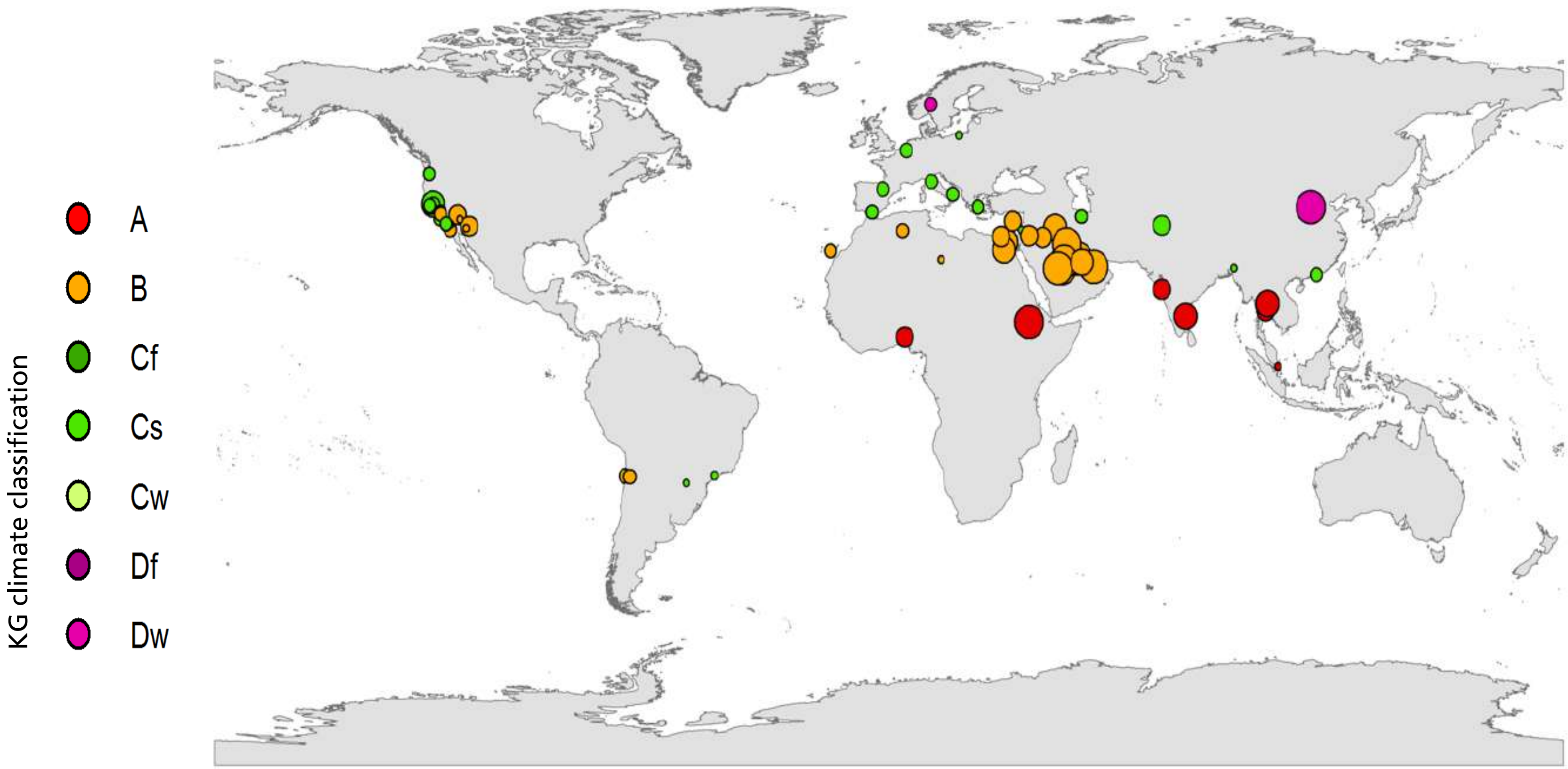
Region specific technical challenges
Soiling: Global long-term dust concentration



J. Herrmann, Leistungszentrum Nachhaltigkeit, GloBeSolar project

Region specific technical challenges

Soiling: Worldwide soiling field case studies



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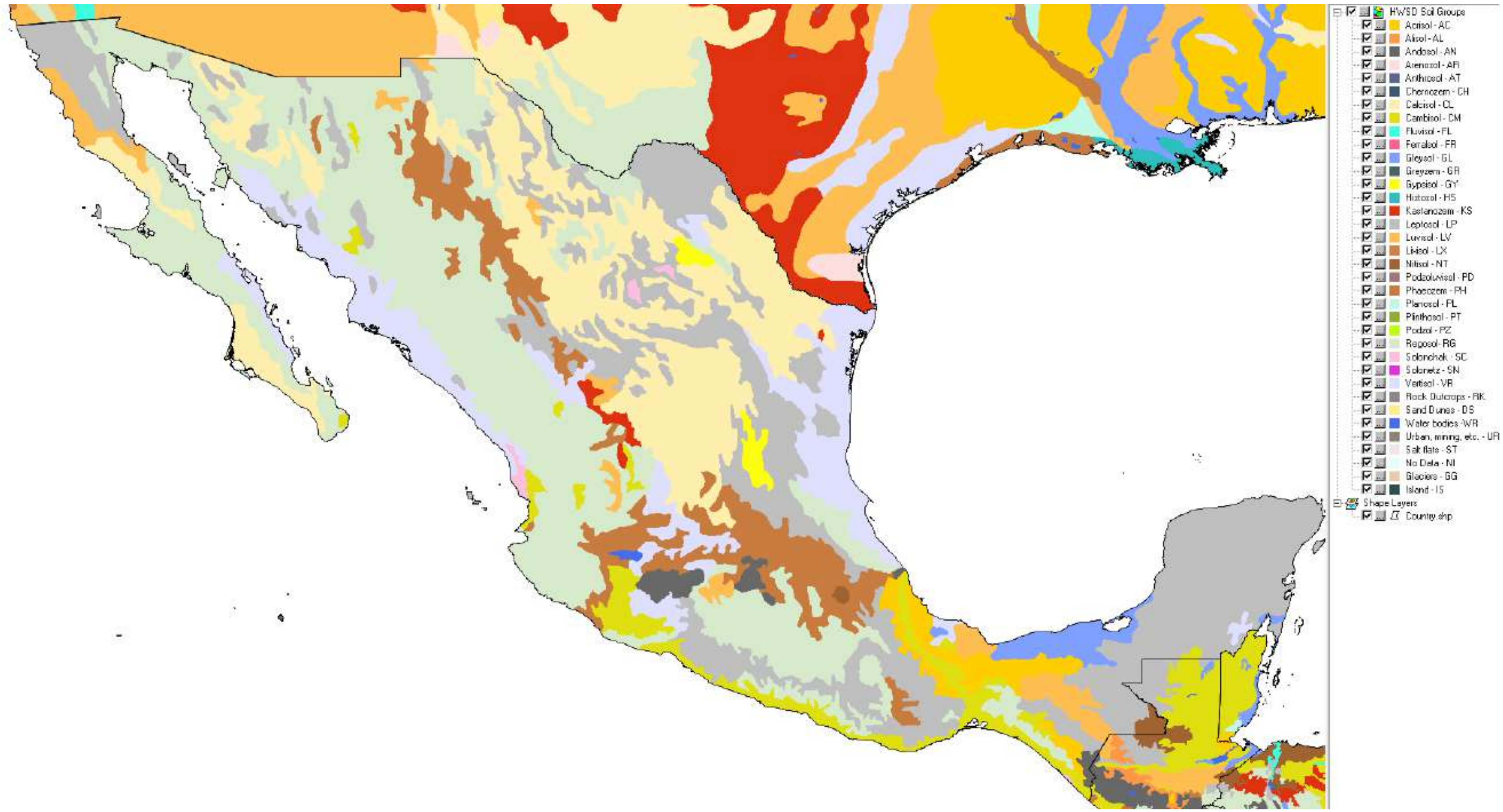
Region specific technical challenges

Soiling: Information on soil types



Source: FAO HWSD soil database

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Region specific technical challenges
Soiling: Example research in Mexico

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Energy Procedia

2013 ISES Solar World Congress

Performance Reduction of PV Systems by Dust Deposition

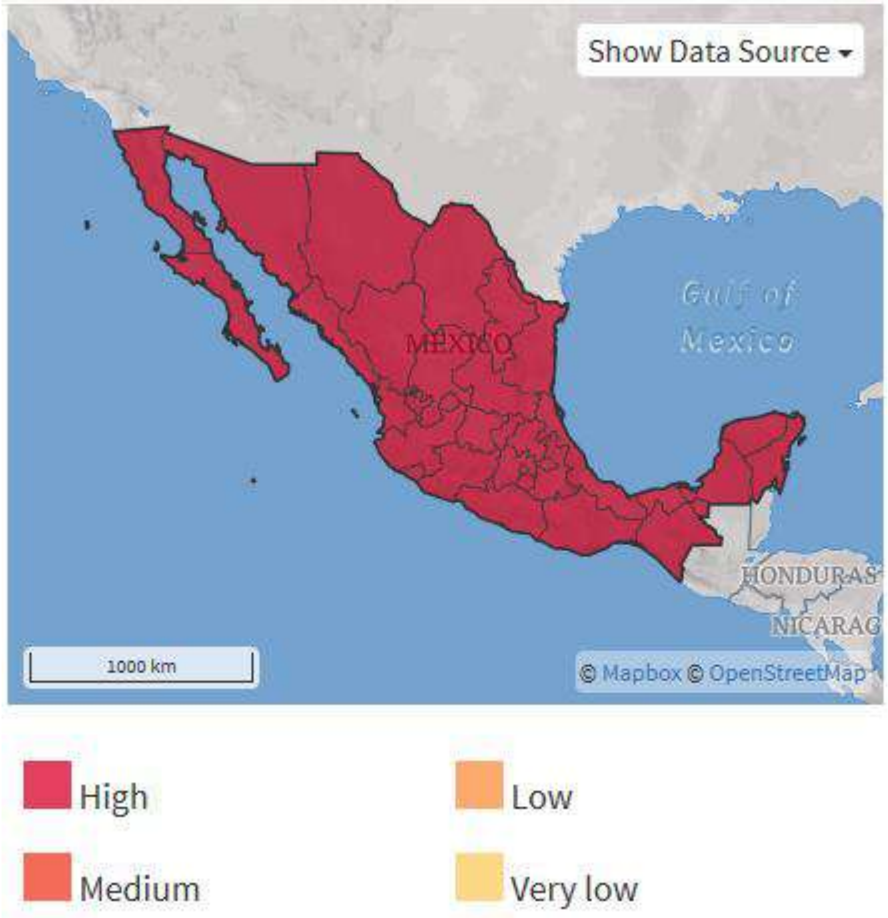
Bernd Weber[a], Angélica Quiñones[b], Rafael Almanza[b], M. Dolores Duran[a]

[a] *Universidad Autónoma del Estado de México (UAEM), C.P. 05130, Toluca, México*

[b] *Instituto de Ingeniería de la Universidad Nacional Autónoma de México (UNAM), C.P. 04510, Coyoacán, México, D.F., México*

Region specific technical challenges
Country specific hazards and risks

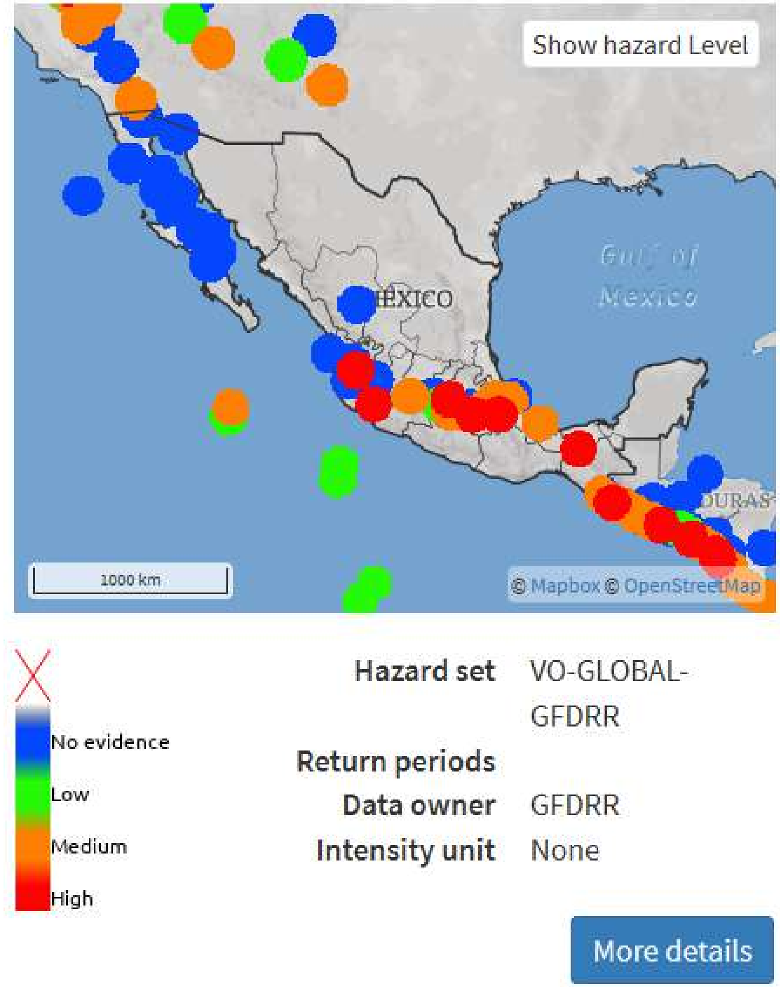
- Cyclones
  - 20% chance of potentially-damaging wind speeds in next 10 years.
  - Climate change: wind speed rising



Source: Thinkhazard/UNISDR layer CY-GLOBAL-GAR15

Region specific technical challenges
Country specific hazards and risks

- Volcanoes
  - Risk of damages
  - Risk of soiling



Source: Thinkhazard/GFDTT layer VO-Global-GFDRR

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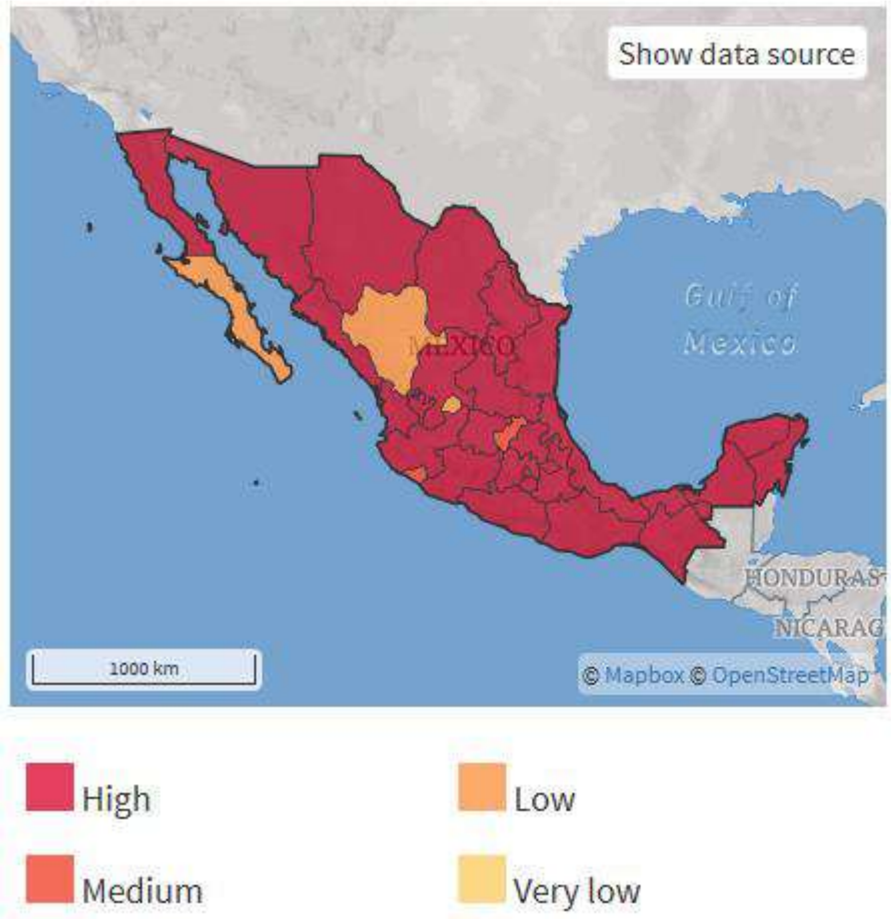
Region specific technical challenges
Country specific hazards and risks

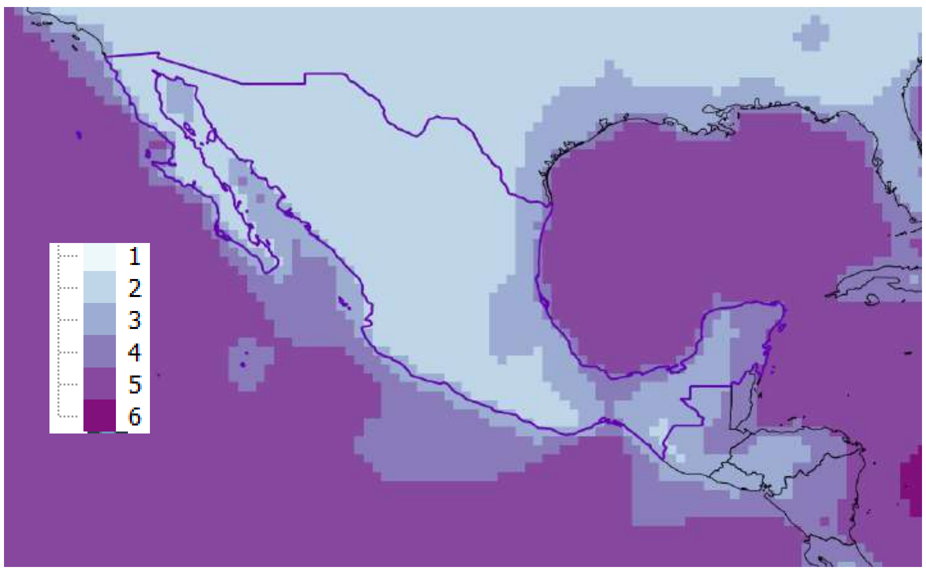
- River flood
  - Project planning
  - Project design
  - construction

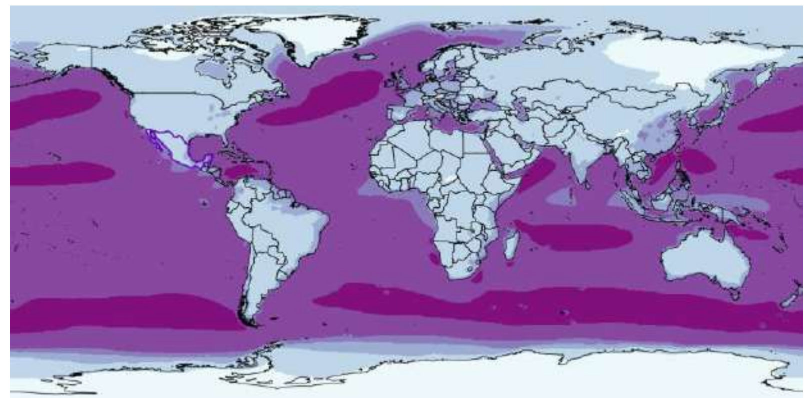


Source: Thinkhazard/GFDDR Innovation Lab/worldbank FL-Global-SSBN layer

Region specific technical challenges
Country specific hazards and risks

- Global Iron corrosion model classification ISO 9223



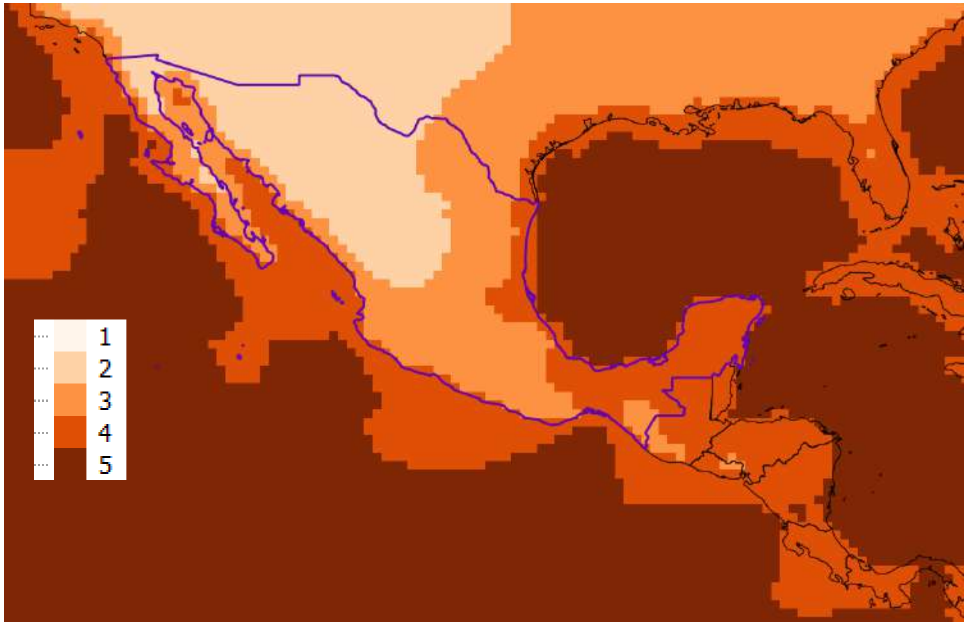


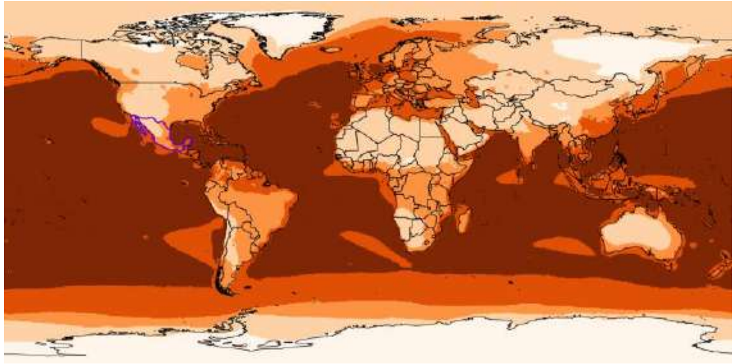
- Severity classes 1-6 by ISO 9223

J. Herrmann, Leistungszentrum Nachhaltigkeit, GloBeSolar project

Region specific technical challenges
Country specific hazards and risks

- Global Copper corrosion model classification ISO 9223





- Severity classes 1-5 by ISO 9223

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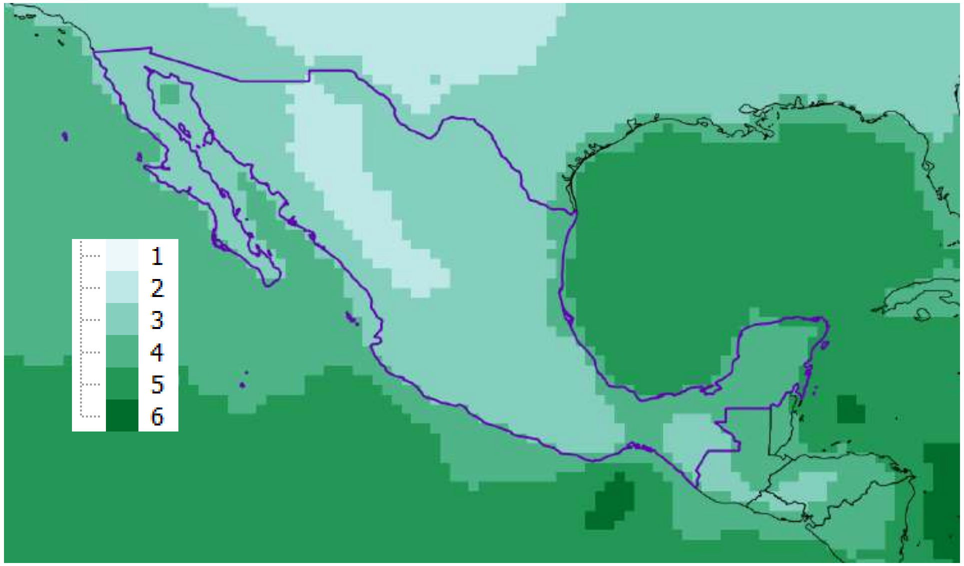
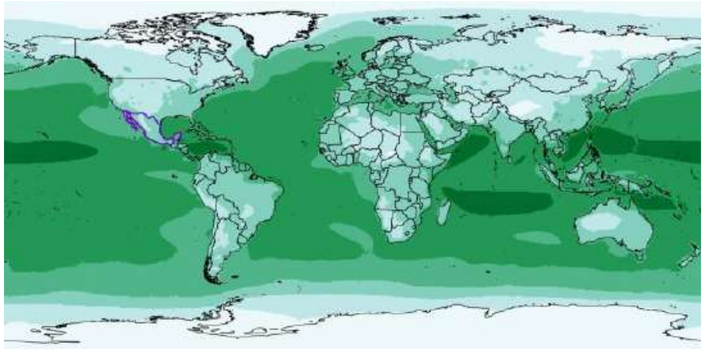
Region specific technical challenges
Country specific hazards and risks

- Global Zinc corrosion model classification ISO 9223





- Severity classes 1-6 by ISO 9223

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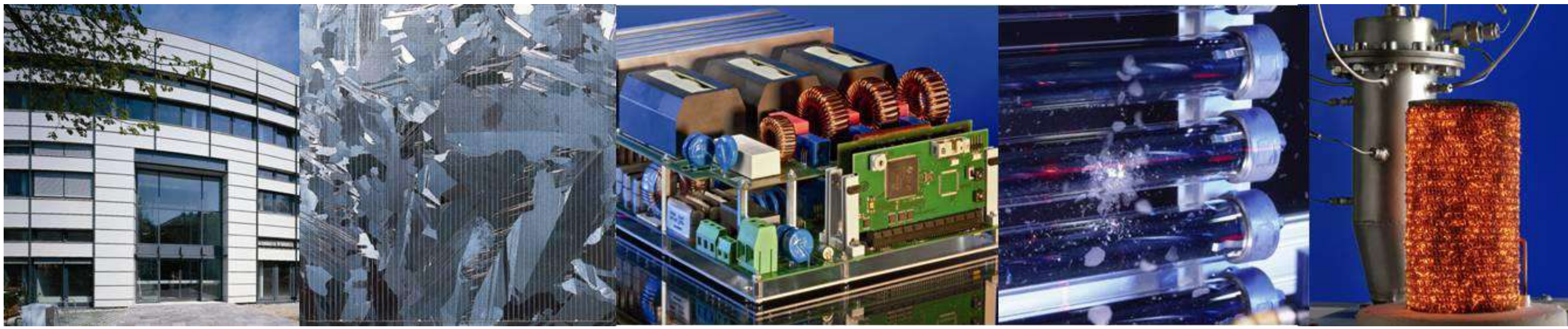
Thank you for your attention!



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The End.

PERFORMANCE EVALUATION DURING OPERATION AND PERFORMANCE GUARANTEE

Boris Farnung, Björn Müller
Fraunhofer Institute for Solar Energy Systems ISE

Workshop "Quality Assurance and Bankability of PV Power Plants"
Mexico City, Friday, 16.11.2018

www.ise.fraunhofer.de

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AGENDA

- Performance measurements on-site
    - Data Acquisition and quality requirements
    - Typical Examples and Results of Performance Measurements
- Performance value and evaluation
    - Short term performance check
- Performance Insurance

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General Monitoring Approaches

- Selection of Approach depend on
  - Type of application
  - Motivation for monitoring
  - Monitoring services required
  - Technical options available and applicable in project
  - Economic value or yield on stake
  - Budget

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General Approaches - General Considerations

- Identify appropriate budget for the potential economic yield on stake
- What are the risks which must be controlled?

- Which services are required?
  - Daily check
  - Analysis of operational behaviour
  - Support of maintenance activities
  - Web visualisation
  - Reporting
  - Benchmarking
  - Consulting to increase PR
  - Quality assurance
  - Bankability approval

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General Approaches - General Considerations (2)

- Which information can be gathered?
  - Energy yield
  - Energy resource
  - Performance Ratio
  - Failures (DC array, inverters, automatic switches)
  - Assessment of generator efficiency and inverter efficiency
  - Information about tracking
  - Software status / inverter operation information
  - Climatic conditions
  - Availability of the electricity grid
  - Logging of power limitation or reactive power requests from utility
  - Long term changes in performance

General Approaches - Typical Applications

- Small and medium sized systems
- Large scale
- Reference systems
- Pilot systems (technology validation)
- Investigative performance evaluation

General Approaches - Typical monitoring configurations

- Minimal configuration
  - Total AC energy
  - Regional irradiation data

- Basic configuration
  - Total AC energy
  - Irradiation measured with a Si sensor

General Approaches - Standard configuration

- Standard configuration
  - Total AC energy
  - Energy of groups of inverters or of each individual
  - Irradiation measured with a Si sensor
  - Irradiation measured with a Pyranometer for P > 600 kWp or Thin Film
  - Module temperatures
  - Ambient temperature
  - DC currents and voltages (maybe only exemplarily)

General Approaches - Limitations of standard monitoring

- Accuracy limited
  - Cost efficient logger systems often with low accuracy at analogue inputs (typ. 1%)
  - Inverter-integrated measurements designed for cost efficient operation control (Current accuracy approx. 3-8 %)
  - Inverter failures may compromise monitoring
  - Often limited options for extensions (e.g. by additional sensors)

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General Approaches - Comprehensive Monitoring

- Additional energy meters
- Additional, accurate DC measurements
- Requires extra wiring
- Additional measurements are independent of
    - component manufacturer
    - component operation errors
- Typically measurement logging technology open for extensions and with unlimited options
    - Webcam
    - Weather station
    - Tracker position
    - Maintenance tracking

General Approaches – Pitfalls for Performance Control

- Irradiation sensor
  - Mount in temporarily shaded part
  - Do NOT clean sensor
  - Refer PR to Si sensor w/o mentioning

- Energy meters
  - Interpret signal disturbances as impulses

- Evaluation
  - Include only selected months or periods with high irradiation
  - Exclude operation interruptions, snow, maintenance and repair
  - Extrapolate from well performing subsystem(s)

Quality Aspects and Analysis Methods

- General Criteria and Remarks
- Irradiation measurement
  - Pyranometer
  - Si sensor
- Energy metering
- Temperature measurements
- Performance Check

Quality Aspects – General Remarks

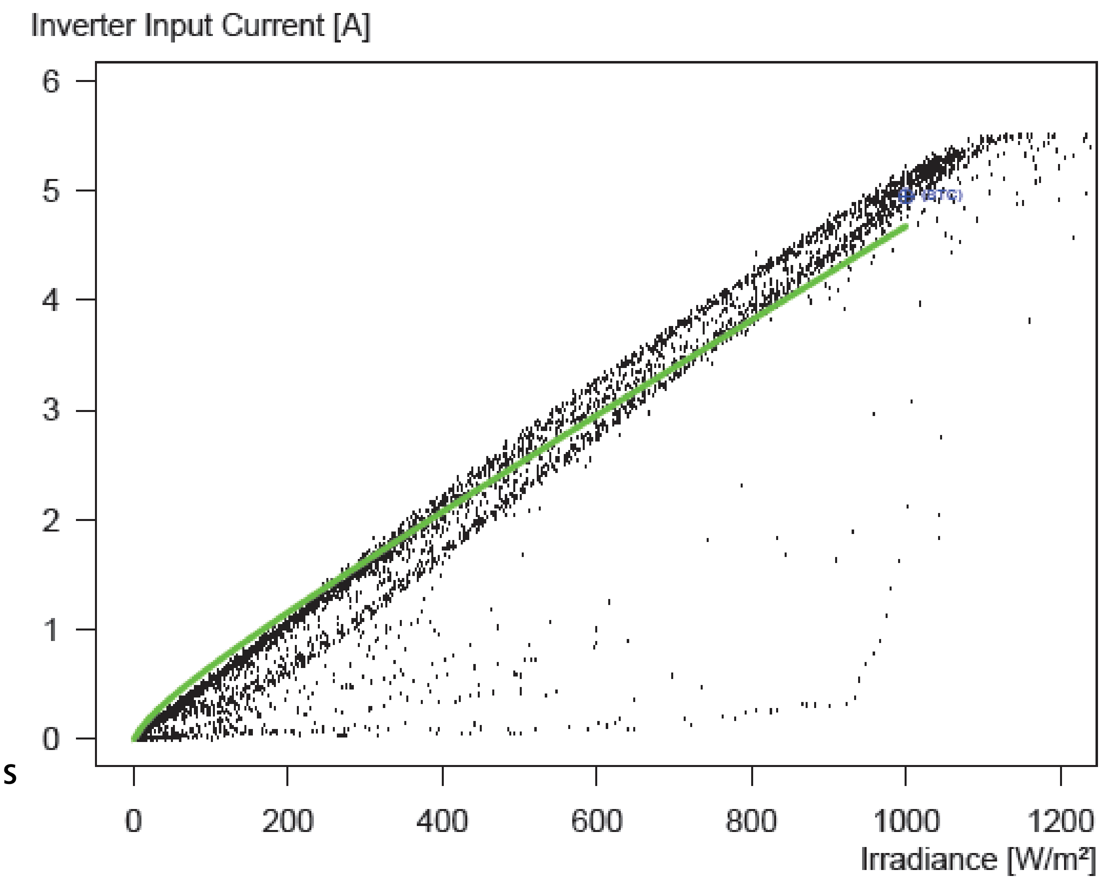
Quality is crucial to ensure…

- Reliability
  - data availability
  - data accessibility
- Accuracy of measurements
  - Absolute and repeatability
  - Calibration and inspection on-site?
  - Maintenance intervals?
  - Distinguish from resolution!

Further aspects:

- Measurement interval and logging interval
- Consideration if samples, averages or integrals are required

Examples – Dimensioning for Monitoring Components



Shunt too tightly dimensioned for
extraordinary high irradiance levels

Quality Aspects – Pyranometer

- Thermopile pyranometer in module plane
  Recommended:
  - Secondary Standard
  - Daily uncertainty < 2%
- Additional horizontal pyranometer may serve as validation of meteorological resource assessment in yield prognosis!

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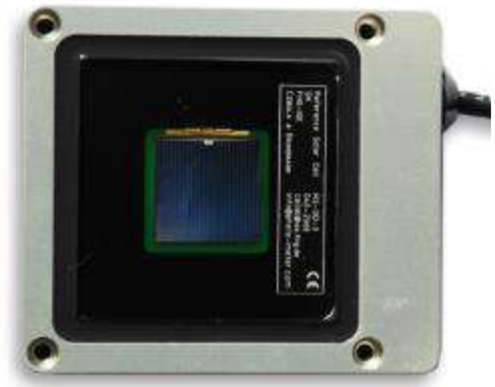
Quality Aspects – Si sensor



Crystalline Si reference cell

- Temperature compensation/correction
- Stability of sensitivity
- Uncertainty < 5%
- Mount in least-shaded part in module plane
- Recommended:
  - Characterisation in certified laboratory (to reduce uncertainty to <2 %)
  - Replacement after 2 years (stability check)
  - Clean weekly (or as required)
- Attention!
  Annual totals can differ up to 5% in comparison with the pyranometer

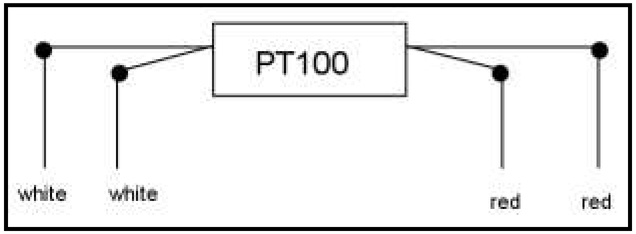
Quality Aspects – Energy Metering

- Calibration
- Ensure operability at high currents over hours
- Check operation temperature at installation location
- Meters approved for PV inverter applications?
- High impulse output rates (resolution) if applicable
- Reactive energy metering by communication bus
- Direct measurement vs. transformers
- Uncertainty <1% (check meter class!)

- Consider power limitation requests from grid!

Quality Aspects – Temperature Measurements

- Temperature measurements (2-wire, 3-wire, 4-wire)
- Ambient temperature
  - Positioning
  - Ventilation
    - without
    - passive
    - active



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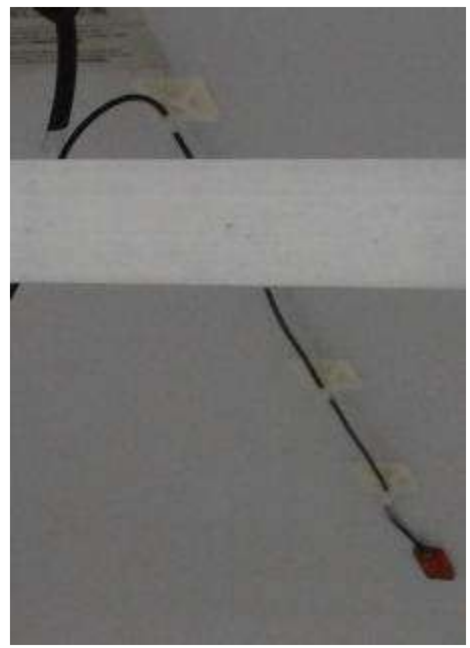
Quality Aspects – Temperature Measurements (2)

- Mounting of sensors for module backside temperature
  Ensure thermally good, long-term contact!



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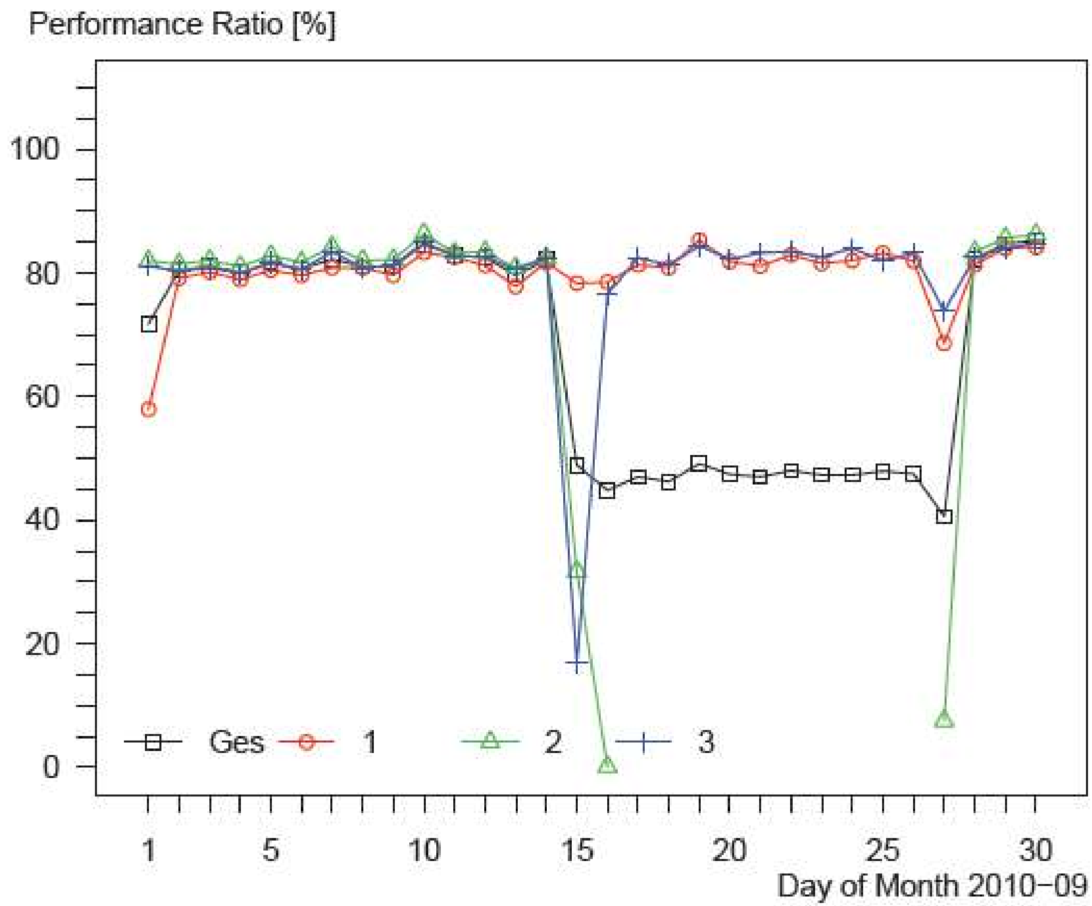
Quality Aspects – Performance Check

- Comparison of subsystems (cross monitoring)
- Expert based Operation Data Analysis System (ODAS)
  - Module failures
  - Inverter failures
  - Inefficient inverter operation
  - Shading effects
  - Snow coverage
  - Limitations induced by the grid
  - Monthly PR expectations
  - Comparison with simulation

Exemplary Experience

- Approaches for Performance Check
- Data processing
- Visualisation
- Reporting

Examples - Comparison of Subsystems



Failures in plant section 2
and partially in section 3.

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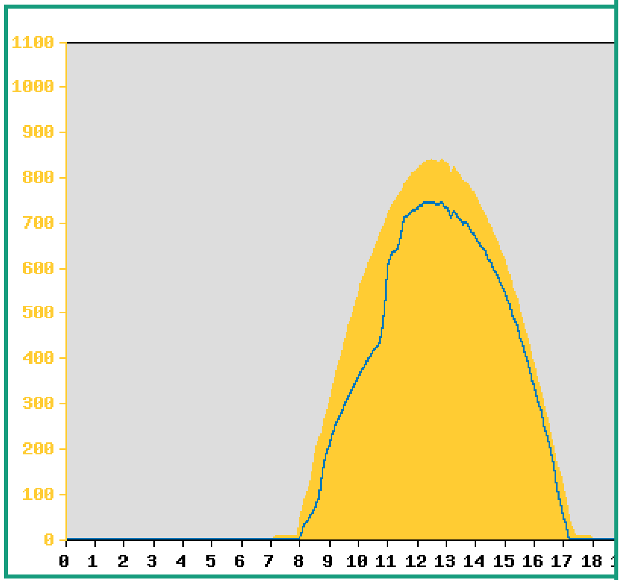
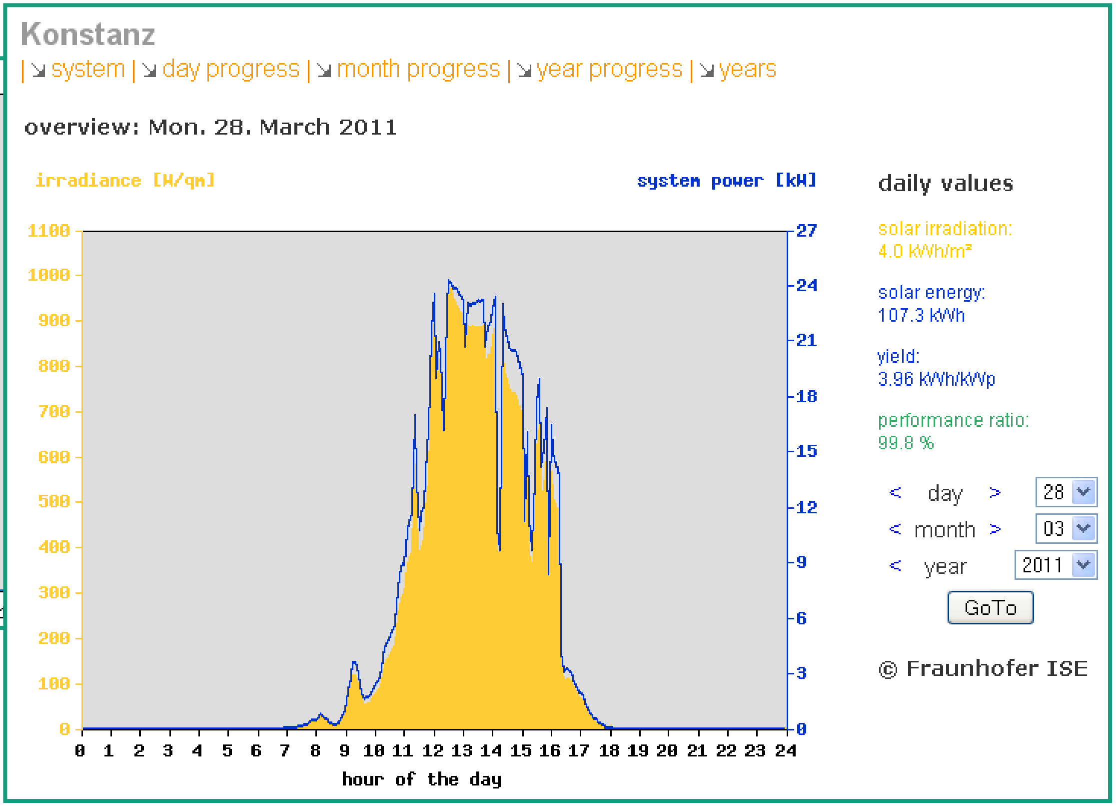
Examples - Analysis of Monitoring Data



Shading in the morning



Temperature effect in the afternoon?

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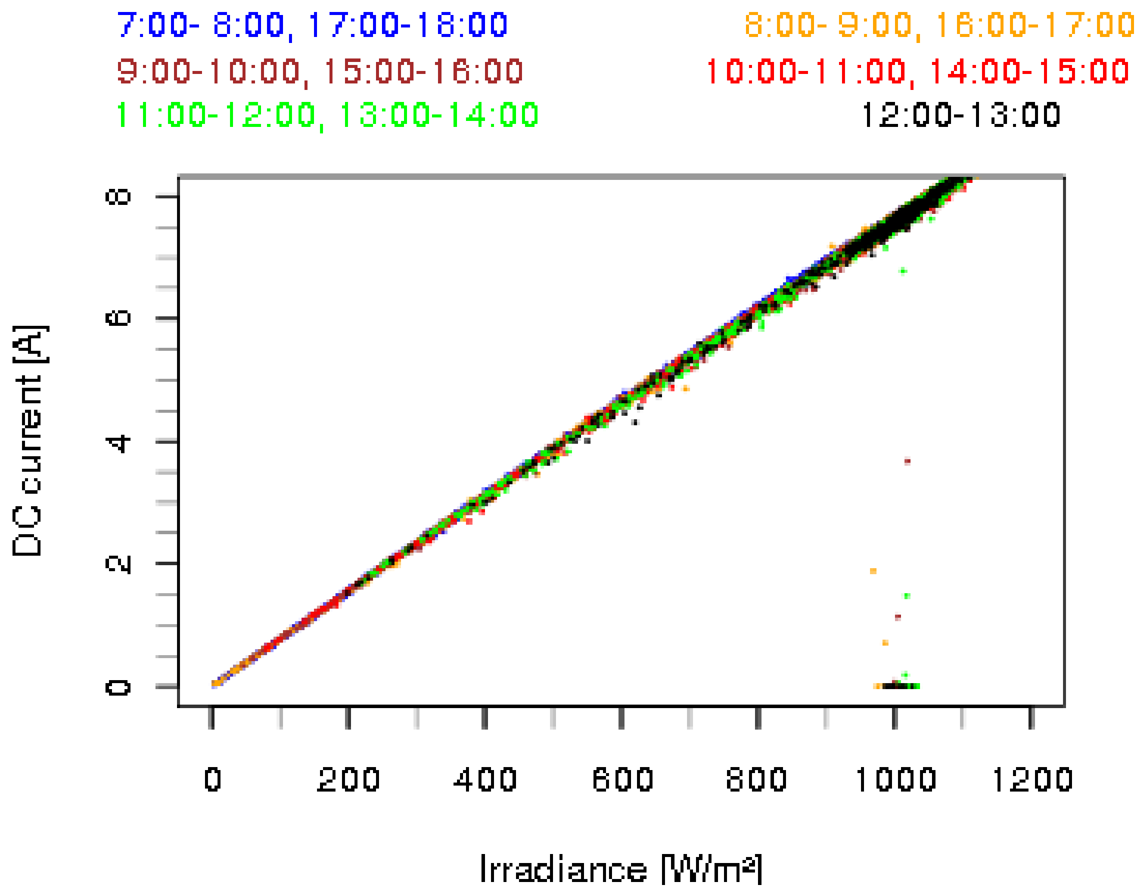
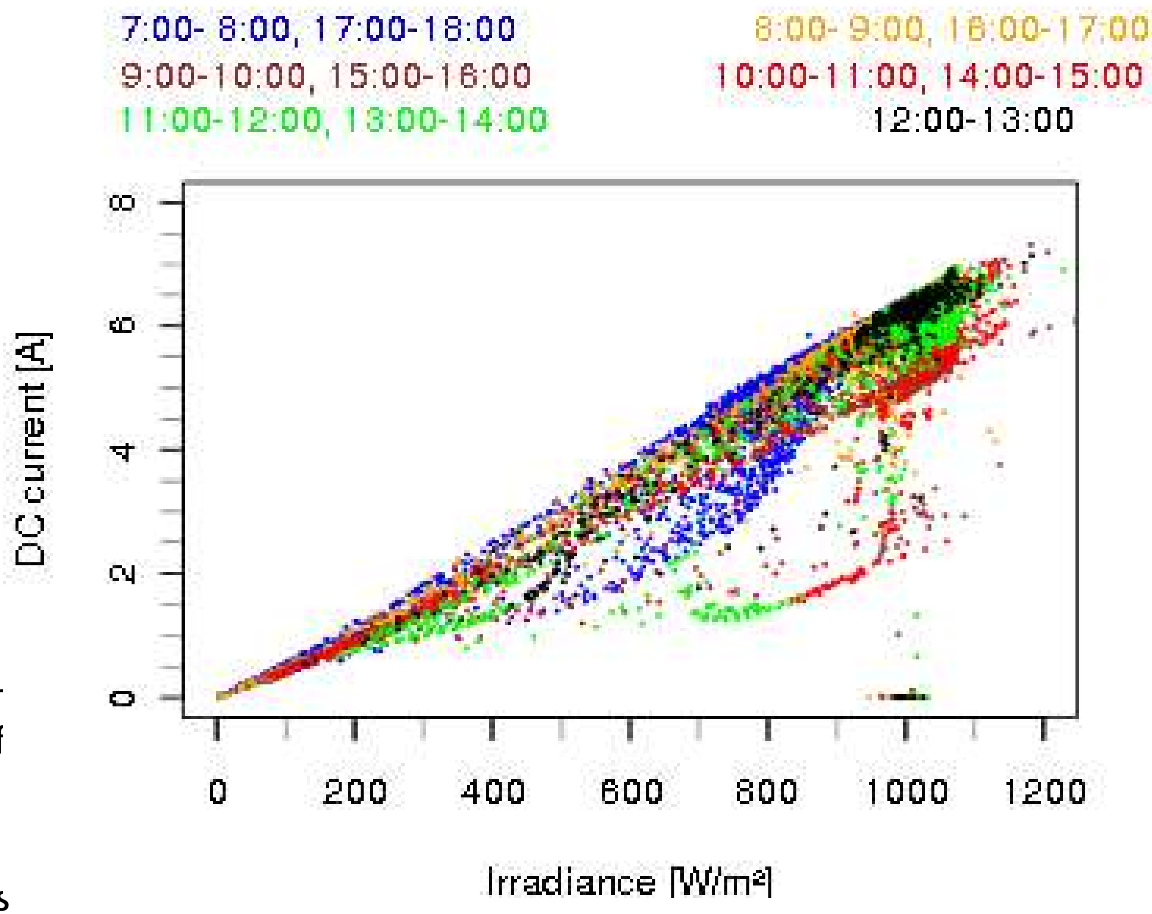
Examples – When does it happen?



String current as function of irradiance and hour of the day

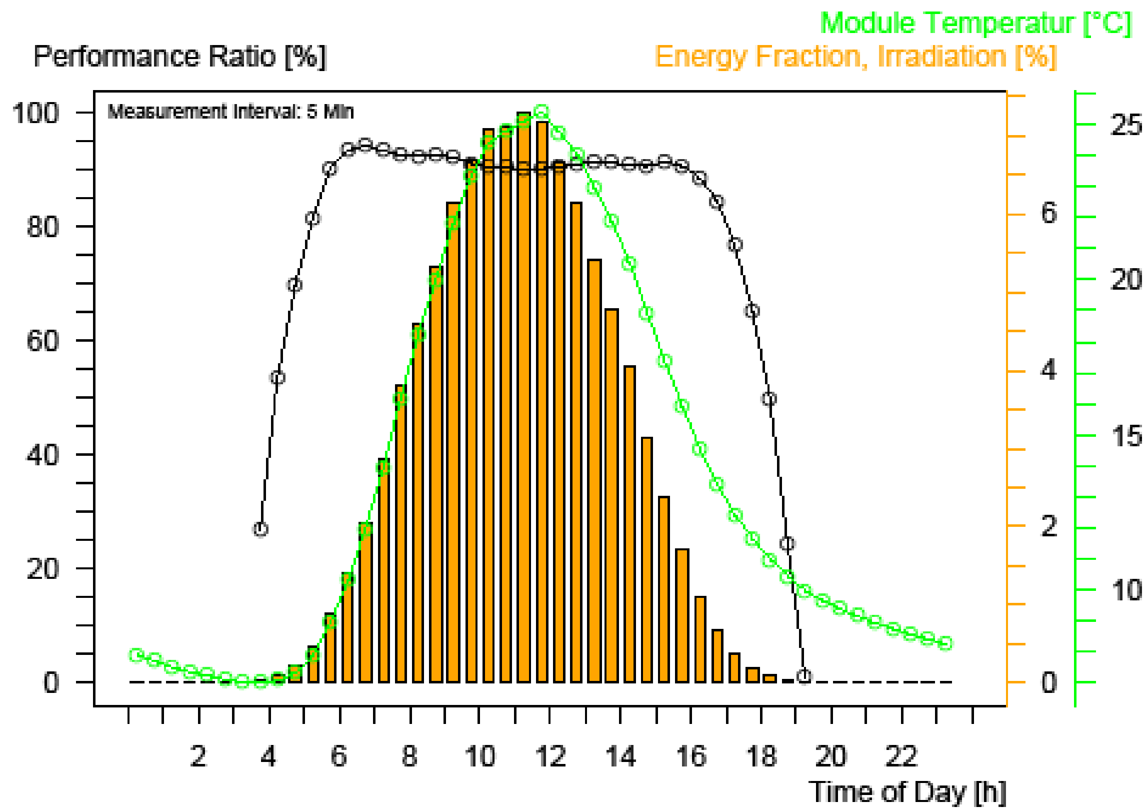
Examples – When does it happen? (2)



String current as function of irradiance and hour of the day

High reflectivity and eventually tracking issues

Examples – Daily Power Curve



Average day curves
on a sunny day

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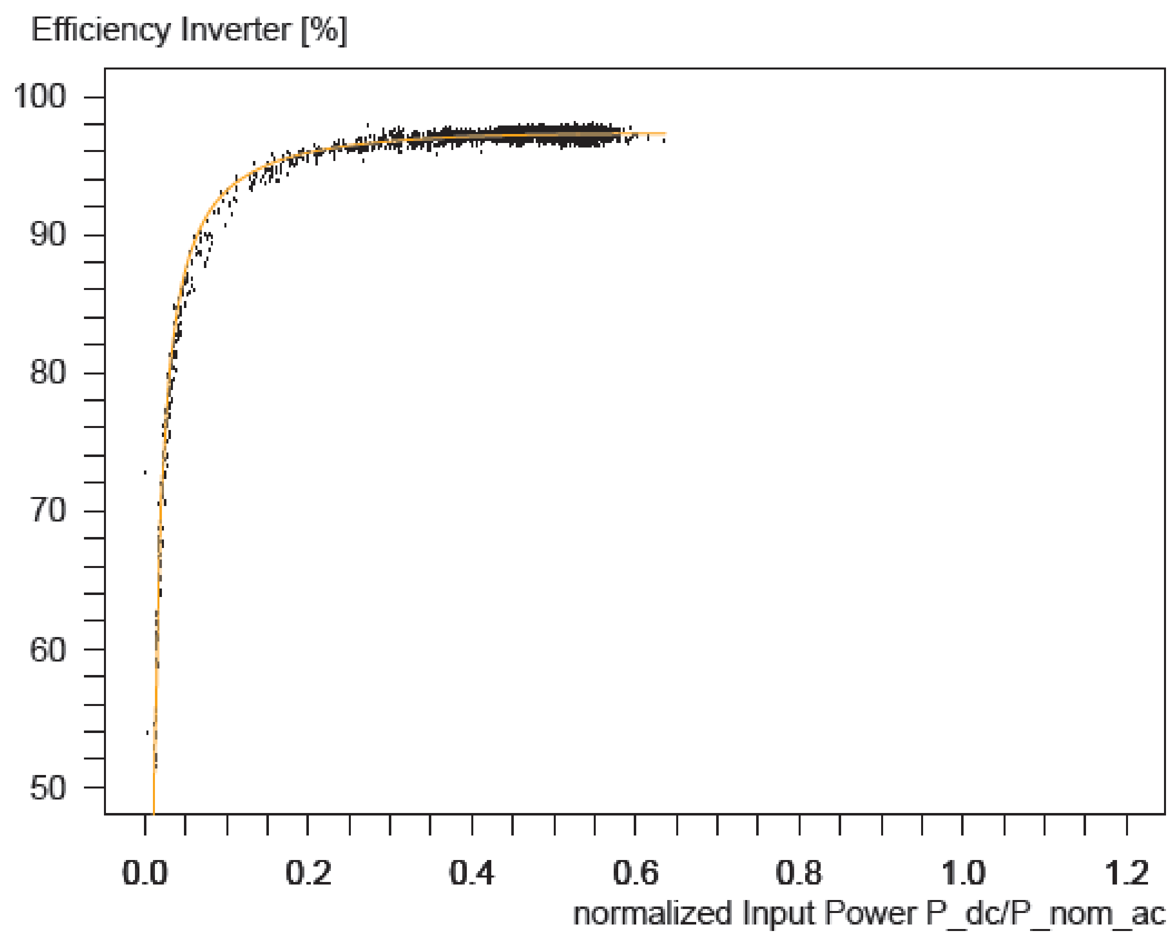
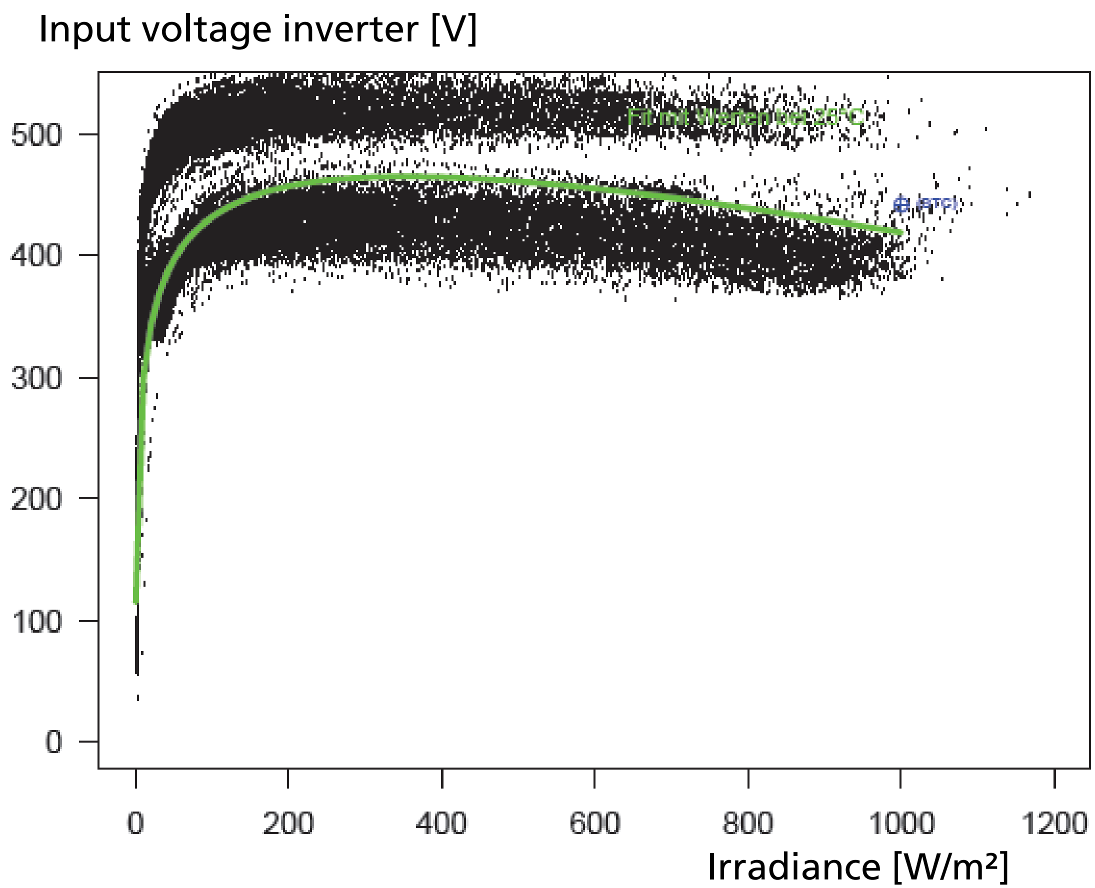
Examples – Inverter Dimensioning



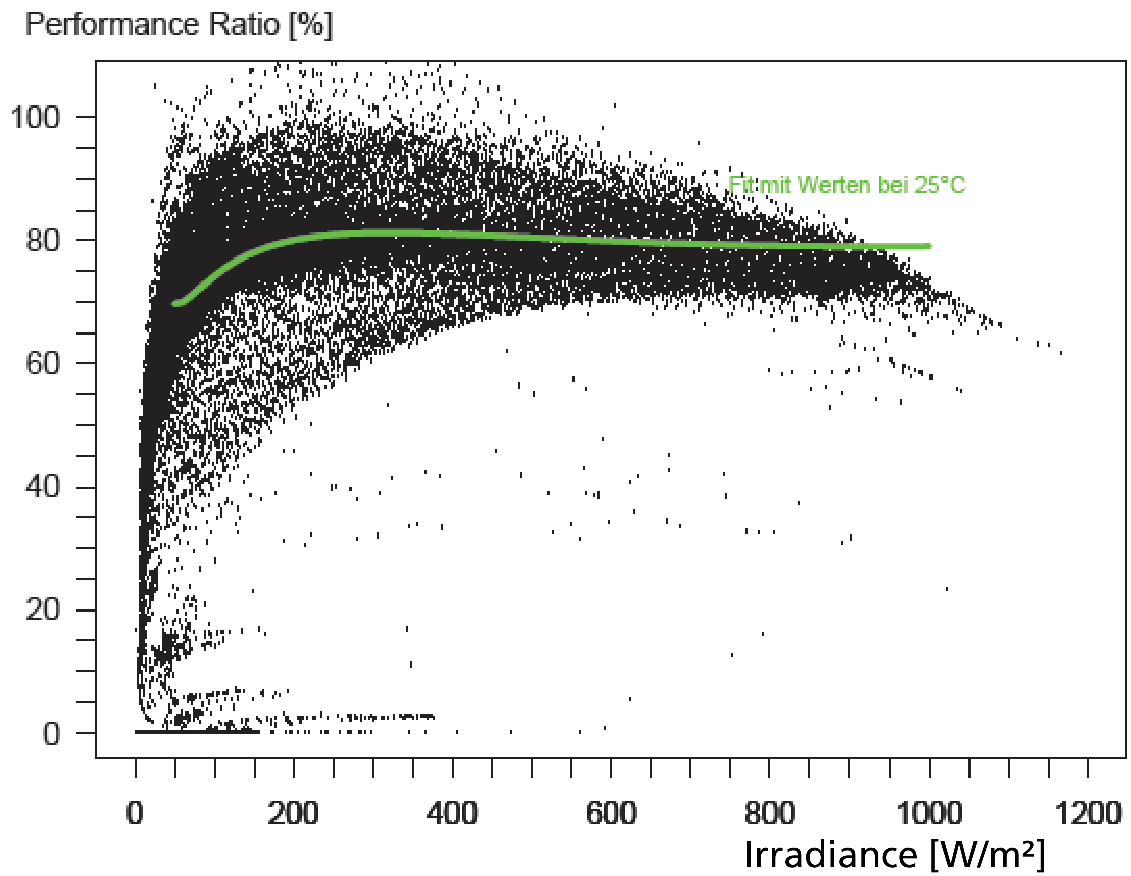
Inverter under-dimensioning

Examples – Inverter Failure



Inverter failure

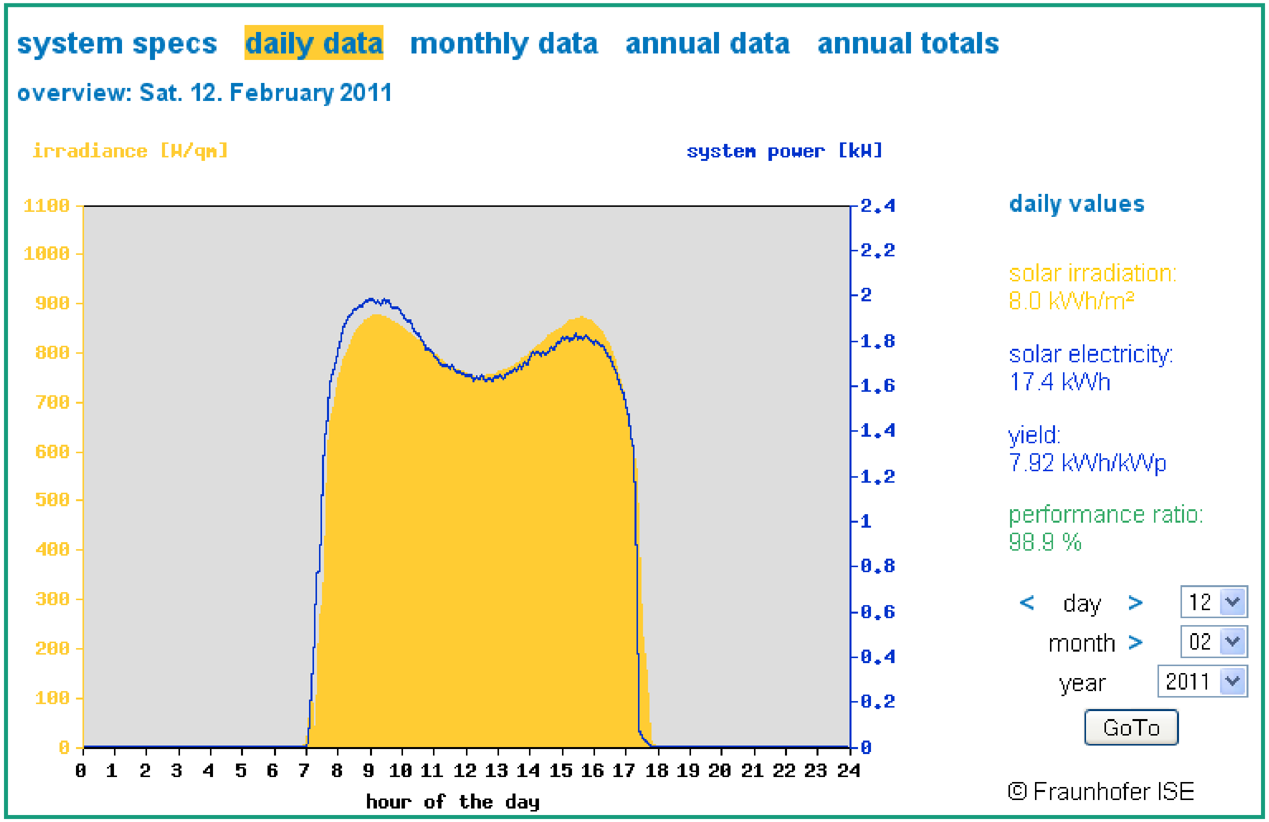
Examples – Inverter Power Limitation



Power limitation by inverter

Examples – Single axis super power

- Single string with underrated power (East-West tracking)



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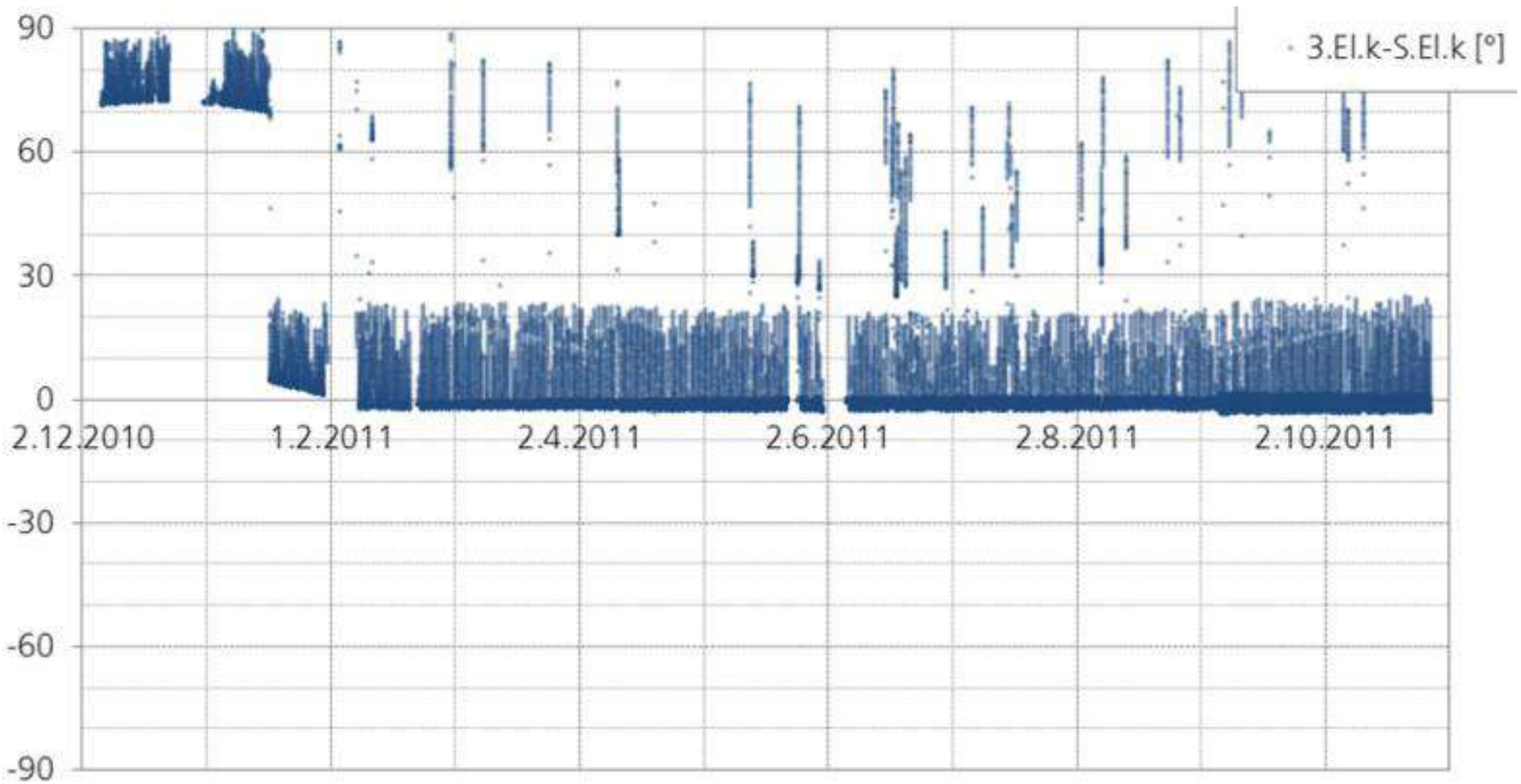
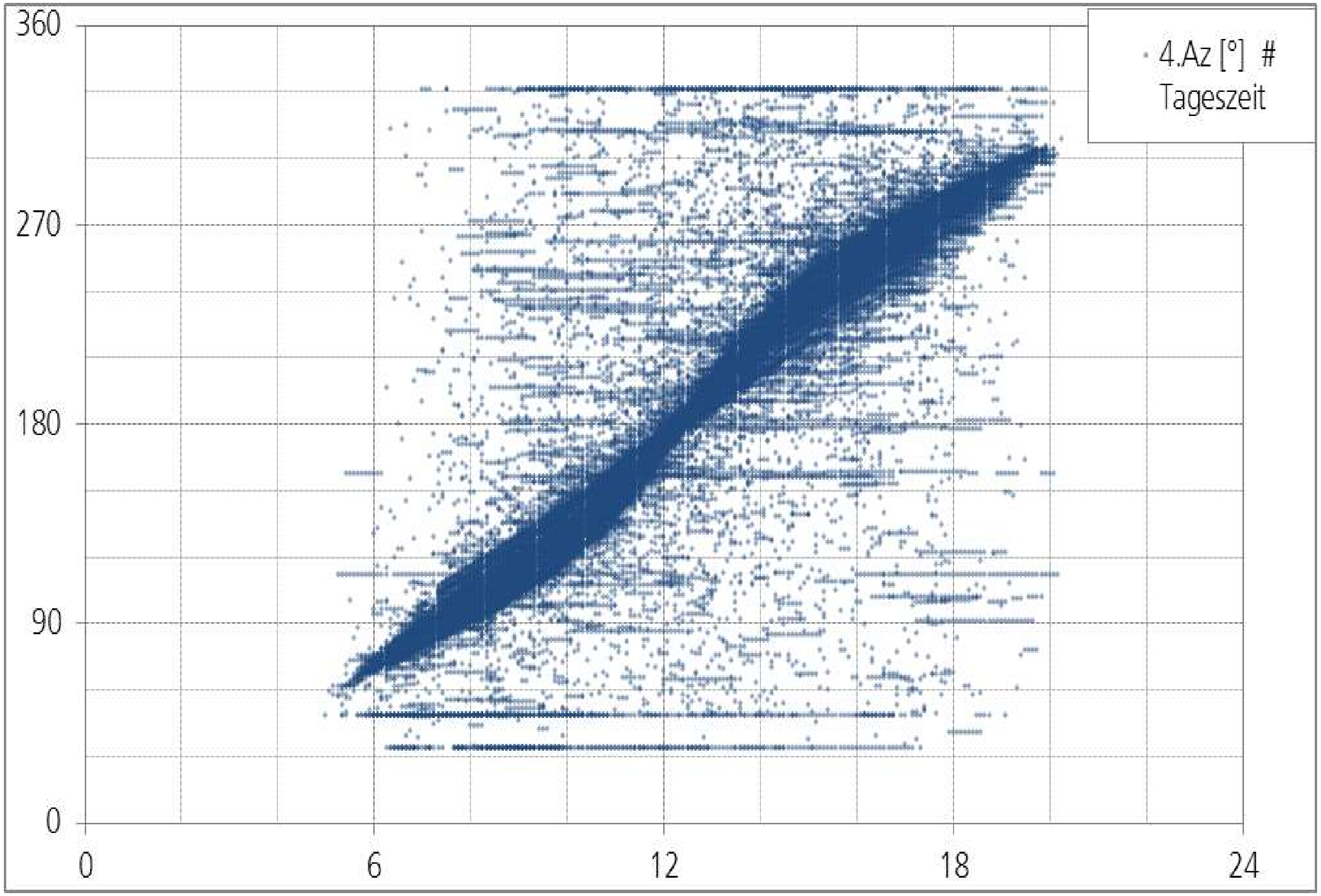
Examples – Dual axis tracker limitations

- Deviation of elevation angle from best position along the year



Examples – Monitoring Tracking

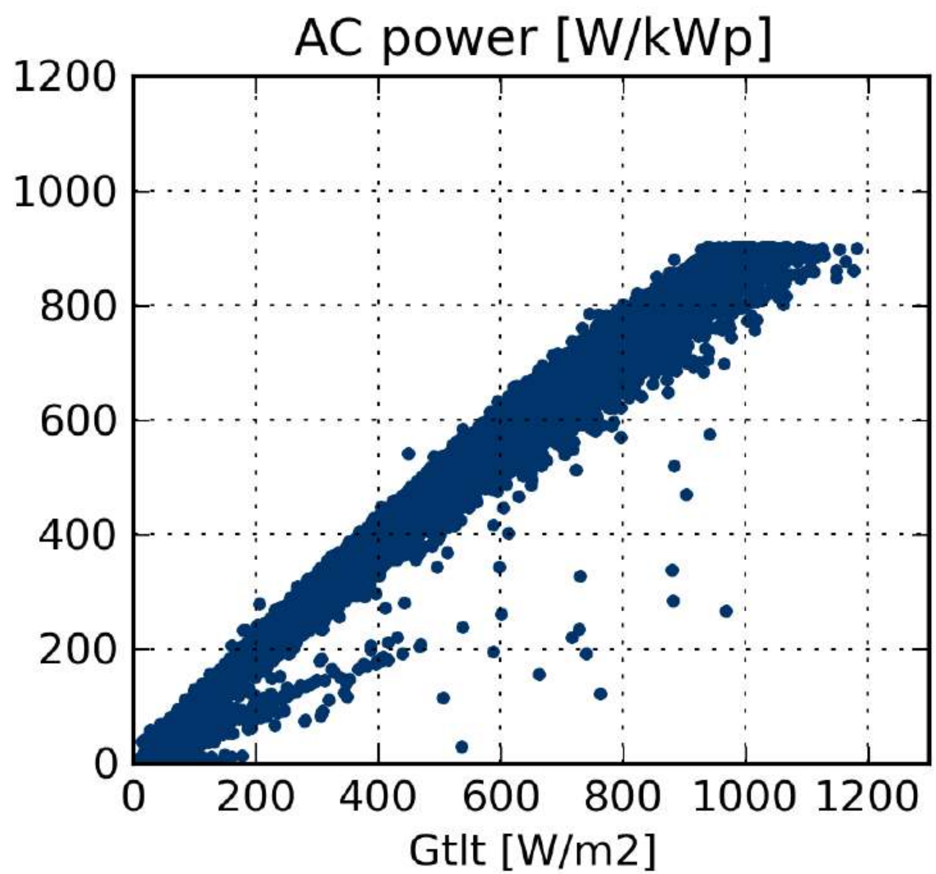


Azimuth angle over hour of the day (six months)

Light sensor controlled tracking unit

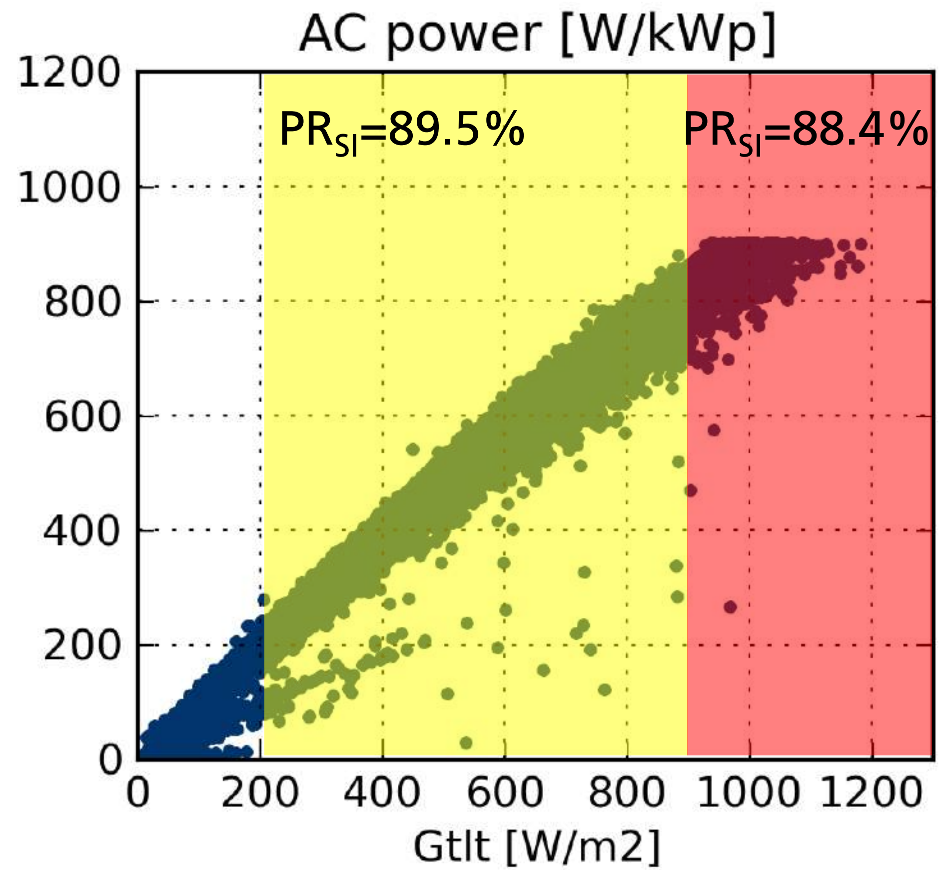
Examples – Inverter Sizing

- Ratio of actual PV STC power to rated (and maximum) inverter AC power is 115% in this example



Examples – Inverter Sizing

- Losses may be determined purely from measured data: compare mean PR values for two irradiance ranges
- If PR_{SI} would be 89.5% in the red region as well, total energy output would be increased by roughly 0.1%



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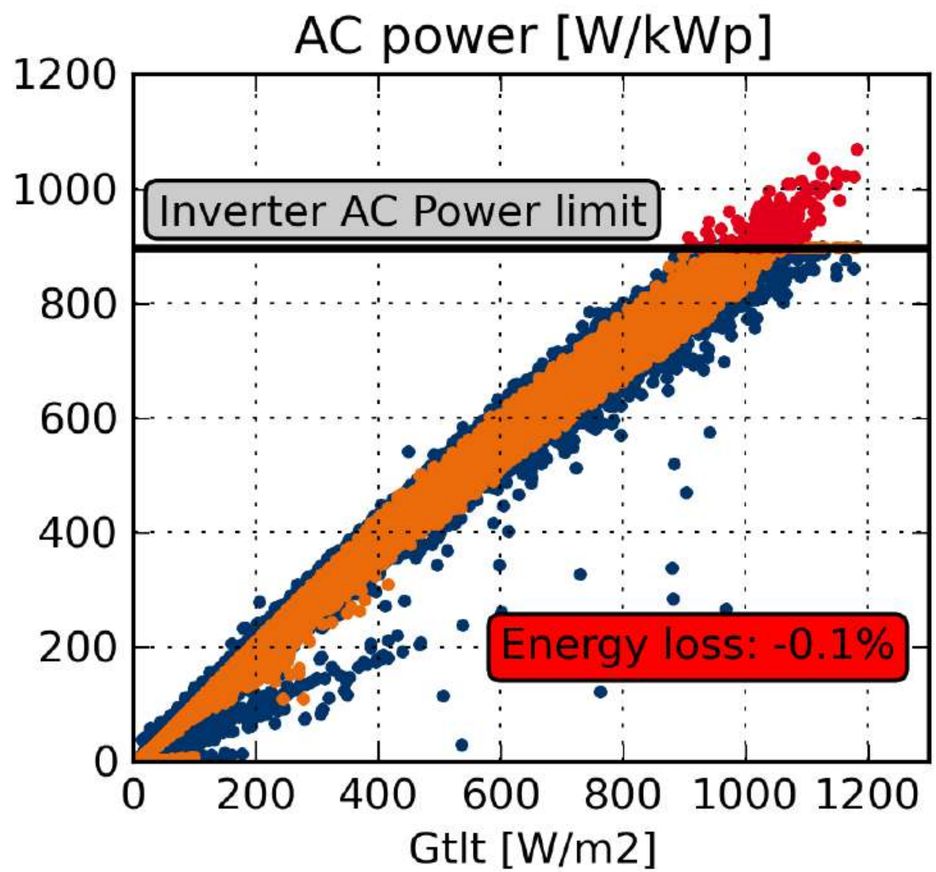
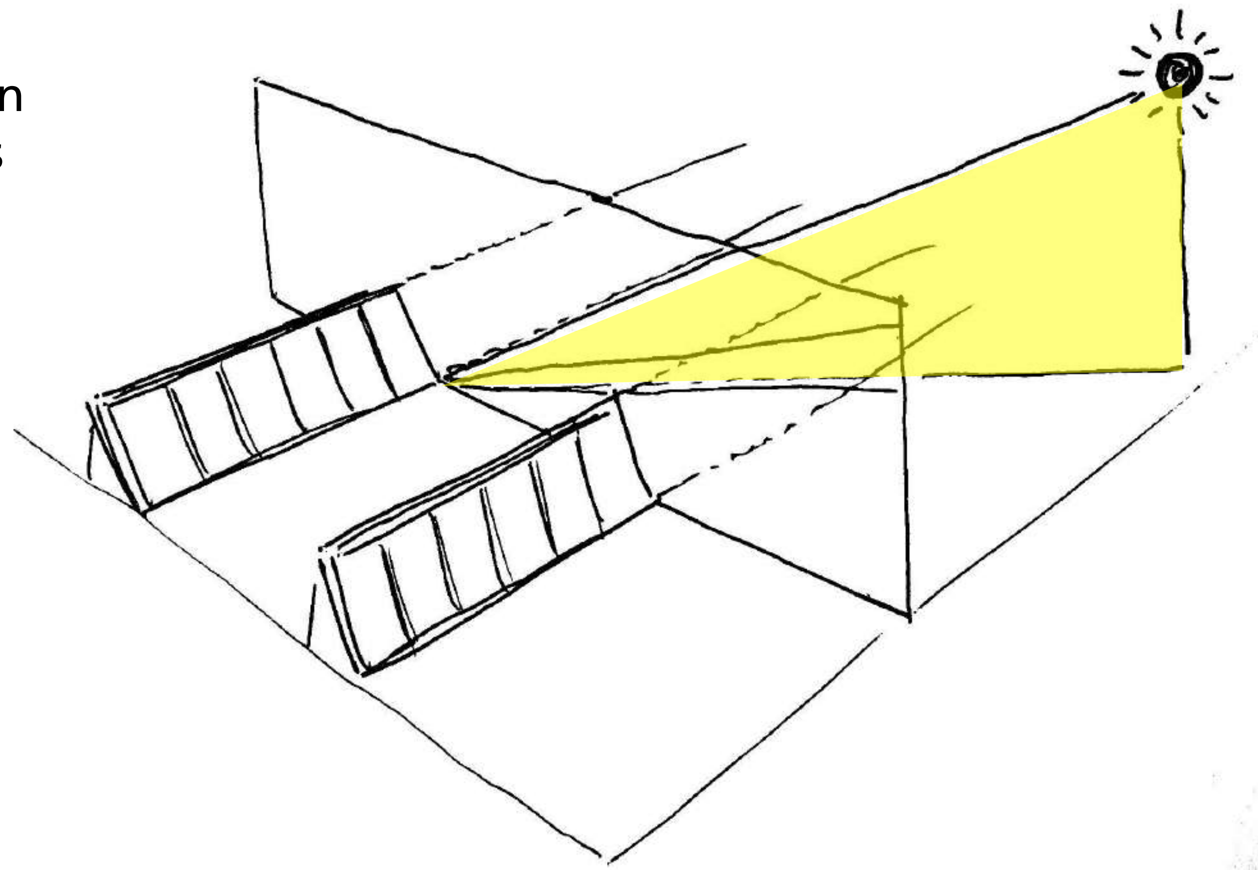
Examples – Inverter Sizing

- Simulations with and without inverter power limitation allow for the prediction of related energy losses – quite comparable to the observed value



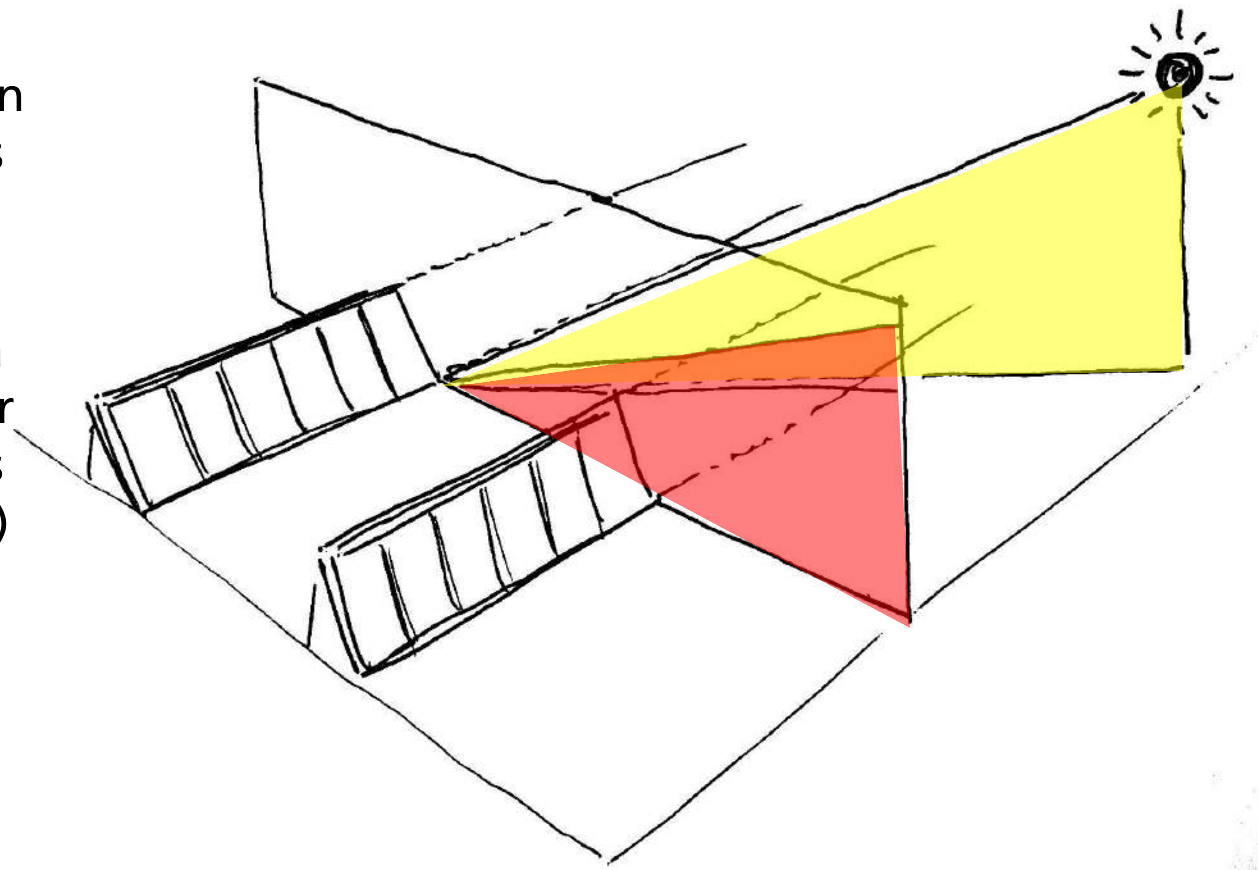
Examples – Shading Losses

- Position of sun is defined by elevation and azimuth angles



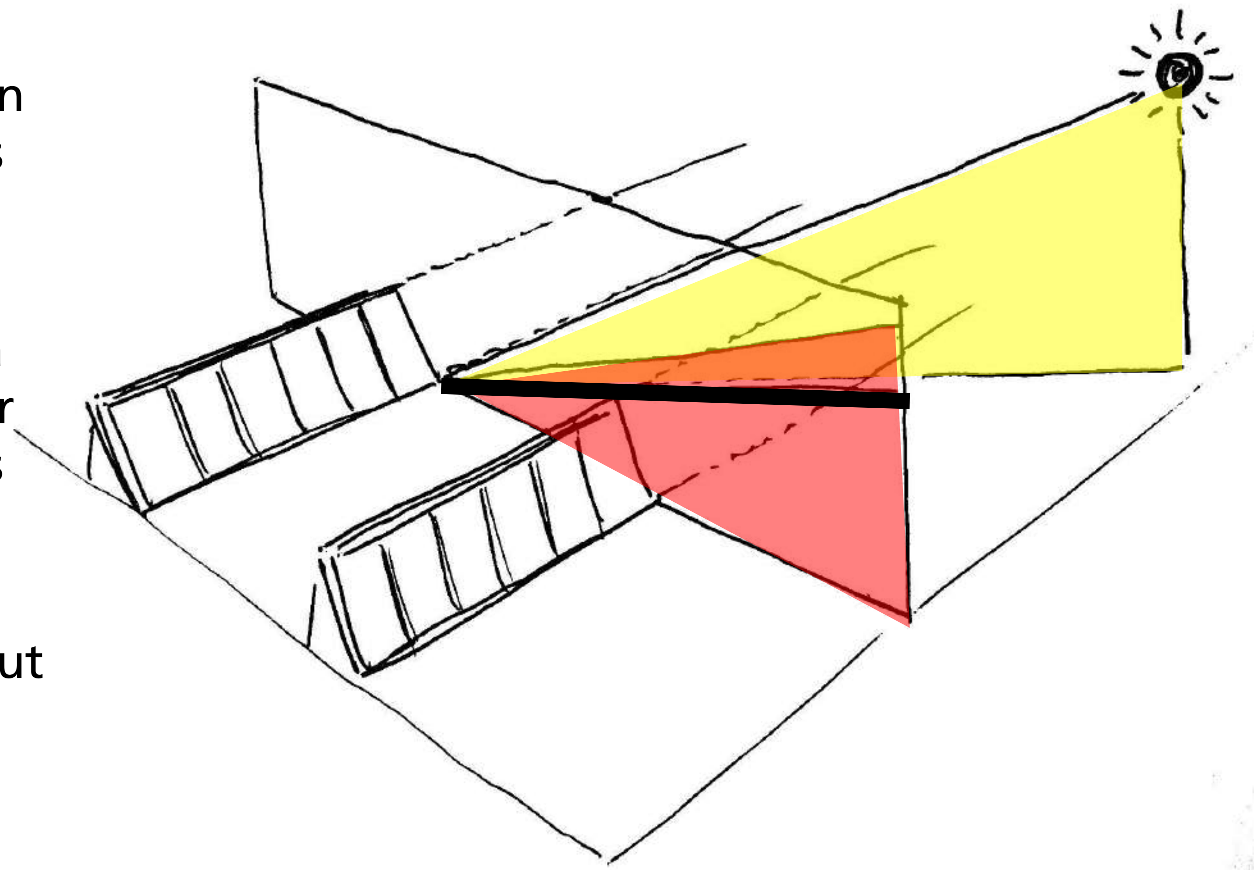
Examples – Shading Losses

- Position of sun is defined by elevation and azimuth angles
- The profile angle is the projection of solar elevation on a plane perpendicular to the module rows (and to the ground)



Examples – Shading Losses

- Position of sun is defined by elevation and azimuth angles
- The profile angle is the projection of solar elevation on a plane perpendicular to the module rows (and to ground)
- There is a minimum profile angle without shading



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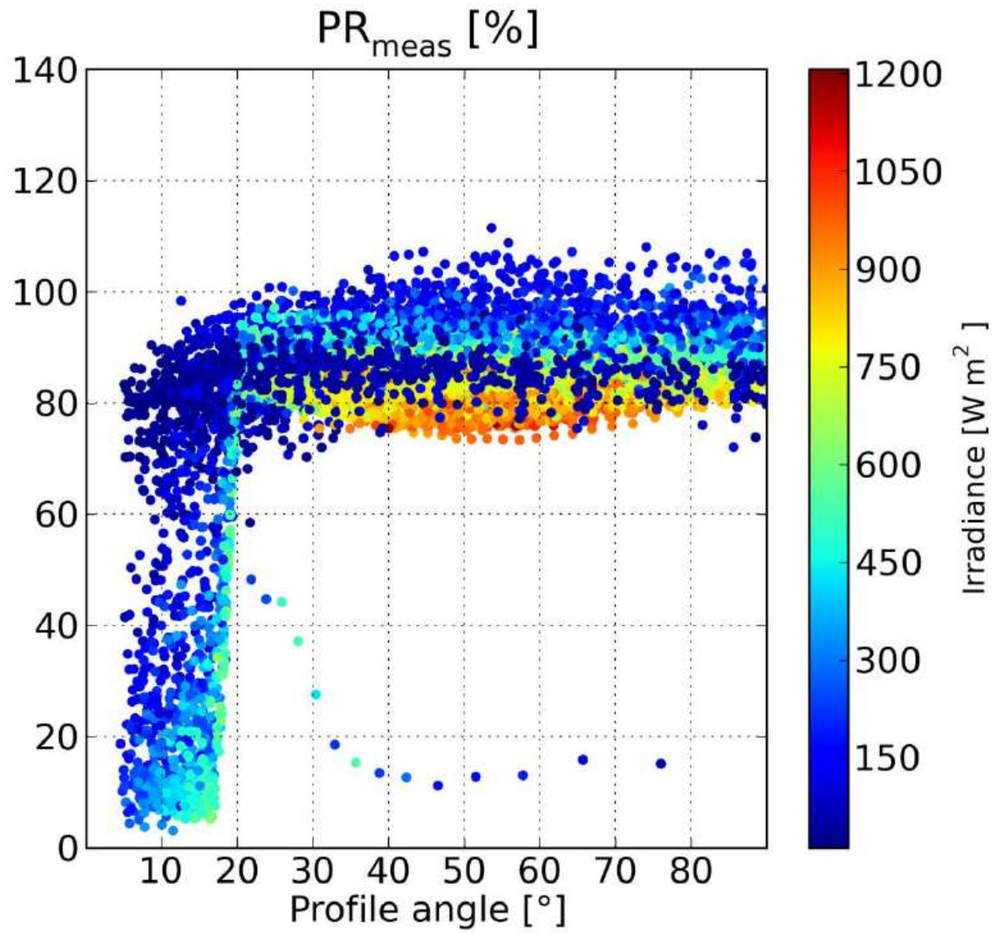
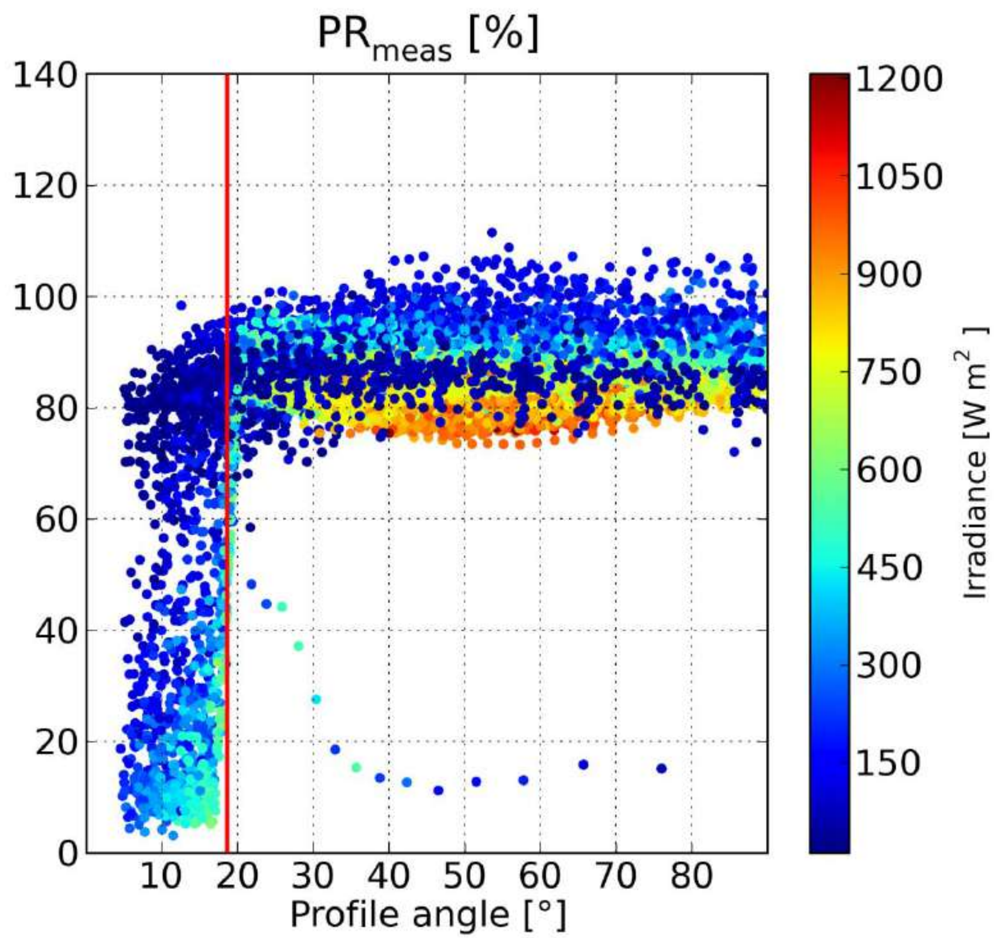
Examples – Shading Losses

- Observed values of PR plotted vs. profile angle



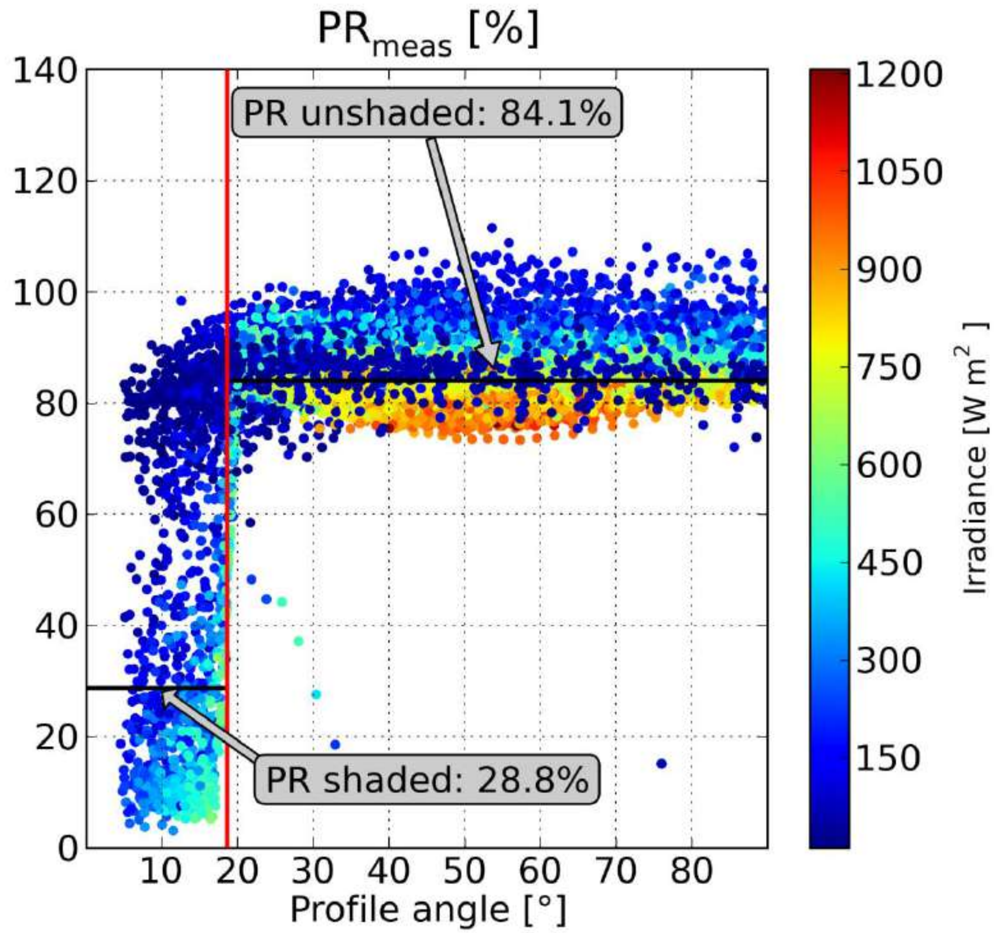
Examples – Shading Losses

- Observed values of PR plotted vs. profile angle
- Clear limit of low values of PR at 18.5 degrees



Examples – Shading Losses

- Observed values of PR plotted vs. profile angle
- Clear limit of low values of PR at 18.5 degrees
- Shading losses as estimated purely from measurements: 4.8%



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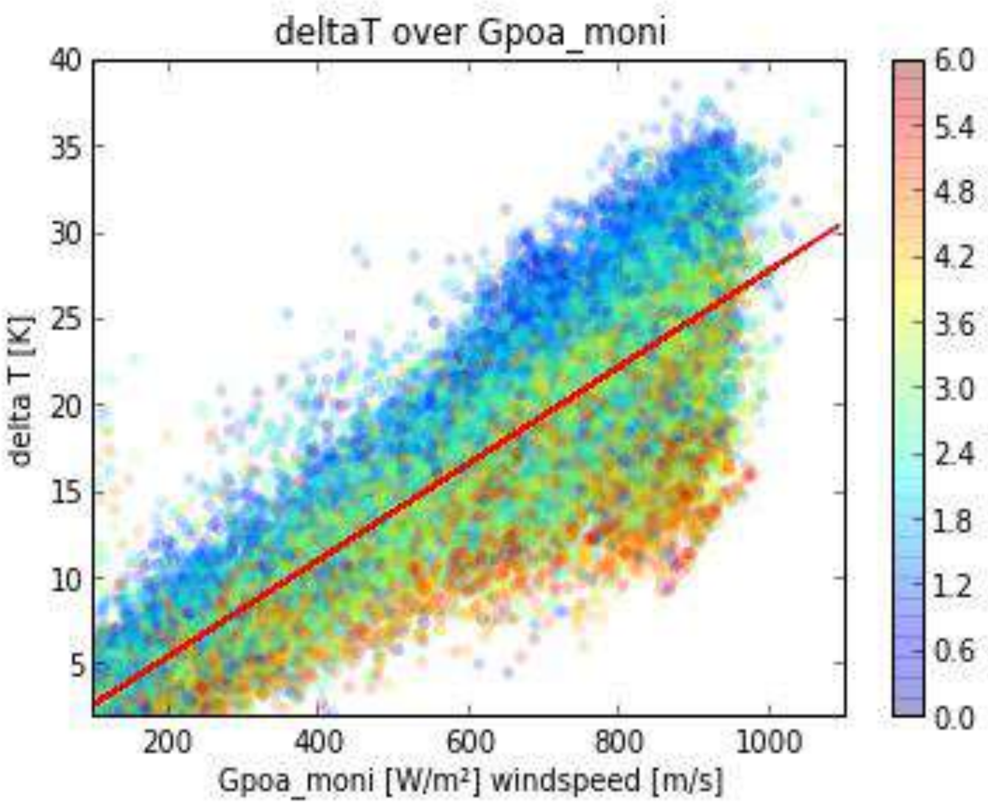
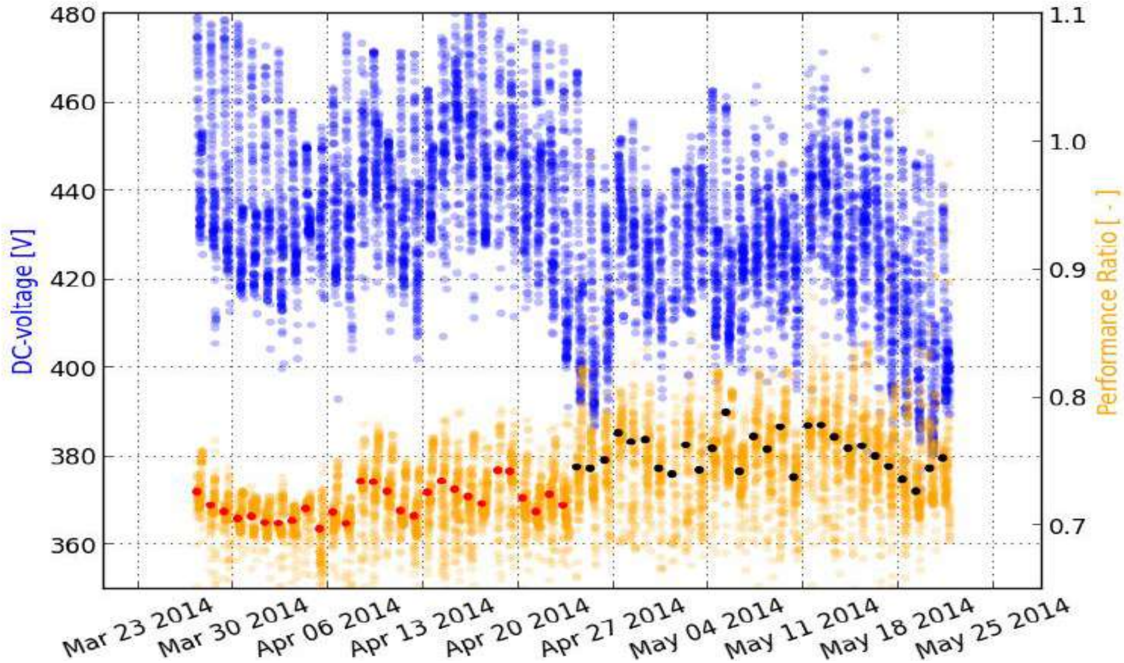
Example – Temperature



Linear over-temperature model used to fit measured module to ambient temperature difference

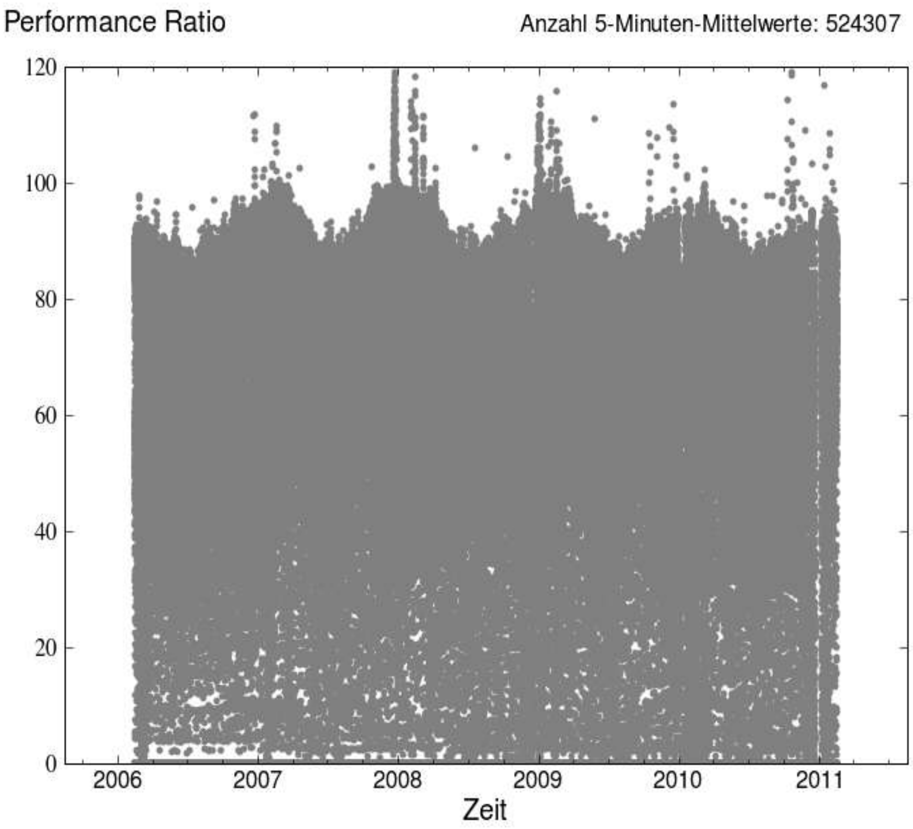
Example – Soiling

- Cleaning lead to ~6% higher performance



Example – Degradation

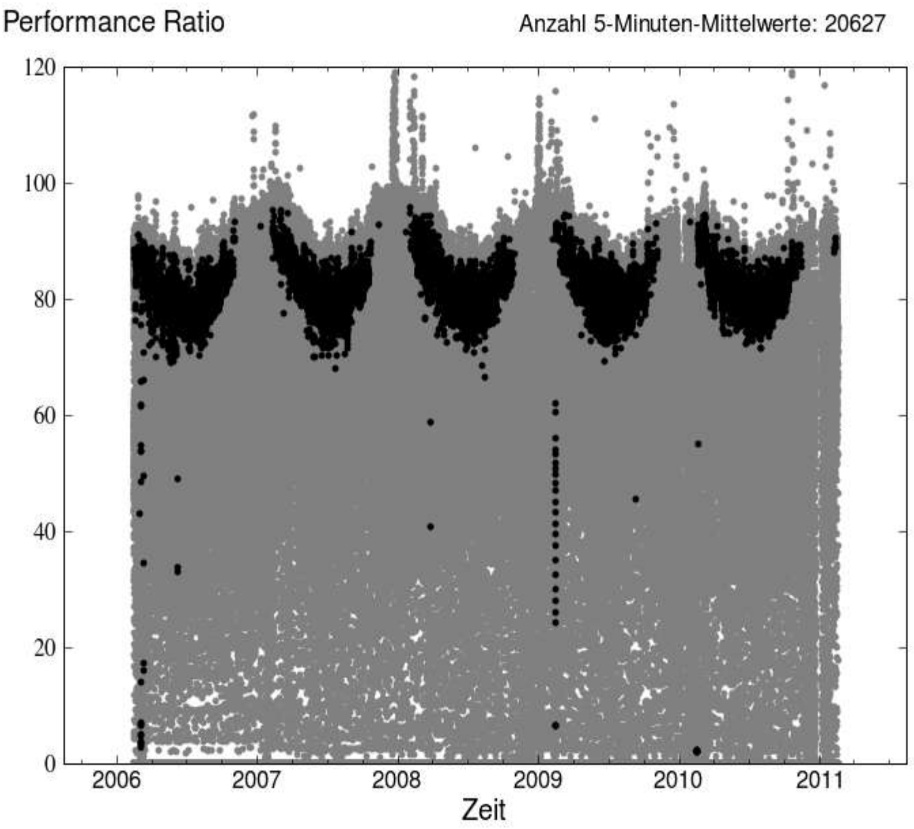
Filtering of 5-min average values:



Example – Degradation

Filtering of 5-min average values:

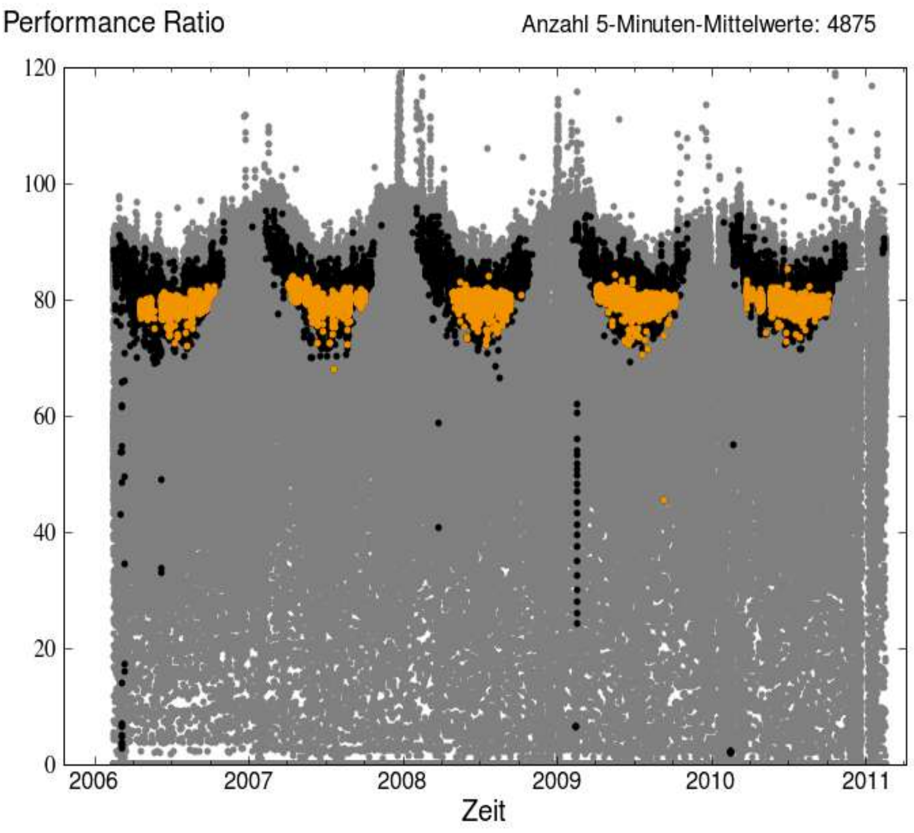
- Irradiance between 800…1000 W/m²



Example – Degradation

Filtering of 5-min average values:

- Irradiance between 800…1000 W/m²
- Module temperature between 40…45 °C



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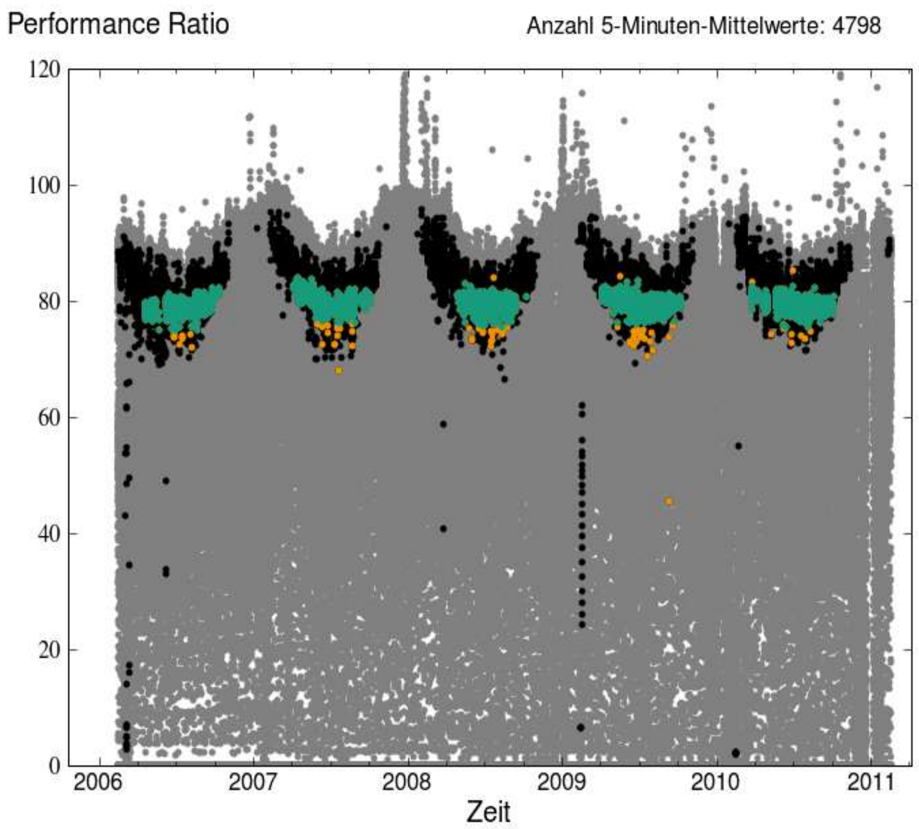
Example – Degradation

Filtering of 5-min average values:

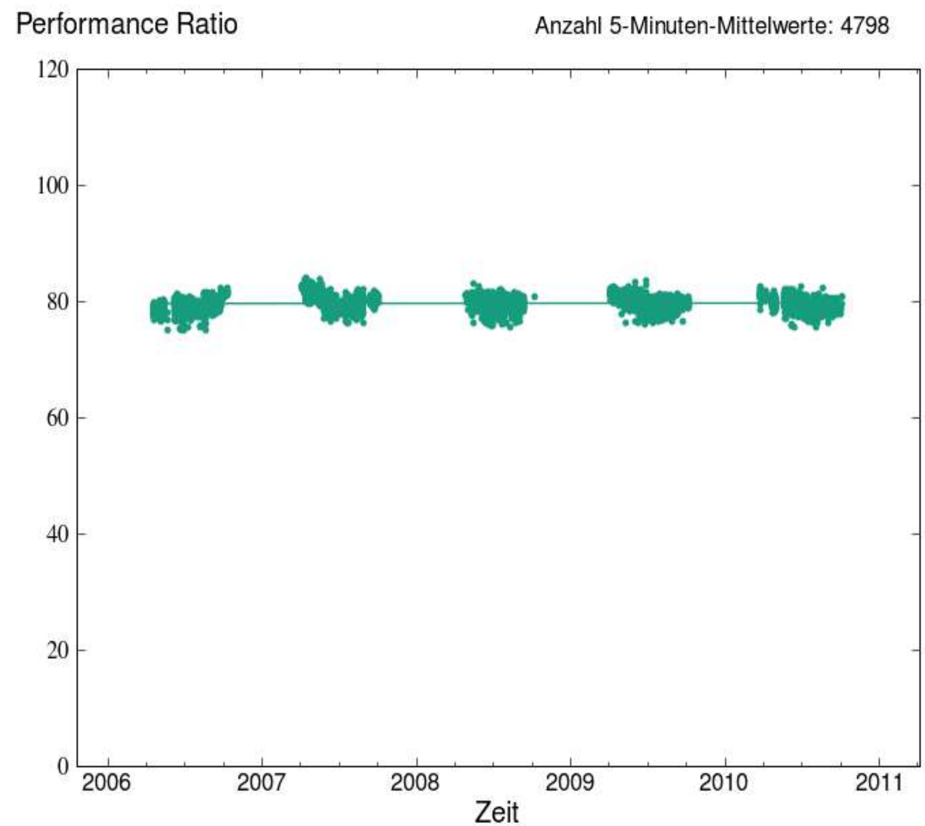
- Irradiance between 800…1000 W/m²
- Module temperature between 40…45 °C
- Values inside median ± 5%



Example – Degradation

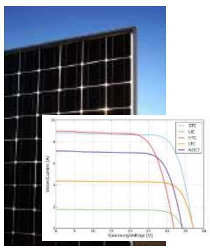
Filtering of 5-min average values:

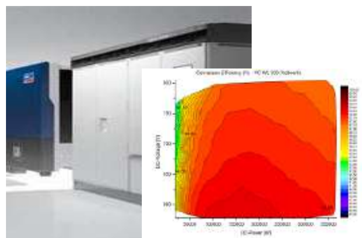
- Irradiance between 800…1000 W/m²
- Module temperature between 40…45 °C
- Values inside median ± 5%
- Calculation of rate of change rate in %/year



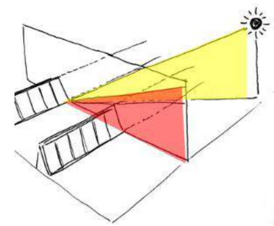
Short-term Performance Check
Independent performance verification in 3 steps

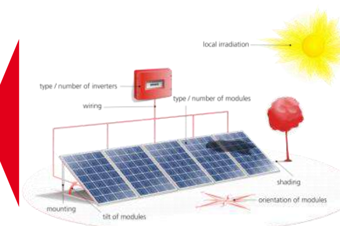
1: Model of the plant as built





PV plant model





module and inverter characteristics
e.g. temperature and irradiance dependence, efficiency

plant construction
e.g. orientation, tilt, shading and wiring losses

2: Validation of PV plant monitoring system (yield, irradiance, temperature)

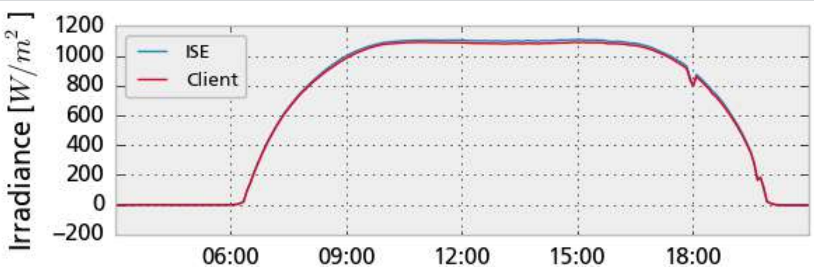


Fig. 1: Measured irradiance of ISE (red) and client (blue) sensor

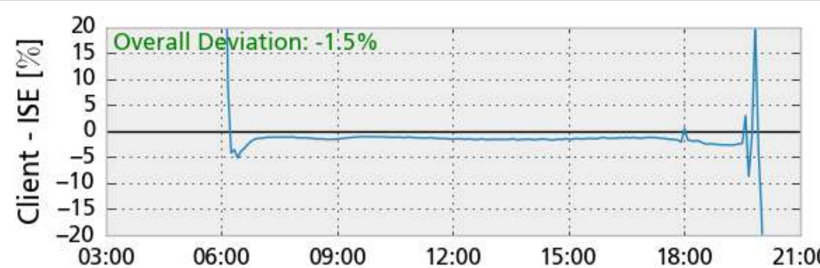


Fig. 2: Comparison of ISE and client pyranometer values

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Short-term Performance Check

3: Plant performance: modelled vs. measured data

on-site measured irradiance and temperature data

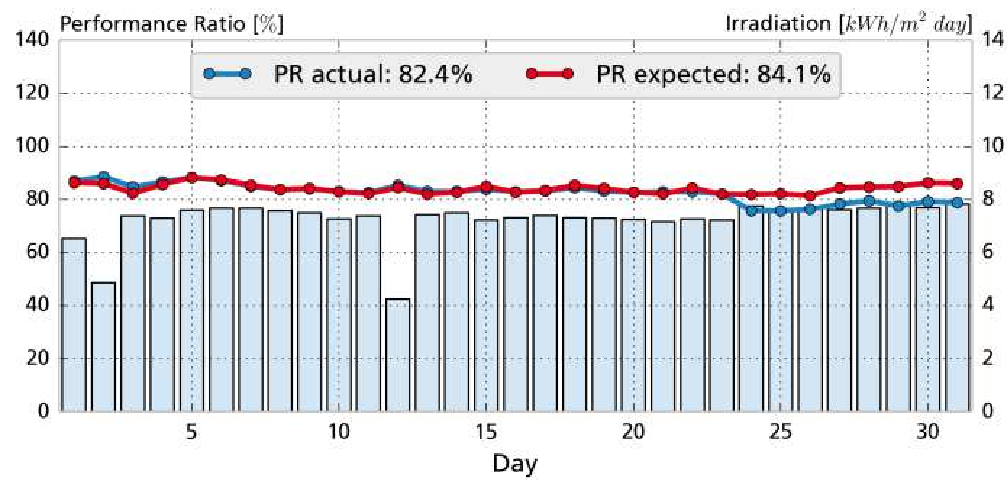
PV plant model

modelled PR

measured PR

PR

comparison and results



- Comparison of actual (measured) and expected (modelled) PR

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Short-term Performance Check

■ **Verification of the monitoring system**

➢ Inspection of the mounting and orientation of the irradiation sensor

Short-term Performance Check

- **Verification of the monitoring system**
  - Inspection of the temperature sensor

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Short-term Performance Check

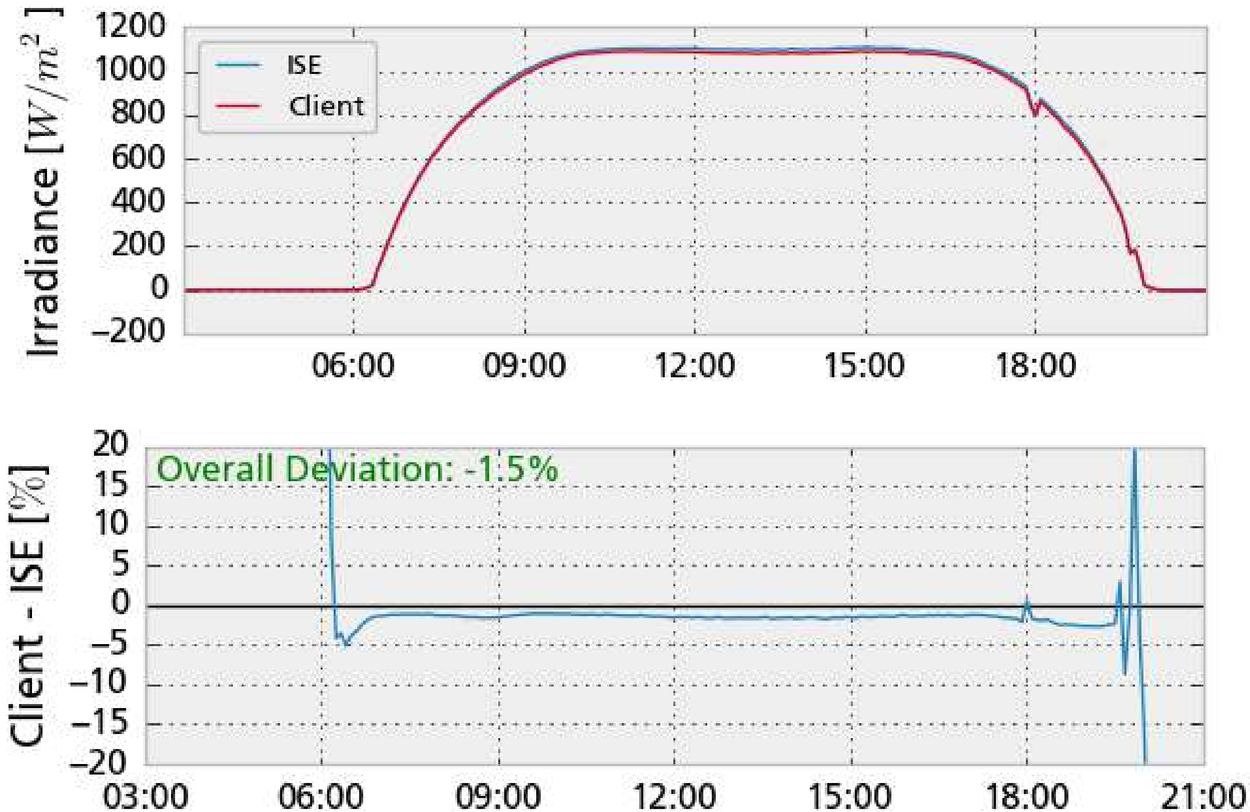
Verification of the monitoring system

- Verification of the calibration values and the time stamps

Short-term Performance Check

■ **Verification of the monitoring system**

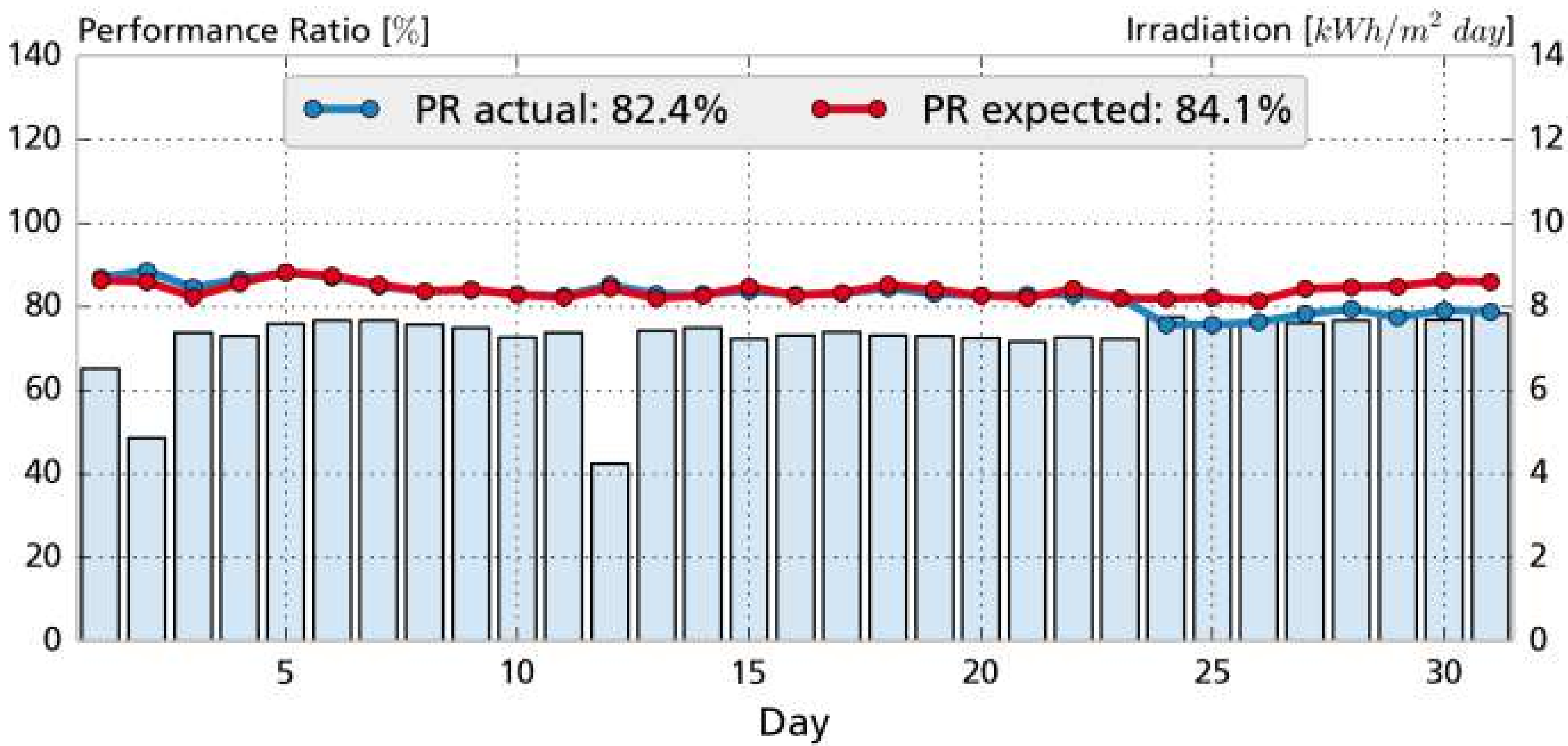
➢ Verification of the measurements



Short-term Performance Check

■Verification of the monitoring system

- ➢ Comparison of actual (measured) and expected (modelled) PR



Short-term Performance Check

- has been applied successfully for utility scale PV plants world wide in the past years
  - However: high quality monitoring data is needed!

- As the plant‘s own monitoring system is validated, third party evaluation of existing and future yield data is possible.

- The procedure allows in addition
  - to analyze underperformance and disruptions in operation
  - to estimate yield loss due to derating of the PV plant

- It can be applied continuously (current research project ALPRO)

Performance Insurance and Guarantees

Performance is a simple number! But is it?

PR =

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Performance Insurance and Guarantees

- Energy yield measurements
  - AC just at the inverter
  - before transformer
  - Before additional cabling to the feed in point
  - at the feed in / billing point
- Irradiance measurements
  - Pyranometer / reference cell / satellite data ???
  - Pyranometer / reference cell standard
  - Cleaning intervals
  - Recalibration
  - …
- Minimum time interval for the Insurance / Guarantee: months, year, …?
- System outages / grid outages included?

Performance Insurance and Guarantees

- For a proper Performance Insurance / Guarantee a lot of details have to be negotiated
  - High transaction costs!
- Performance not energy yield is insured or guaranteed
- A guarantee with a low performance value may be useless
- High data availability is mandatory

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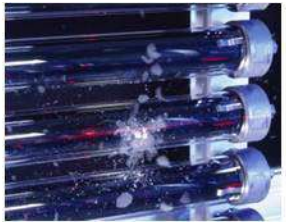
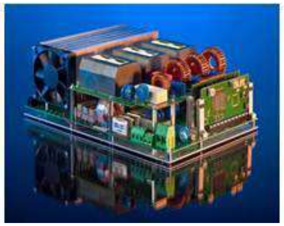
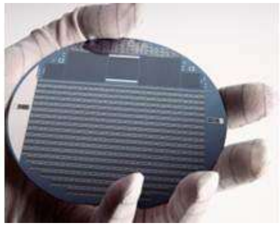
Thank you for your attention!

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BASICS IN PV POWER PLANT TECHNOLOGY

Boris Farnung, Björn Müller

Fraunhofer Institute for Solar Energy Systems ISE

Workshop "Quality Assurance and Bankability of PV Power Plants"
Mexico City, Friday, 16.11.2018

www.ise.fraunhofer.de

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AGENDA

- PV technology
  - PV technology overview, PV module standards
  - Solar Cell efficiencies
  - Degradation of modules
- Plant Components
  - Components of PV Plants
- Norms and standards
  - Relevant international standards and norms for PV projects
  - Relevant national standards (NOM)
- Standard warranties for the main equipment

Ejemplos de Sistemas FV

- España, Barcelona, 1.5 MWp, techo de fábrica, C-Si , inversores descentr

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Ejemplos de Sistemas FV

- Alemania, Friburgo, 2,0 MWp, relleno de basura, C-Si , inversores descentrales

Ejemplos de Sistemas FV

- España, 7.0 MWp, tierra seca y montañosa, C-Si , inversores centrales

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Ejemplos de Sistemas FV

- España, 1.0 MWp, tierra seca, rastreador de un eje, C-Si , inversores centrales

Ejemplos de Sistemas FV

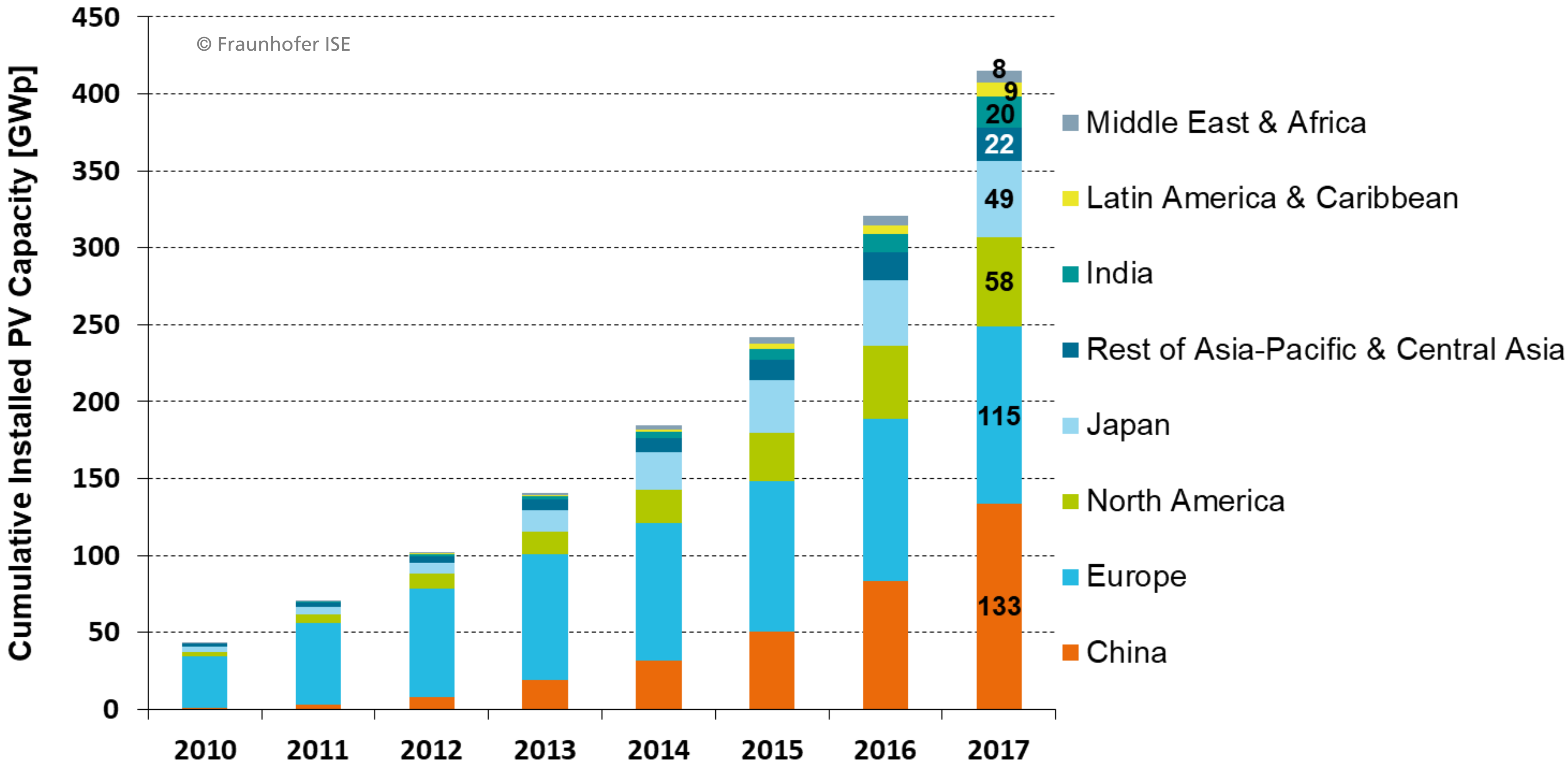
- Chile, 150 MWp, tierra seca, rastreador de un eje, CdTe, inversores centrales

Some of the largest plants in the world (2017)

Rapidly developing!

Data source: Wikipedia, illustration: Fraunhofer ISE

Global Cumulative PV Installation until 2017 (includes off-grid)



Data: IHS. Graph: PSE GmbH 2018

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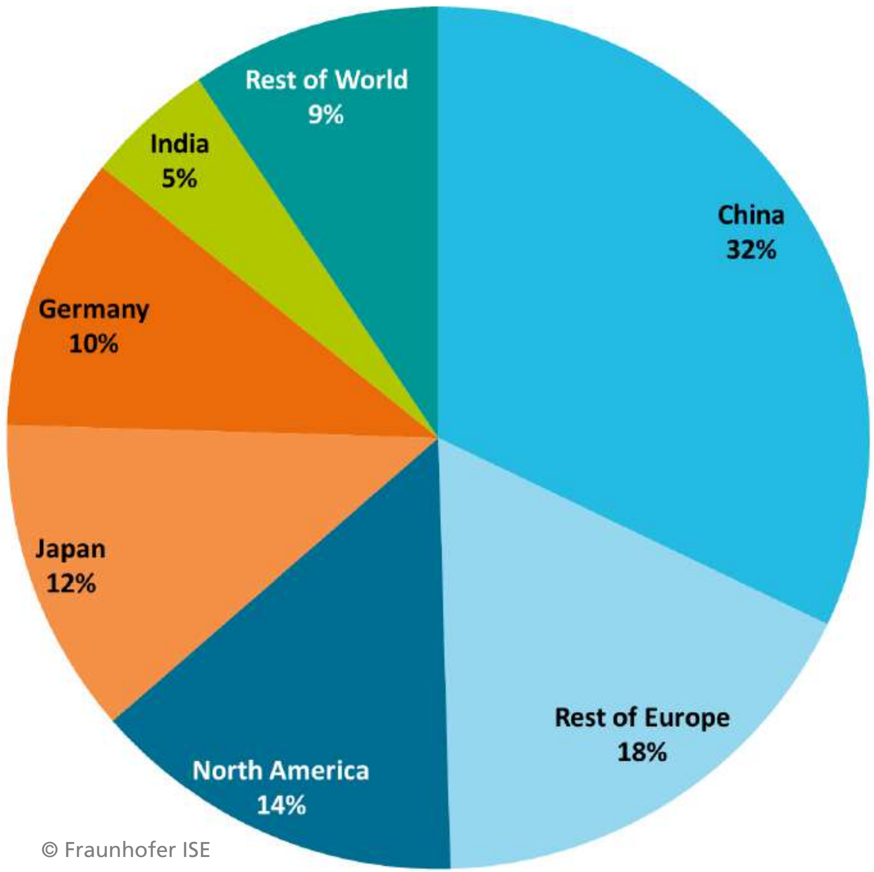
Global Cumulative PV Installation by Region

Status 2017

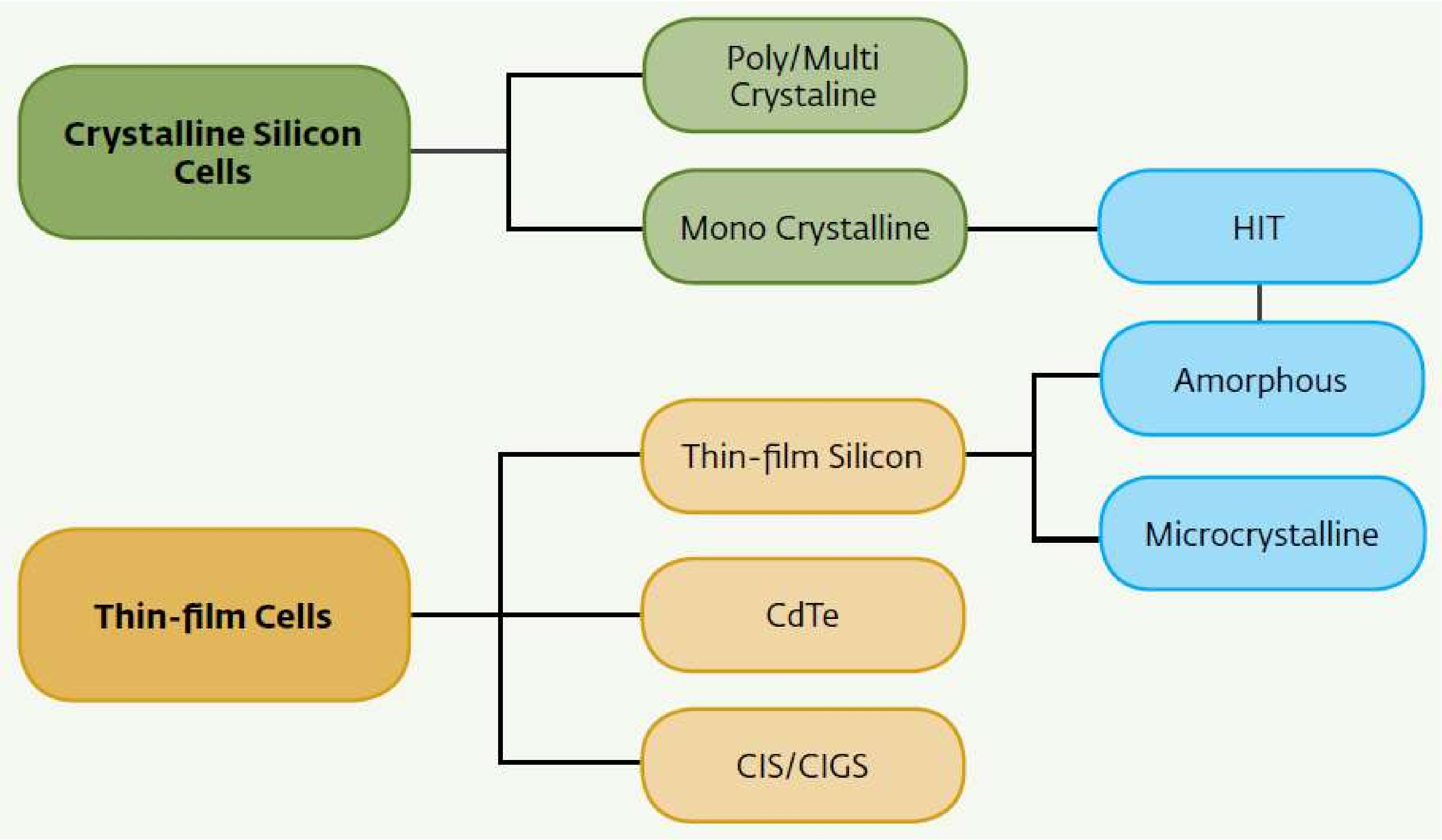


The total cumulative installations amounted to 415 GWp at the end of year 2017.

All percentages are related to total global installations, including off-grid systems.

Data: IHS. Graph: PSE GmbH 2018

PV Technologies – PV technology overview



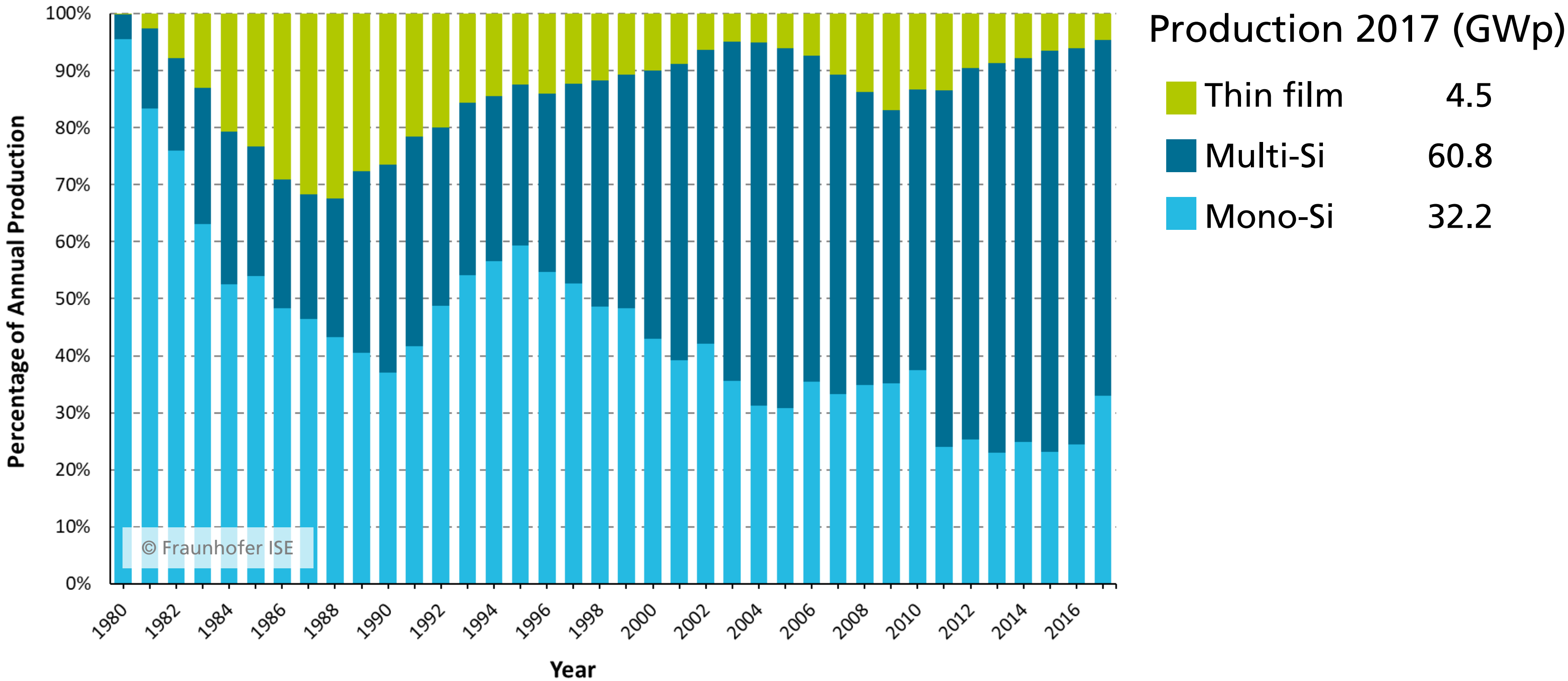
(Ben Lumby et al. 2015)

PV Technologies – PV technology class characteristics

Technology	Crystalline Silicon	Heterojunction with intrinsic thin film layer	Amorphous Silicon	Cadmium Telluride	Copper indium gallium Di-Selenide
Category	C-Si	HIT	a-Si	CdTe	CIGS or CIS
Current commercial efficiency	13%-21%	18%-20%	6%-9%	8%-16%	8%-14%
Temperature coefficient for power (typical)	-0.45%/°C	0.29%/°C	-0.21%/°C	-0.25%/°C	-0.35%/°C

(Ben Lumby et al. 2015)

PV Production by Technology
Percentage of Global Annual Production



Data: from 2000 to 2010: Navigant; from 2011: IHS (Mono-/Multi- proportion from cell production). Graph: PSE GmbH 2018

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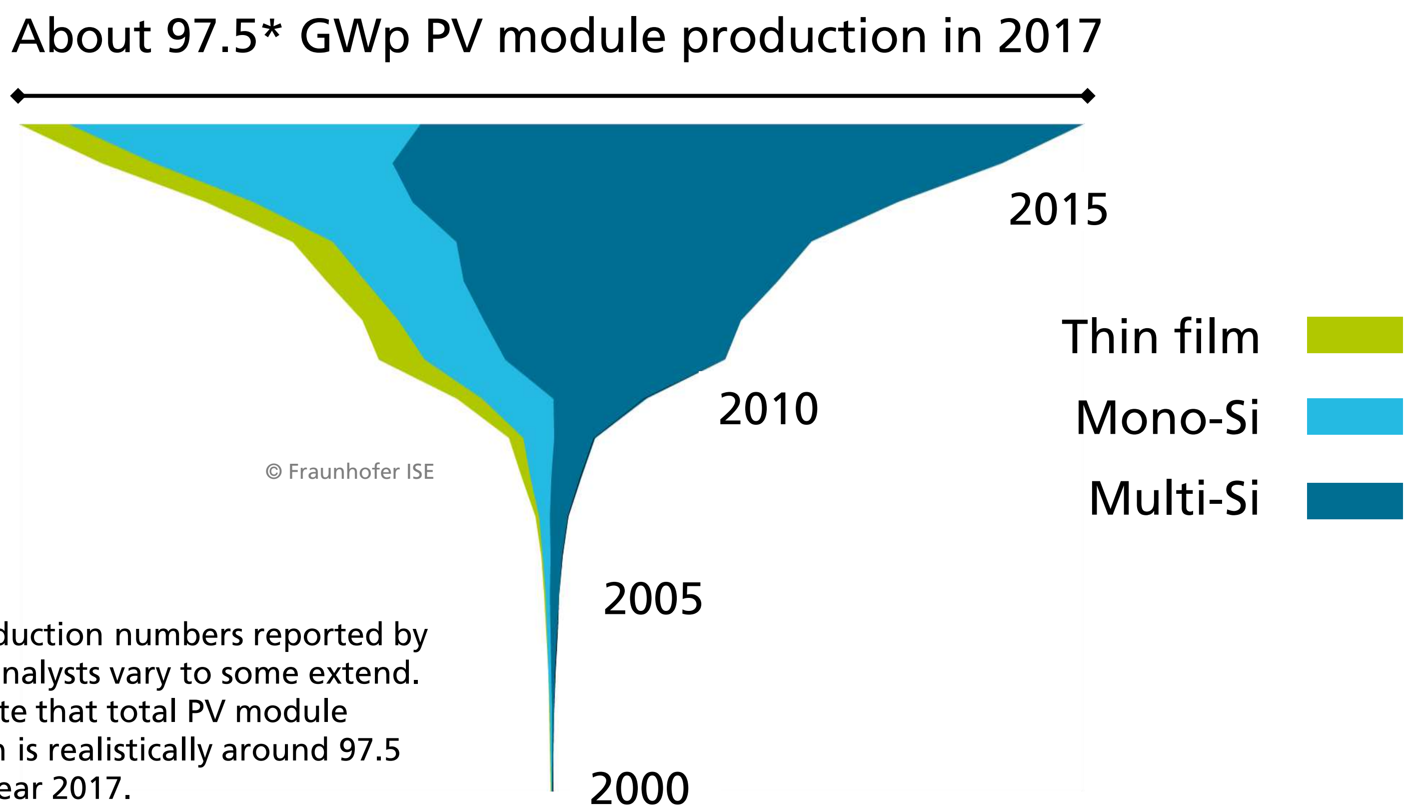
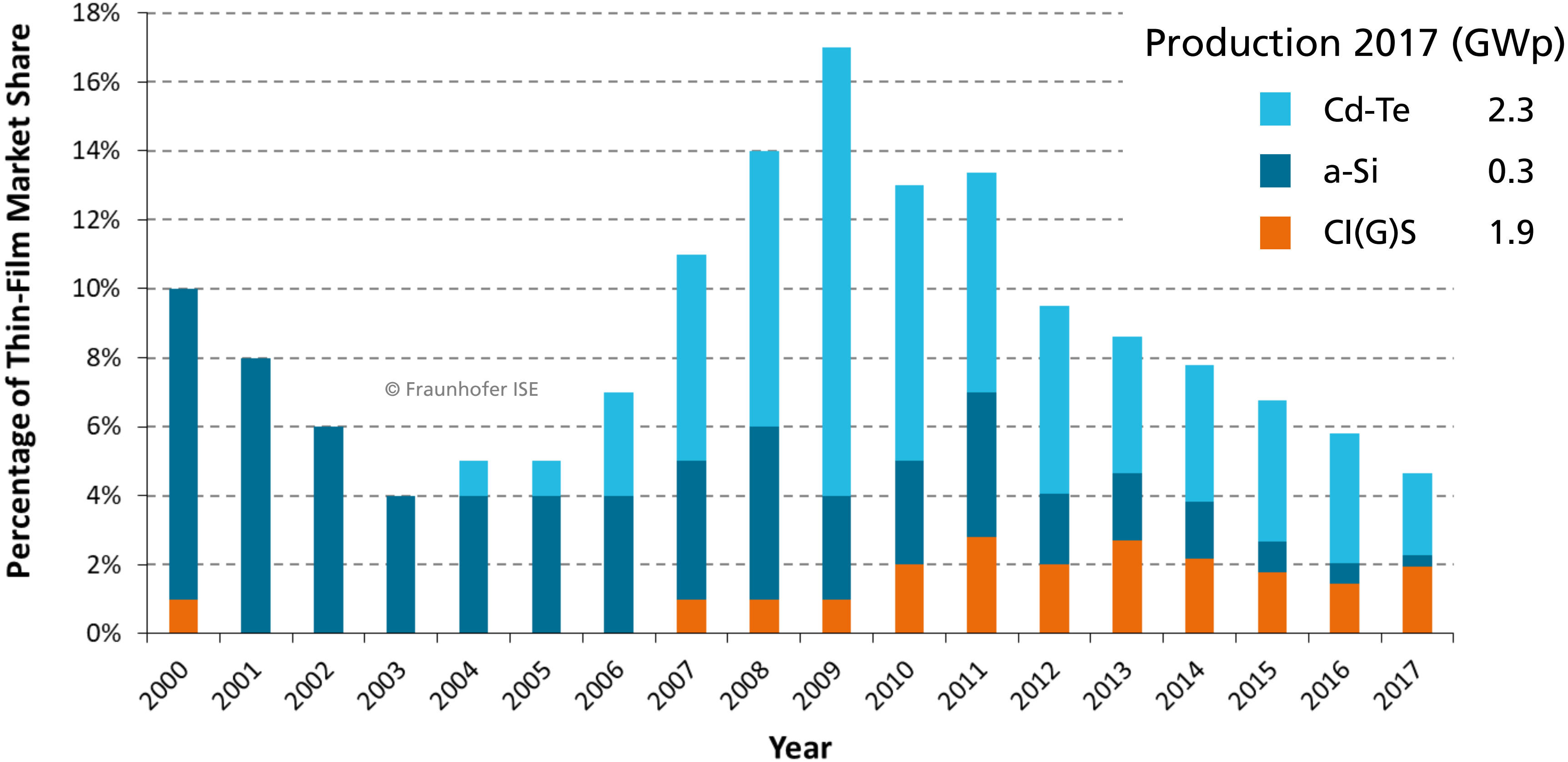
Annual PV Production by Technology
Worldwide (in GWp)



*2017 production numbers reported by different analysts vary to some extend. We estimate that total PV module production is realistically around 97.5 GWp for year 2017.

Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

Market Share of Thin-Film Technologies
Percentage of Total Global PV Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

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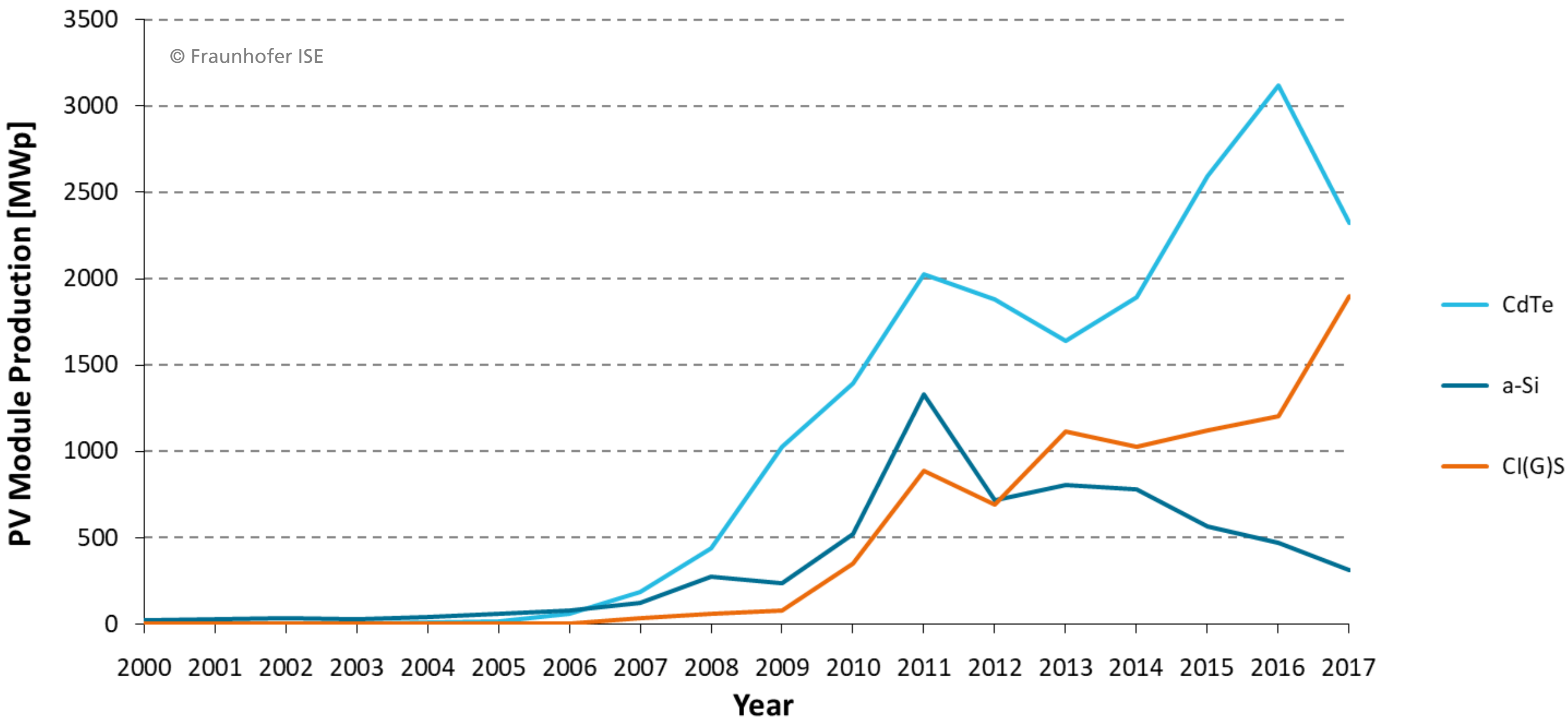
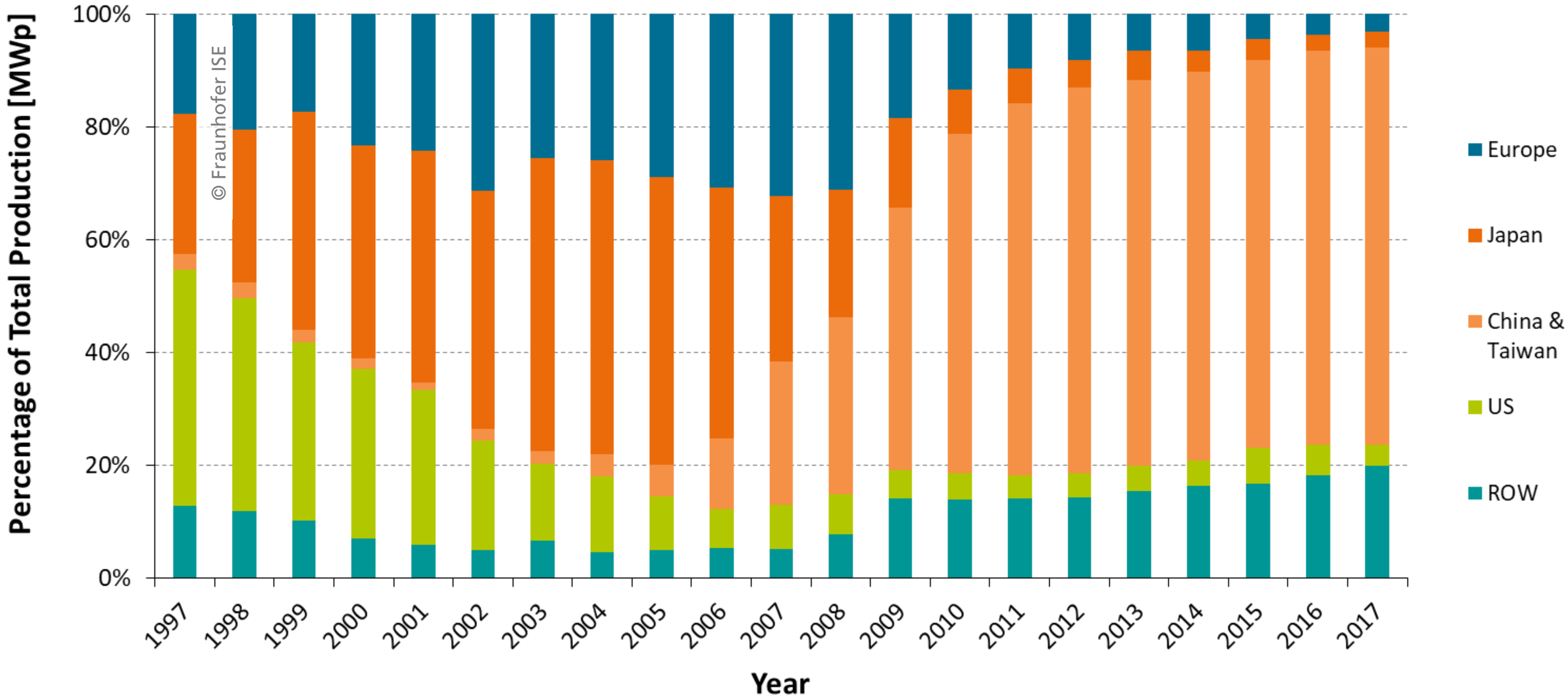
Thin-Film Technologies
Annual Global PV Module Production



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018

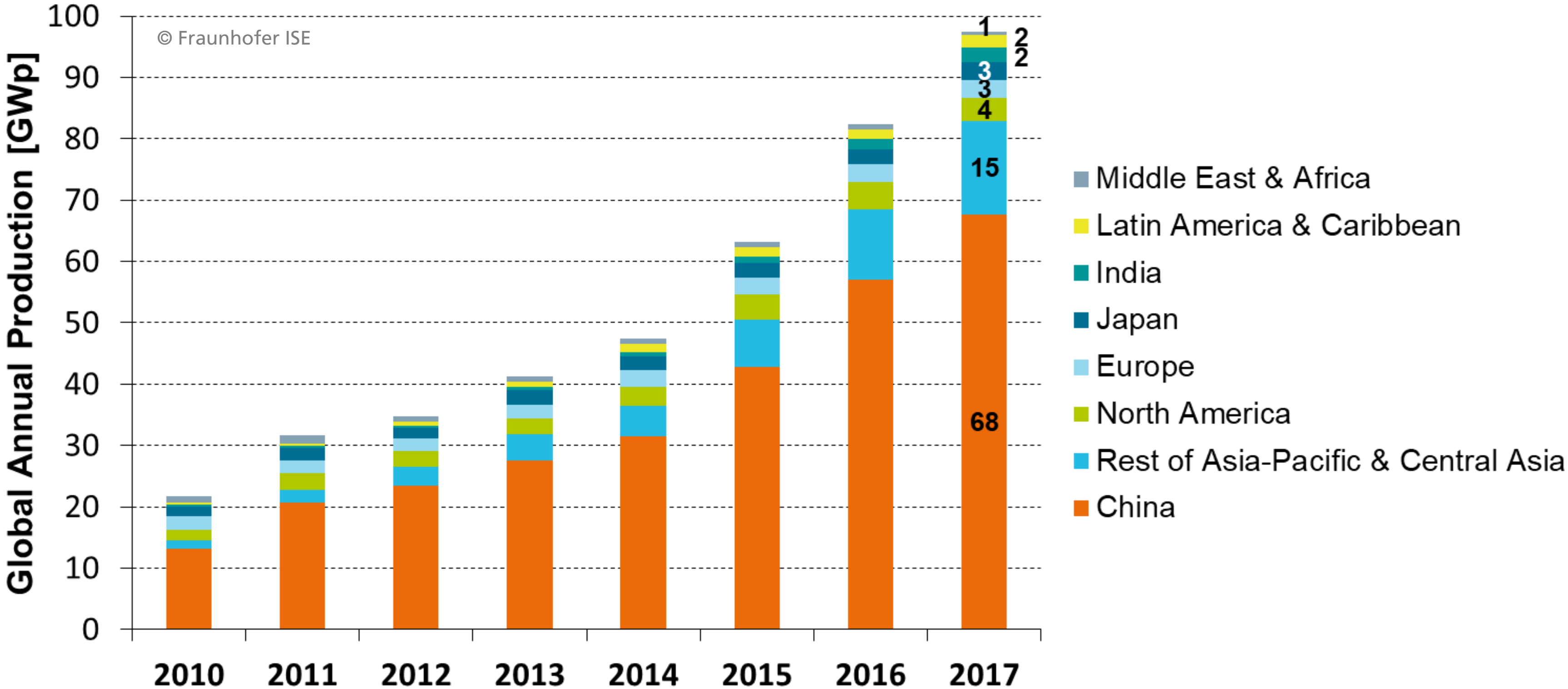
PV Module Production by Region 1997-2017

Percentage of Total MWp Produced



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE GmbH 2018

PV Industry Production by Region
Global Annual Production



Data: Up to 2009: Navigant Consulting; since 2010: IHS. Graph: PSE GmbH 2018

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PV Technologies – Solar cell efficiencies, 2018

- record lab cell efficiencies mono/poly:
  - 26.7% for mono-crystalline and
  - 22.3% for multi-crystalline silicon wafer-based technology.

- record lab cell efficiencies thin film:
  - 22.9% for CIGS and
  - 21.0% for CdTe solar cells.

- In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17% (Super-mono 21%).
- At the same time, CdTe module efficiency increased from 9% to 16%.

For constantly updated figures, see

https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

©Fraunhofer ISE: Photovoltaics Report, updated: 27 August 2018

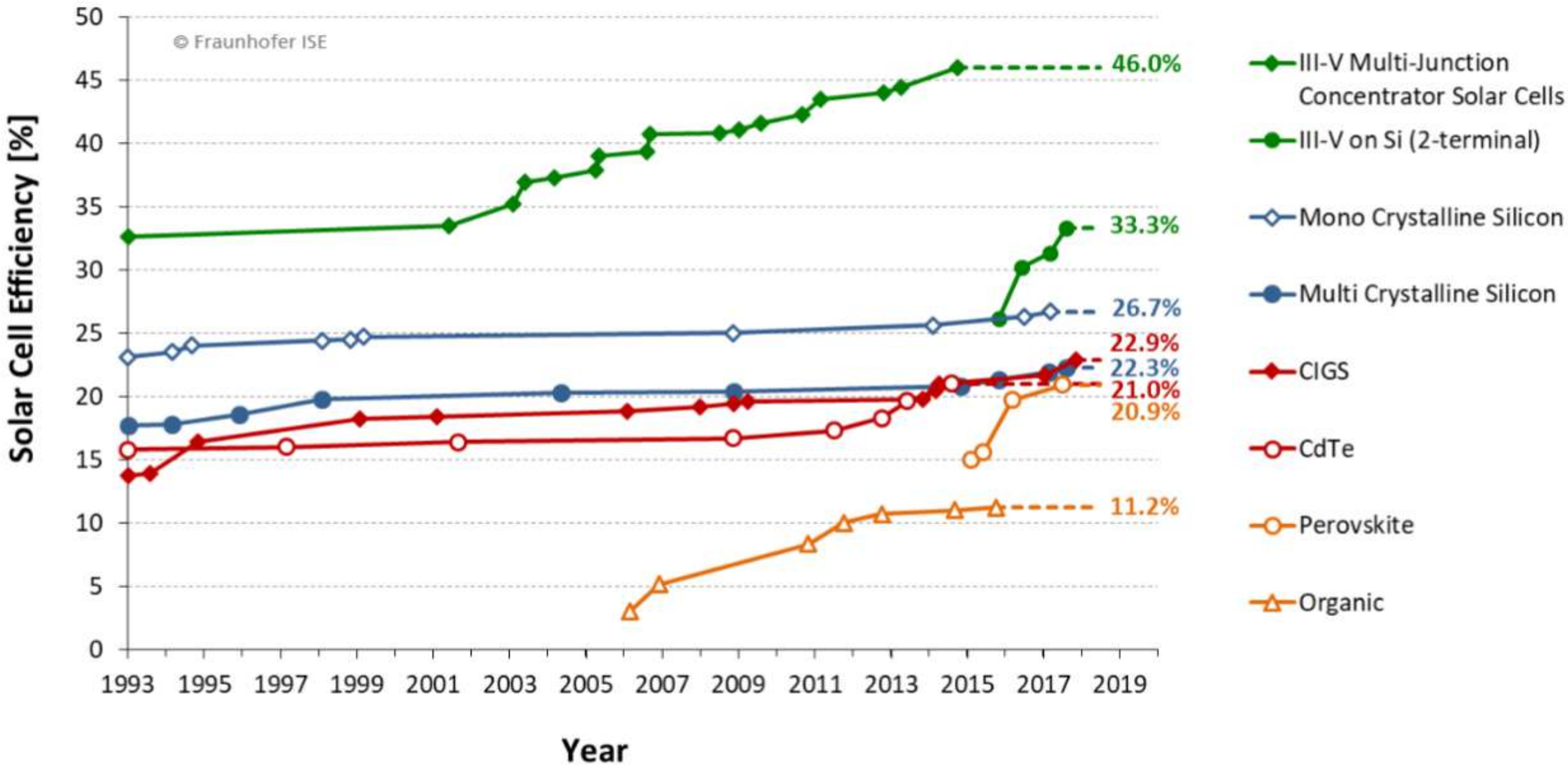
PV Technologies – Solar cell efficiencies, 2018

- In the laboratory, best performing modules are based on mono-crystalline silicon with 24.4% efficiency.
- Record efficiencies demonstrate the potential for further efficiency increases at the production level.
- In the laboratory, high concentration multi-junction solar cells achieve an efficiency of up to 46.0% today.
- With concentrator technology, module efficiencies of up to 38.9% have been reached.

For constantly updated figures, see

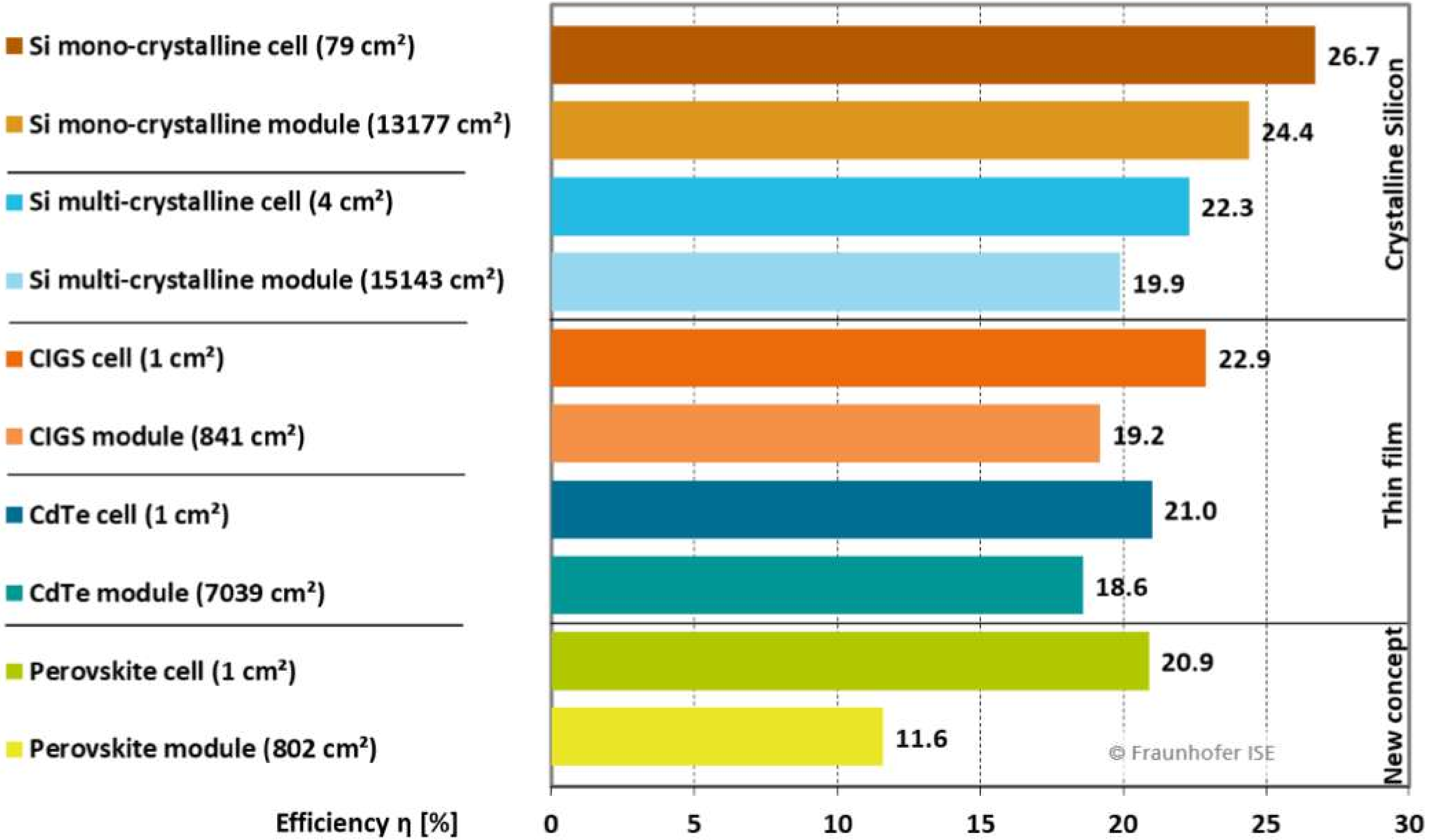
https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

Development of Laboratory Solar Cell Efficiencies



Data: Solar Cell Efficiency Tables (Versions 1 to 52), Progress in Photovoltaics: Research and Applications, 1993-2018. Graph: Fraunhofer ISE 2018

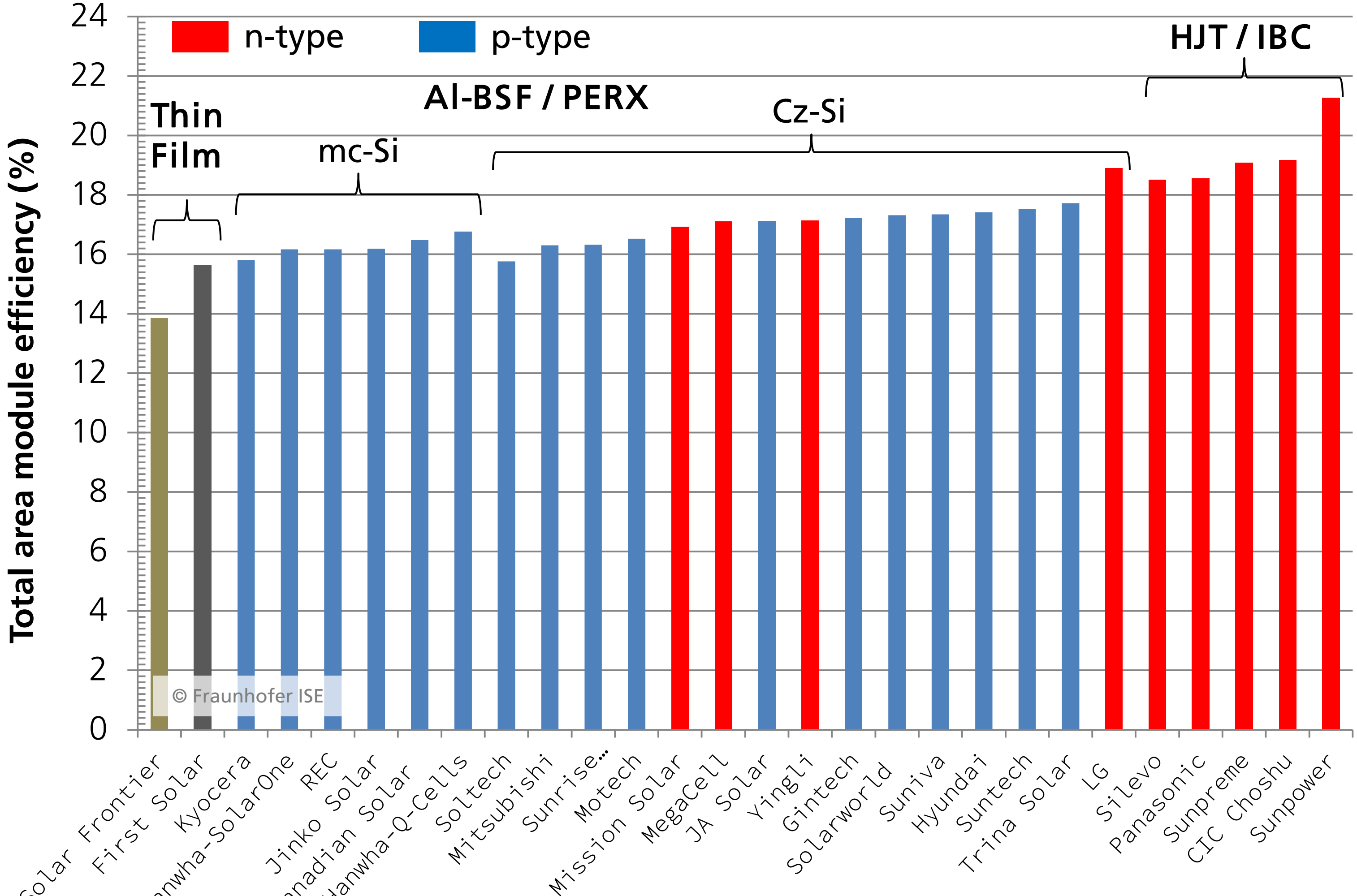
PV Technologies – Best Lab cells vs. best lab modules



Data: Green et al.: Solar Cell Efficiency Tables (Version 52), Progress in PV: Research and Applications 2018. Graph: Fraunhofer ISE 2018

Current Efficiencies of Selected Commercial PV Modules

Sorted by Bulk Material, Cell Concept and Efficiency



Note: Exemplary overview without claim to completeness; Selection is primarily based on modules with highest efficiency of their class and proprietary cell concepts produced by vertically integrated PV cell and module manufacturers; Graph: Jochen Rentsch, Fraunhofer ISE. Source: Company product data sheets. Last update: Nov. 2015.

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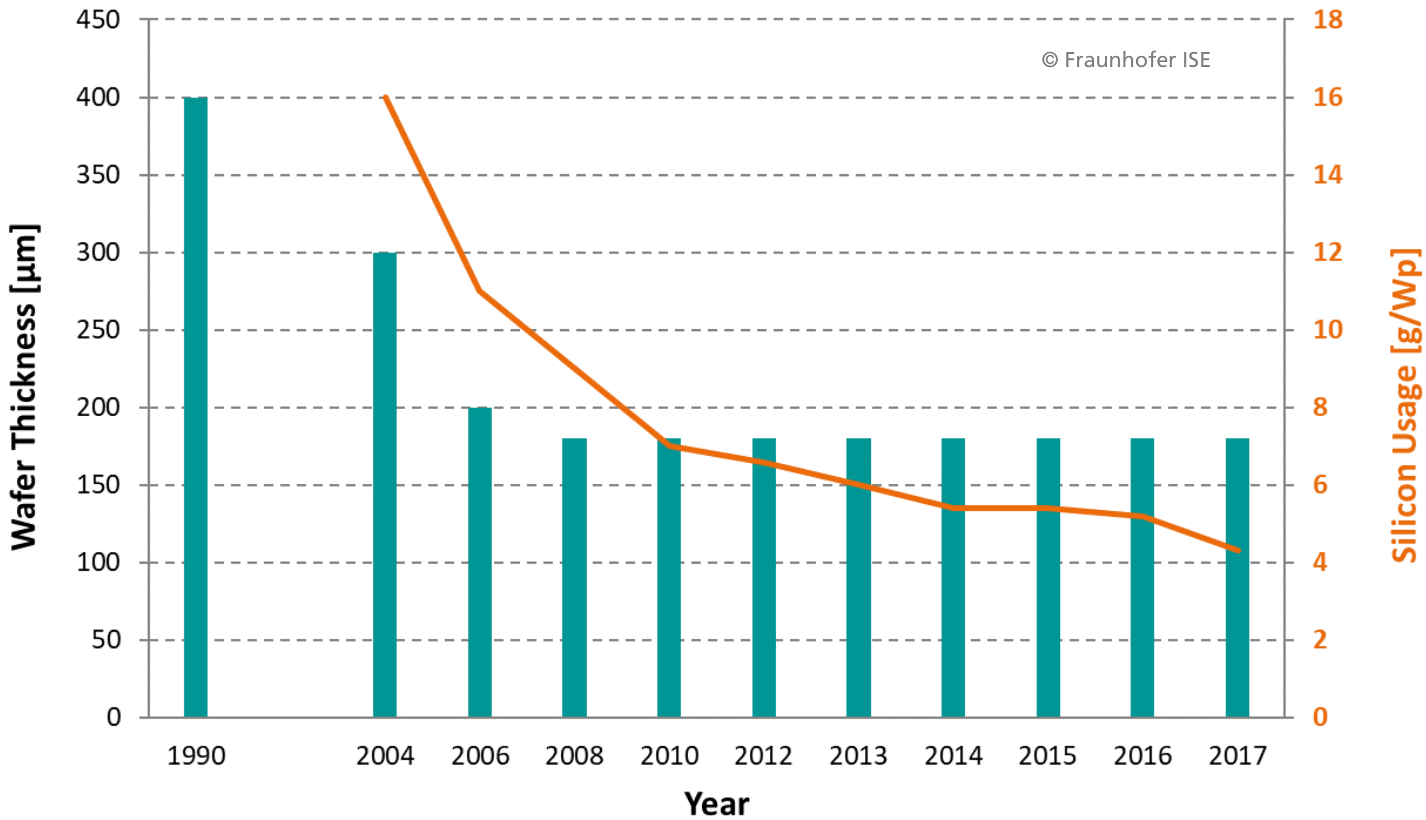
c-Si Solar Cell Development
Wafer Thickness [µm] & Silicon Usage [g/Wp]



Data: until 2012: EU PV Technology Platform Strategic Research Agenda, from 2012: ITRPV 2015; ISE 2016 without and 2017 with recycling of Si. Graph: PSE GmbH 2018

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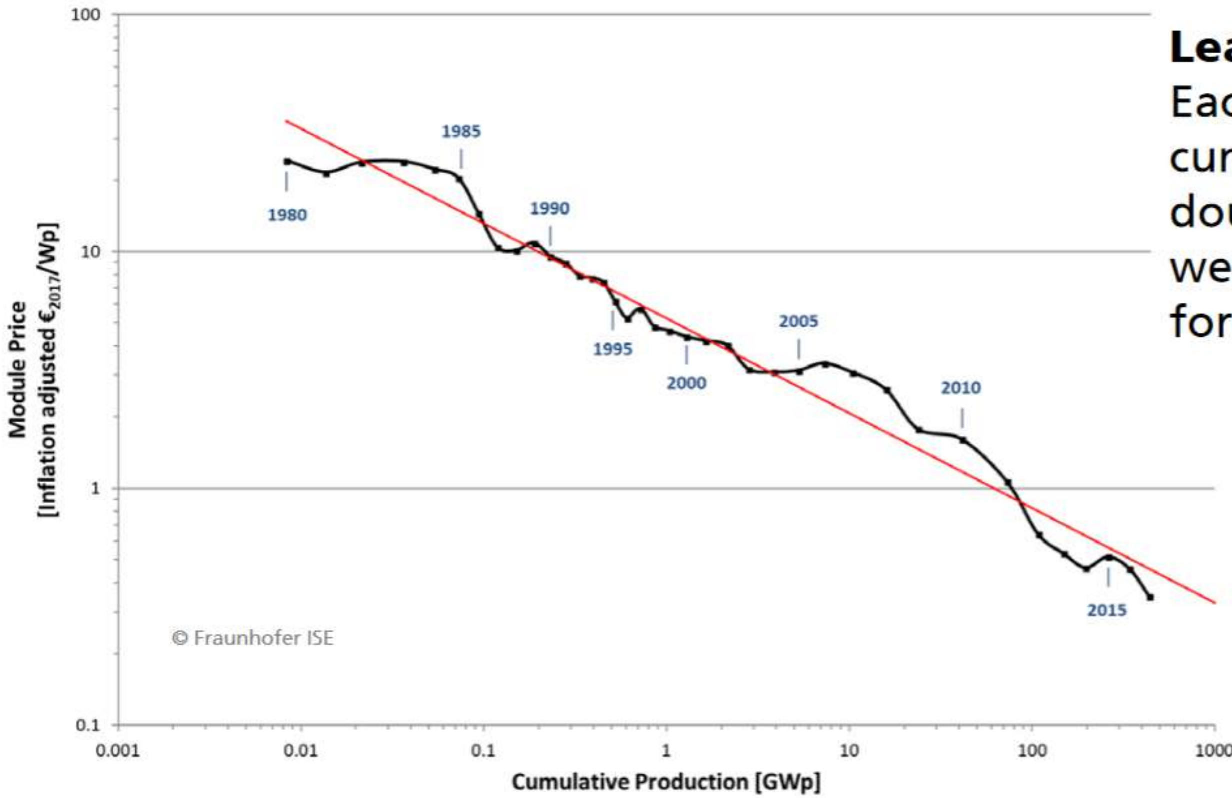
Price Learning Curve

Includes all Commercially Available PV Technologies



Learning Rate:
Each time the cumulative production doubled, the price went down by 24 % for the last 37 years.

Data: from 1980 to 2010 estimation from different sources : Strategies Unlimited, Navigant Consulting, EUPD, pvXchange; from 2011: IHS. Graph: PSE GmbH 2018

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PV Technologies – Degradation

- Performance of a PV module will decrease over time due to a process known as degradation
- Degradation rates depend on different factors such as:
  - Humidity
  - Temperature
  - Solar radiation
  - Voltage bias effects (potential induced degradation PID)
  - Quality of the materials used in manufacture
  - Manufacturing process
  - Quality of assembly and packing of the cells into the module
- The extend and nature of degradation varies among module technologies

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Trends - Module selection for long lifetime

- Back side material:
  - Advantage glas-glas.
  - If glas/backsheet, then high quality components
  - Back side material important!
- Cell technology
  - Clear tendency towards PERC, rather 4-5 busbar than multiwire
- Modules
  - 72 vs. 60 cells
  - Full- vs. half size cells
  - mono vs. poly
- Mono- vs. bifacial
  - Complex topic. Bifacial technology has advantages if applied correctly. Mono however established and well understood.

Inverter/Converter Market 2017

Inverter / Converter	Power	Efficiency	Market Share (Estimated)	Remarks
String Inverters	up to 150 kWp	up to 98%	~ 52%	• 6 - 17 €-cents /Wp • Easy to replace
Central Inverters	More than 80 kWp	up to 98.5%	~ 44%	• ~ 5 €-cents /Wp • High reliability • Often sold only together with service contract
Micro-Inverters	Module Power Range	90%-95%	~ 1%	• ~ 28 €-cents /Wp • Ease-of-replacement concerns
DC / DC Converters (Power Optimizer)	Module Power Range	up to 98.8%	~ 3%	• ~ 9 €-cents /Wp • Ease-of-replacement concerns • Output is DC with optimized current • Still a DC / AC inverter is needed • ~ 3 GWp installed in 2017

Data: IHS 2016. Remarks: Fraunhofer ISE 2018. Design: PSE GmbH 2018

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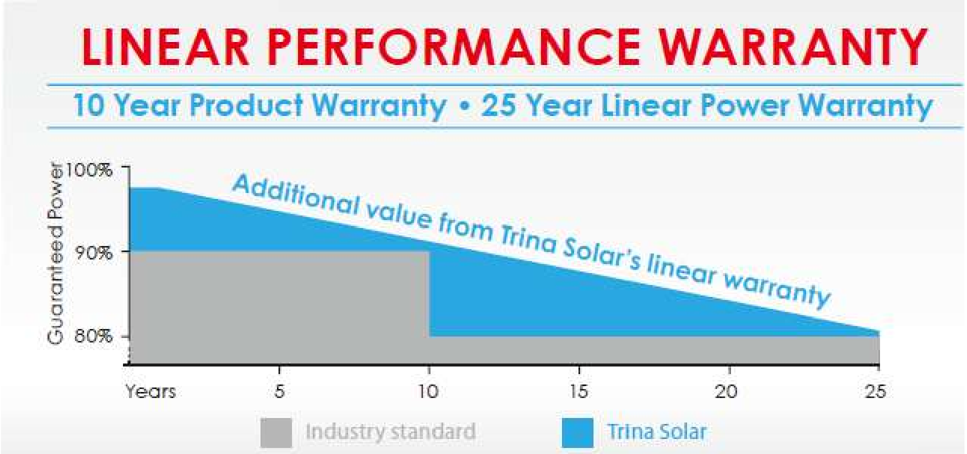
Typical warranties for system components

For Modules

- Product warranty: 5 years
- After that: power output warranty : still 90% after 10 years
- after 20 years: min. 80% Power output
- Or: Linear Performance Warranty, example:



For Inverters

- Typically ranges from 5-10 years

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Standards in the PV world

- National standardization bodies exist, like e.g.
  - NIST (National Institute of Standards and Technology, US)
  - Mexican NOM and NMX
  - DIN (Deutsches Institut für Normung, German)
  - JIS (Japanese Industrial Standards)

- In PV, main body is IEC (“International Electrotechnical Commission”)
  - “Technical Committee 82 on Photovoltaics”
  - eight working groups
  - As of 2018: 105 publications and standards

Source https://webstore.iec.ch/publication/24312#additionalinfo

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Relevant IEC topic families

- Photovoltaic devices
- Terrestrial Photovoltaic Modules
- Photovoltaic module safety qualification
- Measurement procedures for materials used in photovoltaic modules
- Photovoltaic Systems
- Photovoltaic Module and System Performance
- Photovoltaic PV Array
- Solar photovoltaic energy systems
- Photovoltaic inverters
- Photovoltaic concentrators (CPV) and modules
- Recommendations for renewable energy and hybrid systems for rural electrification

IEC most prominent standards for Quality Assurance

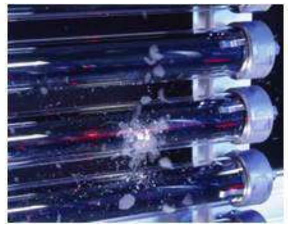
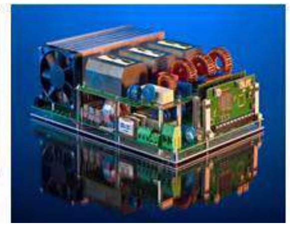
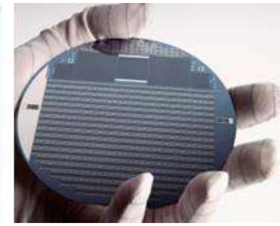
- 60904 family: measurement principles and requirements for reference devices
- 61215 family: design qualification and testing
- 61730 family: module safety qualification
- 61724 family: Photovoltaic system performance
- IEC 61829:2015: PV array on site measurements of IV characteristics
- IEC 62548:2016: PV array design requirements
- IEC 62941:2016: "Guideline for increased confidence in PV module design qualification and type approval"
- IEC TS 63049:2017: "Guidelines for effective quality assurance in PV systems installation, operation and maintenance"
- IEC 62446-1:2016: Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection

Further Reading
Selected studies and analyses

- ISE Energy Charts
- Study: Levelized Cost of Electricity - Renewable Energy Technologies
- Recent facts about photovoltaics in Germany
- Power Generation from Renewable Energy in Germany - Assessment of 2017
- What will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050
- Meta Study: Future Crosssectoral Decarbonization Target Systems in Comparison to Current Status of Technologies
- Study: Current Status of Concentrator Photovoltaic (CPV) Technology

Please click on the link to find the respective information.

Thank you for your attention!

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Abbreviations

Abbr.	Explanation	Abbr.	Explanation
AC	Alternating Current	HCPV	High Concentrator Photovoltaic
Al-BSF	Aluminum Back Surface Field	HJT (also HIT)	Heterojunction with Intrinsic Thin-Layer
BIPV	Building Integrated PV	IBC	Interdigitated Back Contact (solar cells)
BOS	Balance of System	LCPV	Low Concentrator Photovoltaic
CdTe	Cadmium-Telluride	MJ	Multi Junction
CI(G)S	Copper Indium (Gallium)Diselenide	MPP	Maximum Power Point
CPV	Concentrating Photovoltaic	n-type	Negatively doped wafer (with phosphorous)
c-SI	Crystalline Silicon	PERX	Passivated emitter and rear cell
Cz	Czochralski Method	PR	Performance Ratio
DC	Direct current	p-type	Positively doped wafer (with boron)
EEG	Renewable Energy Law (Erneuerbare Energie Gesetz)	PV	Photovoltaic
EPBT	Energy PayBack Time	RE	Renewable Energies
EROI	Energy Return of Invest	ROI	Return on Investment
FZ	Floating Zone	SI	Silicon
GaAs	Gallium Arsenide	SIC	Silicon carbide
GaN	Gallium nitride	VAT	Value Added Tax

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References

- U.S. Energy Information Administration (EIA) (2014): Solar photovoltaic output depends on orientation, tilt, and tracking. Today in Energy. Available online at https://www.eia.gov/todayinenergy/detail.php?id=18871, checked on 3/23/2017.
- Ben Lumby; Vicky McLean; Stratos Tavoulareas (2015): Utility Scale PV Power Plants. A project developer's guide. International Finance Corporation.
- Fraunhofer ISE: Photovoltaics Report, updated: 27 August 2018
- Fraunhofer ISE, PVK material

OPERATION AND MAINTENANCE

Boris Farnung, Björn Müller
Fraunhofer Institute for Solar Energy Systems ISE

Workshop "Quality Assurance and Bankability of PV Power Plants"
Mexico City, Friday, 16.11.2018

www.ise.fraunhofer.de

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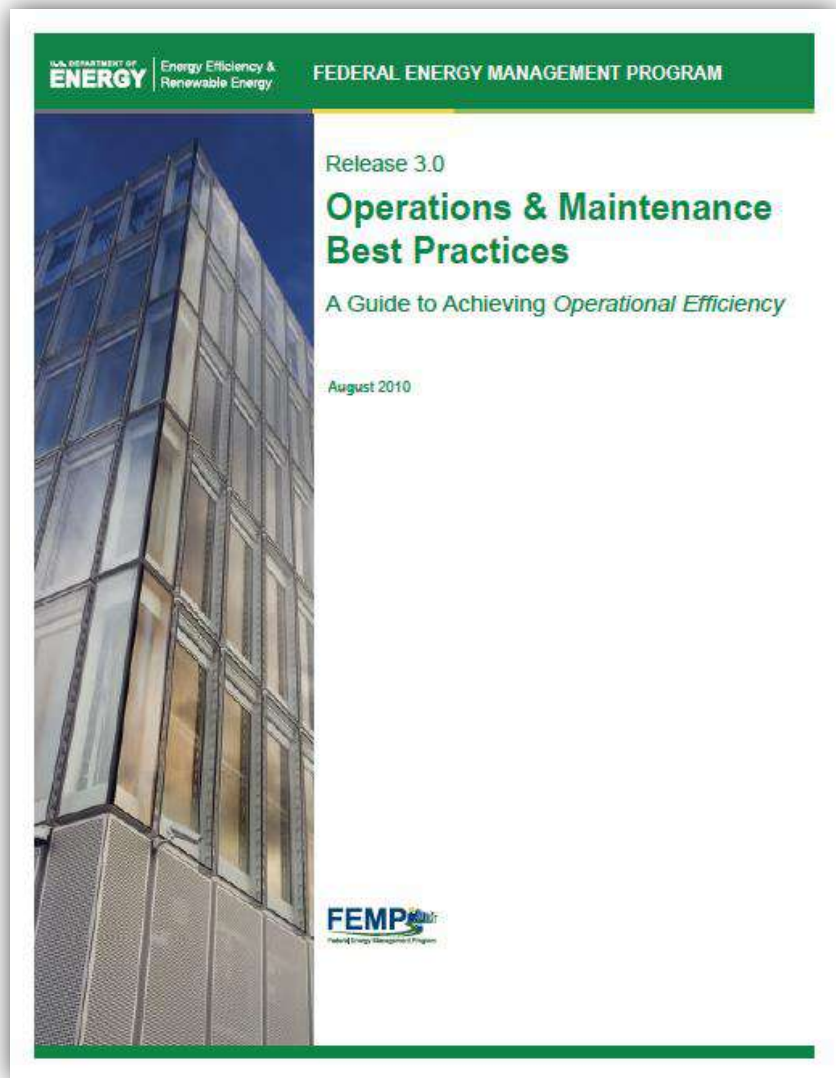
Guidelines and Best Practices


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FEDERAL ENERGY MANAGEMENT PROGRAM

Release 3.0

Operations & Maintenance Best Practices

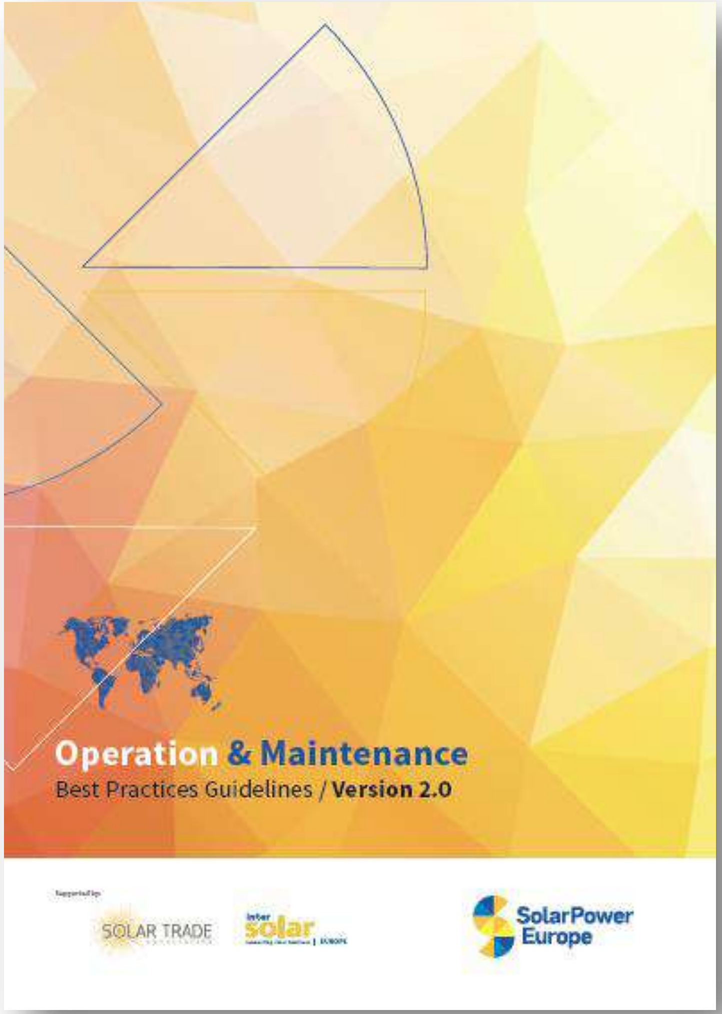
A Guide to Achieving *Operational Efficiency*

August 2010

FEMP

Fraunhofer ISE

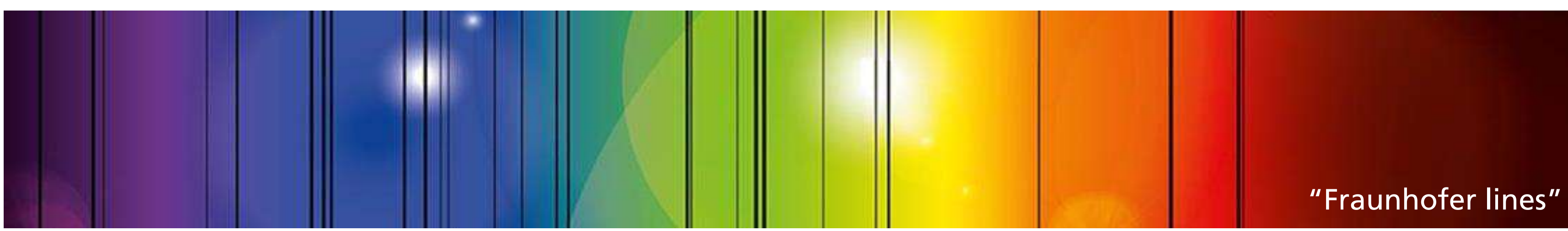
Guidelines and Best Practices



Operation & Maintenance

- High performance and low OPEX can be ensured by
  - Quality Assurance for components e.g. modules
  - Initial and periodic system inspection
  - Profound monitoring system with reliable data analysis will reveal failures, degradation and soiling

- Currently industry endeavor to implement new approaches for failure detection, predictive monitoring, best time to clean by use of machine learning and Artificial Intelligence (AI).



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Quality Assurance for utility scale PV plants

DEVELOPMENT
- solar resource assessment
- site analysis
- environmental stress assessment
- design review and optimization
- feasibility studies

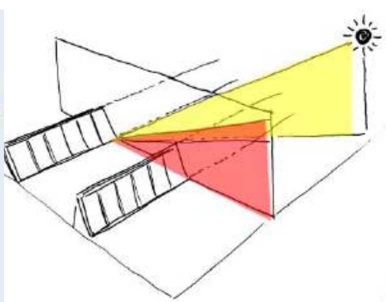
ENGINEERING
- yield assessment
- component bench-marking:
  - module power and energy rating
  - inverter testing

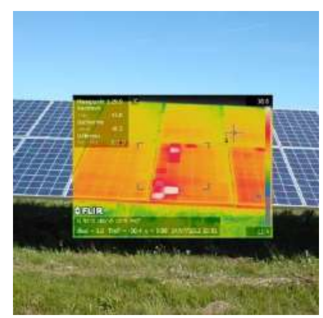
PROCUREMENT
- representative module sampling and checks:
  - performance
  - reliability
  - workmanship

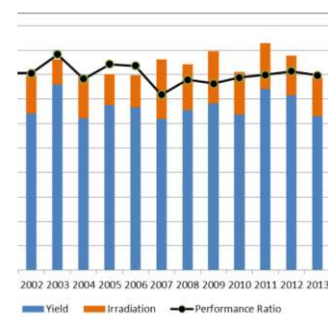
- technical and financial due dilligence*
- comprehensive PV plant certification*

COMMISSIONING
- final power plant test:
  - visual inspection and thermography imaging
  - module power measurements
  - initial performance verification
- final acceptance report

OPERATION
- continuous long-term performance reporting
- failure analysis and reporting
- optimization and re-powering
- warranty check







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Inspection Technics

- **Visual inspection of the PV plant**
- Experiences from the field – lessons learned
- Infrared images of modules and electrical connections
- Measurement of the solar generator to verify module power
- Verification of the monitoring system

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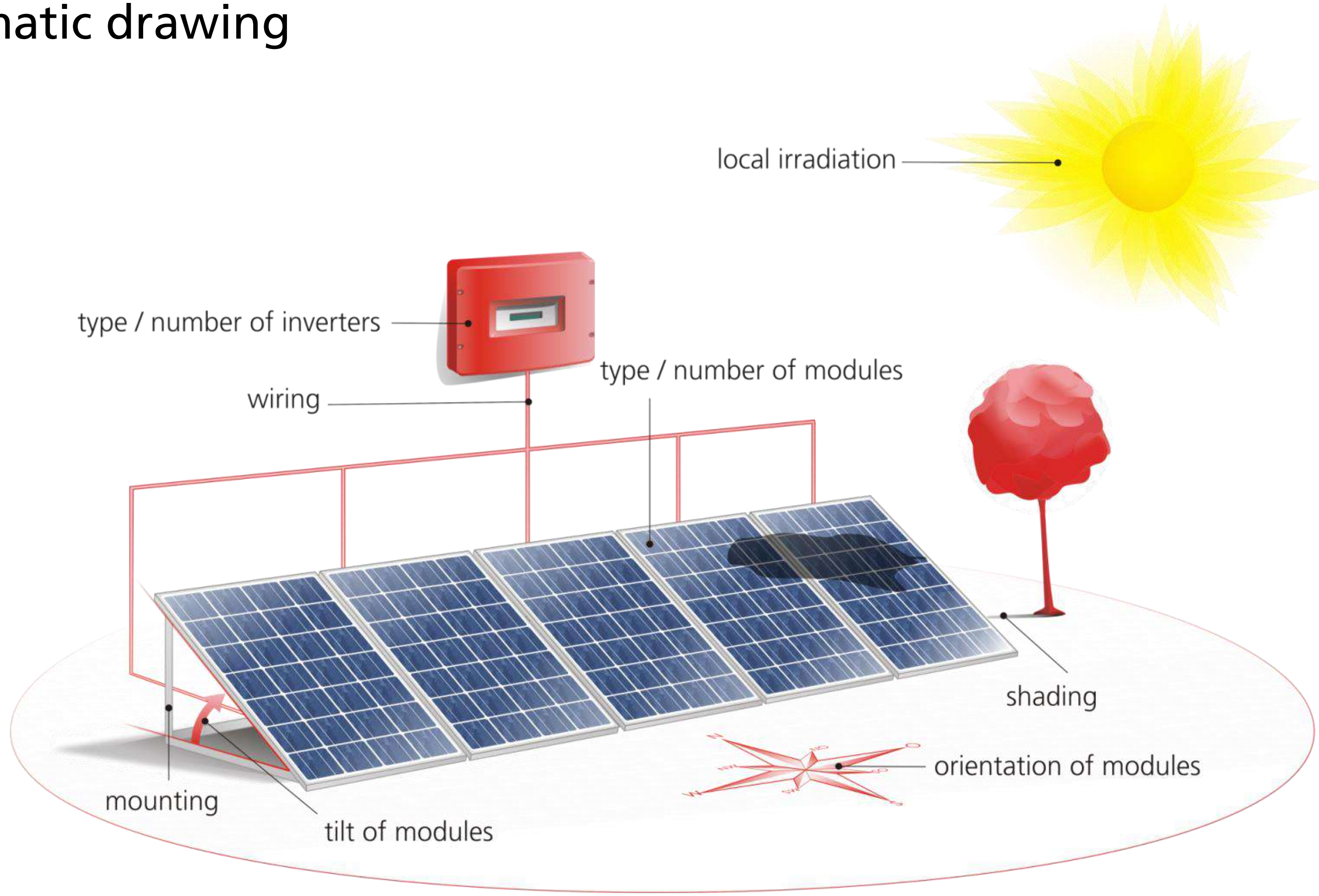
System Inspection and Testing

Visual Inspection of the PV System

- Schematic drawing



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System Inspection and Testing

Visual Inspection of the PV System

➢ PV-Power Plants – free-standing and rooftop

Visual inspection of the PV plant

Comparison of the as-built and as-planned system according to the Fraunhofer ISE Checklist

	Component	Target	Value from documentation	Review	√
Entire Plant	**Solar Plant**	Name/ Place/ Customer			
	Operator	For Report			
	Installation company	For Report			
	Date	DD.MM.YYYY-DD.MM.YYYY			
	Total DC Power	Comparison w/ documentation			
	Modules	Type 1 (no./ power class)			
		Type 2 (no./ power class)			
	Inverters (comparison daily yields & operation hrs)	Type 1 (no./ Allocation)			
		Type 2 (no./ Allocation)			
		Type 3 (no./ Allocation)			
	Orientation	Comparison w/ documentation			
	Fixed Tilt Angle	Comparison w/ documentation			
	Distance between rows	Comparison w/ documentation			
	Hight of module table	Comparison w/ documentation			
	Shading Angle	Comparison w/ documentation			

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Wiring	**DC Cable**	Manufac./ cross-section/ length			
	AC Cable	Manufac./ cross-section/ length			
	Wiring	Optimized			
	Cable conduit	professional/ closed			
Solar Generator (DC)	**Modules**	Interconnection			
	Fuses	Comp. with I_{sc} of string/ inv.			
	String Voltage	Meas: U_{OC}/ docu: U_{MPP}→TKU_{OC}!			
	Inverter	String Allocation/ Installation			
	Module clamps	Tight/ Installation/ Shading			
	Frame/ Substructure	Stability/ expansion gap/ PE			
	Connection Boxes	Moist/ Inst./ Cable lead fittings			
	Labeling	existing/ clear			
	Infrared camera testing	100 %: dT=15 K, E>700 W/m^2			
	STC Power Determination	b./a. cleaning/ 10 %/ Ref-Str.			
Mon	**ISE-Monitoring**	Ref-Cell, Sensors, Fct.			
	Operation mangement	If possible check before			
Shading	**Objects**	Determination/ measuring			
	Inv./ DC-/ AC-distributor	Determination/ measuring			
	Image of horizont				
AC	**Electrical enclosures**	Fuses/ Labeling			
	Transformerr	Comparison w/ documentation			
	Position of meter	Before/ after transformer			

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System Inspection and Testing

Visual Inspection of the PV System

- Shading (typical values)

Row Shading: -1 to -6 %

External Shading: 0 to -3 %

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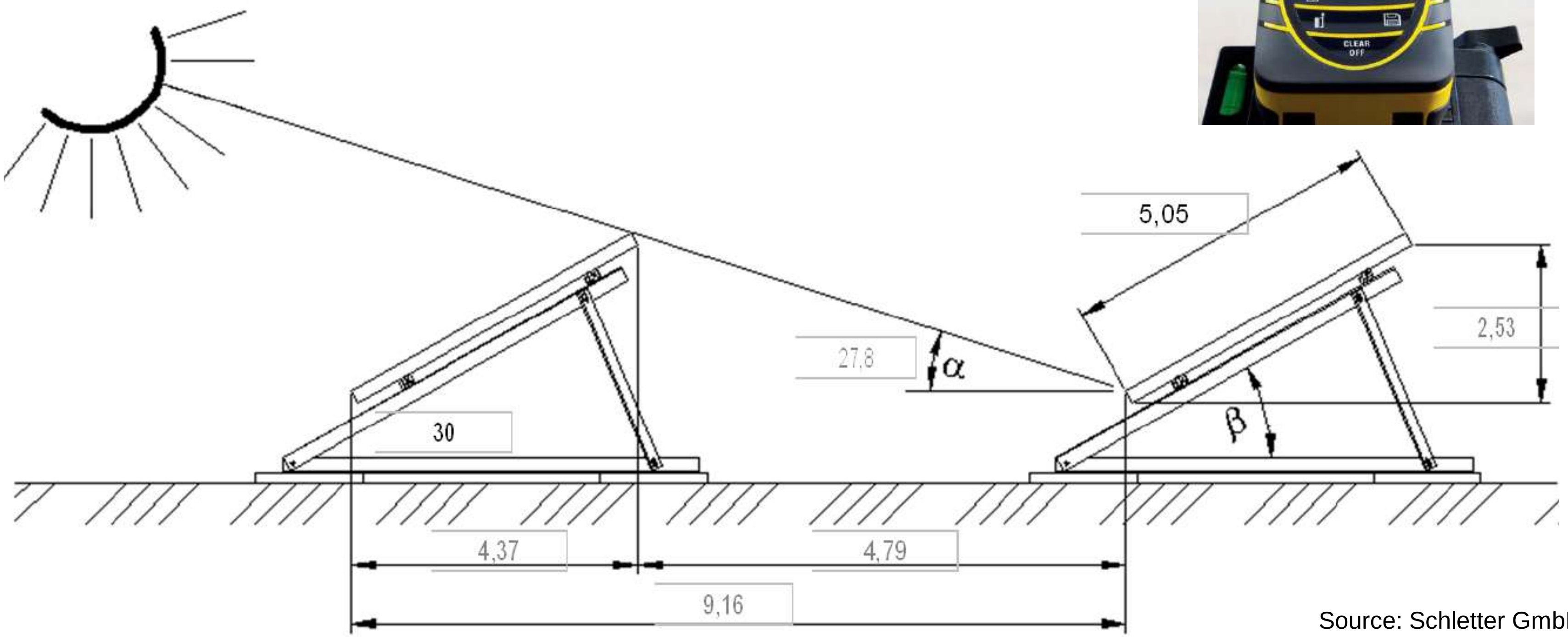
System Inspection and Testing

Visual Inspection of the PV System

- Examination of row shading



Source: Schletter GmbH

System Inspection and Testing

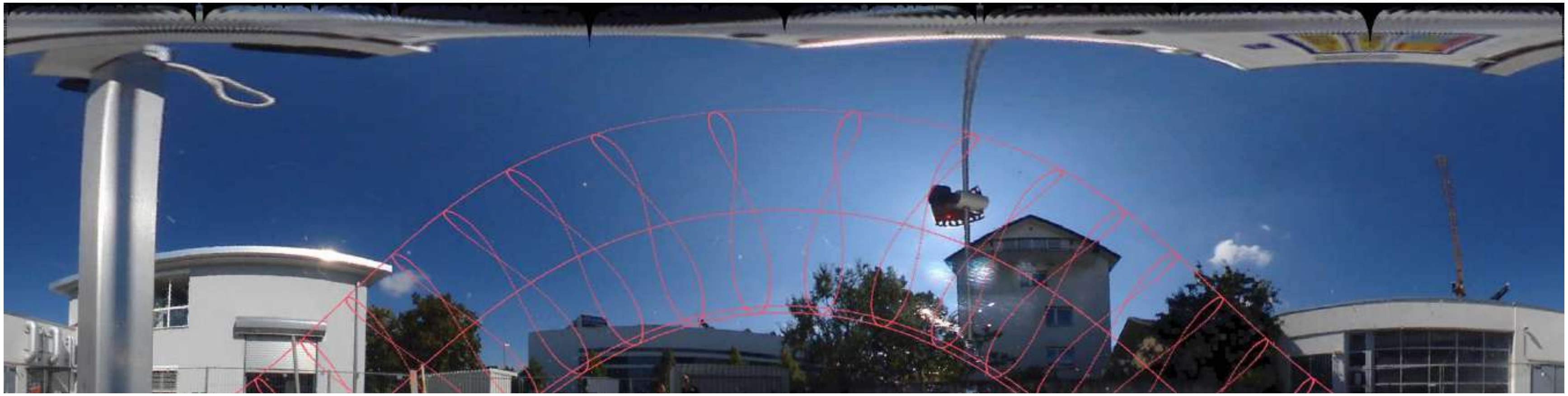
Visual Inspection of the PV System

- Inspection of external shading with HORIcatcher

System Inspection and Testing

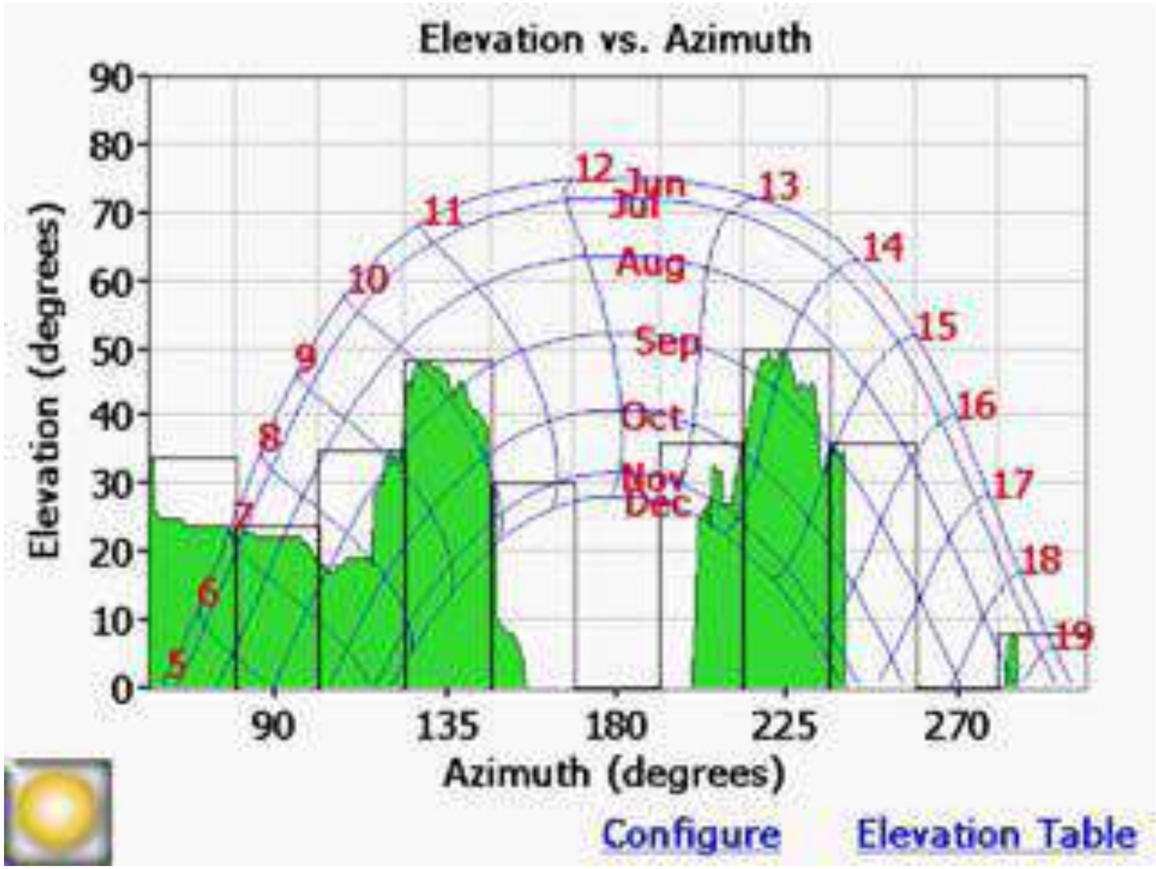
Visual Inspection of the PV System

- Analysis of the external shading



System Inspection and Testing

Visual Inspection of the PV System



Inspection Technics

- Visual inspection of the PV plant
- **Experiences from the field – lessons learned**
- Infrared images of modules and electrical connections
- Measurement of the solar generator to verify module power
- Verification of the monitoring system
- Short-term performance check of the PV plant

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Visual inspection of the PV Power Plant

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Visual inspection of the PV Power Plant

Visual inspection of the PV Power Plant

Experiences from the field

Some screws for mounting the modules are not properly tightened

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Visual inspection of the PV Power Plant

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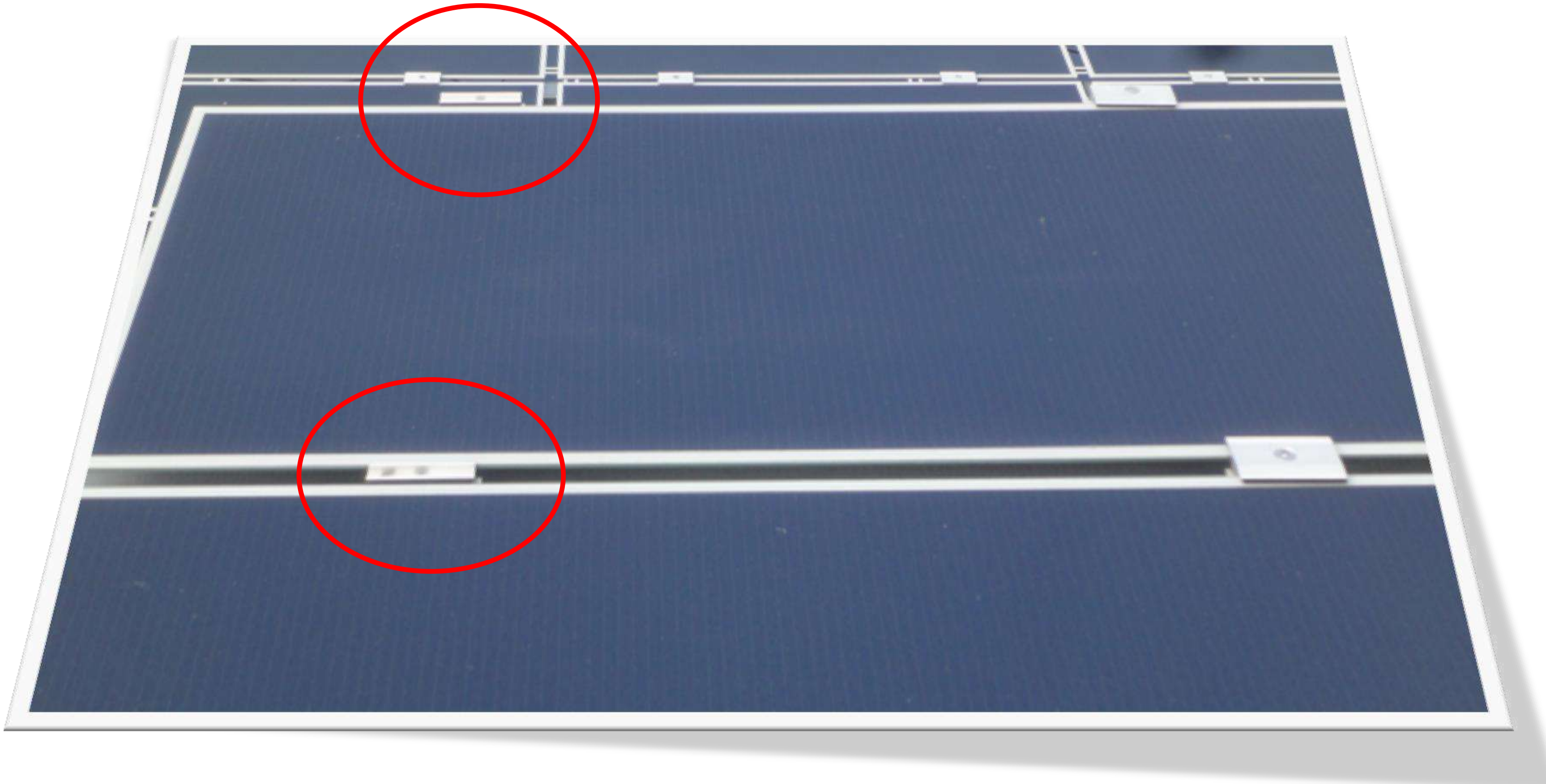
Visual inspection of the PV Power Plant

Visual inspection of the PV Power Plant



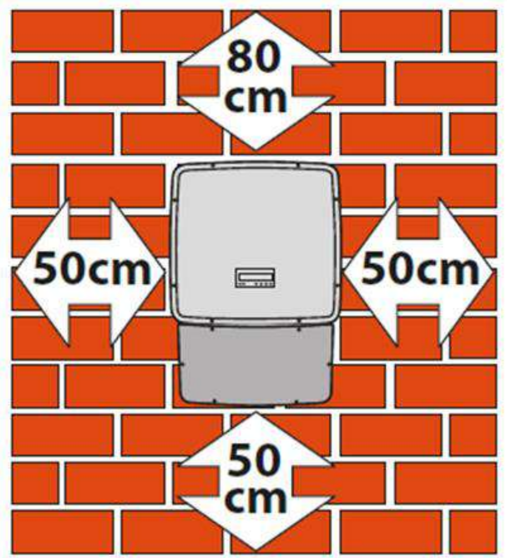
Visual inspection of the PV Power Plant

Mounting of modules

Visual inspection of the PV Power Plant

Visual inspection of the PV Power Plant

Visual inspection of the PV Power Plant



• To carry out maintenance of the hardware and software of the equipment, remove the covers on the front. Check that there are the correct safety distances for the installation that will allow the normal control and maintenance operations to be carried out.
• Comply with the indicated minimum distances.

Visual inspection of the PV Power Plant

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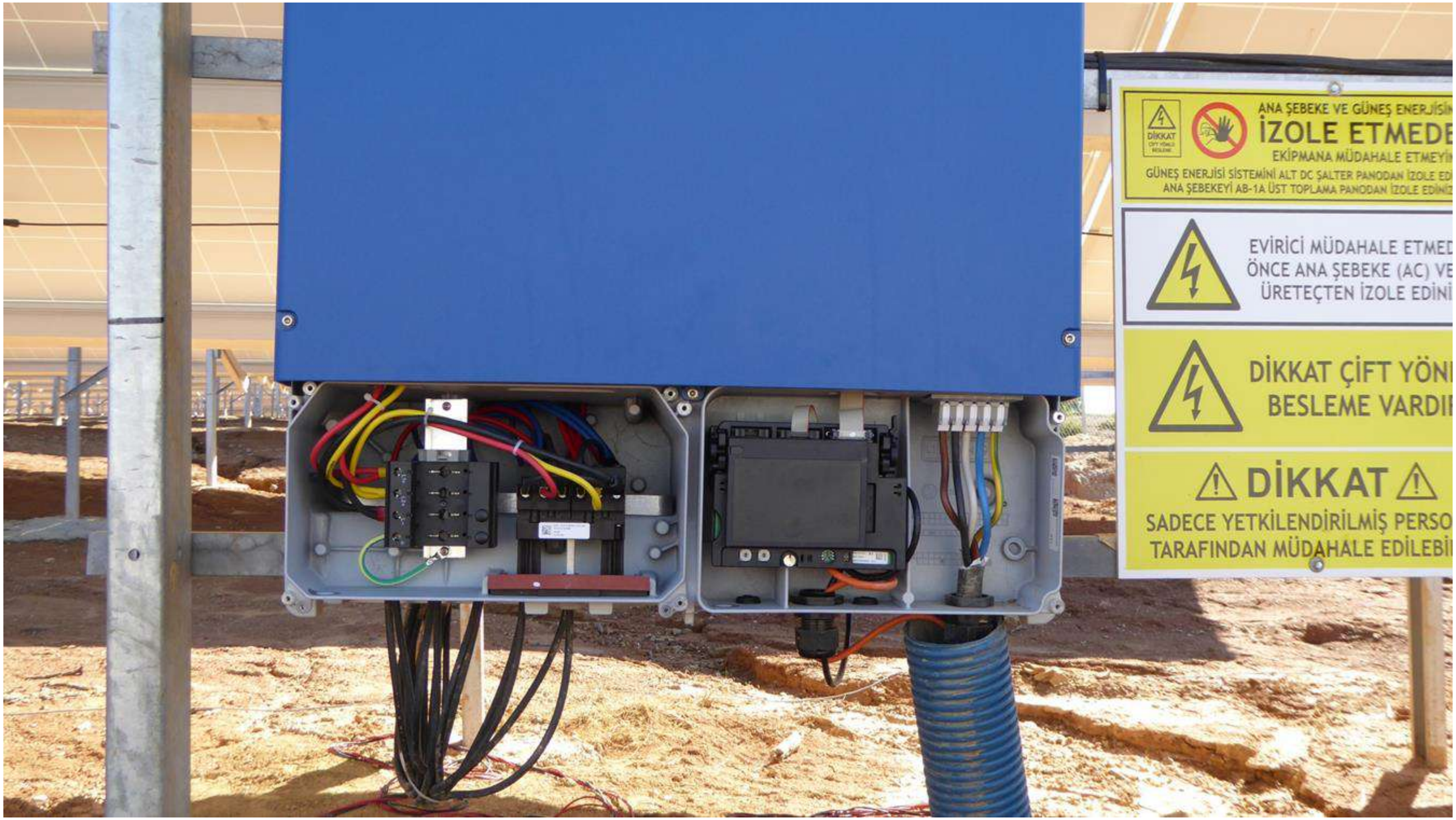
Visual inspection of the PV Power Plant

Visual inspection of the PV Power Plant



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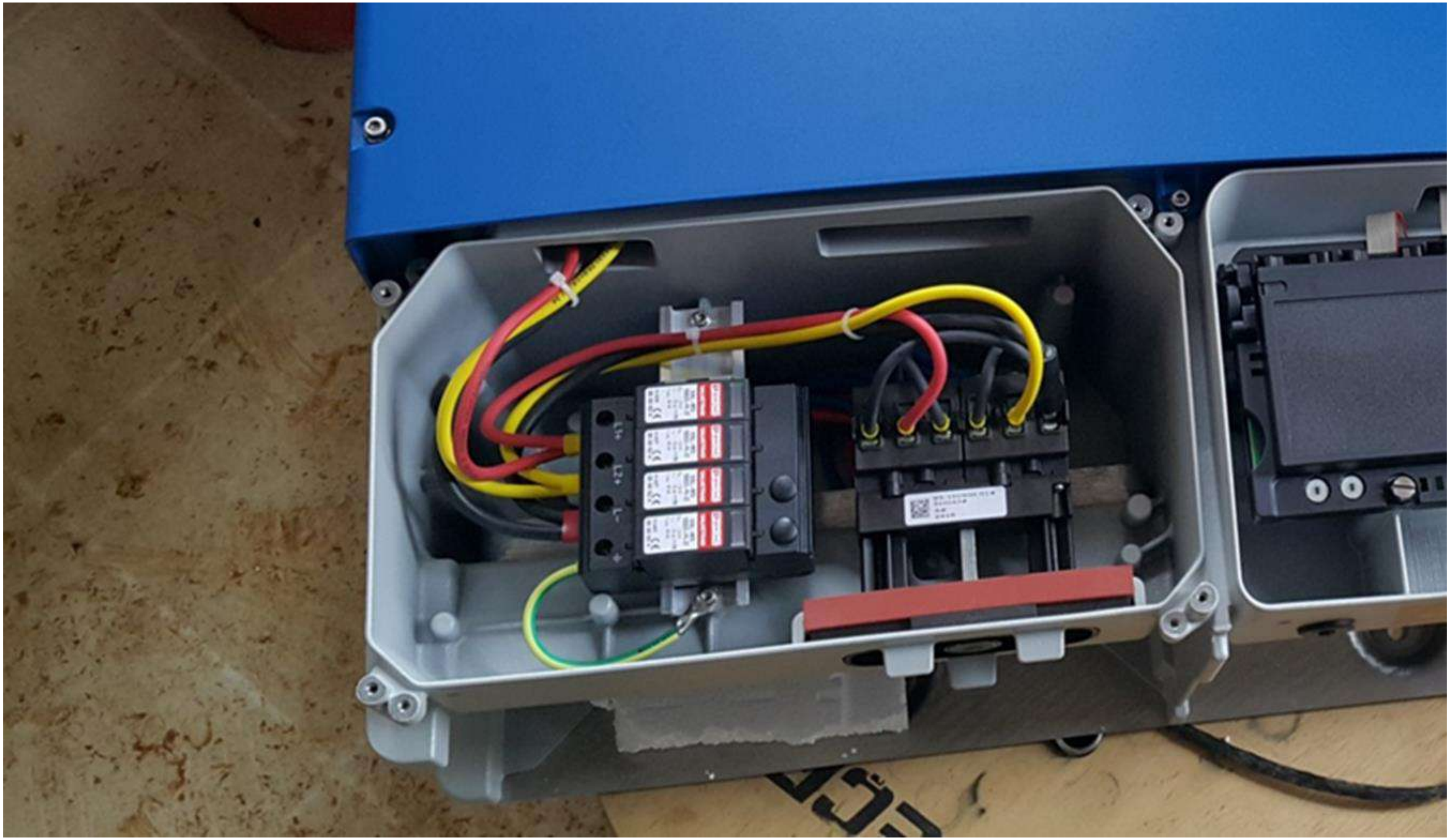
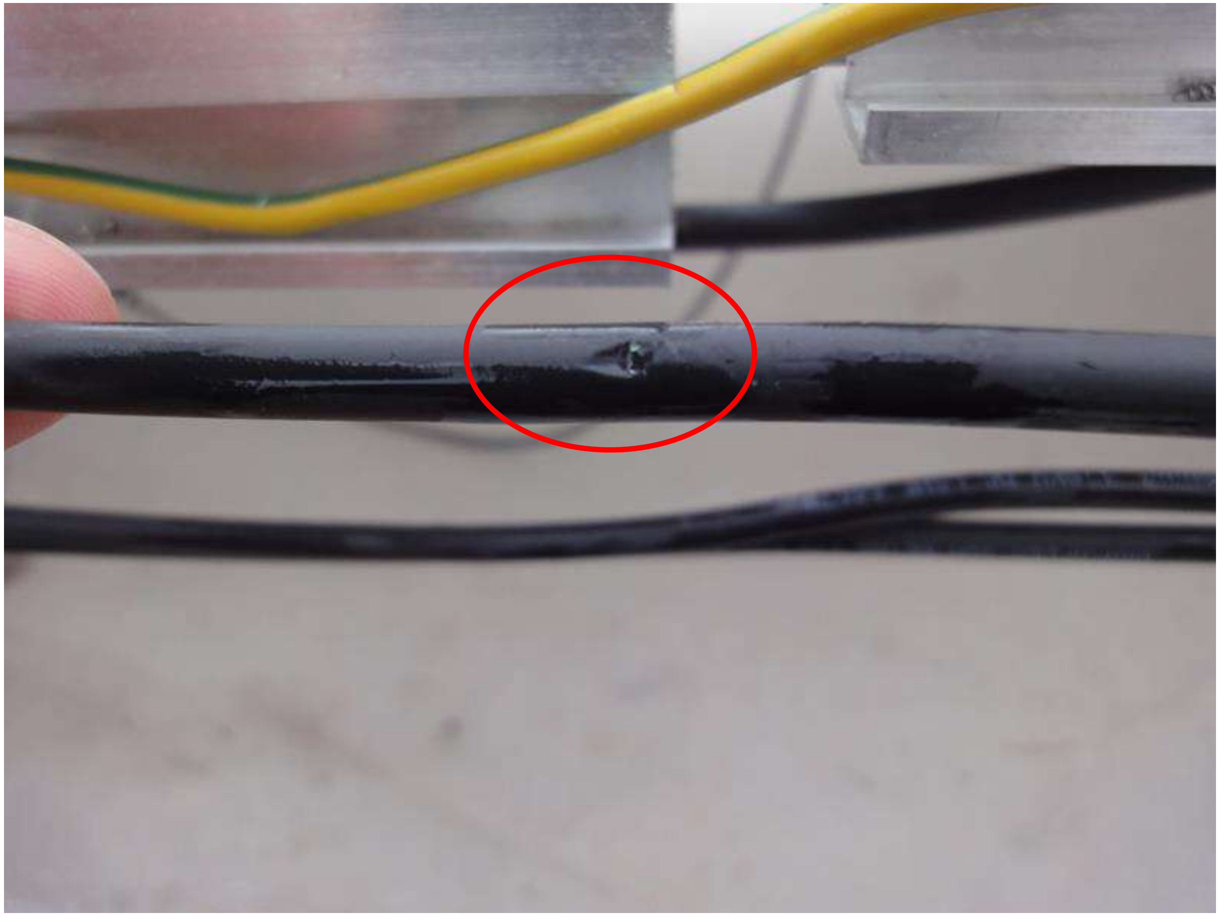
Visual inspection of the PV Power Plant



Visual inspection of the PV Power Plant

DC wiring



Visual inspection of the PV Power Plant

DC wiring

Visual inspection of the PV Power Plant

Fastening of cables

Experiences from the field

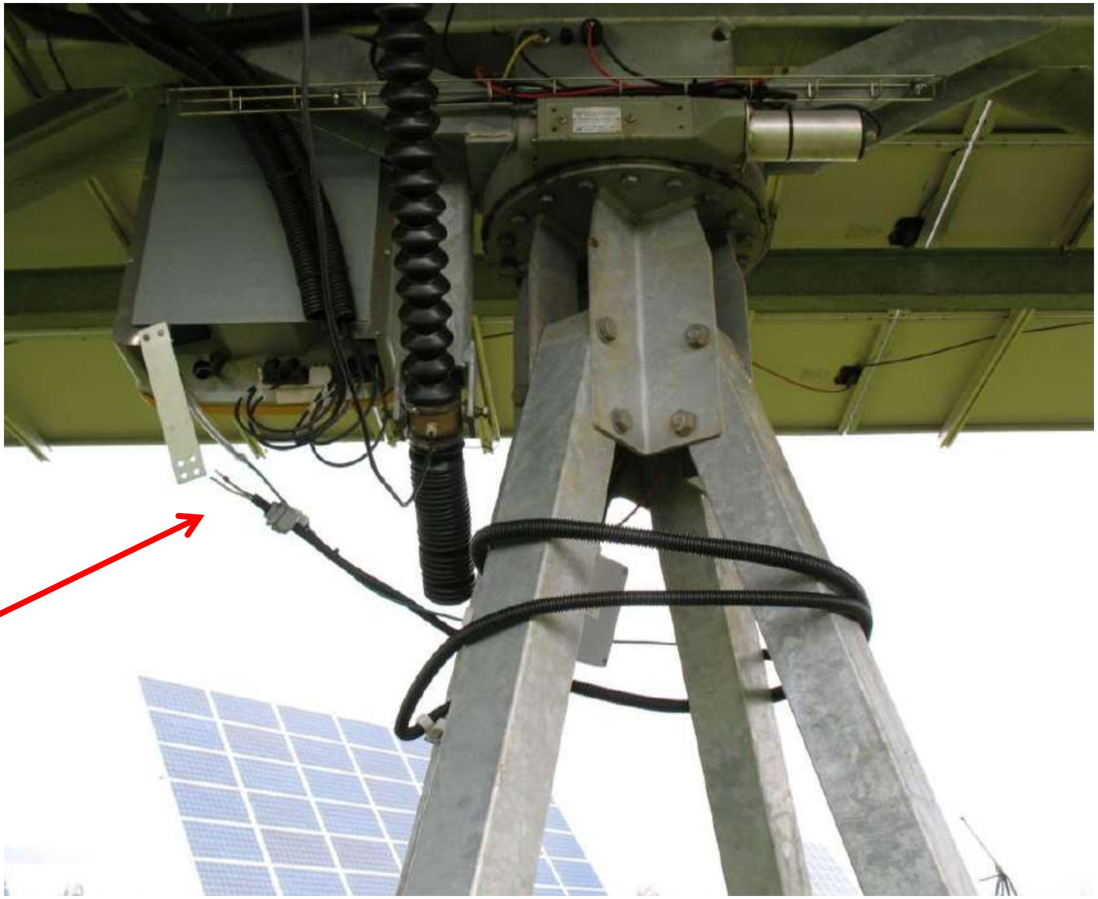
DC wiring

Experiences from the field

DC wiring

Experiences from the field

AC wiring



AC-cable demolition due to failure of the tracker

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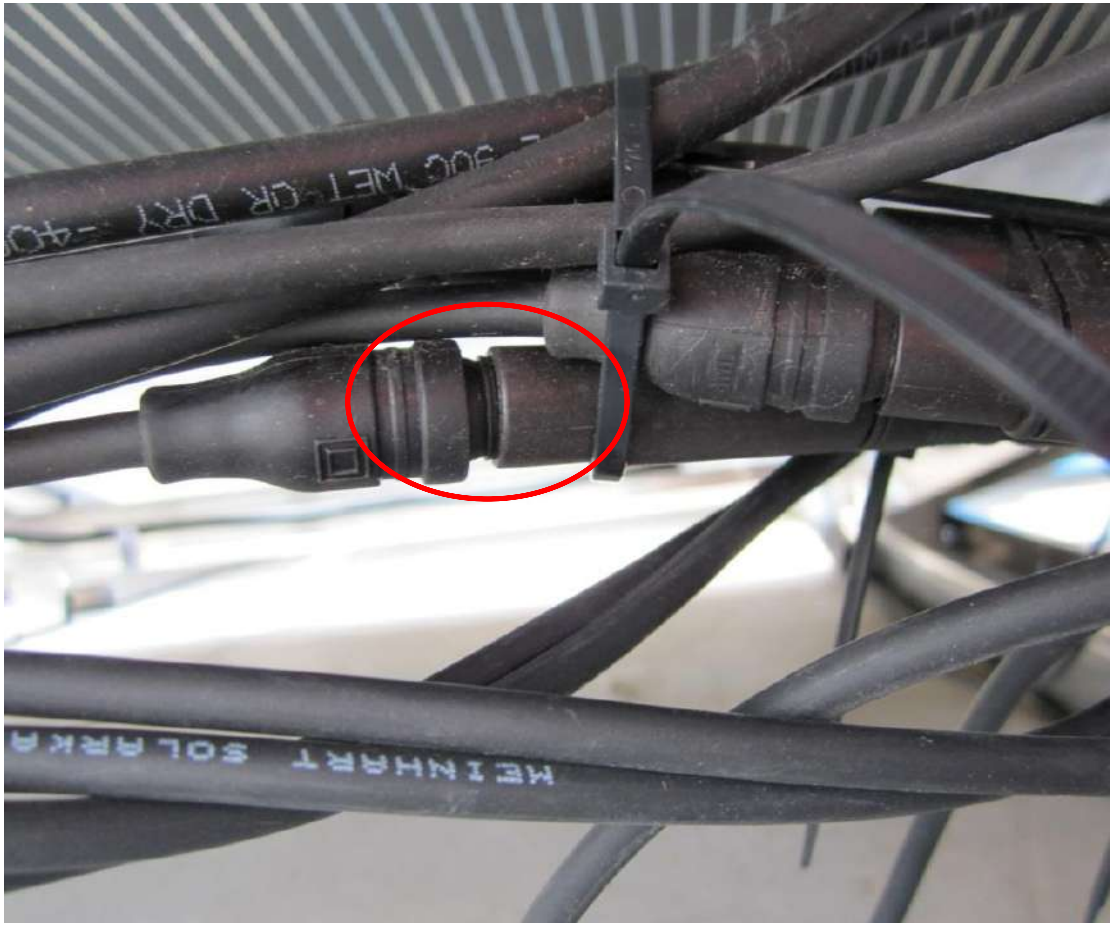
Experiences from the field

DC connectors

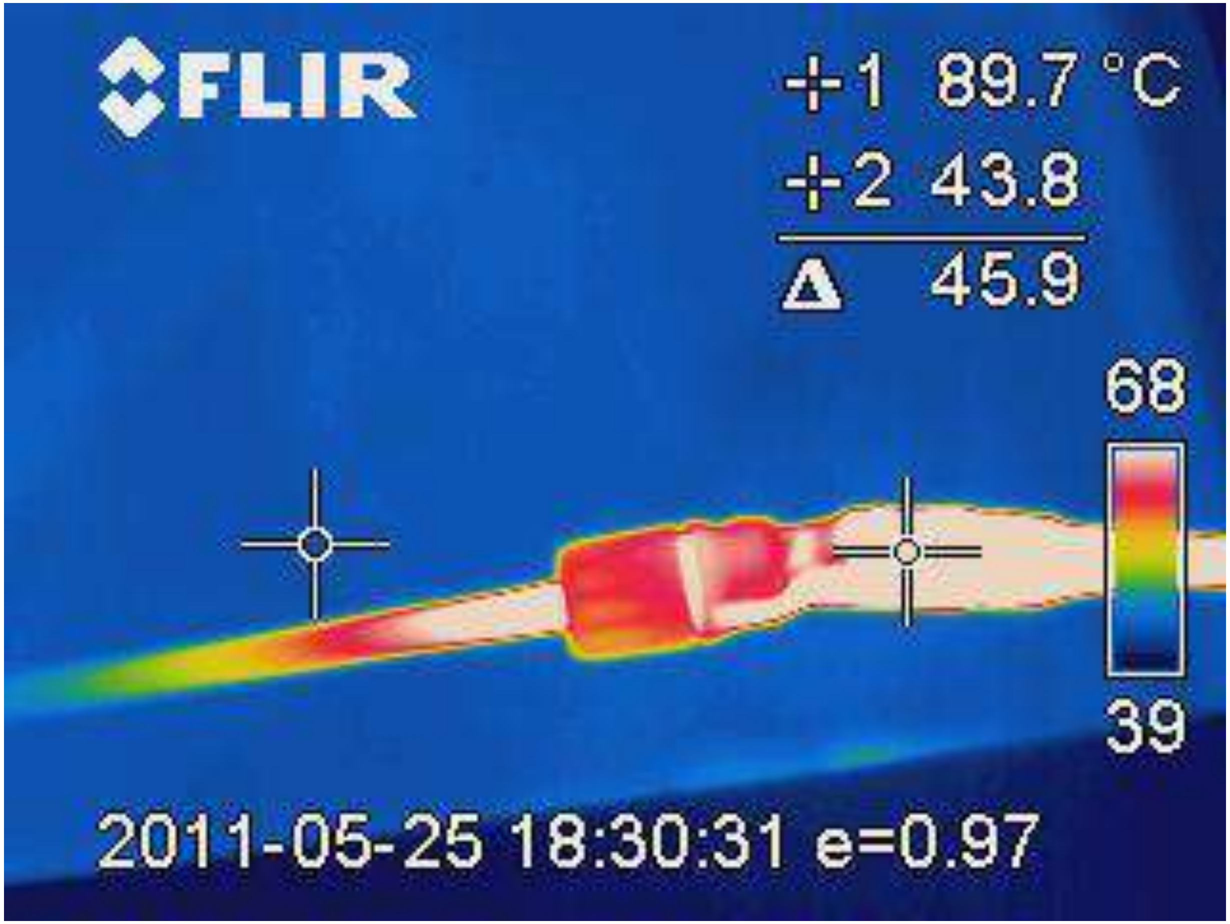


Experiences from the field

DC connectors

Experiences from the field

DC connectors



Experiences from the field

DC connectors

Fraunhofer ISE

Experiences from the field

DC connectors

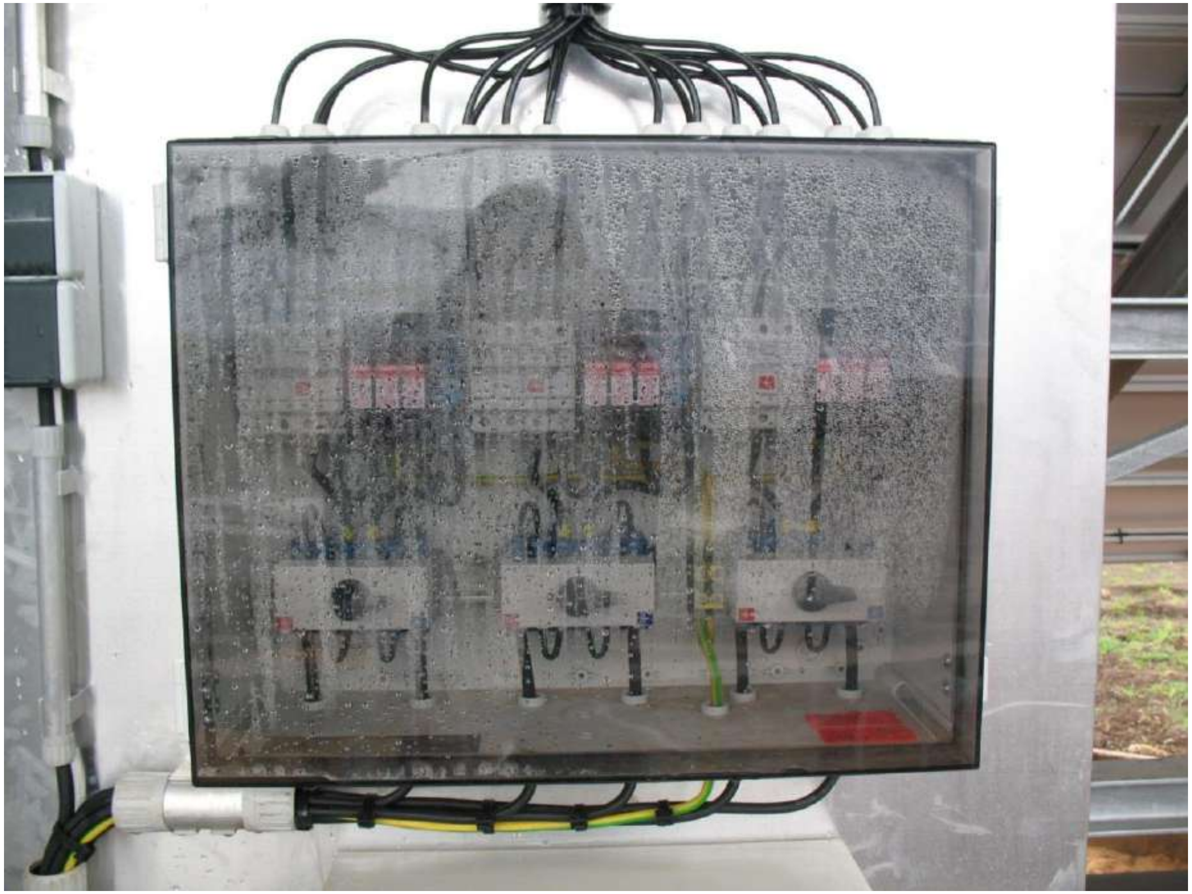
Combination of connectors from different manufacturers

Experiences from the field

Solar modules and junction boxes

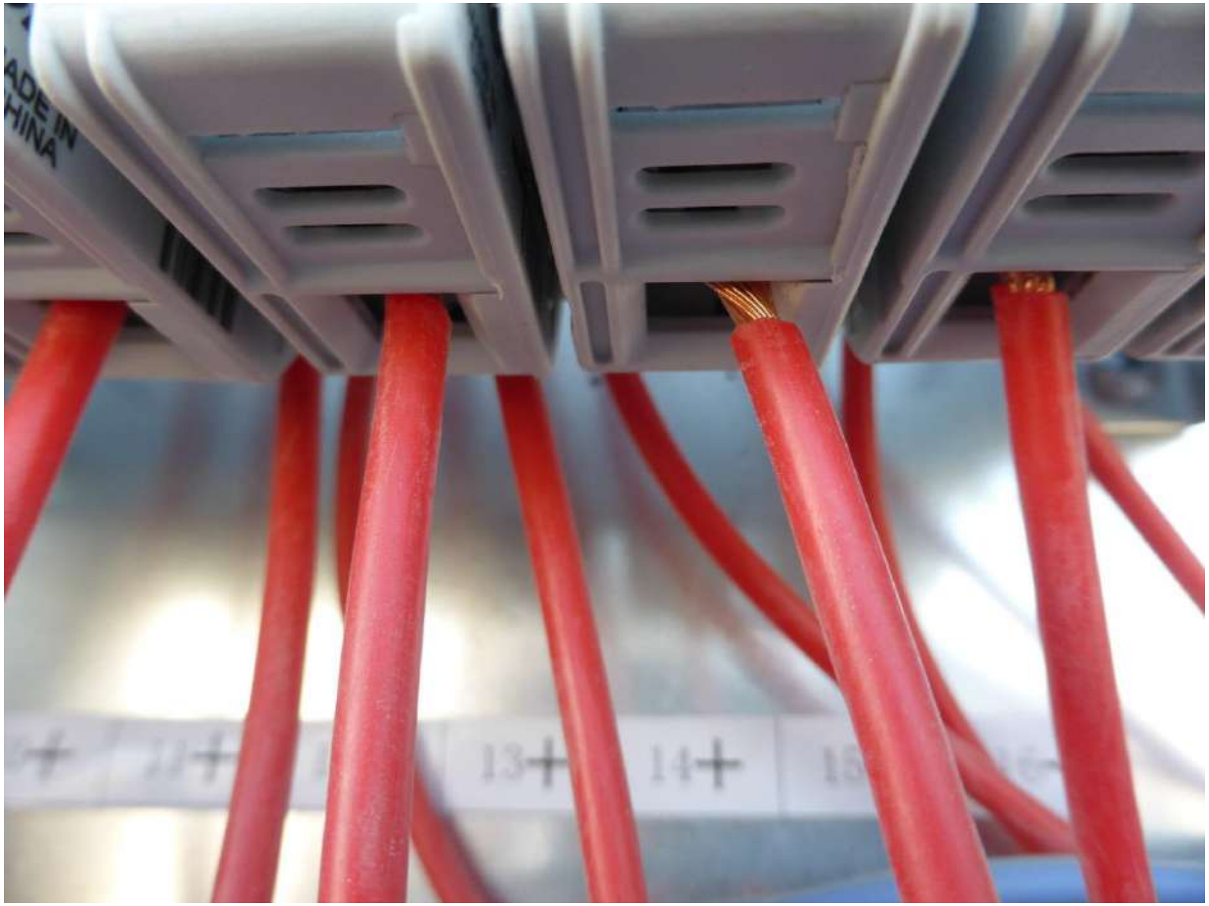
Experiences from the field

DC sub-distribution



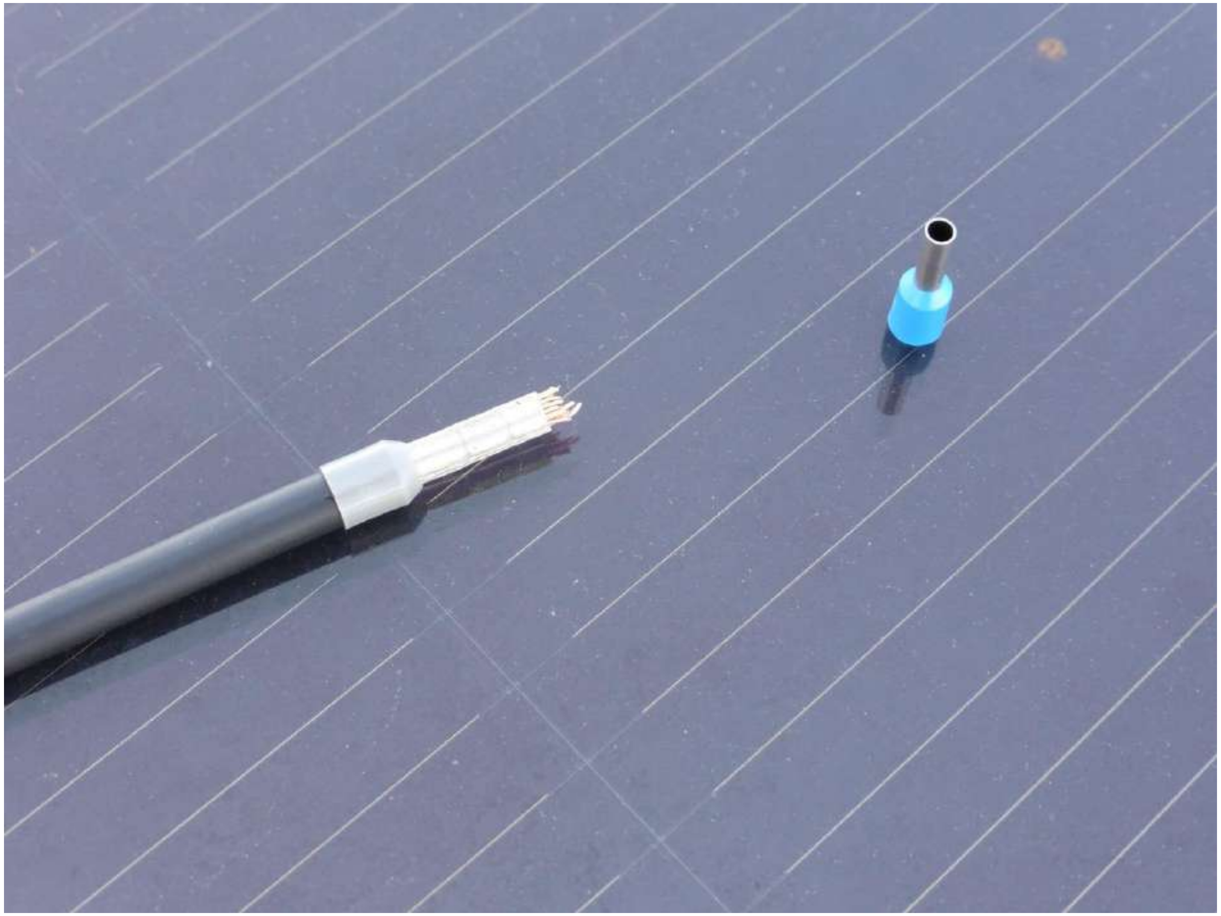
Experiences from the field

Terminal at the end of the DC cables in the string boxes are missing



Experiences from the field

Using the appropriate terminal at every cable



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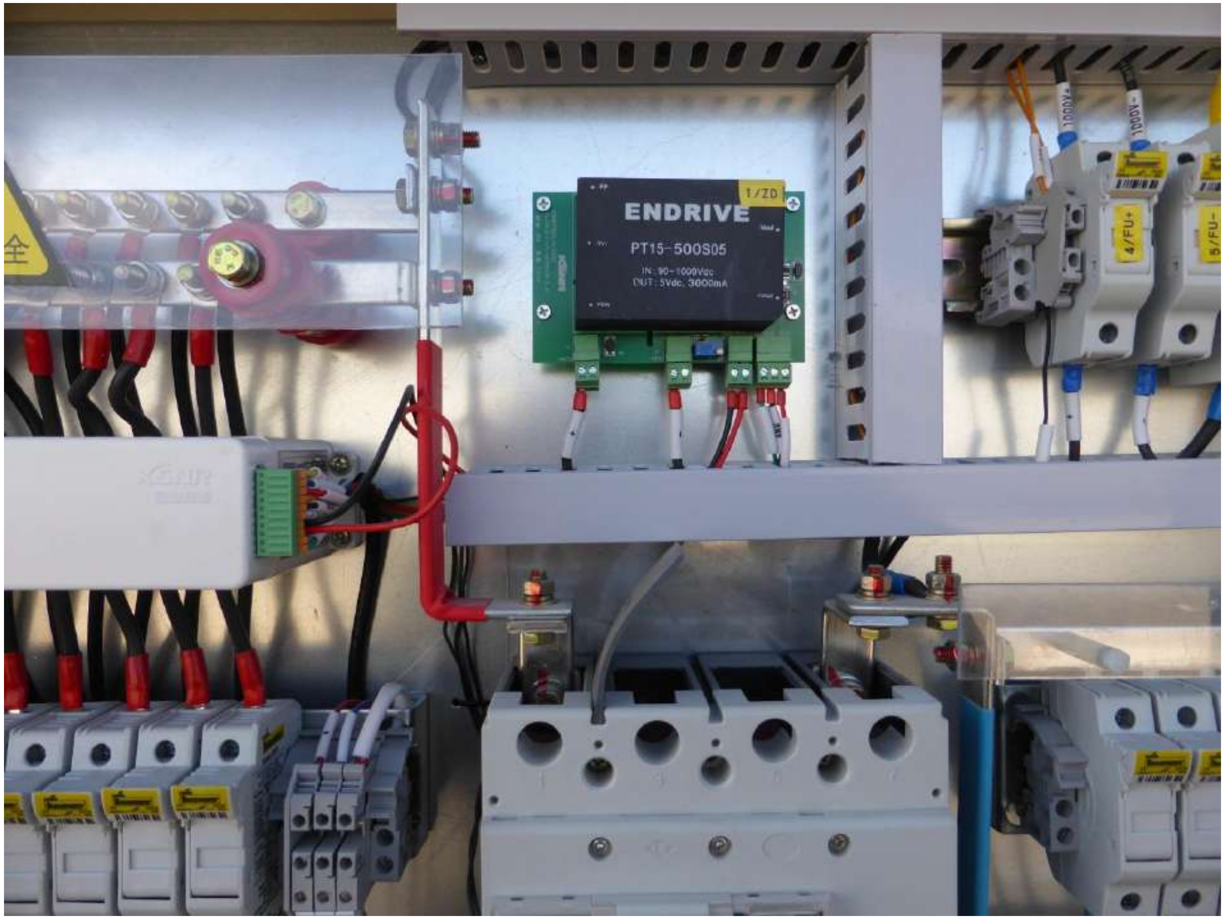
Experiences from the field

Electric shock protection at the DC-circuit breaker is missing



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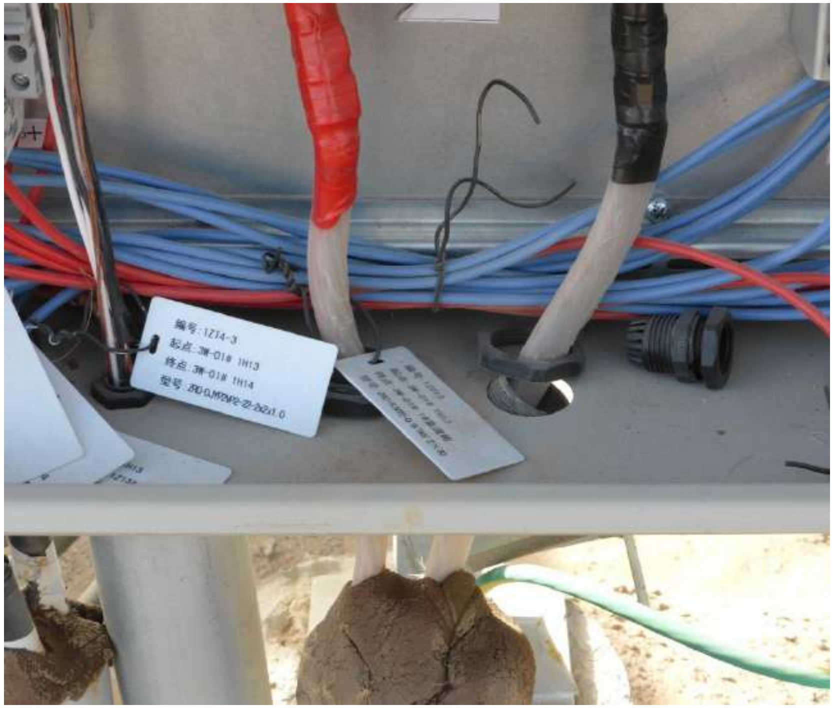
Experiences from the field

Some cable glands are not mounted properly or are missing completely



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Experiences from the field

Transformer

Experiences from the field

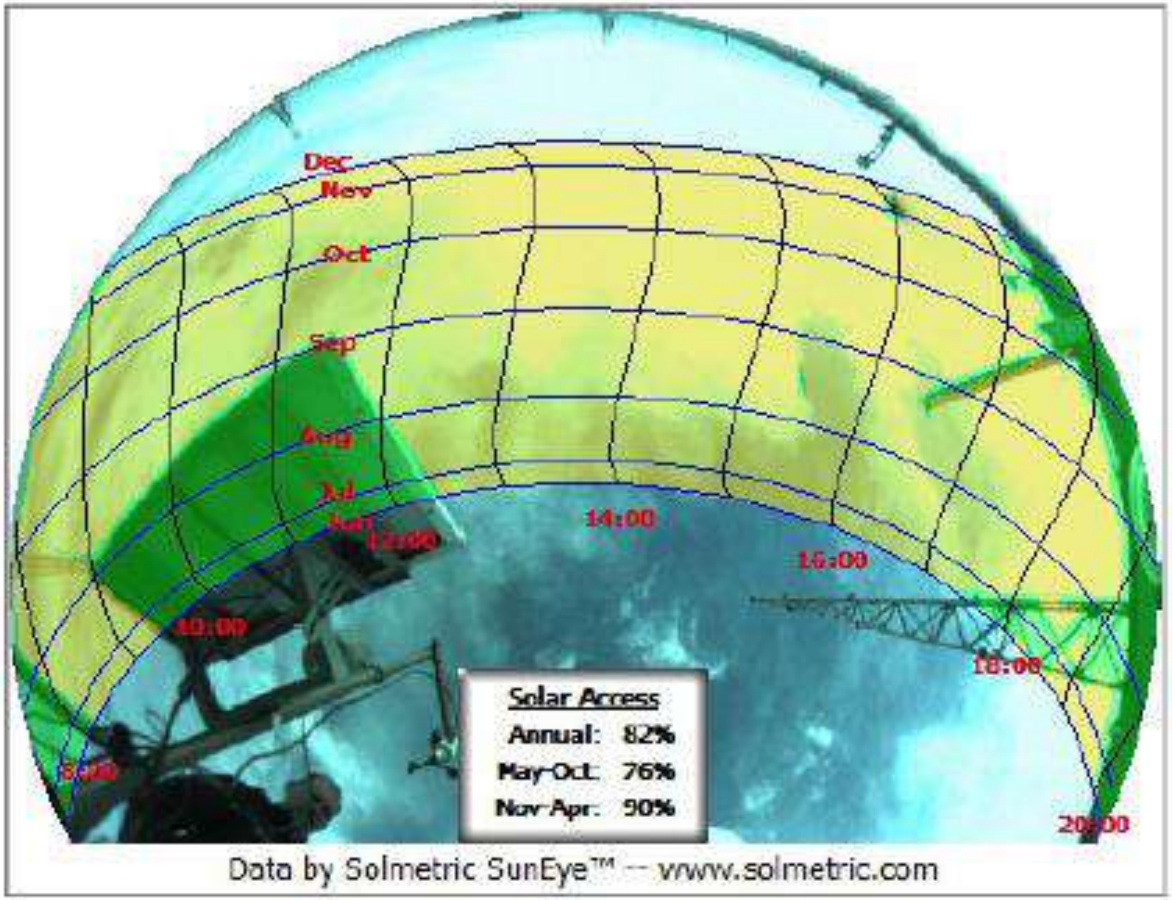
Transformer

Experiences from the field

The horizontally mounted pyranometer is shaded by several obstacles

Experiences from the field

Shading of the horizontally mounted pyranometer



Experiences from the field

Installation of a professional weather station

Inspection Technics

- Visual inspection of the PV plant
- Experiences from the field – lessons learned
- **Infrared images of modules and electrical connections**
- Measurement of the solar generator to verify module power
- Verification of the monitoring system
- Short-term performance check of the PV plant

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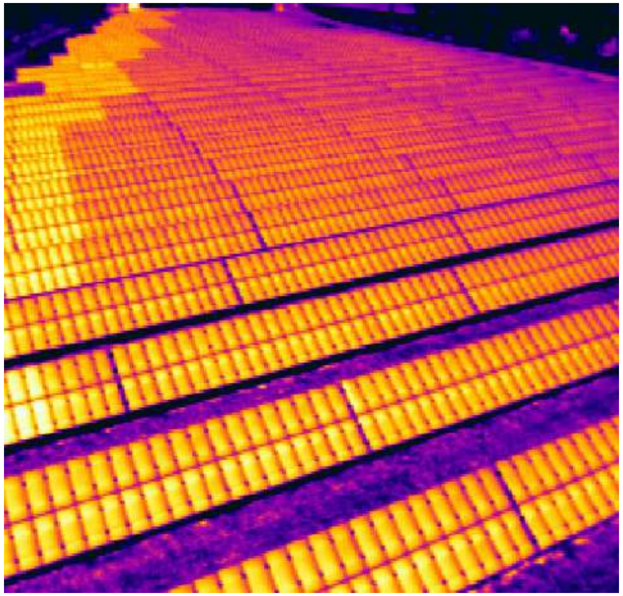
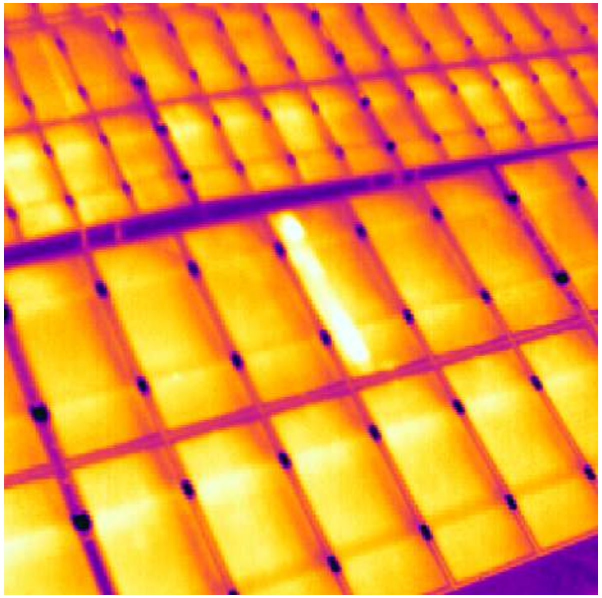
System Inspection and Testing

Infrared images

- Modules

Mobile lifting platform used for infrared camera imaging

Temperature analysis of a large module field

Temperature analysis of a solar module with defective cells

Fraunhofer ISE

System Inspection and Testing

Infrared images

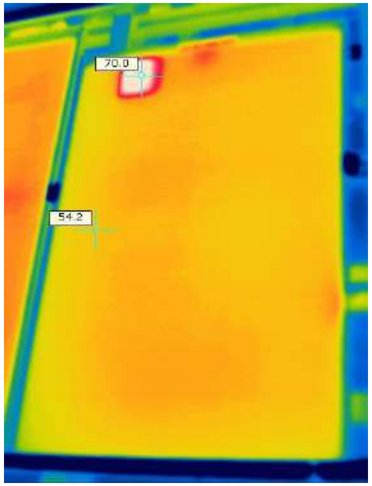
- Modules

Infrared image of a solar module with several hot spots

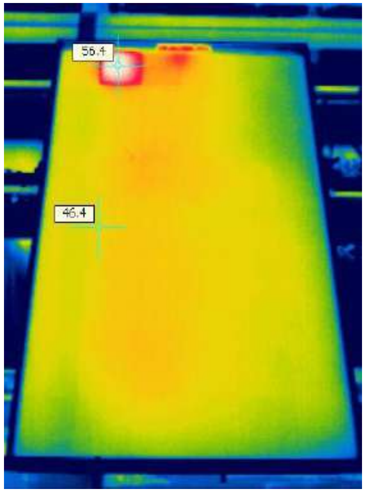
System Inspection and Testing

Infrared images

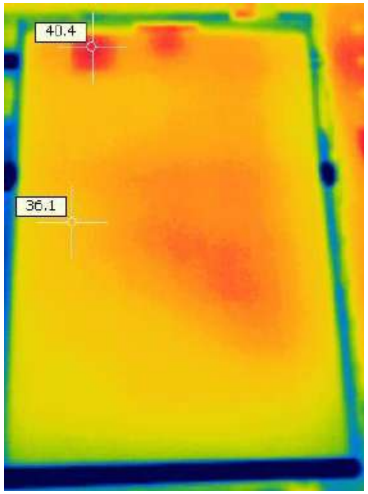
- Modules



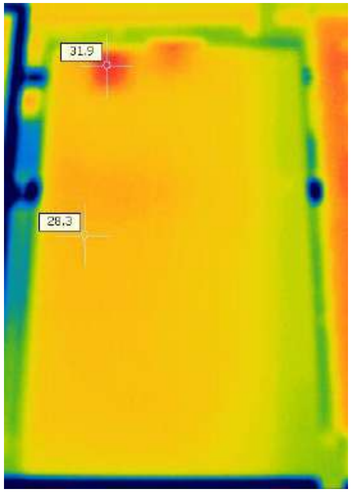
E = 1008 W/m²
ΔT = 15,8 °C



E = 854 W/m²
ΔT = 10,0 °C



E = 754 W/m²
ΔT = 3,9 °C

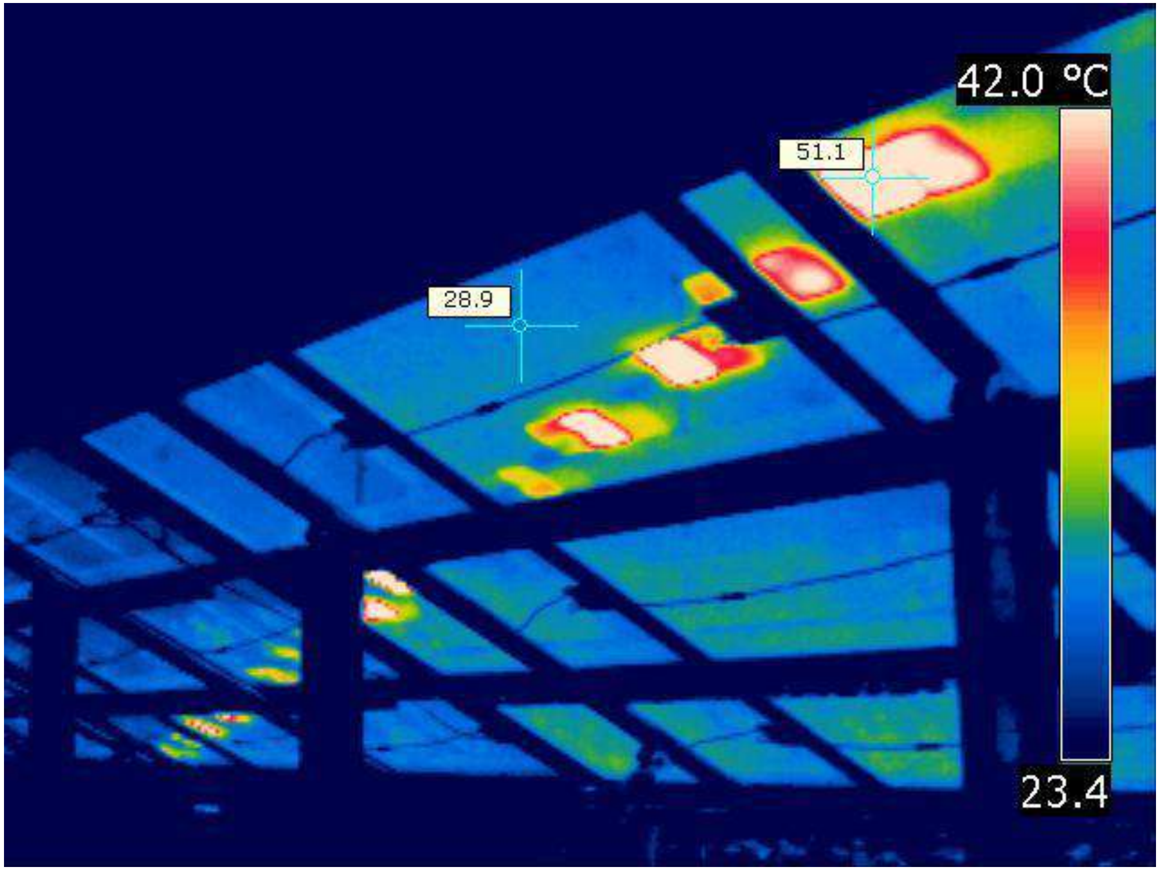


E = 633 W/m²
ΔT = 3,6 °C

System Inspection and Testing

Infrared images

- Modules



Infrared image of solar modules with several hot spots

System Inspection and Testing

Infrared images

- Modules

Front side of the modules with a shadow line

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System Inspection and Testing

Infrared images

- Modules

Shading caused by a power line

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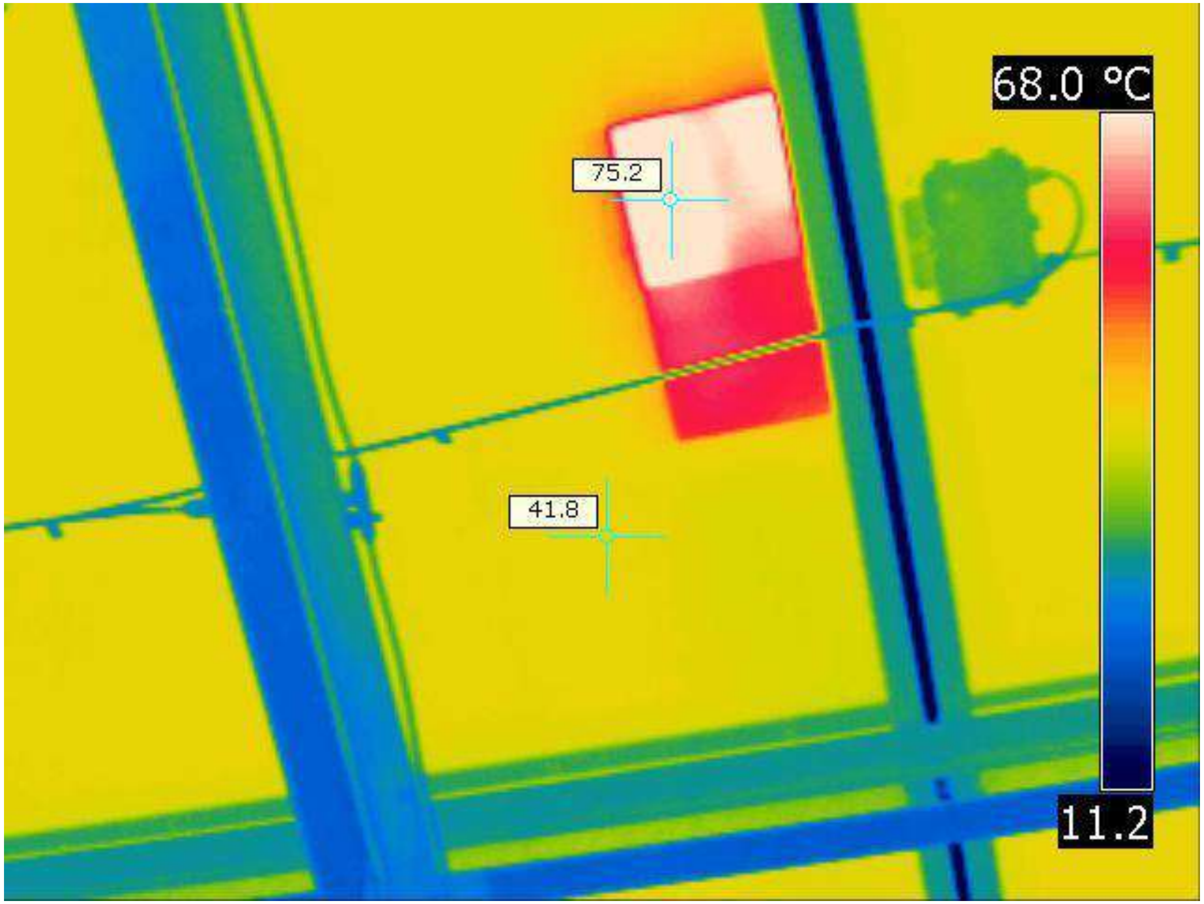
System Inspection and Testing

Infrared images

- Modules



Infrared image of a solar module with one hot spot

System Inspection and Testing

Infrared images

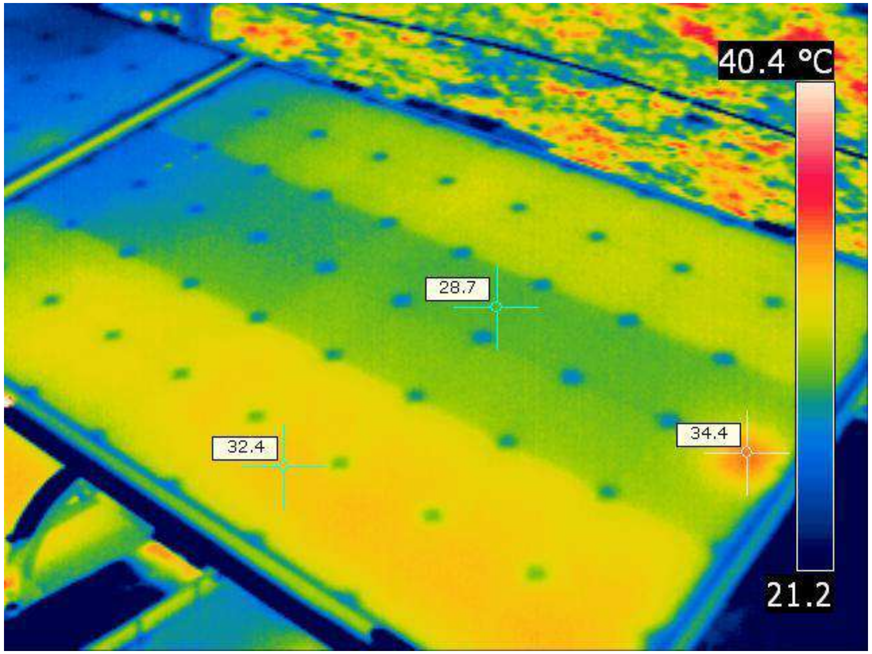
- Modules

Hot spot caused by bird droppings

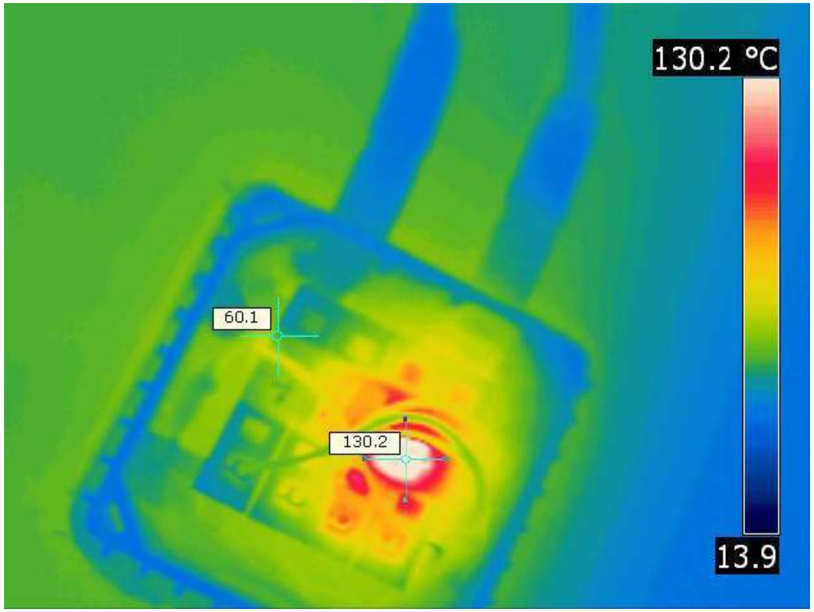
System Inspection and Testing

Infrared images

- Modules



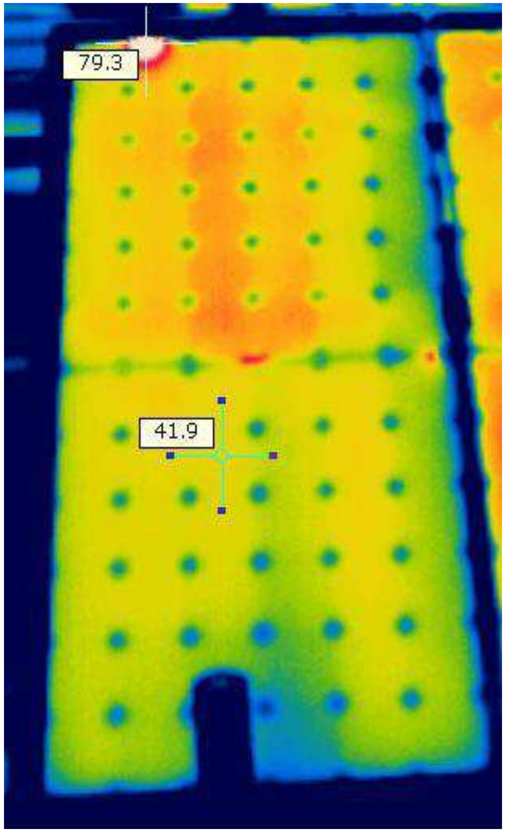
Infrared image of a solar module with a defect diode

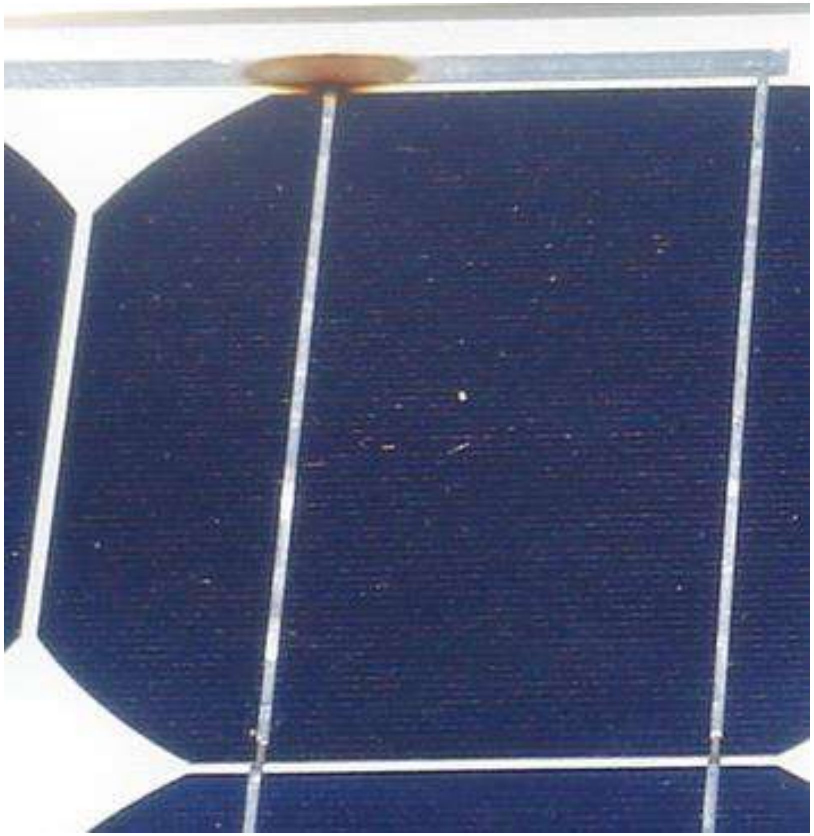


System Inspection and Testing

Infrared images

- Modules



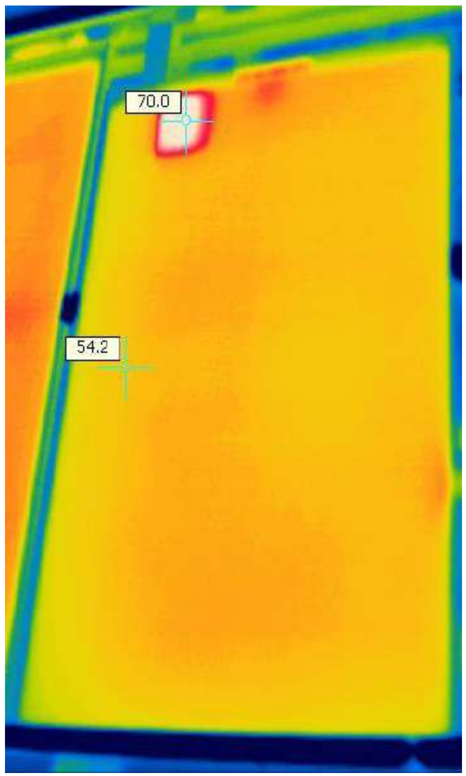


High transition resistance due to poor solder point

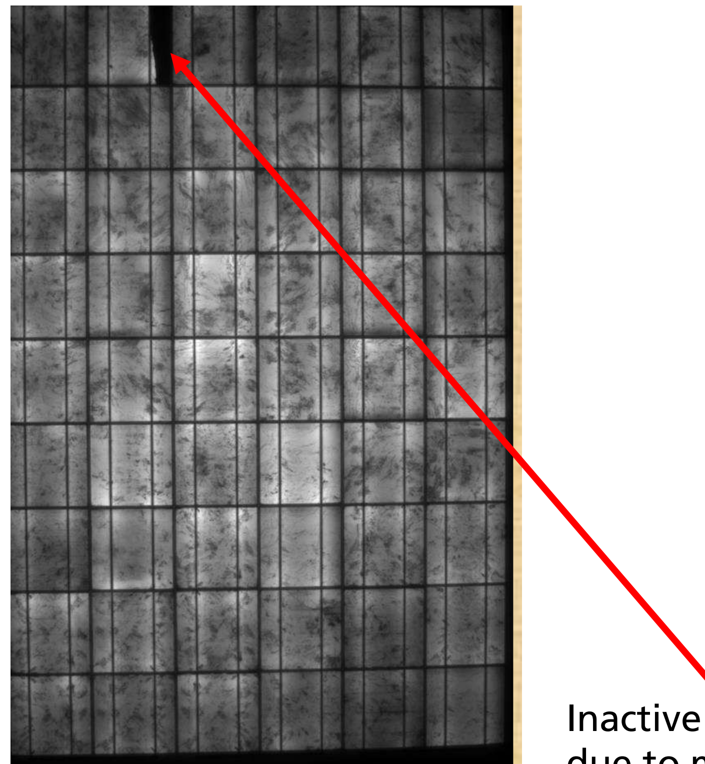
System Inspection and Testing

Infrared images

- Modules



E = 918 W/m²
ΔT = 16 °C



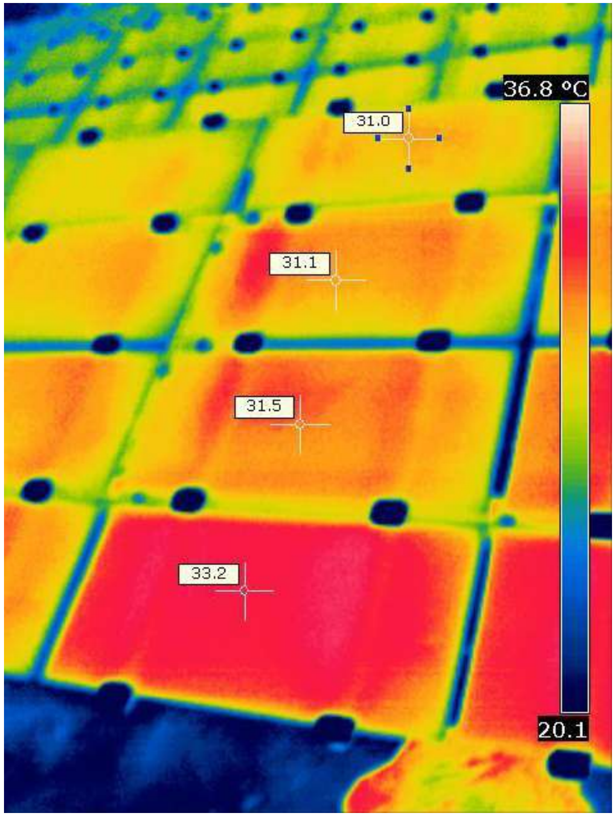
Inactive cell area due to micro crack

System Inspection and Testing

Infrared images

- Electrical connection

Disconnected string



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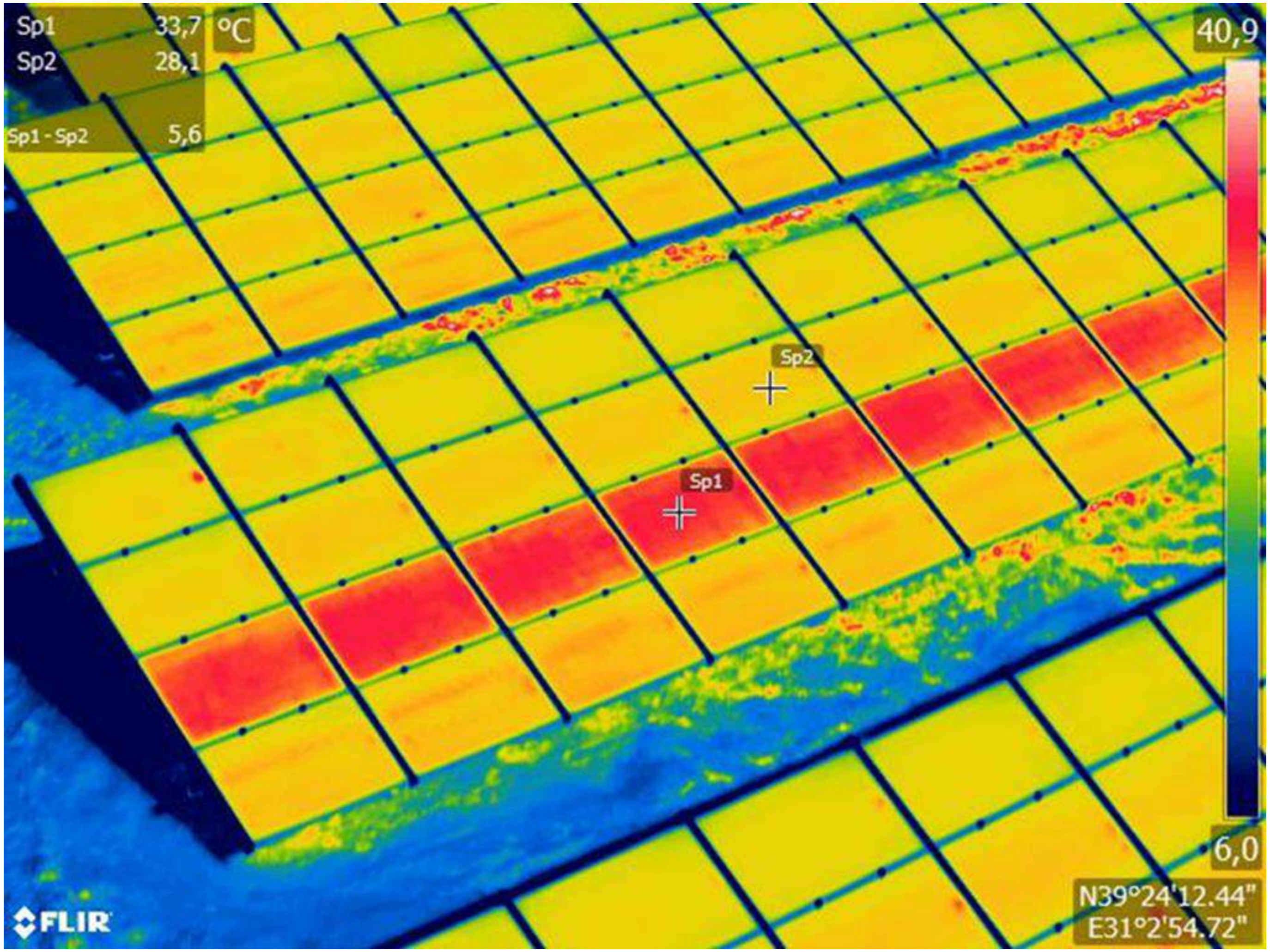
System Inspection and Testing

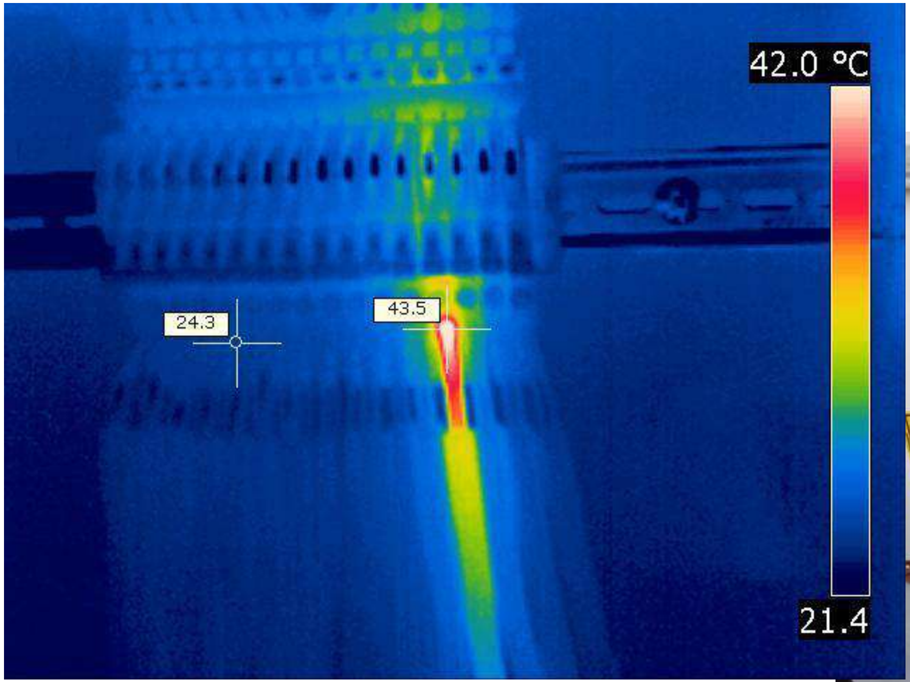


Fraunhofer ISE

System Inspection and Testing

Infrared images

- Electrical connection

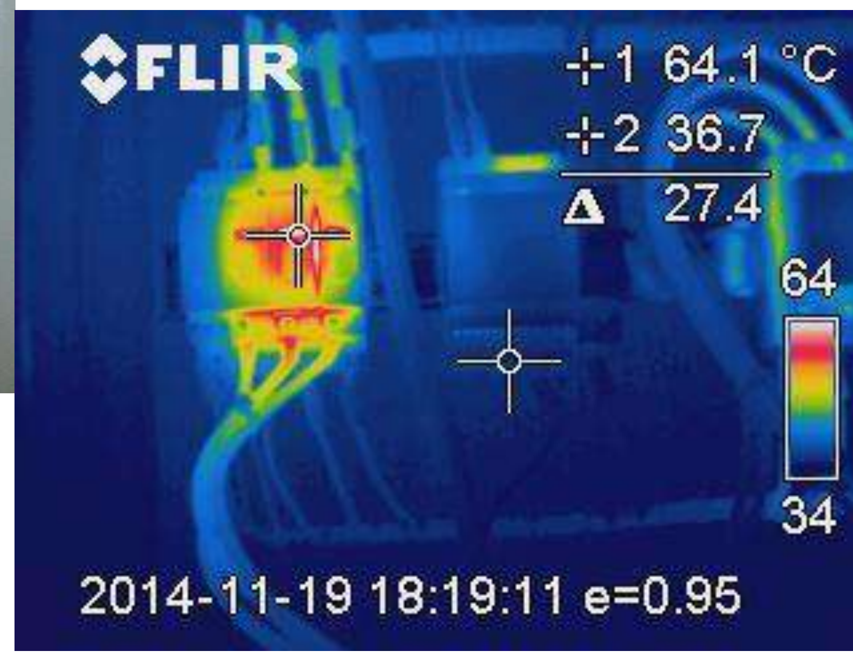


One string with high transition resistance

System Inspection and Testing

Infrared images

- Electrical connection

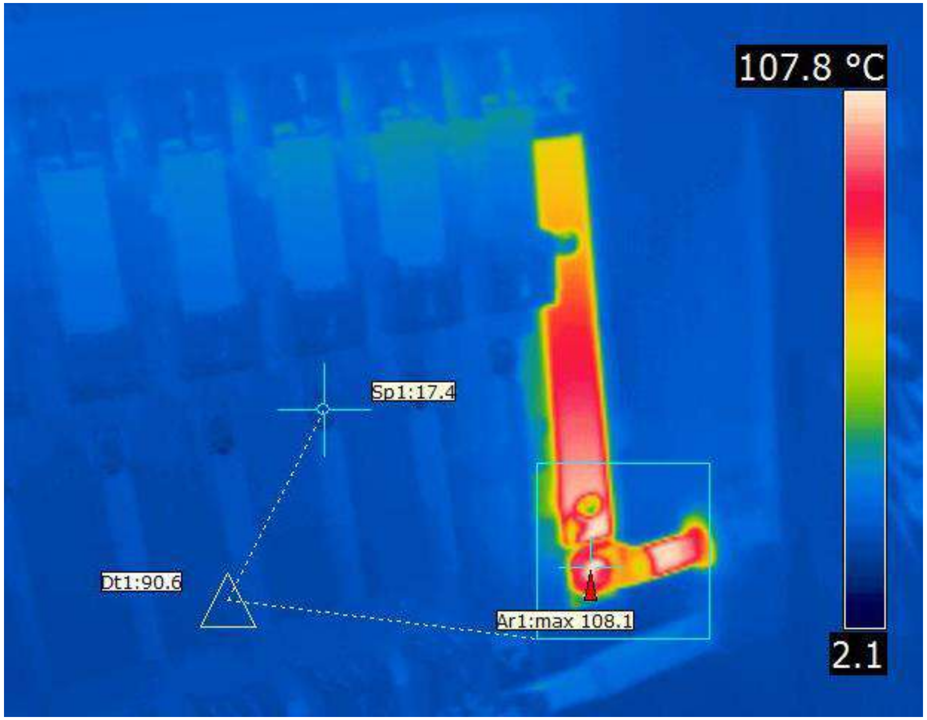


Mal screwing causes hot spot

System Inspection and Testing

Infrared images

- Electrical connection



Thermal fault on the power rail

Prueba de Electroluminescence

En el campo

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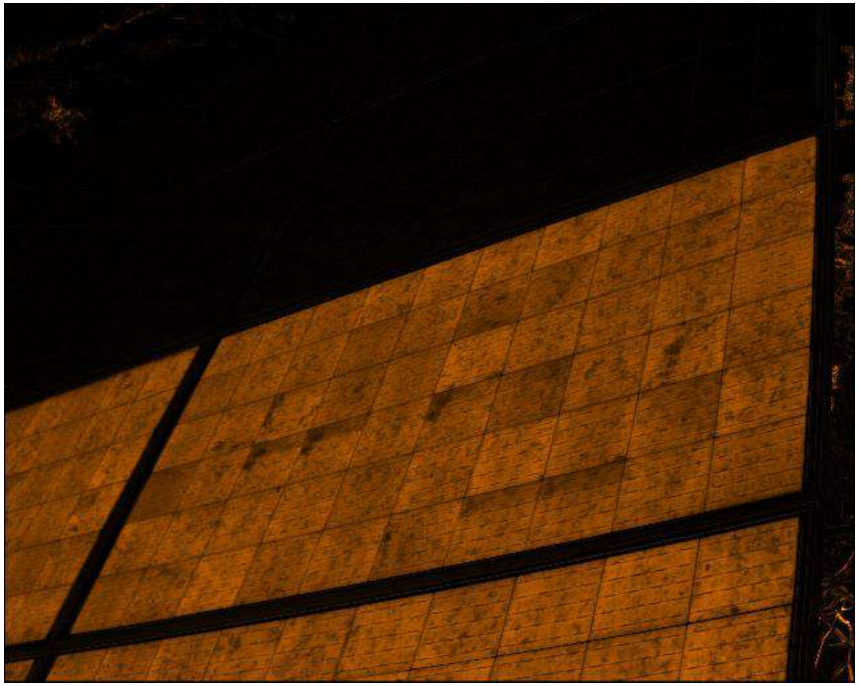
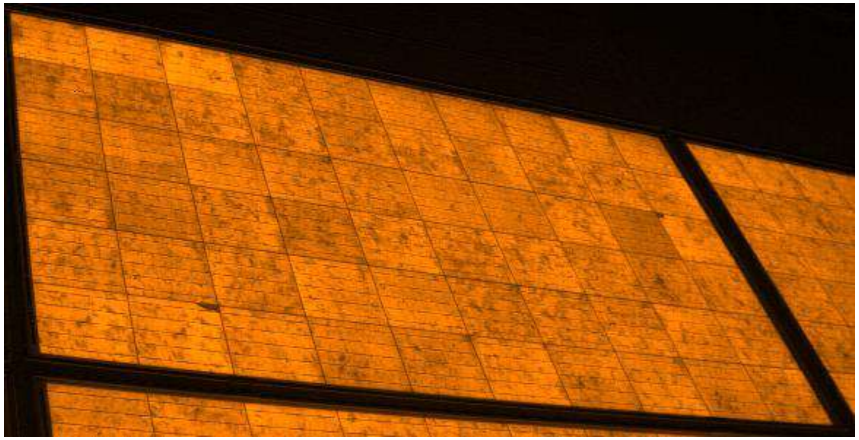
Prueba de Electroluminescence

resultado



Prueba de Electroluminescence

resultado



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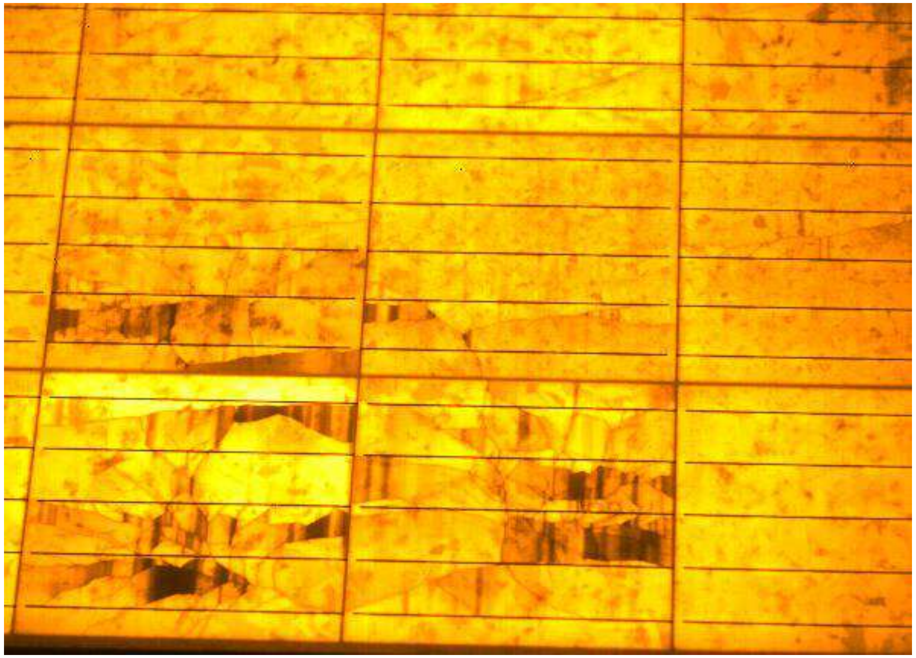
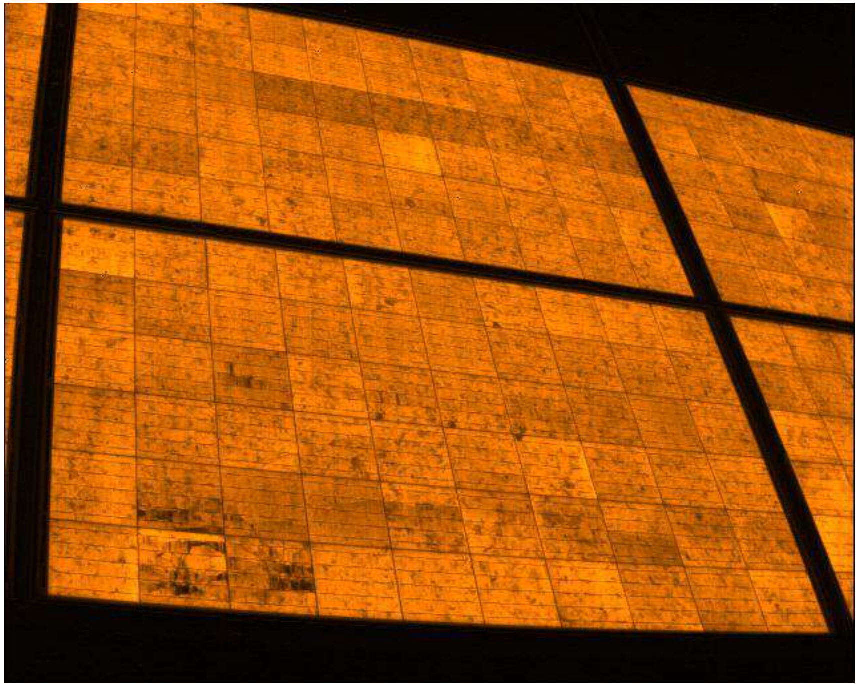
Prueba de Electroluminescence

resultado





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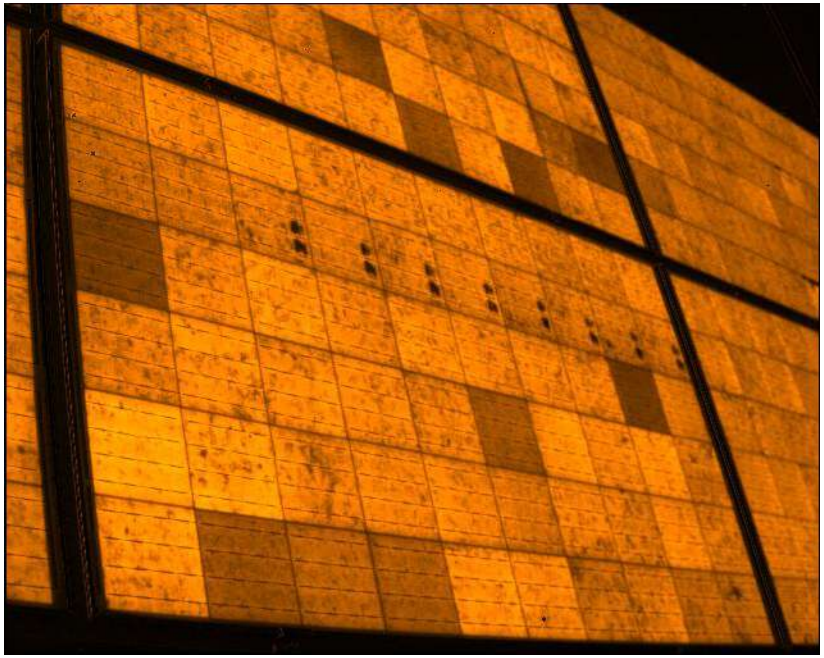
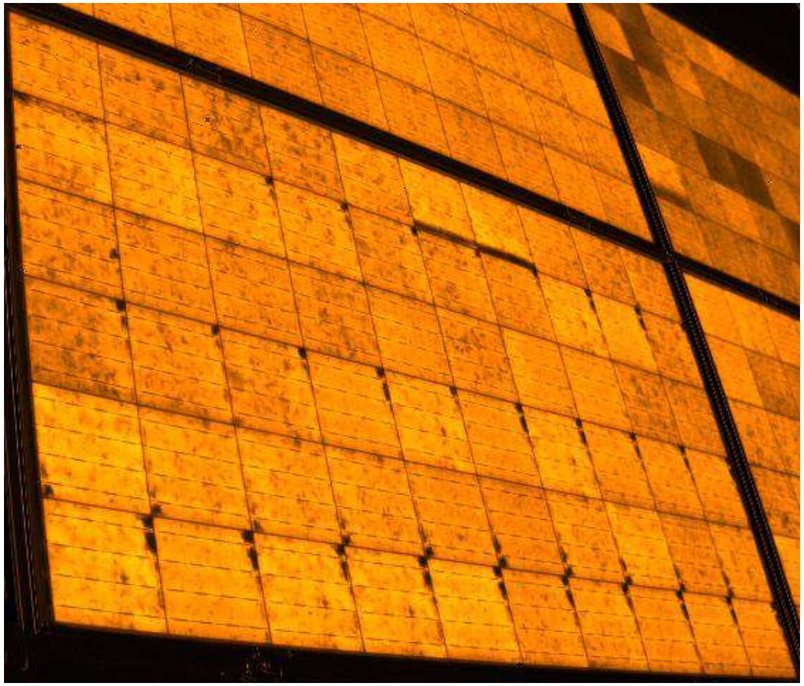
Prueba de Electroluminescence

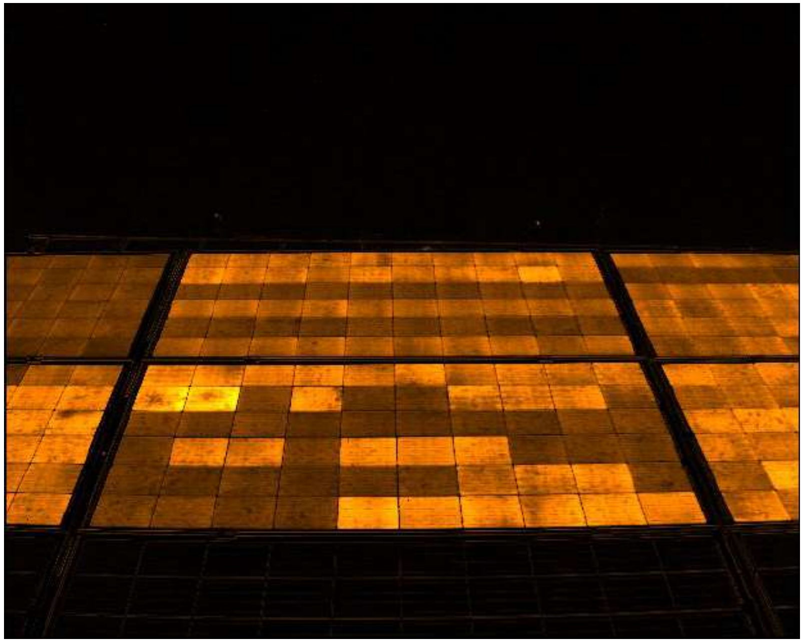
resultado





Prueba de Electroluminescence

resultado



Inspection Technics

- Visual inspection of the PV plant
- Experiences from the field – lessons learned
- Infrared images of modules and electrical connections
- **Measurement of the solar generator to verify module power**
- Verification of the monitoring system
- Short-term performance check of the PV plant

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System Inspection and Testing

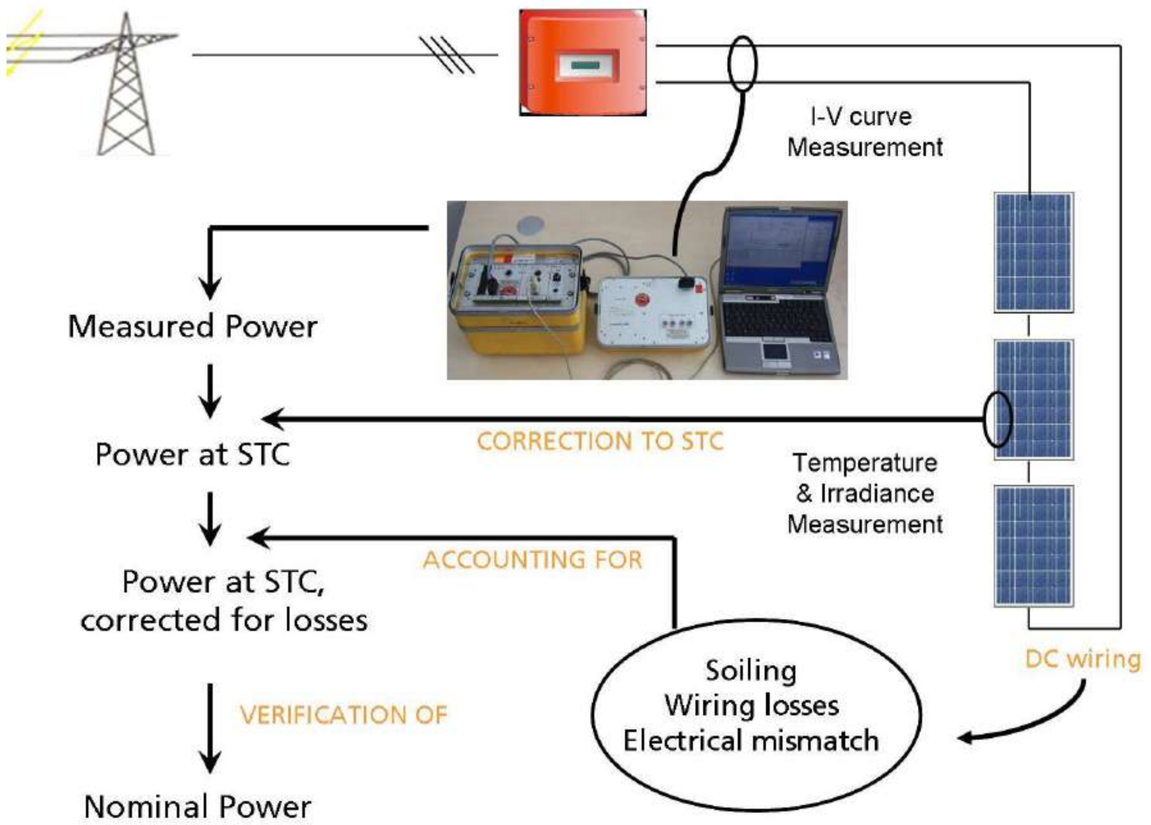
IEC Standards for On Site I-V Curve Measurement

- IEC 61829 Ed. 2
  - Crystalline silicon photovoltaic array – on site measurement of I-V characteristics
- IEC 60891 Ed. 2 Procedure 1
  - Photovoltaic devices - Procedure for temperature and irradiance corrections to measured I-V characteristics

System Inspection and Testing

Field I-V Curve Measurements

- Verifying Module Power



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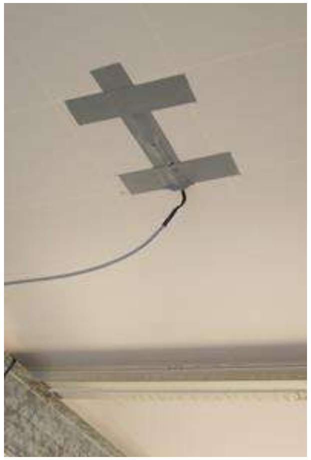
System Inspection and Testing

Field I-V Curve Measurements

- Verifying Module Power in the field



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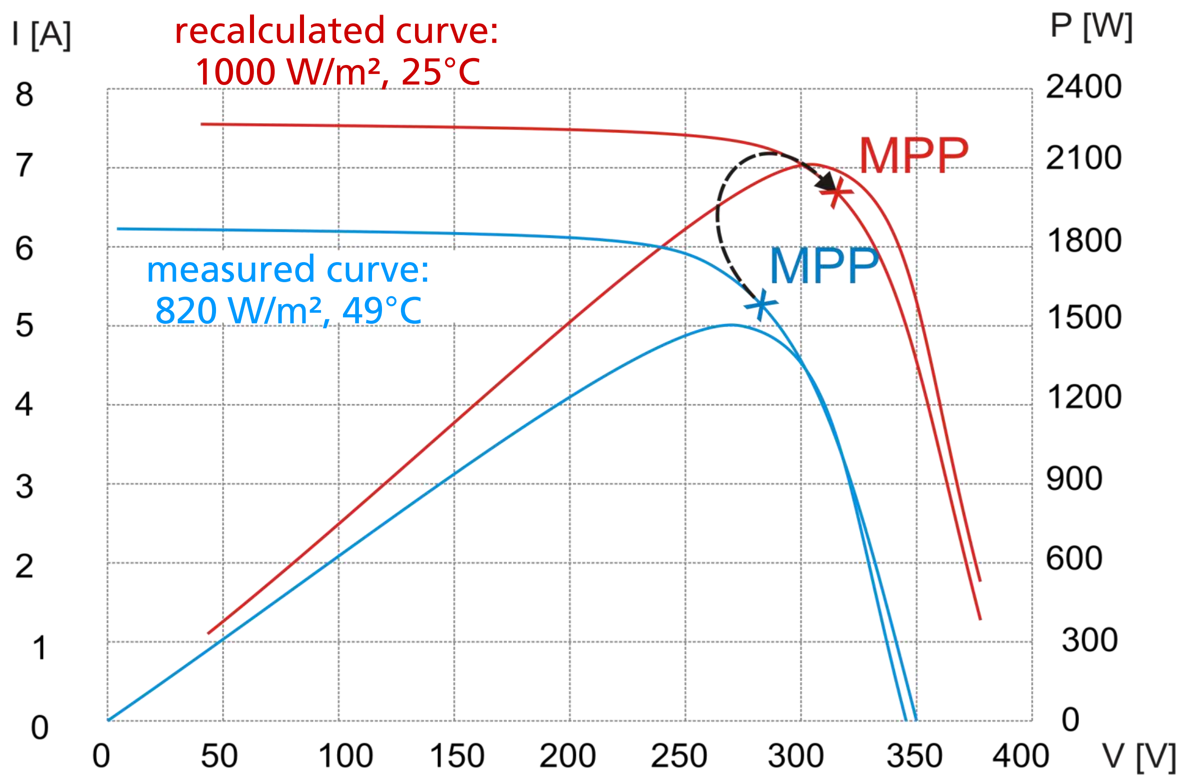
System Inspection and Testing

Field I-V Curve Measurements

- Extrapolation of Measured Solar Generator Characteristics according to IEC 60891 Ed. 2 Procedure 1



System Inspection and Testing

Field I-V Curve Measurements

- Calculation of parameters K and Rs according to IEC 60891

The data used for calculation of parameters should be measured

- based on precise temperature and irradiance dependence measurements in a Laboratory
- in the range of recalculation (800 to 1000 W/m² and 35 to 65 °C)
- on modules of the same type as installed in the PV plant

System Inspection and Testing

Field I-V Curve Measurements

- Determination of soiling losses

System Inspection and Testing

Field I-V Curve Measurements

- Determination of soiling losses

Soiling Losses: 18 %

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System Inspection and Testing

Field I-V Curve Measurements

➢ Conclusion

If field I-V curve measurements are performed

- according to international standards
- using primary calibrated measurement equipment
- involve carefully determined parameters
- at conditions close to STC

measurement uncertainties of 3 % to 4 % are possible

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Inspection Technics

- Visual inspection of the PV plant
- Experiences from the field – lessons learned
- Infrared images of modules and electrical connections
- Measurement of the solar generator to verify module power
- **Verification of the monitoring system**

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System Inspection and Testing

Verification of the monitoring system

- Inspection of the mounting and orientation of the irradiation sensor

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System Inspection and Testing

Verification of the monitoring system

- Inspection of the mounting and orientation of the irradiation sensor

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System Inspection and Testing

Verification of the monitoring system

- Inspection of the mounting and orientation of the irradiation sensor

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System Inspection and Testing

Verification of the monitoring system

- Inspection of the temperature sensor

System Inspection and Testing

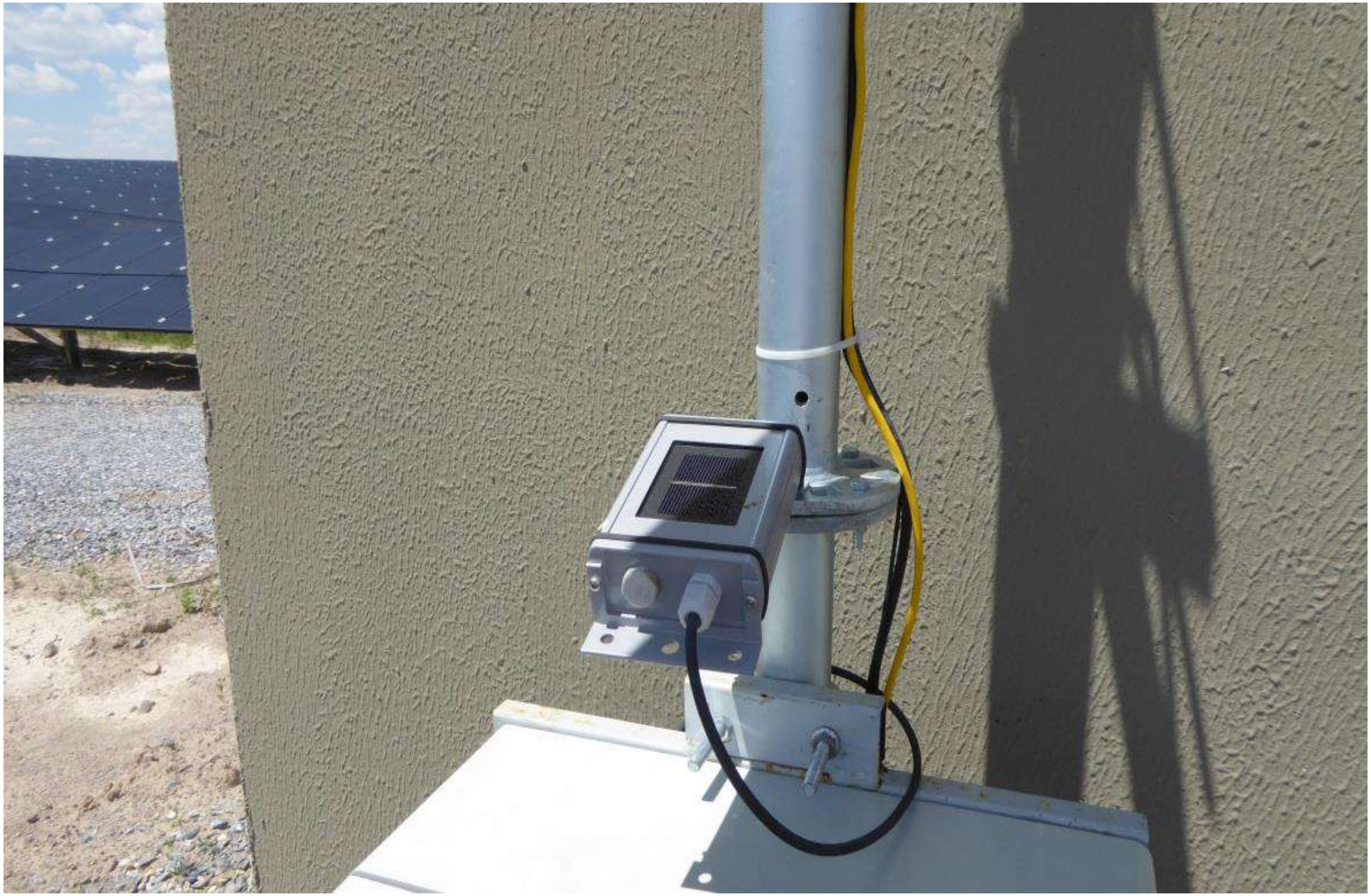
Verification of the monitoring system

- Verification of the calibration values and the time stamps

Comprobación durante la prueba final de aceptación

Comprobación durante la prueba final de aceptación

Comprobación durante la prueba final de aceptación



System Inspection and Testing

Verification of the monitoring system

- Reference measurements for the verification of the measurement equipment

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System Inspection and Testing

Conclusion:

- **General check of the PV plant has to be performed, including**
  - Visual inspection of the PV plant
  - Analysis with infrared camera of modules and electrical connections
  - Measurement of the solar generator to verify module power
  - Short-term performance check of the PV plant
- **The report should**
  - verify the installation regarding to the appropriate standards
  - compare the as-built and as-planned system
  - confirm that the PV system is in operation and free from faults or
  - evaluate and document all defects

Soiling

Soiling - Terms

Deposition: The amount of sediment that impacts on a unit surface in a unit time

Accumulation: The amount of sediment that remains at a unit surface at the end of a particular time interval

Soiling loss: yield loss in PV modules due to particle accumulation

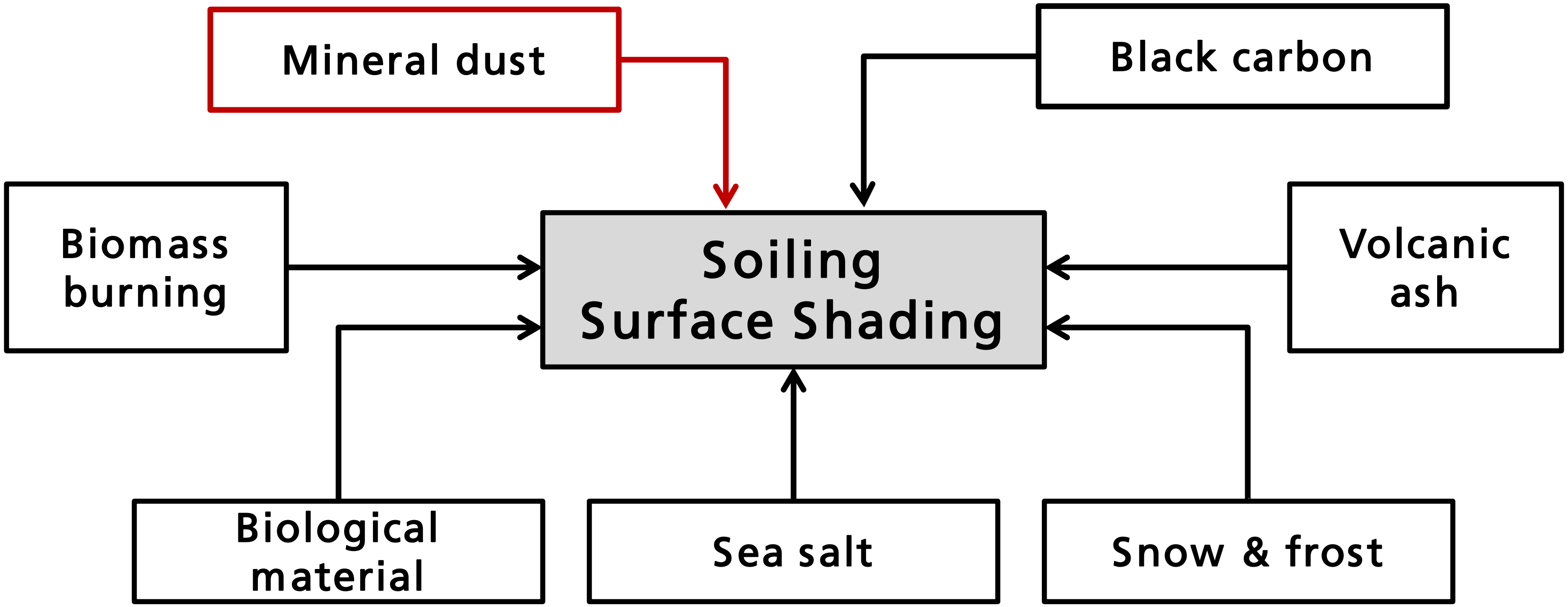
soiling ratio: instantaneously measured ratio of *dirty-to-clean* at any given point in time.

Soiling rate: Average soiling loss per unit period of time

Abrasion: Mechanical degradation of surfaces by wind-driven particles

Source: Jan Herrmann, GloBeSolar project. LZN/ISE/Uni Freiburg

Sources of Soiling



Source: Jan Herrmann, GloBeSolar project. LZN/ISE/Uni Freiburg

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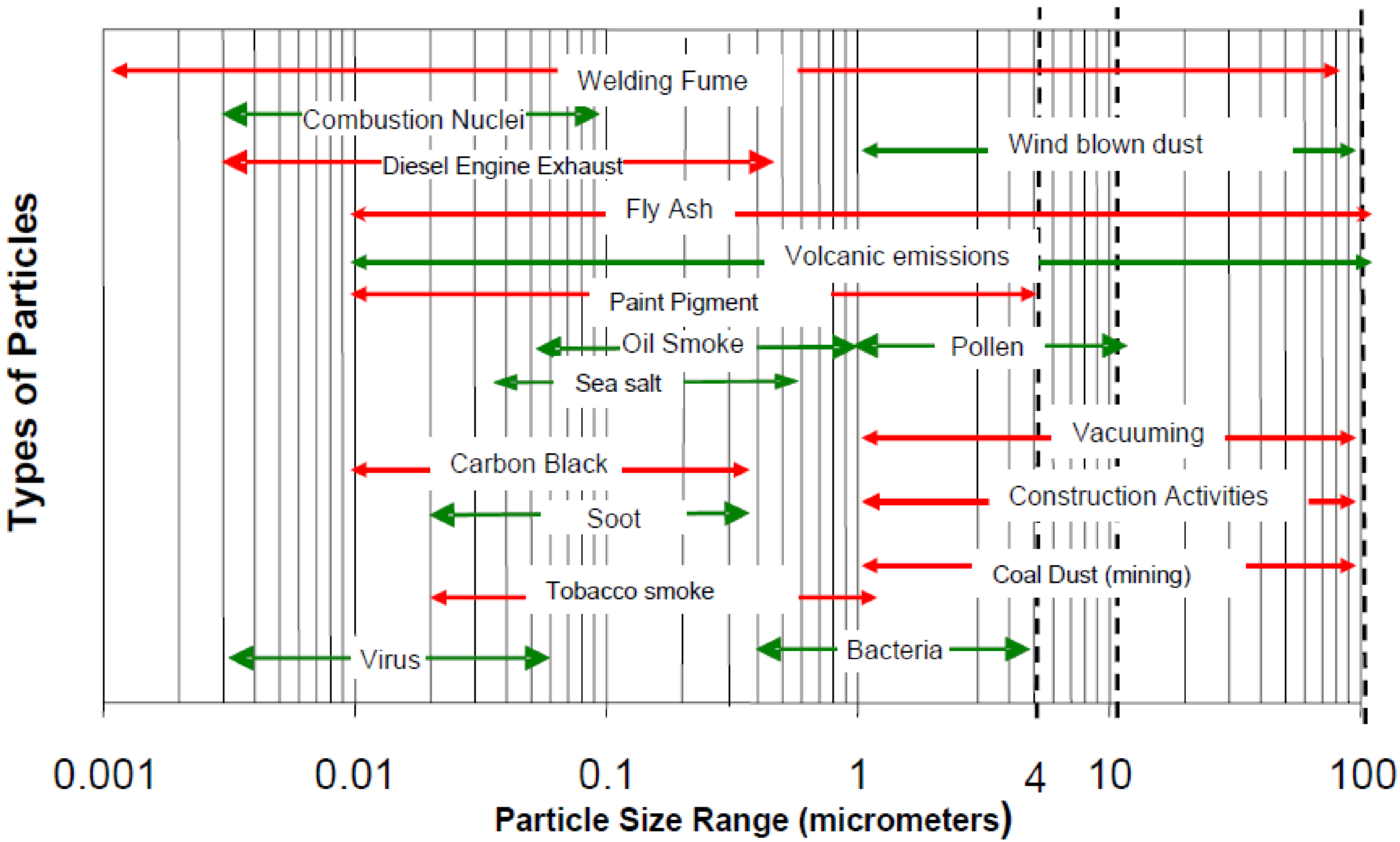
Particle Sizes



Source: TSI Inc.; http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Technical_Notes/Particle_Size.pdf

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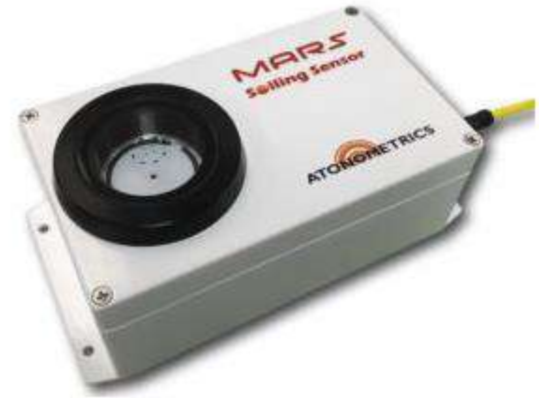
How can it be measured on site?



Commercially available Systems, e.g.

- Left: Atonometrics RDE300 with self-washing refcell
- Middle: Kipp&Zonen Dust IQ
- Right: Atonometrics MARS sensor

Should be with as little maintenance as possible

Also determine rain events (weather station, wind, irr, tamb, rain, humidity)

Measurement principles

Compare washed vs. unwashed output (module/module or module/refcell)

Or detect degree of transmission of reference glass

Or count particles on surfaces

Metrices – how to rate soiling

- Isc
- MPP/Power output/daily yield temperature corrected
- Loss in transmission (directly influences Isc)

How can it be measured?

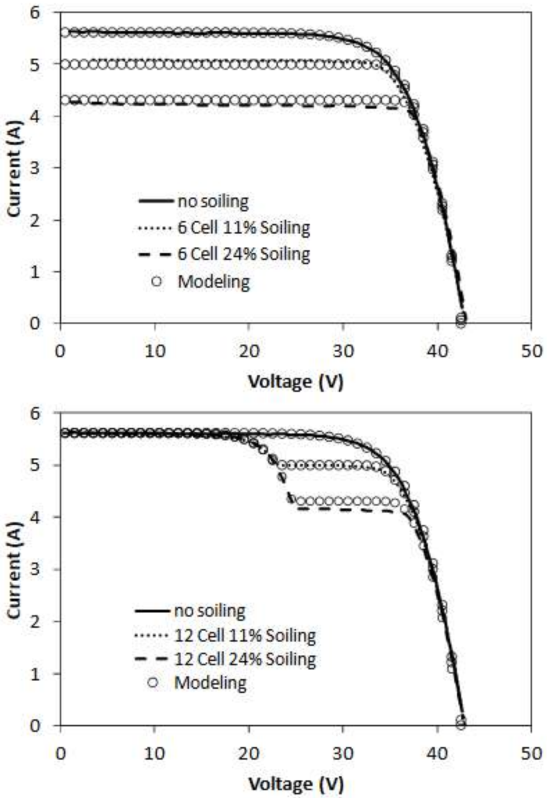


Fig. 3: Measured I-V curves of crystalline silicon module with simulated soiling on 6 cells across the short edge of the module (top figure) and 12 cells across the long edge of the module (bottom figure). Open symbols indicate SPICE model simulation of the measured I-V curve.

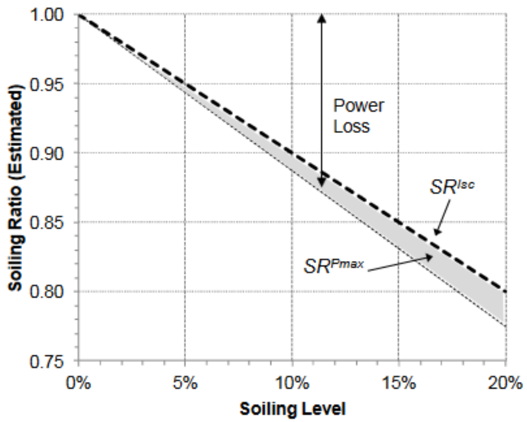


Fig. 1: Comparison of estimated *Isc* and *Pmax* soiling ratios as a function of soiling level for a range of typical PV modules, based on datasheet values. The soiling power loss determined by 1 - SR^{Pmax} may be up to 10% larger than the value of 1 - SR^{Isc}, depending on module parameters.

Gostein, M., Littmann, B., Caron, J. R. & Dunn, L. Comparing PV power plant soiling measurements extracted from PV module irradiance and power measurements. in *2013 IEEE 39th Photovoltaic Specialists Conference (PVSC)* 3004–3009 (IEEE, 2013).

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Effect of rain and humidity

- Strong rain may flush modules completely and restore function
- Light rain my wash particles out of the air, accumulate on lower parts of modules, worsening the problem
- High Relative humidity may lead to form crusts of minerals that are more difficult to wash away

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Selected soiling studies

Gran Canaria, maritime climate

Negev desert, arid

Studies in US

ISE Soiling Study Canary Islands

Fig. 3. Heavily soiled modules on the Gran Canaria Island. A manually cleaned module is visible at the top right corner.

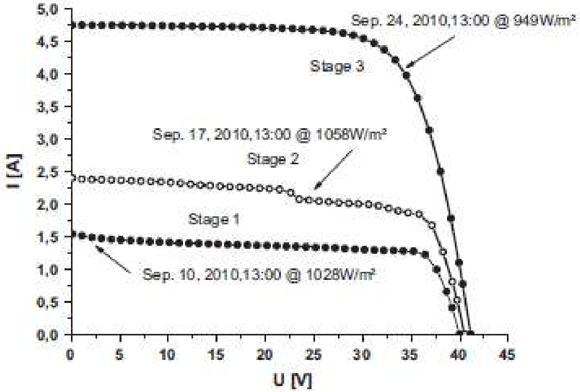

Fig. 5. Typical *IV* curve showing effects of soiling (September 10), partial shading after a minor rainfall event (open circles, September 17) and removing of the soil (September 24).

Decrease in relative efficiency down to ~13%

No "saturation"

Schill, C., Brachmann, S. & Koehl, M. Impact of soiling on IV-curves and efficiency of PV-modules. *Solar Energy* **112,** 259–262 (2015).

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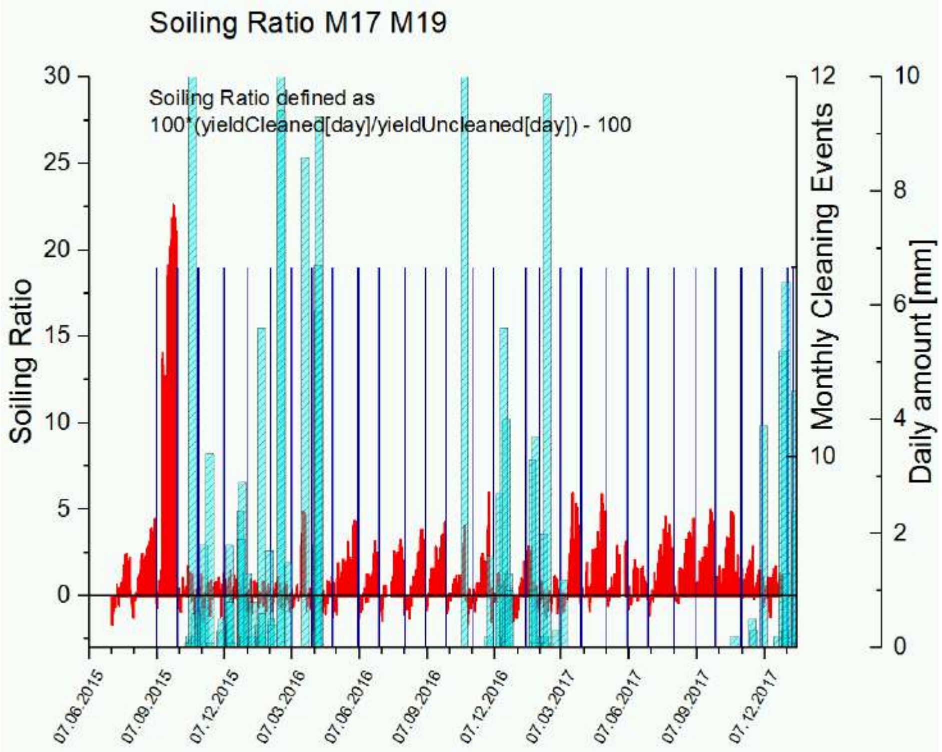
ISE Soiling study Negev desert



Yield as metric

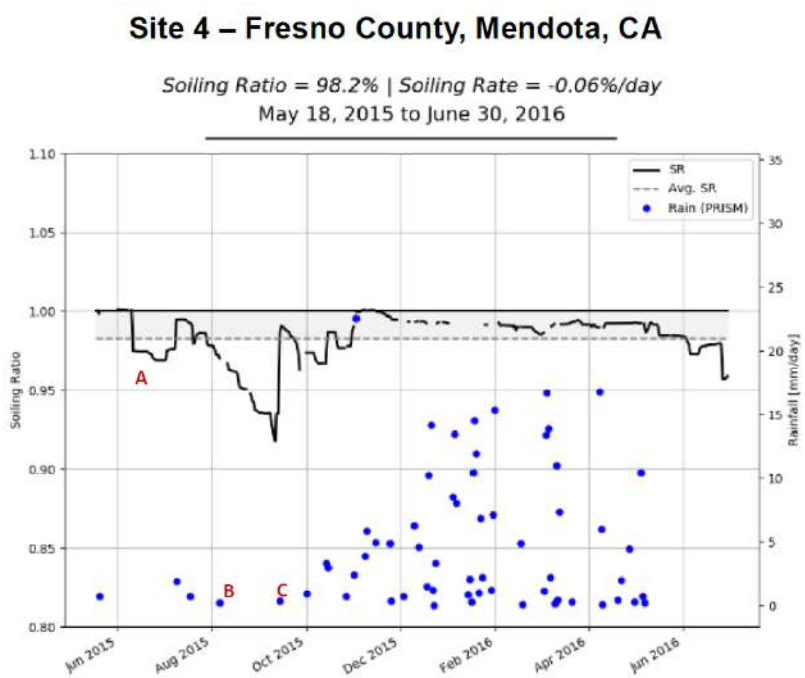
Weekly washed vs. monthly washed

Sandstorm event September 2015

Study by NREL for the US

Micheli, L., Muller, M.T., Deceglie, M.G., 2017. Time Series Analysis of Photovoltaic Soiling Station Data: Version 1.0, August 2017. National Renewable Energy Laboratory (NREL), Golden, CO (United States).

Example values



4	06/18/2015 to 06/30/2016	Mendota, CA	Fresno, CA	Single Axis	98.2	-0.06	✓
5A	02/01/2013 to 01/01/2016	Neenach, CA	Los Angeles, CA	Fixed (25)	98.6	-0.04	✓
5B	07/01/2014 to 01/01/2016	Neenach, CA	Los Angeles, CA	Single Axis	>99	-0.04	✓
6	01/30/2014 to 06/30/2016	Hyder, AZ	Yuma, AZ	Fixed (20)	>99	-0.02	✓
7	05/31/2015 to 07/31/2016	California Valley, CA	San Luis Obispo, CA	Single Axis	>99	-0.08	✓
8	05/01/2013 to 01/01/2016	Avra Valley, AZ	Pima, AZ	Single Axis	>99	-0.05	✓

Best time to clean

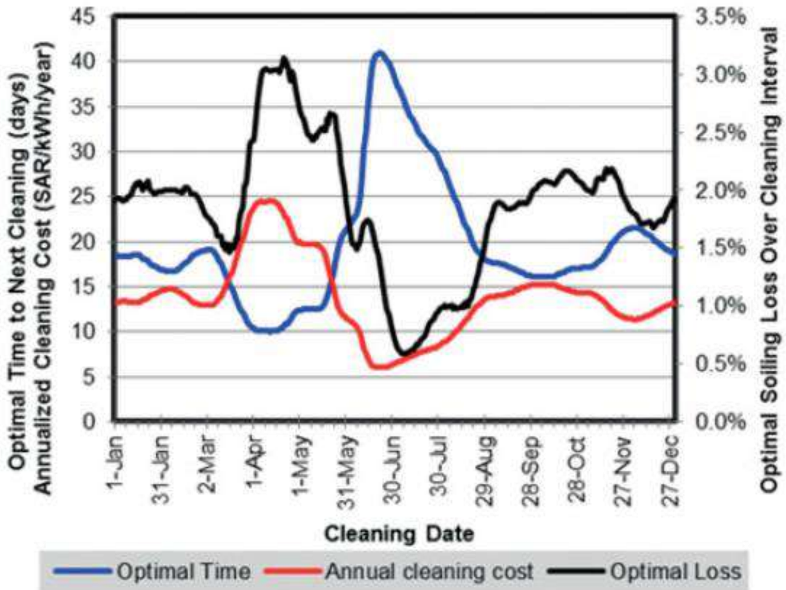
Optimize energy output or monetary return?

Economic decision depending on several factors

- Costs for cleaning per module (either labor or robotic cleaning)
- Feed-in tariff (i.e. cost of lost energy)
- Water consumption of cleaning method/ costs for water
- Seasonal tendencies on site (e.g. agricultural activities, annual variations, wet season rain events etc)
- Middle range weather forecast (sandstorm approaching? Strong rain events coming?)

Best time to clean example studies

E.g. Middle East (strongly affected!) - Saudi-Arabia



	Optimal Days to Next Cleaning	Revenue Loss over cleaning interval	Annualized Cleaning Cost (SAR/kW/year)
Average	19.85	1.85%	13.80
Maximum	41.00	3.15%	24.55
Minimum	10.00	0.58%	5.99

Total annual cost of soiling: 27.2 SAR/kW/year ($7.25/kW/year)

(a)

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Optimized Cleaning Cost and Schedule Based on Observed Soiling Conditions for Photovoltaic Plants in Central Saudi Arabia.
IEEE Journal of Photovoltaics 6, 730–738.
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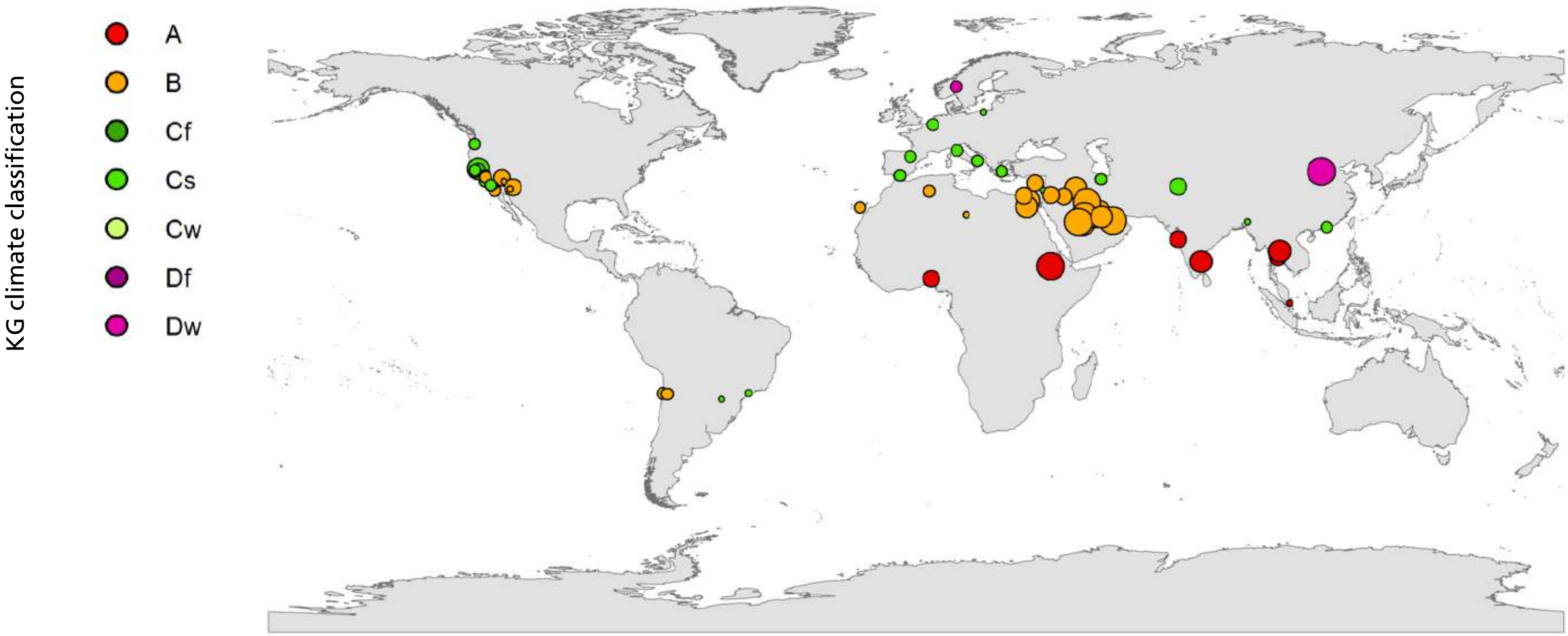
Publications of Soiling studies geo-located



Compiled by Jan Herrmann, Uni Freiburg, GloBeSolar project, from scientific publications

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