Failure Detection in the Field
EU Cost Action PEARL PV Seminar
PV Reliability and Durability
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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 resources, 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 due dates, weak quality assurance during construction

**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

**How to solve these problems?**
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
Introduction

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- Material incompatibility
Degradation mechanisms
Semiconductor device degradation

- **Thermal degradation (general)**
  High temperature and electric fields in a PV module result into a migration of metal ions (impurities) through the p-n junction, due to which crystal defects are continuously introduced. These defects affect the electrical properties of the cell, such as increased series resistance, decreased shunt resistance or deterioration of anti-reflective coatings.

- **Light induced degradation (LID)**
  LID occurs mainly in c-Si cells within the first days of outdoor exposure and can reduce the short-circuit current in the magnitude of a few percent. The effect is attributed to boron-oxygen defects in boron doped mono p-type wafers manufactured with the Czochralski process.

- **LID for amorphous thin-film modules (Staebler-Wronski effect)**
  This effect refers to light-induced metastable changes in the properties of hydrogenated amorphous silicon (a-Si:H). The defect density increases with light exposure and causes an increase in the recombination current, which means a reduction of the conversion efficiency of sunlight into electricity. The Staebler-Wronski effect can yield -20% degradation of the initial performance.

- **PID for p-type c-Si cells**: Effect reversible in the lab, not confirmed by field experience

- **LeTID for PERC cells**: Effect is partly reversible, not understood for multi-PERC
Degradation Mechanisms
Thermo-mechanical stress

- PV modules combine materials with different coefficients of thermal expansion (glass cover, polymeric encapsulation, solar cells, polymeric backsheets, 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
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
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.
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.

<table>
<thead>
<tr>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA-cell delamination</td>
<td>Can occur along the bus-bar caused by material incompatibility (EVA /soldering flux).</td>
</tr>
<tr>
<td>EVA-cell delamination</td>
<td>Can be caused by contamination of the cell surface. Delamination of a larger area can also indicate a poor cross linking of EVA.</td>
</tr>
</tbody>
</table>
## Failure Modes from Visual Inspection

### Discoloration effects – Cell

<table>
<thead>
<tr>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
</table>
| ![Solder ribbon discoloration](image1.png) | **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](image2.png) | **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 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

<table>
<thead>
<tr>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Snail trails" /></td>
<td><strong>Snail trails:</strong> 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.</td>
</tr>
</tbody>
</table>
### Failure Modes from Visual Inspection

#### Backsheet failure

<table>
<thead>
<tr>
<th>Observation</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image0.png" alt="Image" /></td>
<td>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.</td>
</tr>
</tbody>
</table>
| ![Image](image1.png) | 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. |
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
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.

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

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.

![Graph showing Voc variation with different bypass diode defects](image)

- 24 modules in serially connected
- 3 bypass diodes per module
- Reference
- 3 Bypass diodes defect -4.6%
- 6 Bypass diodes defect -9.1%
- 18 Bypass diodes defect

Forward bias operation
Typical inspection methods for failure analysis and quality assurance

- **Visual inspection**
  - Detection of visible defects
  - Localization of array interconnection failures
  - Localization of failures causing heat generation
  - Potential induced degradation

- **Array I-V curve measurement**
  - Electrical performance
  - Potential induced degradation

- **Infrared (IR) analysis**
  - Localization of array interconnection failures
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- **Electroluminescence (EL) analysis**
  - Localization of cracked cells and interconnects
  - Potential induced degradation
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:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>Minimum 600 W/m² in the plane of the PV module</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Maximum 28 km/h</td>
</tr>
<tr>
<td>Cloud coverage</td>
<td>Maximum 2 octa(^1) of sky covered by cumulus clouds</td>
</tr>
<tr>
<td>Soiling</td>
<td>No or low. Cleaning recommended e.g. if bird droplets exist.</td>
</tr>
</tbody>
</table>

\(^1\) _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 $\Delta T < 10$ K
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
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)

<table>
<thead>
<tr>
<th>Heating class</th>
<th>Temperature difference</th>
<th>Recommended action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal / uncritical</td>
<td>&lt;10 K</td>
<td>None</td>
</tr>
<tr>
<td>Noticeable</td>
<td>10 K – 20 K</td>
<td>Regular inspection, report to PV module supplier</td>
</tr>
<tr>
<td>Critical</td>
<td>&gt;20 K</td>
<td>Replace affected modules</td>
</tr>
</tbody>
</table>
# Infrared Thermography of PV Arrays

**IEA PVPS Task 13**

## Review of Failures of Photovoltaic Modules

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Description</th>
<th>Possible failure reason</th>
<th>Electrical measurements</th>
<th>Remarks, Chapter</th>
<th>Safety</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>One row (sub-string) is warmer than other rows in the module</td>
<td>Short circuited (SC) or open sub-string - Bypass diode SC or - Internal SC</td>
<td>Sub-strings power lost, reduction of $V_{oc}$</td>
<td>May have burned spot at the module</td>
<td>B(f)</td>
<td>const, or E</td>
<td></td>
</tr>
<tr>
<td>Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.</td>
<td>Whole module is short circuited - All bypass diodes SC or - Wrong connection</td>
<td>Module power drastically reduced, (almost zero) strong reduction of $V_{oc}$</td>
<td>Check wiring 9.2.7 all diodes shunted</td>
<td>A when ext SC B(f) when Diodes SC</td>
<td>const, or E</td>
<td></td>
</tr>
<tr>
<td>Single cells are warmer, lower parts and close to frame hotter than upper and middle parts.</td>
<td>Massive shunts caused by potential induced degradation (PID) and/or polarization</td>
<td>Module power and FF reduced. Low light performance more affected than at STC</td>
<td>- Change array grounding conditions recovery by reverse voltage 9.2.5 (PID)</td>
<td>A</td>
<td>C (h,t)</td>
<td></td>
</tr>
<tr>
<td>One cell clearly warmer than others</td>
<td>- Shadowing effects - Defect cell - Delaminated cell</td>
<td>Power decrease not necessarily permanent, e.g. shading of cell or lichen</td>
<td>Visual inspection needed, cleaning cell mismatch or shunted cell or lichen</td>
<td>A</td>
<td>B(f)</td>
<td></td>
</tr>
<tr>
<td>Part of a cell is warmer</td>
<td>- Broken cell - Disconnected string, interconnect</td>
<td>Drastic power reduction, FF reduction</td>
<td>9.2.2 (cell cracks) 9.2.4 (burn marks) 9.2.6 (interconnects)</td>
<td>B(f)</td>
<td>C(m, f)</td>
<td></td>
</tr>
<tr>
<td>Pointed heating</td>
<td>- Artifact - Partly shadowed, e.g. bird dropping, lightning protection rod</td>
<td>Power reduction dependent on form and size of the damaged part</td>
<td>Crack detection after detailed visual inspection of the cell possible 9.2.2 (cell cracks)</td>
<td>B(f)</td>
<td>C(m, f)</td>
<td></td>
</tr>
<tr>
<td>Sub-string remarkably hotter than others when equally shaded</td>
<td>Sub-string with missing or open-circuit bypass diode</td>
<td>Massive Iac and power reduction when part of this sub-string is shaded</td>
<td>May cause severe fire hazard when hot spot is in this sub-string</td>
<td>A</td>
<td>B(f)</td>
<td></td>
</tr>
</tbody>
</table>

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
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

<table>
<thead>
<tr>
<th>Bright area</th>
<th>Photovoltaic active area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark area</td>
<td>Shadow from cell connector ribbon and front grid (Ag finger)</td>
</tr>
<tr>
<td>Grey /marbled area</td>
<td>Electrically non-uniform areas originating from wafer or cell processing (i.e. impurities, grain boundaries, dislocation)</td>
</tr>
</tbody>
</table>

![Multi-Si Solar cell](image1.png)

![Mono-Si solar cell](image2.png)
## Electroluminescence Analysis
Cell cracks and broken interconnects

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

**Cell cracks without separating parts of a cell:**
- Negligible impact on power
- Unclear crack propagation and evolution of degradation (snail trail, separation of cell parts, burn marks, etc.)

**Cell crack with separating a part of a cell:**
- Negligible impact on module output power if area of separated part is lower than 10% of cell area.
- Abnormal heating effect if cell area of separated part is larger than $I_{MP}/I_{SC}$ ratio (condition for reverse bias operation).
- Heating will enhance material degradation.
Crack of cell interconnect:
- No or reduced current flow through top cell ribbon
- No noticeable effect on module $P_{\text{MAX}}$
- 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)
## Field Inspection Methods for PV Arrays

### Summary

<table>
<thead>
<tr>
<th>Issue</th>
<th>VIS</th>
<th>IV</th>
<th>IR</th>
<th>EL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delamination, burn marks, discoloration, cracked backsheet</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power loss related to PV module: Production failure, circuit loss due to electrical mismatch, defective bypass diodes</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power loss due to PV array interconnection failures: Dead strings, loose connections, defective bypass diodes</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Power loss related to contacts resistances: Field terminals, cables, connectors</td>
<td>X</td>
<td>(X)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heating effects: Hot spot, contact issues</td>
<td>(X)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Cracked cells or interconnects</td>
<td>(X)</td>
<td>(X)</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Potential induced degradation (PID)</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
### IEA PVPS Task 13: Performance and Reliability of PVS
#### Subtask 3.2 PV Field Inspection Methods

<table>
<thead>
<tr>
<th>A3.2.1</th>
<th>Daylight I-V measurement of PV string and modules</th>
<th>TUV</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3.2.2</td>
<td>Dark I-V measurement of PV string and modules</td>
<td>AIT</td>
</tr>
<tr>
<td>A3.2.3</td>
<td>Module characterization with mobile test center</td>
<td>SUPSI</td>
</tr>
<tr>
<td>A3.2.4</td>
<td>Daylight electroluminescence imaging</td>
<td>ISE</td>
</tr>
<tr>
<td>A3.2.5</td>
<td>UV fluorescence imaging</td>
<td>ISFH</td>
</tr>
<tr>
<td>A3.2.6</td>
<td>Spectroscopic methods for polymeric materials</td>
<td>OFI</td>
</tr>
<tr>
<td>A3.2.7</td>
<td>Electrical impedance spectroscopy</td>
<td>SICON</td>
</tr>
<tr>
<td>A3.2.8</td>
<td>Drone-mounted EL &amp; IR inspection of PV array</td>
<td>MU</td>
</tr>
<tr>
<td>A3.2.9</td>
<td>PV plant testing vehicle</td>
<td>CAS</td>
</tr>
<tr>
<td>A3.2.10</td>
<td>Advanced outdoor photoluminescence imaging (tbd)</td>
<td>UNSW</td>
</tr>
</tbody>
</table>

Strengths and weaknesses of various inspection methods and best practice recommendations will be jointly discussed and published.
## 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
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
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.
Thank You for Your Attention!