Methoden zur Fehlererkennung bei PV-Modulen und Anlagen – Qualitätssicherung im Feld

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Quality Weaknesses in the PV Market

Product quality is often not given
due to the market situation (high competition, low financial recourses, personnel fluctuation, change of suppliers, lack of quality assurance, differences among certifiers and labs)

Low quality of planning and installation
Use of sub- and sub-subcontractors, high competition, lack of knowledge and experience, tight commissioning deadlines, weak quality assurance during construction

How to solve these problems?

Project assumptions and feasibility are imprecise
Energy yield prediction too optimistic, cleaning concept missing or insufficient, lack of fixed contract requirements, lack of experience,

Bankability of involved parties often not given
Unstable market situation, choose of Tier-1 manufacturers is not only a criteria for bankability, warranties are often not reliable

Outline

- Degradation mechanisms
- Failure modes, origin & detection
- Inspection methods for PV power plants
  - Visual inspection
  - On-site I-V measurement
  - Infrared thermography
  - Electroluminescence analysis
- Summary & lessons learnt

Degradation Mechanisms
Introduction

- Semiconductor device degradation
- Thermo-mechanical stress caused by the alternation between day and night
- Diffusion processes, in particular water vapor ingress into the encapsulation
- Photo-degradation of polymers
- Static and dynamical mechanical stress caused by snow load, wind load or transportation.
- Material incompatibility

Degradation Mechanisms
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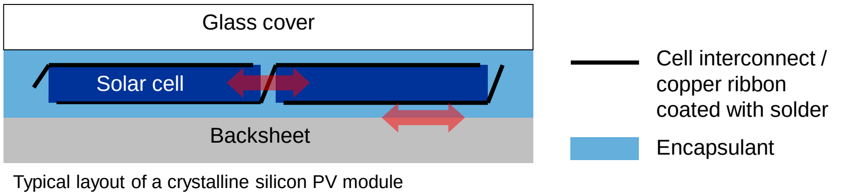
Degradation Mechanisms
Thermo-mechanical stress

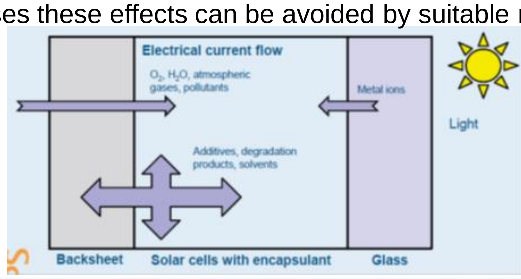
- PV modules combine materials with different coefficients of thermal expansion (glass cover, polymeric encapsulation, solar cells, polymeric backsheet, metal parts of internal wiring)
- Thermo-mechanical stress is caused by the alternation of module temperature between day and night. These stresses can provoke degradation processes such as crack of interconnects (Cyclic movement of cells), loss of adhesion strength at interfaces and delamination between materials.
- Thermo-mechanical stress is increased for locations with high alternation of module temperature between day and night.



Typical layout of a crystalline silicon PV module

Degradation Mechanisms
Material incompatibility

- Interactions between different materials can lead to unintended processes which can be origin of degradation or favor degradation:
  - Chemical reactions: Discoloring, gassing, corrosion, formation of snail trails
  - Diffusion and migration processes (i.e. Na+, PID),
- In many cases these effects can be avoided by suitable materials selection.

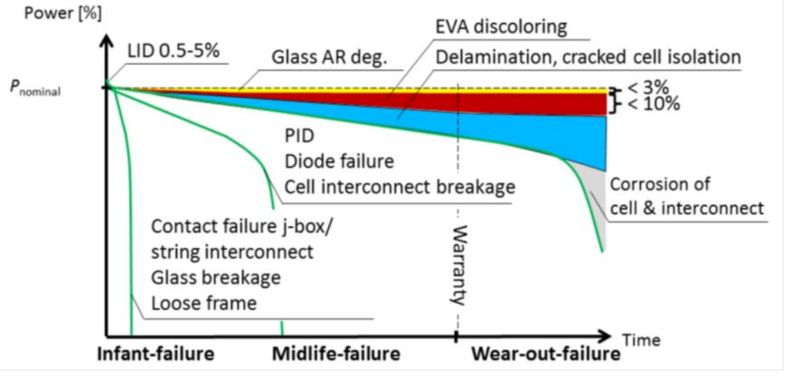


Source: IEA PVPS Task 13
http://iea-pvps.org/index.php?id=435

Failure Modes for PV Modules
Introduction

- Power degradation
- Corrosion of electrical contacts
- Broken cells
- Broken interconnects
- Delamination at encapsulant interfaces
- Formation of bubbles in the encapsulation
- Discoloration of backsheet and encapsulant
- Snail trails
- Fracture of back sheet
- Solder bond failure
- Burn marks due to arcing or hot spot
- Bypass diode failure
- Broken glass
- Ablation of glass coating failure
- Junction box adhesion
- Structural failure of frame

Failure Modes for PV Modules
Time evolution of module failures



Infant failure or early failure occur in the beginning of the working life of a PV module.

Origin: Defective construction, faults in production and non-conforming materials.

Mid-life failure occurring up till 10-15 years of operation are termed as midlife failures.

Wear-out failure occurring late in PV module lifetime.

Source: IEA PVPS Task 13
http://www.iea-pvps.org/index.php?id=57

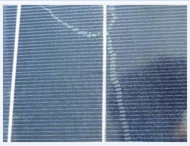
Field Inspection Methods
Overview

Typical inspection methods for failure analysis and quality assurance

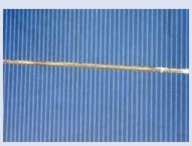
Visual inspection	▪ Detection of visible defects
Array I-V curve measurement	▪ Electrical performance ▪ Potential induced degradation
Infrared (IR) analysis	▪ Localization of array interconnection failures ▪ Localization of failures causing heat generation ▪ Potential induced degradation
Electroluminescence (EL) analysis	▪ Localization of cracked cells and interconnects ▪ Potential induced degradation

Failure Modes from Visual Inspection
Delamination effects

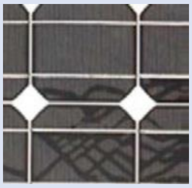
Any delamination can cause voids or air bubbles in the laminate. Air bubbles are potential areas for humidity accumulation, which may lead to corrosion of metallic parts or short circuits.

Observation	Explanation
	**EVA-cell delamination**: Can occur along the bus-bar caused by material incompatibility (EVA /soldering flux).
	**EVA-cell delamination**: Can be caused by contamination of the cell surface. Delamination of a larger area can also indicate a poor cross linking of EVA.

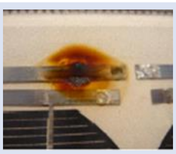
Failure Modes from Visual Inspection
Discoloration effects – Cell

Observation	Explanation
	**Solder ribbon discoloration**: This type of discoloration can be a result of corrosion or the result of light-sensitive flux residues on the ribbon. This type of discoloration will rarely result in power loss.
	**Corrosion of metallic parts:** Humidity ingress into the encapsulation will lead to corrosion of metallic parts in the interconnection circuit. Corrosion effects at cell front electrode (grid finger, busbar, cell interconnect) are most prominent. Corrosion processes can be also caused by formation of formation of acetic acid in EVA. Corrosion will lead to continuous increase of the internal series resistance of the PV module, which is associated with power loss.

Failure Modes from Visual Inspection
Discoloration effects – Cell

Observation	Explanation
	**Snail trails:** Brownish discoloration of the silver fingers (front metallization) of screen printed solar cells. The discoloration occurs at the edges of the solar cell and along invisible cell cracks. Root cause: Moisture ingress through cell micro-cracks leading to chemical reaction (in combination with UV) and resulting in deposition of silver from fingers and bus bars into EVA. Discoloration happens with specific EVA formulations (Peroxide additives) and specific silver paste. For certain material combinations snail trails will not occur. Snail trails are not serious but the crack it reveals can be.

Failure Modes from Visual Inspection
Burn marks

Observation	Explanation
	**Soldering bond failure:** Thermo-mechanical stress can cause cracking of ribbons (between cells, bus wiring, inside the junction box). This can lead to open circuit failures or arcing. Origin: Poor quality of soldering or degradation due to electrochemical corrosion. Both lead to increase of contact resistance, higher power dissipation and localized heating at
	**Formation of hot-spot:** This failure is caused by insufficient resistivity of the cell against reverse voltage or missing bypass diodes. Heat generation >200°C possible. Origin: Shaded cell, cracked cell with electrically isolated part, cell degradation.
	**Cell cracks:** Most critical are cell cracks parallel to bus bars. Accidental contact between the separated and active parts can lead to localized current flow and arcing, which will cause point focal heating.

Failure Modes from Visual Inspection
Back sheet failure

Observation	Explanation
	UV irradiance reaches the backsheet through the cell interspaces, where photo-degradation processes are induced. Low quality backsheets are UV sensitive, resulting in a loss of mechanical properties (elastic behavior) and crack due to thermomechanical stresses. Once the back sheet is broken, it cannot provide the electrical safety. This problem is serious.
	Weathering effects will continuously reduce the thickness of the backsheet outer layer: ▪ Photocatalytic degradation ▪ Erosion by sand abrasion An attending effect can be so-called chalking of the backsheet, which typically appears as a fine powdery residue on the surface. Organic molecules are removed from and the inorganic filler particles such as TiO_2 are exposed. Back sheet chalking and backsheet cracking often occur at the same time.

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On-site I-V Curve Measurement
Overview of power degradation effects

Degradation mechanisms may lead to a continuous reduction in the output power over time or to an sudden reduction due to failure of individual component.

Origin	Effect
▪ Deterioration of AR coating ▪ Delamination at interfaces to the encapsulant ▪ Discoloration of the encapsulant	Less incident sunlight will reach the cells
▪ Corrosion of soldering joints at cells or busbar ▪ Structural changes in the soldering material	Increased series resistance at soldering joints.
Cracks in the cell interconnection circuit	Redirection of current flow or open-circuit failure.
Cell cracks	Separation of active cell parts
Bypass diode failure	Short circuiting a complete cell string
Semiconductor device degradation	

On-site I-V Curve Measurement
Measurement technique

- Performed with commercial **I-V curve tracer**
- Measurement of single PV module or a string of serially connected modules
- 4-wire connection between field terminal box and I-V curve tracer
- Other input channels for **irradiance sensor** and **module temperature sensor**, which are to be installed in the field.

- PV array measurements reveal **interconnection failures** of PV modules or detect **low power** of modules. But it but does not allow conclusion on output power of individual modules.
- This confirmation is possible with **mobile test centers** or shipment of samples to test laboratory.

On-site I-V Curve measurement
Commonly used commercial I-V curve tracers

HT instruments **daystar** **pve engineering**

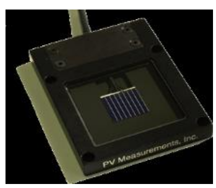
Deficits:

- Implemented **I-V curve correction** to STC not conform with IEC 60891 or inflexible, which makes use of Excel necessary (limited practicability in the field)
- **One temperature channel** for module temperature, which should be representative for the entire array. Additional use of IR camera or ECT.
- Operating software is often not user-friendly as many input parameters, which may cause operating errors

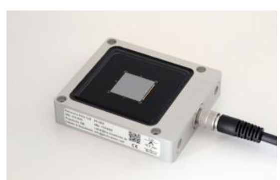
On-site I-V Curve Measurement
Commercial irradiance sensors

Commonly used commercial irradiance sensors

Mencke & Tegtmeyer



PV measurements



Fraunhofer ISE

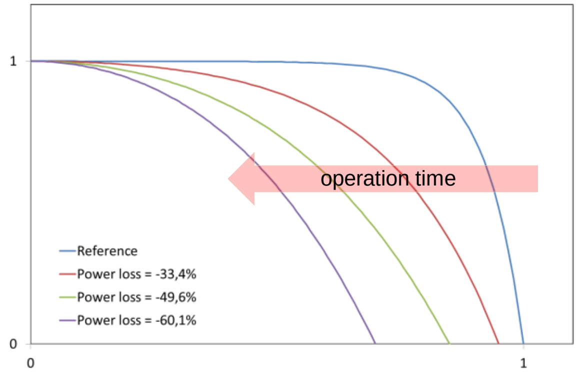
Guideline for accurate on-site I-V measurement:

IEC 61829 Ed. 2 (2015) "Photovoltaic (PV) array - On-site measurement of current-voltage characteristics"

- Requirements for test equipment
- Requirements for meteorological conditions
- Procedure for on-site I-V curve measurement
- Use of translating I-V curve to STC
- **Approach for addressing field uncertainties**

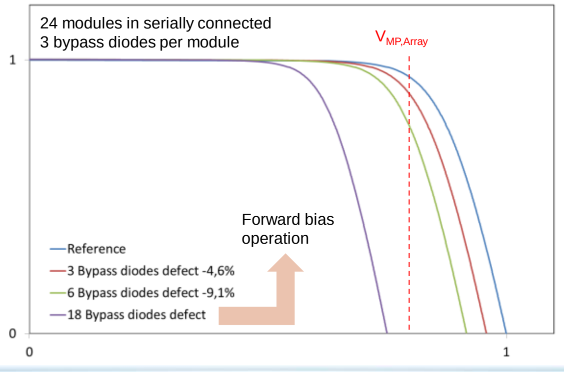
On-site I-V Measurement
PID effect

- If PID sensitive modules are installed, the
- Local climatic conditions influence the degradation rate (humidity, time of wetting, etc.)
- Degradation increases with operation time of the PV power plant
- PID affects the slope of the I-V curve at Isc and causes a Voc decrease



On-site I-V Measurement
Defective bypass diodes

- Defective bypass diodes are typically conductive (thermal overload, electromagnetic pulse, etc.)
- The respective section of the cell interconnection circuit in a PV module is shorted
- High number of defective bypass diodes may lead to Voc variation of module strings, which may cause reverse current flow.



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Infrared Thermography of PV Arrays
Introduction

- Infrared (IR) thermography is a well-established and powerful tool for the quality check of the PV installations:
  - Localization of failures that reduce the PV systems performance
  - Localization of abnormal heat generation
  - Proof of the quality of installation

- Today flying robots and drones for professional use are available on the market, which allow quick panoramic IR images. These can be used as basis for further analysis.

Infrared Thermography of PV Arrays
Harmonization of measurement and evaluation methods

IEC 62446-3: Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography

- The standard defines procedures for daylight thermographic (infrared) inspection of PV modules and plants in operation.
- This inspection supports the preventive maintenance for fire protection, the availability of the system for power production, and the inspection of the quality of the PV modules.
- This document lays down requirements for the measurement equipment, ambient conditions, inspection procedure, inspection report, personnel qualification and a matrix for thermal abnormalities as a guideline for the inspection.

IEC 60904-12 (CD): Photovoltaic devices - Infrared thermography of photovoltaic modules

- The standard defines procedures for daylight thermographic (infrared) inspection of PV modules and plants in operation.

Infrared Thermography of PV Arrays
Harmonization of measurement and evaluation methods

Inspection conditions of IEC 62446-3:

Parameter	Limits
Irradiance	Minimum 600 W/m² in the plane of the PV module
Wind speed	Maximum 28 km/h
Cloud coverage	Maximum 2 octa[1] of sky covered by cumulus clouds
Soiling	No or low. Cleaning recommended e.g. if bird droplets exist.

[1)] **okta** is a unit of measurement used to describe the amount of cloud cover. Sky conditions are estimated in terms of how many eighths of the sky are covered in cloud, ranging from 0 oktas (completely clear sky) through to 8 oktas (completely overcast).

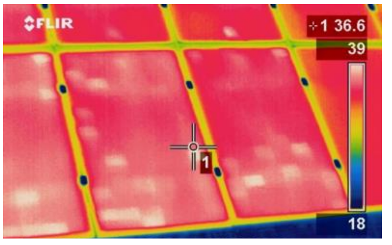
Infrared Thermography of PV Arrays
Heat generation on array level

- IR thermography can resolve even smallest temperature differences
  - Temperature scale must be adjusted to technically reasonable values
  - Influences from surroundings (reflection, angular effects) must be avoided or correctly interpreted

Not all visible temperature abnormalities are module failure or cause power loss. !

Operation temperature of fielded PV modules

- The temperature distribution of a PV module is typically not uniform (chessboard pattern)
- Temperature differences less than 10 K, which are caused by cell production tolerances (bulk resistance), can regarded as normal.



Normal heat generation ΔT<10 K

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Infrared Thermography of PV Arrays
Heat generation on array level

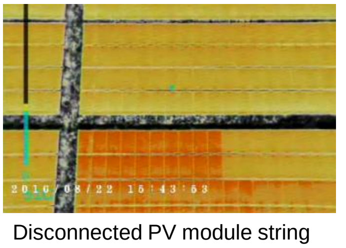
Inter-connection failures detected by drone thermography

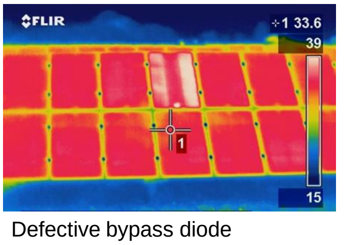
- Disconnected PV module string caused by blown series fuse or open connector.
- Defective bypass diodes or string disconnect in a PV module

  Origin of this failure type can be production failure, overheating or electro-magnetic pulse caused by lightning strike i . These are shorted and .

  Power dissipation of a few Watt per diode will lead to junction box heating.

Disconnected PV modules are operated at Voc and show slightly higher temperature compared to MPP operation. !


Disconnected PV module string



Defective bypass diode

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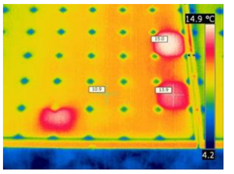
Infrared Thermography of PV Arrays
Heat generation on module level

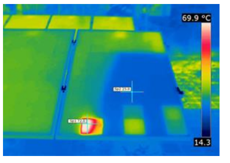
Electrical mismatch of cells

If single cells in the module do not electrically match in short circuit current, or if various power classes for cells are used in a module temperature difference larger than 10 K can be observed. Cell with lower I_{SC} will generate heat.



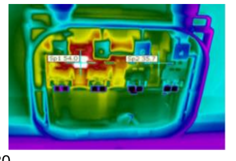
Cell cracks / Burn marks:

If a crack separates a part from a solar cell, this cell is driven in reverse bias and will dissipate power. This defect will only lead to abnormal heating if the size of the separated part is larger than (1- I_{MP}/I_{SC}) of the cell size, which is approx. 10%.



Active bypass diodes:

Bypass diodes turn on when single cells deliver less photocurrent than the maximum power current of the string. Power dissipation due active bypass diode leads to higher module temperature in the module area around the junction box.



Source: IEA PVPS Task 13
http://iea-pvps.org/index.php?id=480

Infrared Thermography of PV Arrays
Classification of abnormal heat generation

Long-term effect:

Ageing of polymeric materials is temperature driven. Accordingly, areas with higher temperature will degrade faster, which can lead to long-term effects such as discoloration of EVA or backsheet and delamination.

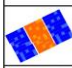
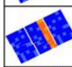
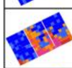
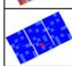
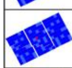
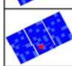
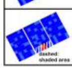
Short-term effects

Localized heating is most critical as it leads to immediate module damage or safety issues: Melting of encapsulant, formation of bubbles (critical is continuous path to the module edge), burning of backsheet, glass breakage

Classification of temperature differences in PV modules
(Solar irradiance > 800 W/m²)

Heating class	Temperature difference	Recommended action
Normal / uncritical	<10 K	None
Noticeable	10 K – 20 K	Regular inspection, report to PV module supplier
Critical	>20 K	Replace affected modules

Infrared Thermography of PV Arrays
IEA PVPS Task 13

Pattern	Description	Possible failure reason	Electrical measurements	Remarks, Chapter	Safety	Power
	One module warmer than others	Module is open circuited - not connected to the system	Module normally fully functional	Check wiring	A	System failure
	One row (sub-string) is warmer than other rows in the module	Short circuited (SC) or open sub-string - Bypass diode SC, or - Internal SC	Sub-strings power lost, reduction of V_{oc}	May have burned spot at the module 6.2.7 One diode shunted	B(f)	const. or E
	Single cells are warmer, not any pattern (patchwork pattern) is recognized	Whole module is short circuited - All bypass diodes SC or - Wrong connection	Module power drastically reduced, (almost zero) strong reduction of V_{oc}	Check wiring 6.2.7 all diodes shunted	A when ext. *SC*, B(f) when *Diodes SC*	const. or E
	Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.	Massive shunts caused by potential induced degradation (PID) and/or polarization	Module power and *FF* reduced. Low light performance more affected than at STC	- Change array grounding conditions - recovery by reverse voltage 6.2.5 (PID)	A	C (v,h,t)
	One cell clearly warmer than the others	- Shadowing effects - Defect cell - Delaminated cell	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch) or shunted cell 6.1.1 (delam.)	A B(f)	A, B, or C(m, tc, h)
	Part of a cell is warmer	- Broken cell - Disconnected string interconnect	Drastic power reduction, *FF* reduction	6.2.2 (cell cracks) 6.2.4 (burn marks) 6.2.6 (interconnects)	B(f)	C(m, tc)
	Pointed heating	- Artifact - Partly shadowed, e.g. bird dropping, lightning protection rod	Power reduction, dependent on form and size of the cracked part	Crack detection after detailed visual inspection of the cell possible 6.2.2 (cell cracks)	B(f)	C(m, tc)
 dashed: shaded area	Sub-string part remarkably hotter than others when equally shaded	Sub-string with missing or open-circuit bypass diode	Massive *Isc* and power reduction when part of this sub-string is shaded	May cause severe fire hazard when hot spot is in this sub-string	A, B(f)	A C

http://www.iea-pvps.org/index.php?id=57

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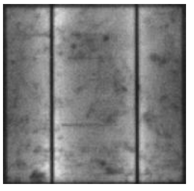
Electroluminescence Analysis
Introduction

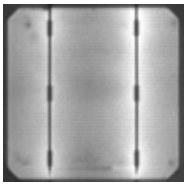
- **Electroluminescence analysis** of PV modules uses the electromagnetic radiation, which is generated by recombination of excited charge carriers in solar cells.
- Excitation occurs by injection of a reverse current into the module in the magnitude of its nominal short circuit.
- The intensity of the emitted radiation is weak, which means that EL cameras must have a high responsivity in the wavelength range 900 nm to 1100 nm.
- In order to avoid daylight effects EL analysis is typically performed in the dark.

Principle interpretation of EL images	
Bright area	Photovoltaic active area
Dark area	Shadow from cell connector ribbon and front grid (Ag finger)
Grey /marbled area	Electrically non-uniform areas originating from wafer or cell processing (i.e. impurities, grain boundaries, dislocation)

Multi-Si Solar cell



Mono-Si solar cell



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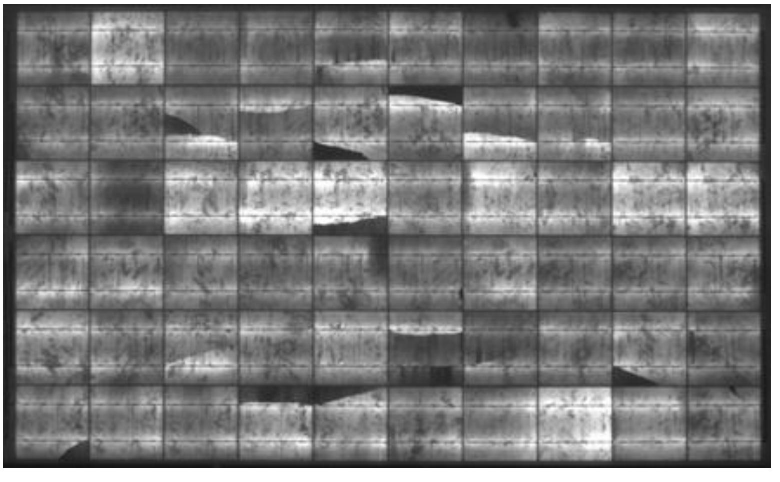
Electroluminescence analysis
Example



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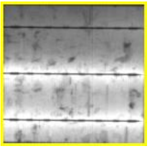
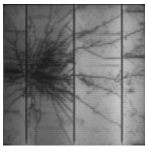
Electroluminescence analysis
Cell cracks and broken interconnects

Origin	Effect
Module manufacturing Mechanical stress on cells during processing and assembly	▪ Permanent visible cracks ▪ Latent cracks, which are not detectable on manufacturing inspection, but can appear sometime later during field operation.
Mechanical induced micro-cracks Transportation, installation, hail impact, snow load	▪ Formation of new cracks ▪ Propagation of existing cracks ▪ Electrical separation of cell areas ▪ Variation of crack pattern
Thermal stress during field operation: Continuous thermo-mechanical stress caused by variation of irradiance during the day and by day-night temperature cycling	

Electroluminescence Analysis
Cell cracks and broken interconnects



Crack of cell interconnect:
- No or reduced current flow through top cell ribbon
- No noticeable effect on module P_{MAX}
- Unclear long-term effects due to thermo-mechanical stress (burn mark caused by arcing)



Cell cracks caused by hail impact

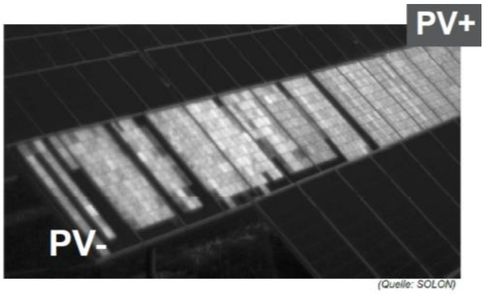
Potential Induced Degradation (PID)
Detection in the field

Electroluminescence Imaging

PID-affected cells appear darker during current injection in the dark (Lower cell voltage due to shunting)

Typical PID patterns:

- Half of the string, which is close to the positive PV+ pole, shows no PID
- Patchwork of PID affected modules is caused by variable operating conditions (electrical contact, condensation, rain)
- Bottom row of cells is heavily affected (worst conditions for PID)
- Stripes of affected cells indicate use of two cell types (two stringers for cell feed in production line)



(Quelle: SOLON)

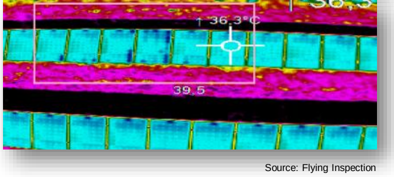
Field Inspection Methods for PV Arrays
Summary

	VIS	IV	IR	EL
Delamination, burn marks, discoloration, cracked backsheet	X			
Power loss related to PV module: Production failure, circuit loss due to electrical mismatch, defective bypass diodes		X		
Power loss due to PV array interconnection failures: Dead strings, loose connections, defective bypass diodes			X	
Power loss related to contacts resistances: Field terminals, cables, connectors		X	(X)	
Heating effects: Hot spot, contact issues	(X)		X	
Cracked cells or interconnects	(X)		(X)	X
Potential induced degradation (PID)		X	X	X

Risk Mitigation by PV Power Plant Services

During Construction & Commissioning

- Pre-shipment testing and inspections
- Factory acceptance testing
- Construction monitoring & supervision
- Punch list
- Mechanical completion inspection
- Performance acceptance testing & verification
- Provisional and final acceptance
- O&M concept, contract & manual review



Source: Flying Inspection

Design | Commissioning | Operation and Maintenance

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Risk Mitigation by PV Power Plant Services

After Construction

- Performance Ratio (PR) verification & Independent energy analysis
- Periodic inspection
- First year capacity test
- Warranty inspections
- Technical DD
- Module status (quality) analysis
- Failure analysis, Performance optimization
- Monitoring, data analysis & sensor calibration
- Arbitration services

Design | Commissioning | Operation and Maintenance

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Lessons Learnt

- Measurements of PV module performance show that a significant number of PV modules underperform, even more after LID. Technology and product specific **performance verification is necessary**.
- A growing number of PV installations world-wide fail to fulfil **quality and safety standards**. There is little knowledge on the extent of bad installations, failure mechanisms and failure statistics.
- Improved methods to detect failures in the field and modeling of PV module power degradation will lead to more qualified assessments of PV systems and thus **lower risk in PV investments**.

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Vielen Dank für Ihre Aufmerksamkeit !