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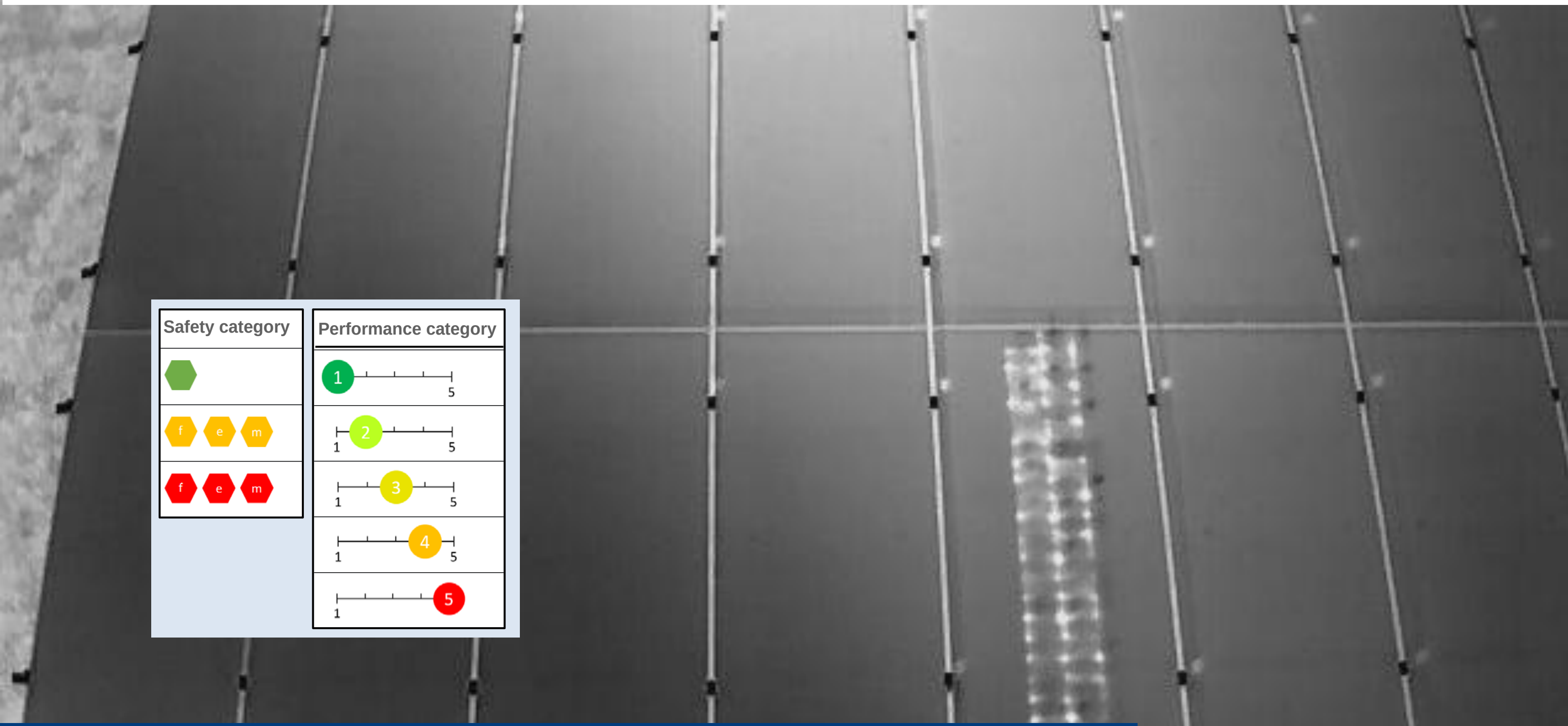

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

Photovoltaic Failure Fact Sheets (PVFS) 2025

Report IEA-PVPS T13-30:2025

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programme (TCP) was created with a belief that the future of energy security and sustainability starts with global collaboration. The programme is made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCP's within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." In order to achieve this, the Programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating countries are Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, and the United States of America. The European Commission, Solar Energy Research Institute of Singapore and Solar Power Europe are also members.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, the reliability and the quality of PV components and systems. Operational data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

Task 13 has so far managed to create the right framework for the calculations of various parameters that can give an indication of the quality of PV components and systems. The framework is now there and can be used by the industry who has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS countries participating in Task 13 are Australia, Austria, Belgium, Canada, Chile, China, Denmark, Finland, France, Germany, Israel, Italy, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, Thailand, the United States of America, and the Solar Energy Research Institute of Singapore.

COVER PICTURE

Infrared image of an energised module string at night. One module has a not connected bypass diode. Thanks to photovoltaikbuero Ternus & Diehl GbR for the permission to use the image.

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1 INTRODUCTION

The photovoltaic failure fact sheets (PVFS) summarise some of the most important aspects of single failures. The target audience of these PVFSs are PV planners, installers, investors, independent experts and insurance companies, and anyone interested in a brief description of failures with examples, an estimation of risks and suggestions of how to intervene or prevent these failures.

The failure sheets are not intended to provide an in-depth exploration of the theoretical background of PV failures and their detection. Instead, they aim to summarize the key points outlined in the various IEA PVPS Task 13 technical reports [Herz22, Köntges14, Köntges16, Köntges17, Schill21, Jahn18, Herrmann21] and reference documents [Sinclair17, Packard12, Eder19, Moser17, Yang19, Walsh20, Petter11, India18, India13, PVSurvey19, DuPont20] that were used to prepare the PVFSs listed in Table 2. These failure sheets are specific to the component where the failure occurs.

The PVFS have been reviewed in 2024 to include latest PV module failures observed in the field and discussed in more detail in a technical IEA PVPS Task 13 report [Köntges25].

1.1 PVFS structure

The format of the PVFS is based on the failure description presented within the H2020 Solar Bankability project [SolBank20]. A rating system for the estimation of the severity of a failure is used here which simplifies the approach proposed within the IEA PVPS Task 13 [Köntges14] by implementing the rating system proposed by the Sinclairs [Sinclair17]. The correlation between the different failures is highlighted in the text by using bold characters. Each PVFS is structured into 1 to 3 pages. The first page is a descriptive page, whereas the remaining pages contain examples composed of a picture, a legend and an estimation about its severity. The first page is structured as follows:

Component

The PV system components are divided into:

(1) PV module (including junction box)

(2) Cables and interconnectors (at module, string and combiner box level)

(3) Mounting (structure, clamps and screws)

(4) Inverter

Defect

Short name describing the failure/defect.

Appearance

Description of how the defect looks like.

Detection

Description of methods which can be used to detect the failure. Detection methods in brackets lists secondary methods, which do not detect the failure with absolute certainty or which can be used in addition to other methods. Following abbreviations are used:

Table 1: Abbreviations of detection methods.

Abbreviation	Detection methods
VI	Visual inspection
IRT	Infrared thermography
EL	Electroluminescence
IV	Daylight I-V measurement
UV	UV fluorescence
STM	Signal transmission method
MON	Data monitoring
dIV	Dark I-V measurement
BYT*	Bypass diode testing
VOC	V_{oc} measurement
INS	Insulation testing

*useful background information
https://photovoltaikbuero.de/en/pv-know-how-blog-en/checking-bypass-diodes-on-solar-panels-part-1/
https://www.hioki.com/euro-en/products/pv/solar-panel/id_6647
https://emazys.com/pv-module-test/

Origin

Description of the failure and its main causes and origin (1. Material and production, 2. Transport and installation, 3. Operation and maintenance).

Impact

Description of the impact on the safety, performance and reliability of the component and system and its severity. For every failure, a range of possible ratings is given, one for the safety and one for the performance.

A failure is defined as a safety failure when it endangers somebody who is applying or working with PV modules or simply passing the PV modules. Three categories are defined in Figure 1.

Safety category	Description
	Failure has no effect on safety.
	Failure may cause a fire (f), electrical shock (e) or a physical danger (m) if a follow-up failure and/or a second failure occurs.
	Failure can directly cause a fire (f), electrical shock (e) or a physical danger (m).

Figure 1: Safety categories.

A failure is defined as a performance failure when it impacts the performance and/or reliability of a system. Five categories are defined in Figure 2. They go from 1 (low severity) to 5 (high severity).

Performance category	Description
1	The defect has no direct effect on performance.
2	The defect has a minor impact on performance.
3	The defect has a moderate impact on performance.
4	The defect has a high impact on performance.
5	The defect has a catastrophic impact on performance.

Figure 2: Performance categories.

For each category, the expected loss is estimated on the component level and if no mitigation measure is implemented. It can range from no power degradation (0%), over power degradation below detection limit (<2-3%), power degradation within warranty (<0.7-1%/year) and power degradation out warranty (>0.7-1%/year) to catastrophic power degradation (>3%/year).

Mitigation

Description of the corrective actions to be done on a short and medium term when detecting a failure and preventive actions to be implemented to avoid the failure from the beginning. Preventive actions are separated into recommended actions, representing the minimum requirement for small residential systems and optional actions for large scale systems.

The general rule for intervention in case of a failure is: All components with a direct safety risk or a performance severity of 5, highlighted in red, should be replaced or repaired. Regular inspections should be performed to monitor the status of the not replaced or repaired components.

1.2 Example PVFS: Front delamination

The delamination of the encapsulant **FS1-3: Front delamination** is used here as an example to explain the FS structure and rating system.

<table>
<tr><td>Component
Defect</td><td colspan="2">Module
Front delamination</td><td>PVFS 1-3vs.01</td></tr>
<tr><td>Appearance</td><td colspan="3">Any local separation of the layers between (i) the front glass and the encapsulant or (ii) the cell and the encapsulant, visible as bubbles or as bright, milky area/s. It may appear continuous or in spots. The position and size of the delamination or bubble depends on the origin and progress of the failure.</td></tr>
<tr><td>Detection</td><td colspan="3">VI, (INS)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="3">The adhesion between the glass, encapsulant, active layers, and back layers can be compromised for many reasons. Typically, it is caused by the manufacturing process (e.g. poor cross linking of EVA, too short lamination times, too high pressure in the laminator, contaminations, improper cleaning of the glass, incompatibility of EVA with soldering flux, inadequate storage of the raw material) or environmental factors (e.g. thermal stresses, external mechanical stresses, UV). Delamination is generally followed by moisture ingress and corrosion. It is therefore more frequent and severe under hot and humid conditions.</td></tr>
<tr><td>Production ■</td><td>Installation □</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="3">Delamination or bubbles do not automatically pose a safety issue, but they can result in reduced insulation of the component and increased safety risk when they form a continuous path between electric circuit and the edge due to possible water ingress. Moisture in the module will decrease performance due to an increase of series resistance, affect long term reliability and in some cases also the structural integrity of the module. Moreover, delamination at interfaces in the optical path will result in additional optical reflection and subsequent decrease in current. This can be the origin of current mismatch. If the mismatch is significant, it will trigger the bypass diode and cause further power loss. The inverter might also shut down due to leakage current's leading to a further performance loss. Manufacturing related delamination issues often affects a relevant percentage of modules within the same production batch and consequentially has a big impact on system performance.</td></tr>
<tr><td colspan="2">Safety:</td><td>Performance: 1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td>Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules. In case of individual module testing all modules which failed the insulation and/or wet-leakage test should be replaced.</td><td>Check validity of IEC 61215 certification and BOM, ground fault detection by inverter or other devices at all time.</td><td>Extended testing (e.g. damp heat), pre-shipment inspections (e.g. cross linking level of EVA) regular visual system inspections.</td></tr>
</table>

Figure 3: First page of PVFS example with general information.

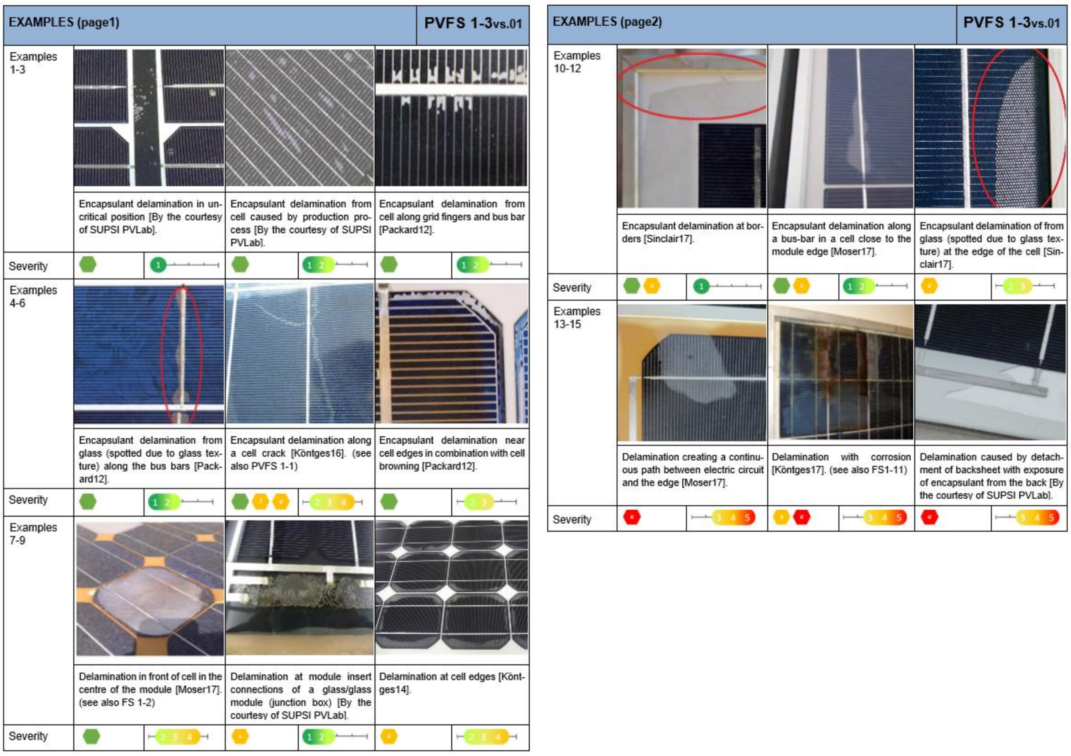

Figure 4: Remaining pages of a PVFS contain examples composed of a picture, a legend, and an estimation about its severity.

The first section of the sheet describes the **appearance** or how to recognise a specific failure and which **detection** methods are available. Delamination is generally easily detectable by visual inspection (VI) of the modules from the front. Insulation measurements (INS) can give a hint of a severe delamination, but it is not the first method to detect an early delamination, reason why it is put in brackets.

The second section describes the **origin** or in which phase of the lifetime of a PV system the failure occurs and what the main causes are. Delamination problems have its origin mainly in the quality of the raw material, the manufacturing process and/or the environmental factors to which the modules are exposed during its operational lifetime. Transport and installation do not generate any delamination problems.

The third section describes the **impact** the failure has on the safety and performance of the component and PV system. Below the general description the severity rating according to Figure 1 and Figure 2 is given. The severity rating in the first page gives the full range of possible ratings observable in the field and how the failure can evolve over the whole lifetime of a PV system. The rating in the examples gives instead a snapshot of the gravity of the failure for a specific case at a certain time. The pictures are taken from literature or case studies and give only a partial picture of the situation and are used to explain the potential levels of impact here.

The delamination of the potting material does not automatically pose a **safety risk.** It is therefore often rated as not critical (see example 1.3.1-1.3.7, 1.3.10 and 13.11 in Annex 1), but depending on the propagation of the failure it can develop into a more severe safety failure. When creating a continuous path between the electric circuit and the edge of the module (see example 1.3.13-1.3.15), delamination can lead to electric leakage currents with a direct risk of electrical shock or the risk can occur later, due to the progress of the delamination and/or the ingress of moisture. This is particularly the case when the original delamination is close to the edge of the module or the junction box, or if it is going over a very extended area (see example 1.3.8-1.3.12). The **performance loss risk** for modules with delamination problems ranges from 1 to 5. Very small delamination areas on top of a cell or outside the cell area and not combined with other failures, are classified as having no impact (1) or a minor power loss typically below the detection limit (2), if the failure is not increasing over time (see example 1.3.1-1.3.4, 1.3.8, 1.3.10 and 1.3.11). The severity is in the range of (2-4) when the delamination area is getting larger (see example 1.3.7 and 1.3.9) or if it is occurring in combination with follow-up failures like moisture ingress (see example 1.3.14) or an insulation failure (see example 1.3.13). It increases also when occurring in combination with a second failure like discoloration (yellowing or browning) of the encapsulant or backsheet (see example 1.3.6, 1.3.7, 1.3.13), or cell cracking (see example 1.3.5). A catastrophic performance loss of (5) is reached when the cell mismatch is so large that one or more bypass diodes could be activated (see example 1.3.13 and 1.3.14).

The last section describes the **mitigation** measures. In case of delamination, all modules that no longer guarantee the electrical safety or insulation resistance or have an active bypass diode, have to be replaced. Not replaced modules with minor delamination have to be monitored by regular visual inspections and ground fault detection. Basic preventive measures consist in selecting certified and tested products only. In case of large-scale systems regular system inspection is recommended.

1.3 List of PVFS

Table 2: List of PV Failure Fact Sheets.

No	Component	Failure name
1-1	PV module	Cell cracks
1-2	PV module	Discolouration of encapsulant or backsheet
1-3	PV module	Front delamination
1-4	PV module	Backsheet delamination
1-5	PV module	Backsheet cracking
1-6	PV module	Backsheet chalking (whitening)
1-7	PV module	Burn marks
1-8	PV module	Glass breakage
1-9	PV module	Cell interconnection failure
1-10	PV module	Potential induced degradation
1-11	PV module	Metallisation discolouration/corrosion
1-12	PV module	Glass corrosion or abrasion
1-13	PV module	Defect or detached junction box
1-14	PV module	Junction box interconnection failure
1-15	PV module	Missing or insufficient bypass diode protection
1-16	PV module	Not conform power rating
1-17	PV module	Light induced degradation in c-Si modules
1-18	PV module	Insulation failure
1-19	PV module	Hot spot (thermal patterns)
1-20	PV module	Soiling
2-1	Cable and Interconnector	DC connector mismatch
2-2	Cable and Interconnector	Defect DC connector/cable
2-3	Cable and Interconnector	Insulation failure
2-4	Cable and Interconnector	Thermal damage in combiner box
3-1	Mounting	Bad module clamping
3-2	Mounting	Inappropriate/defect mounting structure
3-3	Mounting	Module shading
4-1	Inverter	Overheating (temperature derating)
4-2	Inverter	Incorrect installation
4-3	Inverter	Complete failure (not operating)

The list does not pretend to be exhaustive or updated. The complete list with all PVFS

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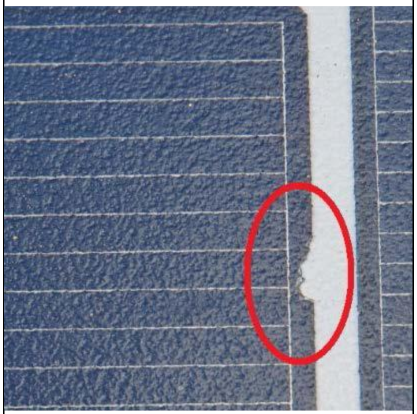
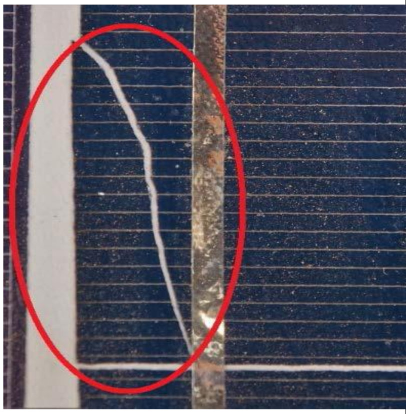
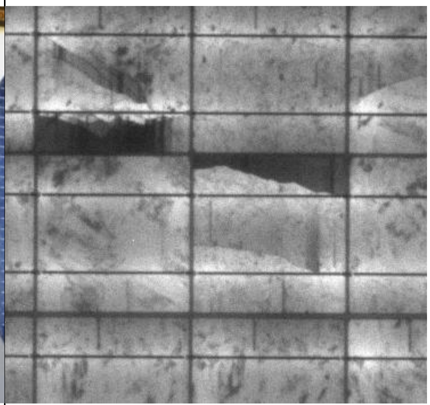
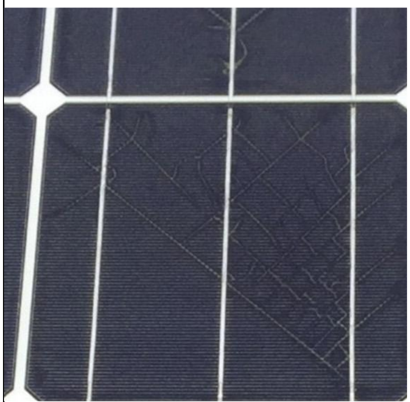
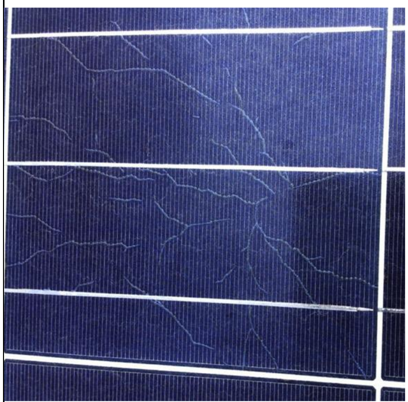
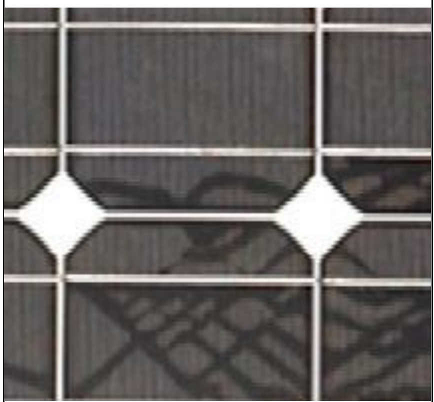
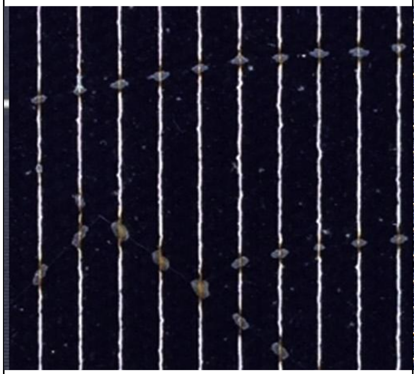
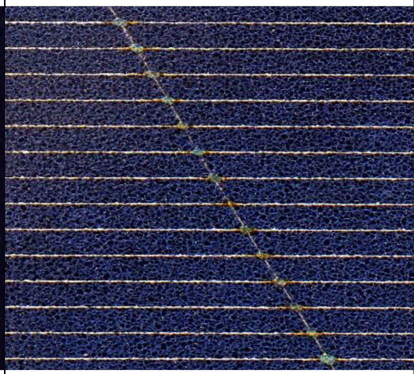
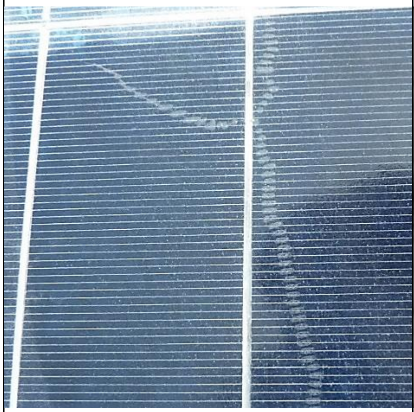
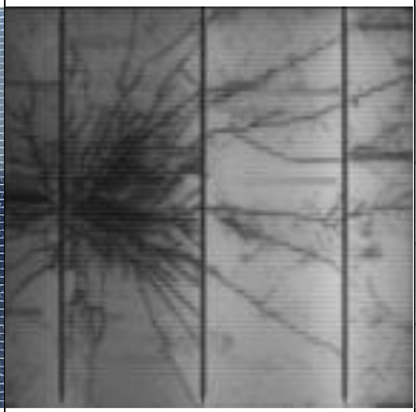
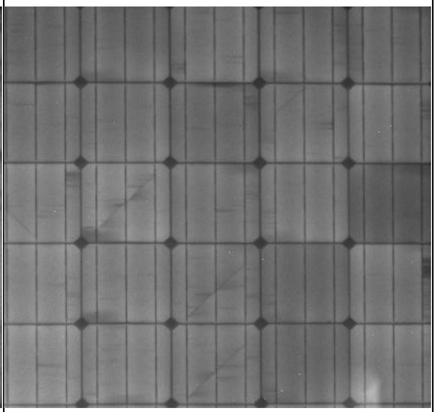
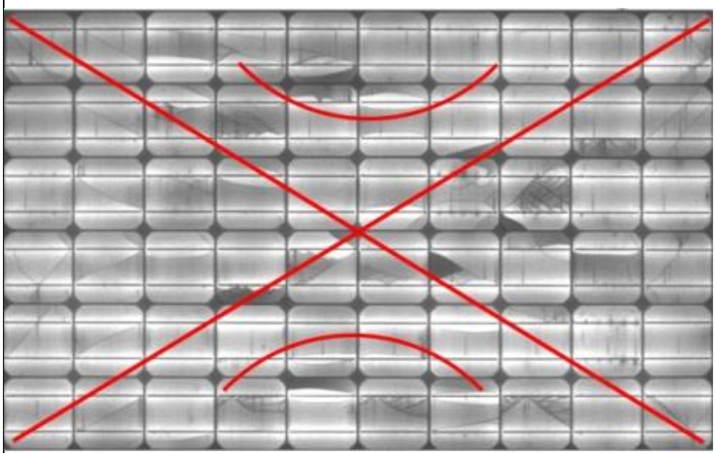
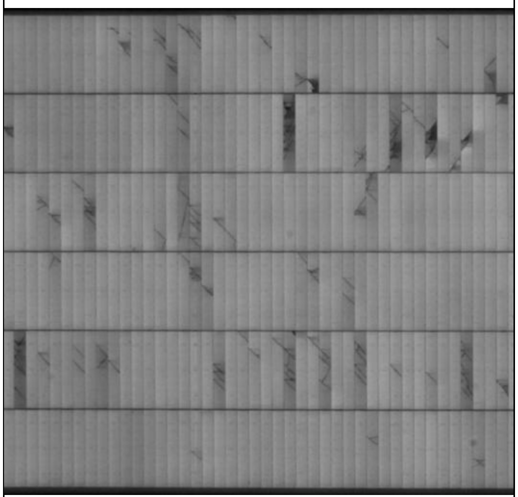
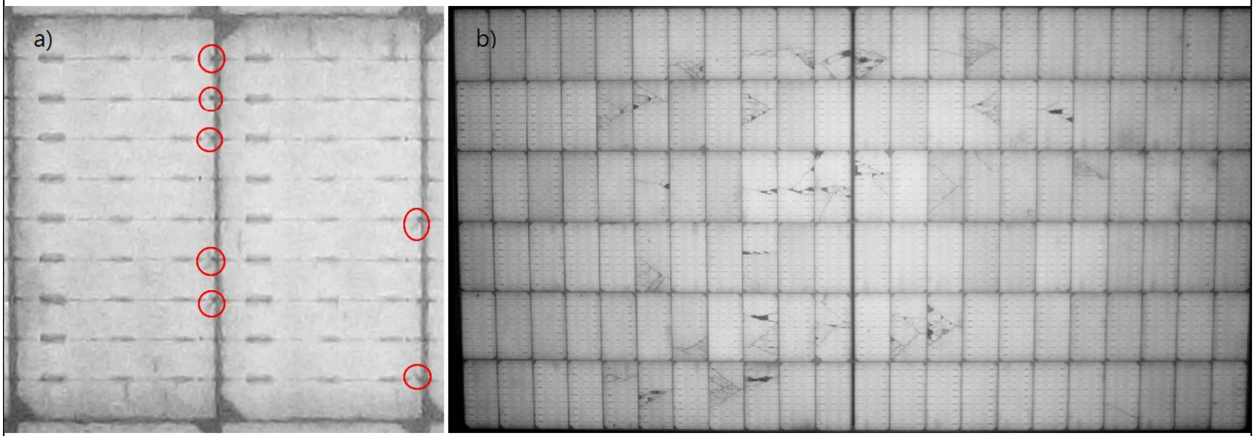
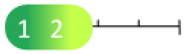
ANNEX (PV FAILURE FACT SHEETS)

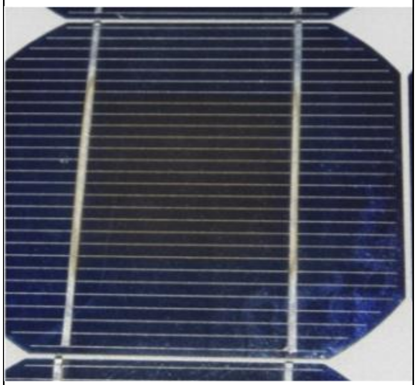
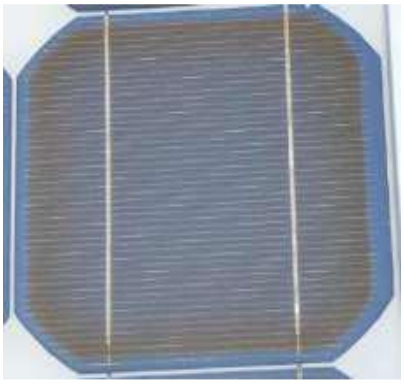
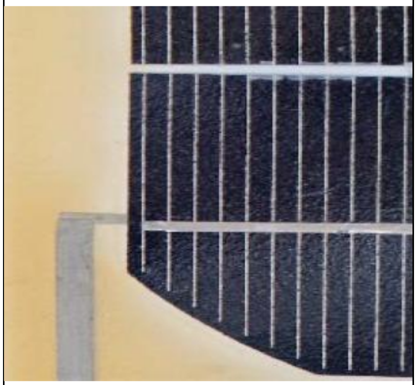
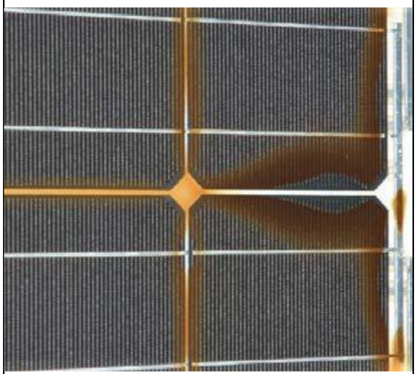
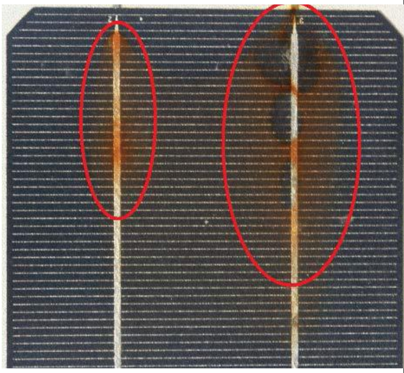
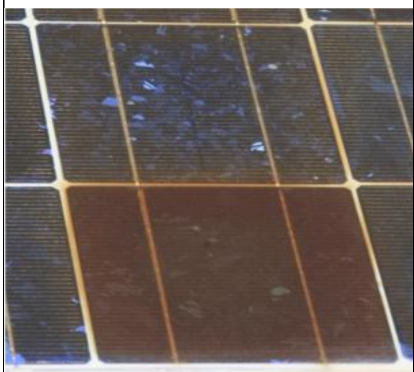
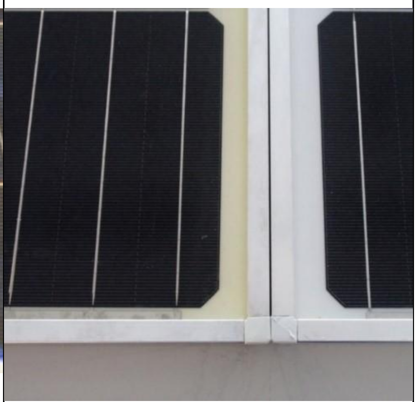
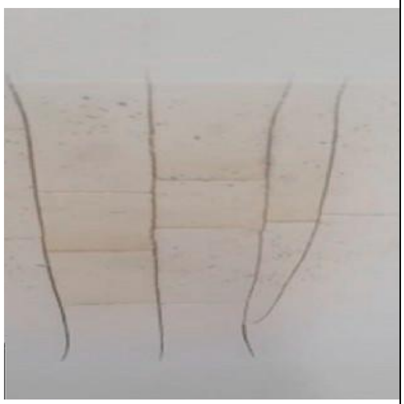
<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Cell cracks</td><td>PVFS 1-1vs.02</td></tr>
<tr><td>Appearance</td><td colspan="4">Cell cracks are cracks in the silicon substrate of the photovoltaic cells. Most of the cell cracks cannot be seen by the naked eye. Only large cracks or where the backsheet is visible through the cracks can be seen. Cell cracks can be easily detected through imaging techniques like electroluminescence or UV fluorescence. Cell cracks can have different lengths and orientations (crack patterns). Small cell cracks (micro-cracks) become visible by eye when they form snail tracks or when photobleaching or delamination takes place along the cracks. A snail track is a discoloration of the silver paste of the front metallisation of solar cells which occurs typically 3 months to 1 year after installation of the PV modules. Affected metal fingers on cells may be silver, yellow or brown in appearance, this effect can also be seen on cell edges. Photobleaching is a counteracting effect to the yellowing of the encapsulant and it occurs along the cracks and the borders of the cells. Sometimes delamination along cracks is visible as small bubbles along the cell cracks.</td></tr>
<tr><td>Detection</td><td colspan="4">EL, UV (IRT, VI, IV)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="4">Cell cracks can have origin in all lifetime phases of a PV module: production, transport, installation and operation. In production, cell cracks can occur during wafer, cell and module manufacturing. Especially the stringing and soldering process of the solar cells can damage the cells. Furthermore the cutting of full cells to half or multiple cut cells can lead to cracking at the cutting cell edge. After production, major sources for cell cracks are the packaging and transport of the modules, and the installation. After installation, external forces like hail, heavy snow weight or strong wind may result in cell cracks. Once cell cracks are present, further mechanical and thermomechanical stresses can lead to the propagation of the cracks into longer and wider cracks. Some crack patterns can give indications on the origin of the failure, but the final cause of cell breakage is not always easy to identify. A repetitive crack pattern can be for example caused by a production failure, whereas PV modules showing dendritic crack patterns have been probably exposed to heavy mechanical loads. Snail tracks can be found in a great variety of solar modules, but not in all. The combination of different materials (encapsulant and back sheets) with UV radiation and temperature plays an important role in the creation of snail tracks.</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="4">Cell cracking does not necessarily lead to a failure of the module. The presence of a crack of any size that does not, or likely will not through its propagation, remove more than 10% of that cell's area from the electrical circuit can be considered to have limited to no impact on the performance. Even if each cell in a 60 full-cell module is cracked, but do not lead to a separated cell area, the power loss of the module is typically below 2.5 % of the nominal power. Compared to former ribbon based modules with 2 to 4 cell interconnect ribbons, more recent multi wire/busbar solar modules demonstrates much lower power losses due to cell cracks. For multi wire PERC modules 0.2% power loss per dendritic like cracked half-cell is typical. In cold and snow climate zones cell cracks seem to have a more pronounced impact. Here relatively high mean degradation rates of up to 7%/y can be found for full cell modules. Besides the risk of power loss there is a risk of hot spots and burn marks due to inactive cell parts. Snail tracks are reported to have no influence on the performance of the PV module.</td></tr>
<tr><td colspan="2">Safety: f e</td><td colspan="2">Performance: 1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules.</td><td>Adequate transport procedures, installation and cleaning by trained personal, in case of higher snow or hail risk use of therefore certified modules. Multiwire modules mitigate degradation risk.</td><td colspan="2">Request EL pictures from production, pre-shipment or warehouse inspection, EL images with mobile laboratory before or during installation, regular EL inspection or after sever weather conditions.</td></tr>
</table>

EXAMPLES (page1)			PVFS 1-1vs.02
Examples 1-3	 Cell chipping. A very small region is missing from the edge of the cell, but does not enter metallized region [Köntges14].	 Large crack at cell corner visible by eye - small portion of the cell (<10%) is no longer electrically connected [Köntges14].	 Cell crack with snail track. No isolation of any cell part. The propagation could isolate a cell area >10% [Köntges14].
Severity	1	2	2
Examples 4-6	 Cell cracks visible by the photobleaching effect. This may not be mistaken for snail tracks [Köntges14].	 Two cell cracks with extensive delamination, EVA browning and photo bleaching [Yang19].	 EL image of 2 cell cracks which isolates more than 10% of the cell area [By the courtesy of TUV Rheinland].
Severity	f e · 2 3 4	f e · 2 3 4 5	f e · 2 3 4
Examples 7-9	 Snail track example [Yang19].	 Snail track example [Yang19].	 EL of cell cracks with snail tracks [Köntges14].
Severity	f e · 2 3 4	f e · 2 3 4	f e · 2 3 4

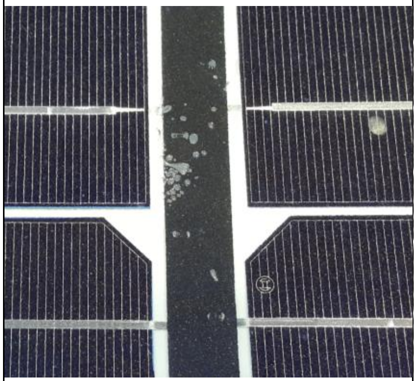
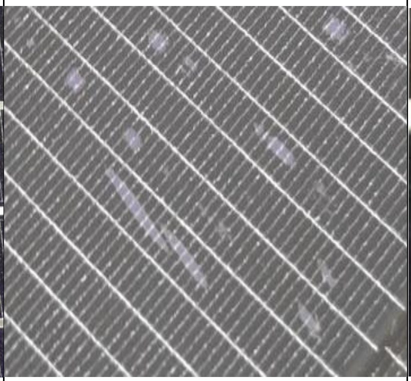
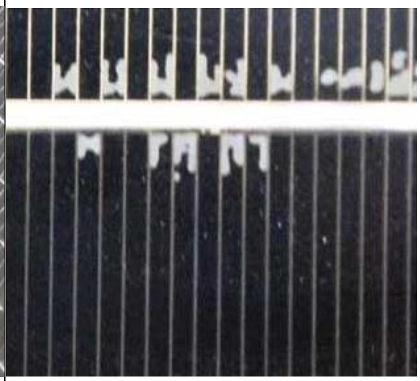
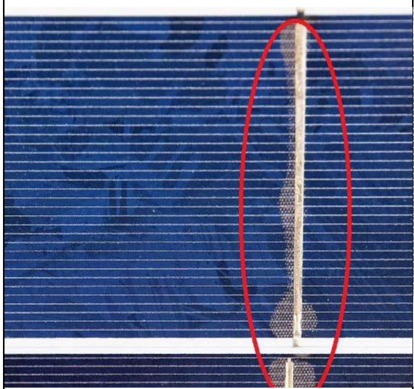
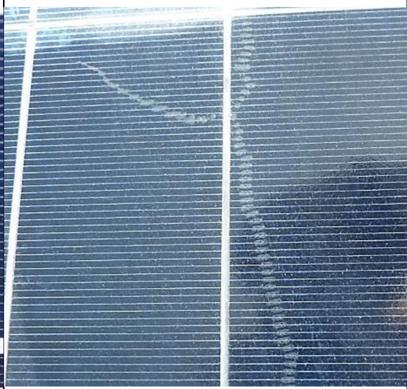
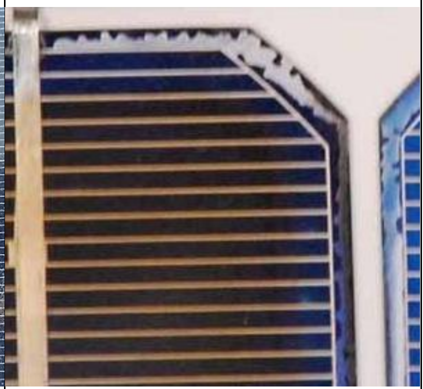
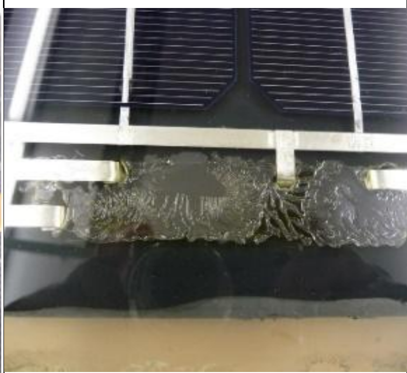
EXAMPLES (page2)			PVFS 1-1vs.02
Examples 10-12			
	Zoom of snail track with delamination [Yang19].	Zoom of snail track with browned fingers [Sinclair17].	Zoom of snail track with delamination [By the courtesy of SUPSI PVLab].
Severity	f e · 2 3 4	f e · 2 3 4	f e · 2 3 4
Examples 13-15			
	Cell crack with EVA delamination [By the courtesy of TUV Rheinland]. (see also PVFS 1-3)	Typical EL picture of a cell crack caused by hail [By the courtesy of TUV Rheinland].	Repetitive crack pattern due to impact of soldering machine [By the courtesy of SUPSI PVLab].
Severity	f e · 2 3 4	f e · 2 3 4	2
Examples 16-17			
	Typical EL picture of cell cracks caused by a heavy homogeneous mechanical load (X-crack pattern) also without glass breakage [Köntges14].		Cell cracks in a module with shingled solar cells [By the courtesy of Aerial Inspection].
Severity	f e	3 4	1 2

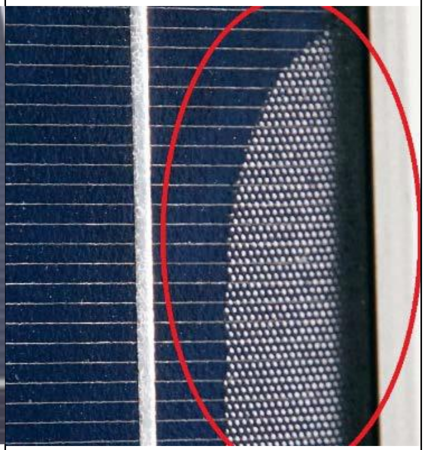
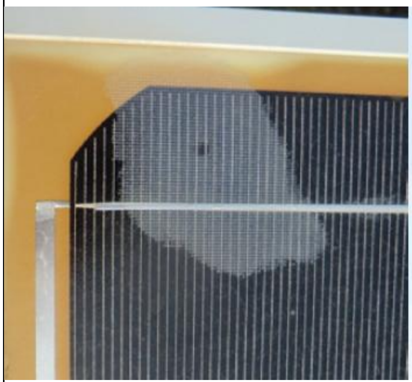
EXAMPLES (page3)	PVFS 1-1vs.02
Example 18	 Manufacturer related cell cracks (a) in half cut cells and they grew into larger ones after transportation with inactive cell areas below 5% per cell (B) [Köntges24] .
Severity	

Component Defect	**Module** **Discolouration of encapsulant or backsheet**		**PVFS 1-2vs.02**
Appearance	The degradation of the encapsulation or backsheet materials is becoming visible as a light yellow to dark brown discolouration. Colour can be next to or above the cells, along the bus-bars or cell interconnects or on the back or front side of the backsheet. Often discolouration is inhomogeneous and follows spatial patterns depending on the type of module construction. Typically, for glass/backsheet modules the encapsulant discolouration occurs in the central region of the cells with wide clear encapsulant areas, or “frames” around the cell edges. Discolouration of the backsheet can be observed at the module edges of between neighbouring solar cells. For glass/glass module constructions the encapsulant discolouration is mostly spatially uniform but can also show patterns of clearer areas over some cells. In glass/backsheet modules the location of these patterns generally correlates with **cell cracks**. In some cases, the discolouration is more pronounced in one or more cells of the module.		
Detection	VI, (IV, IRT)		
Origin	In the past, yellowing or browning was mostly associated with the degradation of the mostly used encapsulant ethylene vinyl acetate (EVA) but this problem was greatly solved by improved stabilisation of the polymer with additives, including UV absorbers and thermal stabilizers. If the choice of additives and/or their concentrations are inadequate, or the lamination process is inadequate or incomplete, the encapsulation material may discolour over time. The root cause of backsheet discolouration is either degradation of the cell side layer of the backsheet or caused by reactions of inter-diffusing additives at the encapsulant backsheet interface. The patterns of discolouration observed in the field can be very complex because of the diffusion of oxygen or the products of reaction, such as acetic acid, generated when heat and UV light interact with EVA. The presence of oxygen leads to the so-called **photobleaching** effect which creates a ring of transparent EVA around the perimeter of a cell or a cell crack. The case of single cells which are far darker than the adjacent cells, implies that the most discoloured cell was at higher temperature than the surrounding cells, perhaps because of differences between the cells or the cell being located above the junction box.		
	Production ■	Installation ☐	Operation ■
Impact	Discoloration is a sign that the polymeric compounds within the module started to degrade. This type of degradation is predominantly considered to be first an aesthetic issue before a decrease of module current and power production is detected. Typically, mean yearly degradation rates due to yellowing are about 0.5%/a and may reach up to 1%/a in hot and humid or moderate climates. While it is uncommon for EVA discolouration to induce other failures within the cell, it may correlate to: high temperatures in the field, the generation of acetic acid and concomitant **corrosion** and **embrittlement**. Unless discolouration is very severe and localized at a single cell, where it could cause a substring bypass-diode to turn on, the discolouration of EVA does not present any direct safety issues. More critical is the discolouration of UV sensitive backsheets that in dependence of the used backsheet materials can be a precursor to a loss of mechanical properties (elastic behaviour) and **cracking of backsheet** due to thermo-mechanical stresses.		
	Safety: 	Performance: 	
Mitigation	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules.	Check validity of IEC 61215 certification and BOM.	Regular system inspections For areas with harsh climate, request modules pass higher test standards, like double or triple IEC 61215 test condition.

EXAMPLES (page1)			PVFS 1-2vs.02
Examples 1-3			
	Slightly browned EVA in the centre of the cell with photobleaching at the edges [Köntges14].	Slightly browned EVA in the centre of the cell with photobleaching at the edges [India18].	Yellowed backsheet from the inside [Sinclair17].
Severity	2	2 3	1 2
Examples 4-6			
	Dark discolouration at cell edges, between cells and over gridlines and busbars [Sinclair17].	Dark discolouration over metalization [Sinclair17].	Backsheet air side yellowing [Sinclair17].
Severity	2 3	2 3	e — 1 2
Examples 7-9			
	Single cell browned much faster than the others due to local heating [Köntges14].	Yellowed backsheet from the inside [By the courtesy of PCLL].	Yellowing of the backsheet in combination with cracked backsheet caused by hot cell [Eder19].
Severity	f e — 2 3	1 2	f m e — 2 3 4 5

<table>
<tr><td>Component
Defect</td><td colspan="5">Module
Front delamination</td><td>PVFS 1-3vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">Any local separation of the layers between (i) the front glass and the encapsulant or (ii) the cell and the encapsulant, visible as bubbles or as bright, milky area/s. It may appear continuous or in spots. The position and size of the delamination or bubble depends on the origin and progress of the failure.</td></tr>
<tr><td>Detection</td><td colspan="6">VI, (INS)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">The adhesion between the glass, encapsulant, active layers, and back layers can be compromised for many reasons. Typically, it is caused by the manufacturing process (e.g. poor cross linking of EVA, too short lamination times, too high pressure in the laminator, contaminations, improper cleaning of the glass, incompatibility of EVA with soldering flux, inadequate storage of the raw material) or environmental factors (e.g. thermal stresses, external mechanical stresses, UV). Delamination is generally followed by moisture ingress and corrosion. It is therefore more frequent and severe under hot and humid conditions.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation □</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">Delamination or bubbles do not automatically pose a safety issue, but they can result in reduced insulation of the component and increased safety risk when they form a continuous path between electric circuit and the edge due to possible water ingress. Moisture in the module will decrease performance due to an increase of series resistance, affect long term reliability and in some cases also the structural integrity of the module. Moreover, delamination at interfaces in the optical path will result in additional optical reflection and subsequent decrease in current. This can be the origin of current mismatch. If the mismatch is significant, it will trigger the bypass diode and cause further power loss. The inverter might also shut down due to leakage current’s leading to a further performance loss. Manufacturing related delamination issues often affects a relevant percentage of modules within the same production batch and consequentially has a big impact on system performance.</td></tr>
<tr><td>Safety:</td><td colspan="2">f e e</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules. In case of individual module testing all modules which failed the insulation and/or wet-leakage test should be replaced.</td><td colspan="2">Check validity of IEC 61215 certification and BOM, ground fault detection by inverter or other devices at all time.</td><td colspan="2">Extended testing (e.g. damp heat), pre-shipment inspections (e.g. cross linking level of EVA) regular visual system inspections.</td></tr>
</table>

EXAMPLES (page1)			PVFS 1-3vs.01
Examples 1-3			
	Encapsulant delamination in uncritical position [By the courtesy of SUPSI PVLab].	Encapsulant delamination from cell caused by production process [By the courtesy of SUPSI PVLab].	Encapsulant delamination from cell along grid fingers and bus bar [Packard12].
Severity	1	1 2	1 2
Examples 4-6			
	Encapsulant delamination from glass (spotted due to glass texture) along the bus bars [Packard12].	Encapsulant delamination along a cell crack [Köntges16]. (see also PVFS 1-1)	Encapsulant delamination near cell edges in combination with cell browning [Packard12].
Severity	1 2	f e 2 3 4	2 3
Examples 7-9			
	Delamination in front of cell in the centre of the module [Moser17]. (see also FS 1-2)	Delamination at module insert connections of a glass/glass module (junction box) [By the courtesy of SUPSI PVLab].	Delamination at cell edges [Köntges14].
Severity	2 3 4	e 1 2	e 2 3 4

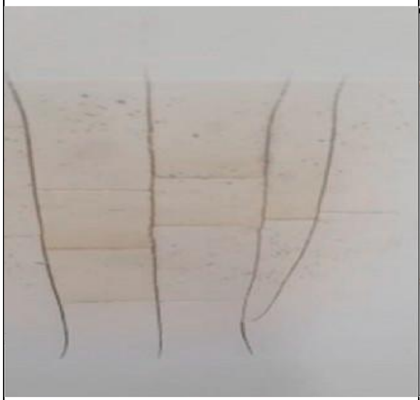
EXAMPLES (page2)			**PVFS 1-3vs.01**
Examples 10-12			
	Encapsulant delamination at borders [Sinclair17].	Encapsulant delamination along a bus-bar in a cell close to the module edge [Moser17].	Encapsulant delamination of from glass (spotted due to glass texture) at the edge of the cell [Sinclair17].
Severity	e — 1	e — 1 2	e — 2 3
Examples 13-15			
	Delamination creating a continuous path between electric circuit and the edge [Moser17].	Delamination with corrosion [Köntges17]. (see also FS1-11)	Delamination caused by detachment of backsheet with exposure of encapsulant from the back [By the courtesy of SUPSI PVLab].
Severity	e — 3 4 5	e e — 3 4 5	e — 3 4 5

Component Defect	**Module** **Backsheet delamination**	**PVFS 1-4vs.01**
Appearance	Any local separation of the polymeric back sheet layers leading to an air gap between the backsheet and the rest of the module, or within the multilayer backsheet (=internal delamination). The backsheet may appear wavy, with locally limited bumps, bubbles or ripples. In the worst case, one or more layers may peel off. The position and extent of the delamination will depend on the cause and progression of the failure.	
Detection	VI, (INS)	
Origin	There are many different forms and compositions of polymeric multilayer backsheets on the market. With laminated backsheets (polymeric layers adhered to each other by a thin adhesive layer) internal delamination can appear: the multiple layers may delaminate upon adhesive degradation, which may lead to local delamination of two subsequent layers or a peel-off of one or more layers. Co-extruded backsheet are prone to internal lamination. Delamination of the backsheet from the encapsulant can appear with all types of backsheets and originates from a lack of adhesion between the backsheet and the encapsulation. The major drivers for the delamination of or within the the backsheet are (i) thermo-mechanical stress originating from differing CTE of the individual polymeric layers, (ii) chemical reactions at the interfaces (material incompatibility) or deteriorated interfacial bonding as a result of the attack from heat, UV and moisture or (iii) external mechanical stress applied on the module. Therefore, it is more frequent and severe under hot and humid conditions. Delamination can be also caused by an insufficient lamination process e.g. too short lamination times.	
	Production ■ | Installation □ | Operation ■	
Impact	If delamination occurs forming bubbles in a central, open area of the back, it will not present an immediate safety issue. That area would likely operate at slightly higher temperatures as the heat conduction/dissipation through the backsheet is disturbed. But as long as the bubble is not further mechanically cracked or expanded, the performance and safety concerns are minimal. However, if delamination of the backsheet occurs near a junction box, or near the edge of a module there would be more serious safety concerns. Delamination at the edge may provide a direct pathway for liquid water to enter the module during a rainstorm, or in response to the presence of dew. That can provide a direct electrical pathway to ground creating a very serious safety concern. Similarly, delamination near a junction box can cause its loosening, putting mechanical stress on live components with the danger of breakage. A break might cause a connection failure to a bypass diode and possibly result in an unmitigated arc at full system voltage. In multilayer backsheets the severity depends also on which layer is affected.	
	Safety: f e e | Performance: 1 2 3 4	

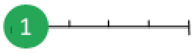
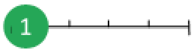
Mitigation	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules. In case of individual module testing all modules which failed the insulation and/or wet-leakage test should be replaced.	Check validity of IEC 61215 certification and BOM. Ground fault detection by inverter or other devices at all time.	Regular system inspections.

EXAMPLES (page1)			PVFS 1-4vs.01
Examples 1-3			
	Multiple bubbles in the centre and edge of the backsheet [Köntges16].	Blisters because of vapour barrier, such as aluminium foil [Köntges17].	Big central bubble + wavy delamination [Köntges14].
Severity	e / 2 3 4	e e / 1 2 3 4	e / 1
Examples 4-5			
	Backsheet delamination with direct exposure of encapsulant [By the courtesy of SUPSI PVLab].	Delamination of top layer without exposure of encapsulant [By the courtesy of SUPSI PVLab].	
Severity	f e / 2 3 4	f e / 1 2 3	

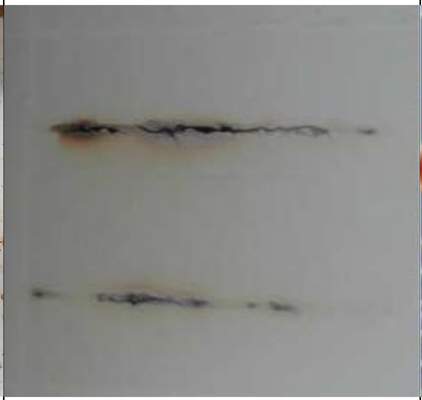
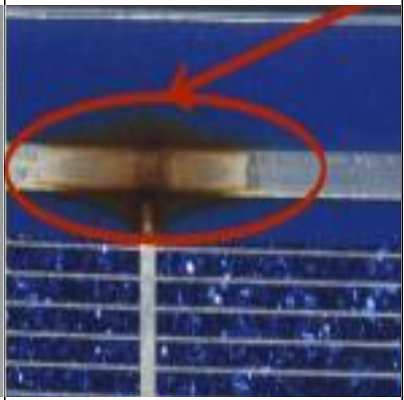
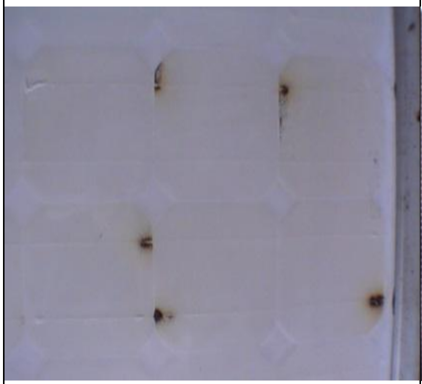
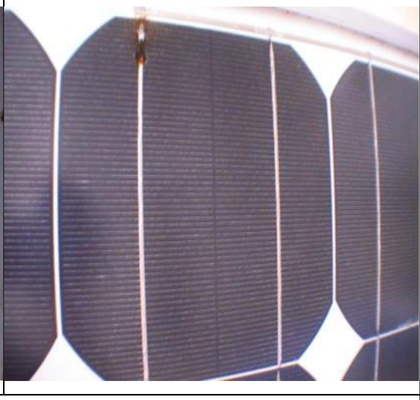
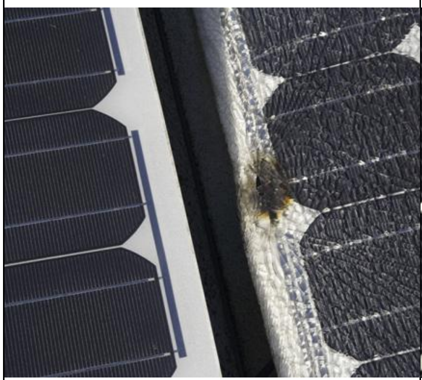
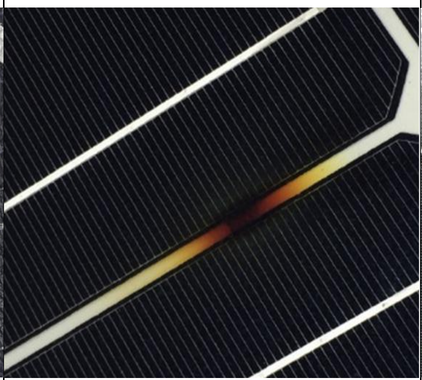
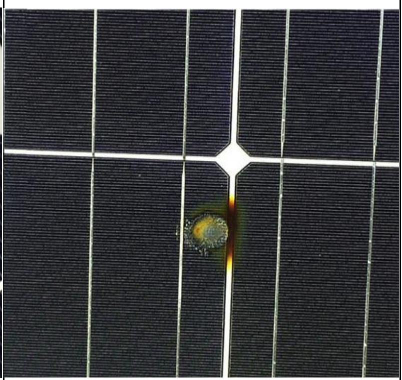
Component Defect	**Module** **Backsheet cracking**		**PVFS 1-5vs.02**
Appearance	Any damage of the backsheet (surface or whole stack) that is visible as crack, burst or scratch. The location and extent of the cracks depend on the cause and progression of the failure. The cracked area may be localized (e.g bursted bubble, scratch), extend along specific module areas (e.g. long or between the cells, along the busbars) or extend over large or the full area of the module (e.g embrittled surface). The crack can be very deep and affect the back sheet stack.		
Detection	VI, (INS)		
Origin	The degradation of the backsheet can be caused by environmental factors like UV-irradiation, thermal stress, external mechanical stress or by internal stress (e.g. thermomechanical stress with the multimaterial composite PV-module) or incorrect handling during transport and installation (local cuts, scratches). Deep backsheet cracking (whole backsheet stack split) is often followed by moisture ingress and **corrosion**. This is more frequent and severe under hot and humid conditions. The use of low-quality material (e.g. low UV resistance) or incompatible material combinations (backsheet ↔ encapsulant) causes most of the premature degradation failures. **Discolouration** and strong **chalking** can be precursors for backsheet cracking. Deep cracks or bursted bubbles can be the result of local **hotspots/burn marks** that split or break the backsheet.		
	Production ■	Installation ■	Operation ■
Impact	A broken backsheet can cause **electrical insulation** failure, posing a safety hazard and a potential ground fault. On the long-term, power degradation due to the penetration of moisture into the module which induces further failures (e.g. corrosion, delamination) can occur. In the case of deep cracks reaching the active part of the cells, the insulation is immediately compromised and safety is not anymore fulfilled.		
	Safety: f e m e	Performance: 1 2 3 4 5	
Mitigation	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules. In case of individual module testing all modules which failed the insulation and/or wet-leakage test should be replaced.	Ground fault detection by inverter or other devices at all time, check validity of IEC 61215 certification and BOM, visual inspection before installation.	Regular system inspections. Installation of arc detection tool.

EXAMPLES (page1)			PVFS 1-5vs.02
Examples 1-3			
	Cracked backsheet in combination with yellowing under a hot cell [Eder19].	Squared cracks beneath cell interspaces [Eder19].	Cracking between cells [Packard12].
Severity	f m e | 2 3 4 5	f m e | 2 3 4 5	f m e | 2 3 4 5
Examples 4-6			
	Longitudinal cracks located under bus bars [Eder19].	Backsheet cracking [DuPont20].	Backsheet cracking [DuPont20].
Severity	f m e | 2 3 4 5	f m e | 2 3 4 5	f m e | 2 3 4 5
Examples 7-8			
	Localized superficial damage [Köntges17].	Deep scratch on backsheet [By the courtesy of TUV Rheinland].	PVDF outer layer cracking [By the courtesy of PCCL].
Severity	f e m | 1	f m e | 1 2	f e m | 2 3 4 5

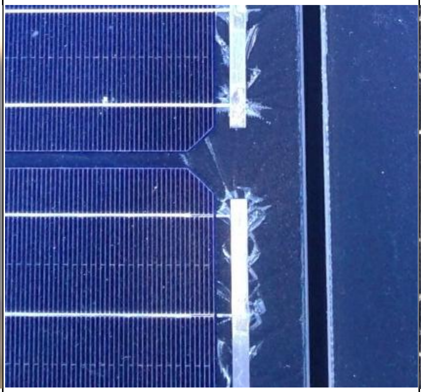
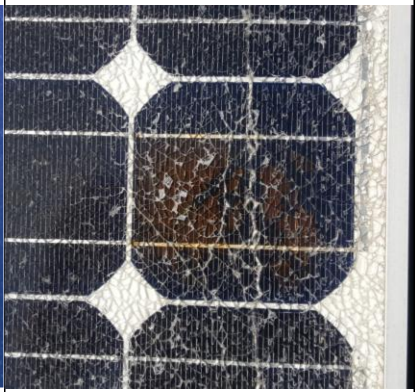
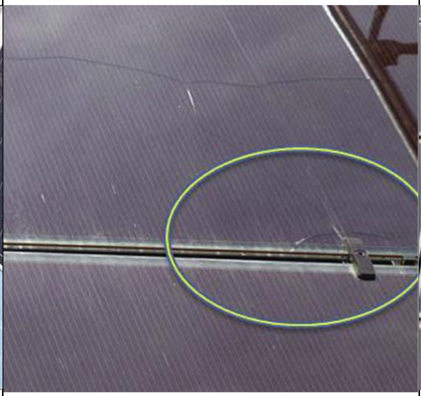
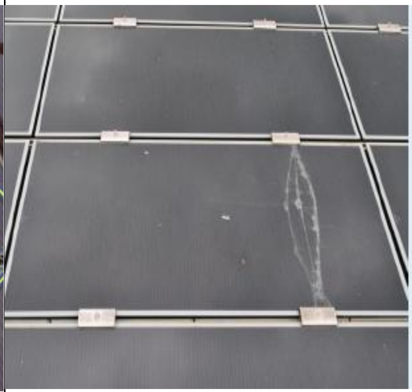
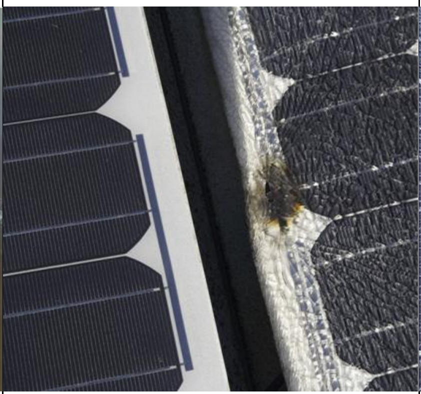
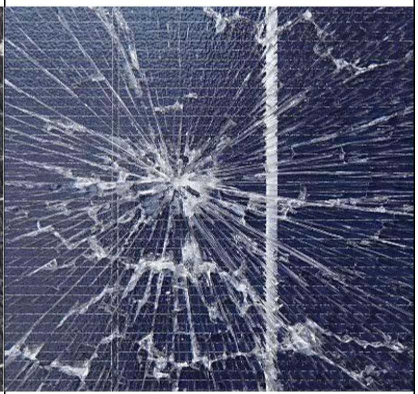
<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Backsheet chalking (whitening)</td><td>PVFS 1-6vs.01</td></tr>
<tr><td>Appearance</td><td colspan="4">White powder is detectable on the external surface of the backsheet. It can be seen by passing a finger over the backsheet. It can be removed. The backsheet has usually a rough or dull appearance.</td></tr>
<tr><td>Detection</td><td colspan="4">VI</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="4">Chalking is caused by the photothermal degradation of the polymers in the outer backsheet layer containing inorganic pigments. For example, TiO_2 pigments are often used in the outer layers as UV blocker.</td></tr>
<tr><td>Production ■</td><td>Installation ☐</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="4">Chalking does not affect module safety or performance on first sight, but it can be a sign for an ongoing degradation of the backsheet and a precursor for severe backsheet cracking. Due to the degradation-induced reduction of UV protection, more serious failures, such as back-sheet cracking and insulation failures can occur. Enhanced moisture diffusion into the en-capsulant/active PV-parts can lead to corrosion of cells and connectors, having a negative impact also on the performance.</td></tr>
<tr><td>Safety:</td><td>e</td><td>Performance:</td><td>1</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Regular inspections should be done to monitor the progress of the observed failure. Ground fault detection by inverter or other devices at all time.</td><td>Check validity of IEC 61215 certification and BOM.</td><td colspan="2">Regular system inspections.</td></tr>
</table>

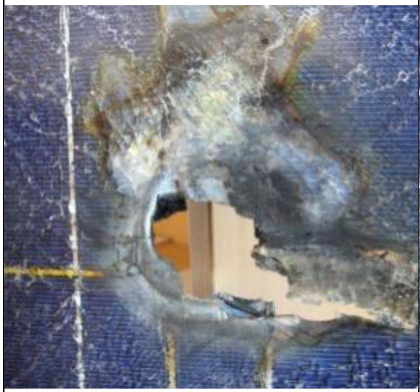
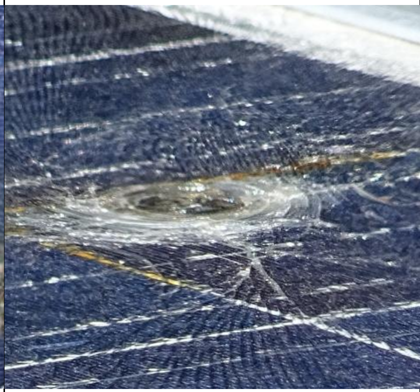
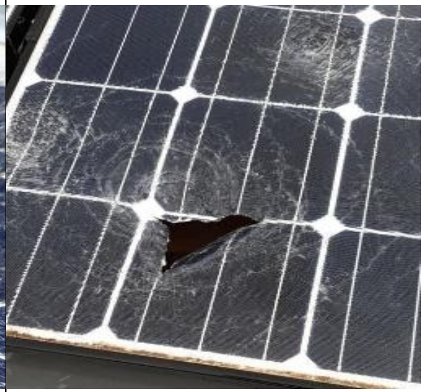
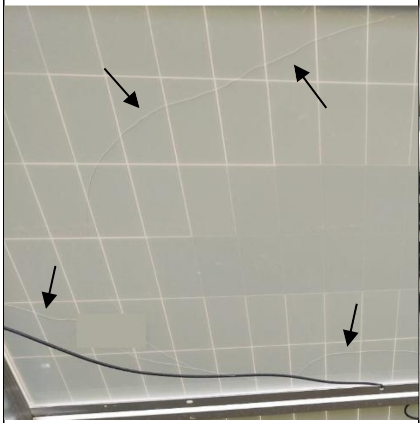
EXAMPLES (page1)			**PVFS 1-6vs.01**
Examples 1-2			
	Finger with white powder [By the courtesy of TUV Rheinland].	Fingerprint on a module with chalking [By the courtesy of TUV Rheinland].	
Severity	 	 	

<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Burn marks</td><td colspan="2">PVFS 1-7vs.01</td></tr>
<tr><td>Appearance</td><td colspan="5">Burn marks are visible with the naked eye as burnt, blackened area/s. The burn mark may lead to bubbling or melting of the polymeric encapsulant, and/or glass breakage or a hole in the backsheet. Burn marks on the backheet may be not visible from the front requiring an inspection with an IR camera if the back of the module is not accessible. They may however not be visible by IR inspection in case no further or ongoing heating occurs.</td></tr>
<tr><td>Detection</td><td colspan="5">VI, IRT, (EL)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="5">The defect is associated with parts of the module that became very hot because of production errors (e.g weak solder bonds, ribbon breakage, incomplete cell edge isolation, alignment errors, metal particles) and/or transportation/handling errors (e.g, cracked cells, damaged back-sheet) in combination with one or more operational factors (e.g. shadowing, open circuited bypass diodes, reverse current flows). Physical stress during PV module transportation, heavy snow loads, a lightning strike, thermal cycling, and/or hot spots by partial cell shading during long-term PV system operation forces mechanical weak(ended) cell/connection parts to break. Burn marks occur for example when a reverse current flow causes heating that further localizes the current flow, leading to a thermal runaway effect and the associated burn mark.</td></tr>
<tr><td>Production ■</td><td colspan="2">Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="5">Burn marks on interconnections are often associated with power loss, but if redundant electrical interconnections are provided, a failed solder bond may have negligible effect on the power output. If all solder bonds for one cell break, then the current flow in that string is completely blocked and an electric arc can result if the current cannot be bypassed by the bypass diode and the system operates at high voltage. Performance, reliability and safety are likely to be severely compromised. Such an arc can cause a fire if there happen to be flammable material around. If there is a question about whether the existence of the burn mark requires replacement of the module, an infrared image under illuminated and/or partially shaded conditions will quickly identify whether the area is continuing to be hot and/or whether current flow has stopped in that part of the circuit. Temperature difference between neighbouring cells should not be over 30 K. At this stage safety risk may still be not so high because the temperature of this hot spot cell does not increase to more than around 100 °C. Also edge isolation faults on the solar cell level are under normal conditions not problematic, but when the bypass diode is in open-circuit, the current is driven in reverse through the shunts of the solar cells and burns the encapsulation.</td></tr>
<tr><td>Safety:</td><td>f e m f e m</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Visual inspection before installation, commissioning of system with IRT.</td><td colspan="2">Regular system inspections.</td></tr>
</table>

EXAMPLES (page1)			**PVFS 1-7vs.01**
Examples 1-3			
	Burn mark at the backsheet with cracked backsheet [Sinclair17].	Burn marks at the backsheet due to heating along a busbar [Köntges14].	Burn mark associated with over-heating along the metallic inter-connection (without back-sheet damage) [Köntges14].
Severity	f e m — 5	f e m — 3 4 5	f e m — 2 3
Examples 4-6			
	Front and back side view of burn marks caused by open-circuited by-pass diodes and current mismatch conditions (due to shading or cracked cells) [Köntges14].		Burn marks caused by defect bypass diodes or an intercon-nect failure in the junc. box [Köntges14].
Severity	f e m	3 4 5	f e m — 3 4 5
Examples 7-9			
	Burn mark with broken glass caused by poor bussing ribbon soldering [Yang19]. (see also PVFS 1-8 and PVFS 1-8)	Burn mark due to intrinsic shunt-ing caused by error in manufac-turing process [Yang19].	Burn mark due to intrinsic shunting caused by error in manufacturing process [Yang19].
Severity	f e m — 3 4 5	f e m — 1 2 3	f e m — 1 2 3

<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Glass breakage</td><td colspan="2">PVFS 1-8vs.02</td></tr>
<tr><td>Appearance</td><td colspan="5">Glass is cracked locally or over the full area of the module. Glass breakage looks different depending on the type of glass and the origin of the glass breakage. Thermally toughened or tempered glass will shatter into small pieces, whereas annealed glass breaks into larger pieces. Heat-strengthened glass stays in between. Cracks occurring on the rear glass of glass/glass modules are more difficult to see by eye especially in the case of thin heat-strengthened glass.</td></tr>
<tr><td>Detection</td><td colspan="5">VI, (IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="5">Glass breakages of the front glass can be caused by heavy impacts such as hail or stones or other extreme mechanical stress onto the module frame due to external stresses or bad mounting or internal stress due to high temperatures originating from hot-spots or arcing. Annealed glass can break due to thermal gradients or stress induced by the lamination process or cleaning of the modules. A relatively frequent failure in the field is glass breakage of frameless PV modules and glass/glass modules. In particular bifacial modules with thin glasses with a thickness of 2 mm to 1.6 mm, are more sensitive to glass breakage. This is due to the fact that thin glass cannot be fully tempered like 3 mm thick glass, reducing the surface resistance against stress, impacts and scratches. Very often the cracking of thin glass starts on the rear glass. The origin is not fully understood. In some cases the origin is in the preparation of the cutting edges or the drilling of the holes for the connection to the junction box. At the planning and installation stage failure occurs due to either (a) poor clamp geometry for the module, e.g. sharp edges, (b) too short and too narrow clamps or (c) the positions, kind or number of the clamps on the module not being chosen in accordance with the manufacturer's manual. The second origin which induces glass breakage could be excessively tightened screws during the mounting phase or torsion of the module, not respecting requirements for planarity. The glass of some PV modules may also break due to vibrations and shocks occurring during transportation or handling. Another reason for glass breakage comes from impact stresses on the glass edge. Sometimes vandalism or damages by animals occurs (e.g. animals climbing on the modules or birds dropping stones or other objects from the sky).</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="5">Module mechanical integrity is compromised when the glass is broken. Over time glass breakage leads to loss of performance due to cell and electrical circuit corrosion caused by the penetration of oxygen and water vapour into the PV module. Shattering of tempered glass usually also breaks the cells reducing the power of the module and increasing the risk of hot spots and arcs. Mechanical and electrical safety is thus compromised. Firstly, the insulation of the modules is no longer guaranteed, in particular in wet conditions and ground fault and inverter shutdown can occur. Secondly, glass breakage causes hot spots, which lead to overheating of the module and possible fire injection. A module with a completely broken glass lead to current and power reductions in the whole string.</td></tr>
<tr><td>Safety:</td><td>f e m f e m</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td colspan="2">All damaged modules have to be replaced. In case of known origin, the error must be rectified. Regular visual inspections are recommended in case of unknown causes not related to external impact.</td><td colspan="2">Adequate transport procedures, installation and cleaning by trained personal, in case of higher snow or hail loads use of certified modules.</td><td>Qualification of modules and mounting configuration with expected mechanical load.</td></tr>
</table>

Examples 1-3			
	Chipped glass at the corner [Packard12].	Glass breakage along the string interconnect ribbons due to weak manufacturing process [By the courtesy of SUPSI PVLab].	Glass breakage of tempered glass induced by a hot-spot [By the courtesy of SUPSI PVLab].
Severity	m 1	f m e m 2 3	f e m 3 4 5
Examples 4-6			
	Glass breakage caused by too tight screws [Köntges14]. (see also PVFS 3-1)	Glass breakage caused due to poor clamp design [Köntges14].	Glass breakage caused due to poor clamp design [Köntges17]. (see also PVFS 3-1)
Severity	f m e m 2 3 4	f m e m 2 3 4	f m e m 2 3 4
Examples 7-9			
	Glass breakage through high temperature gradient and not tempered glass [Köntges14].	Glass breakage of tempered glass induced by burn mark [Köntges17]. (see also PVFS 1-7 and PVFS 1-9)	Breakage of tempered glass [Köntges17].
Severity	f e m 3 4 5	f e m 3 4 5	f e m 3 4 5

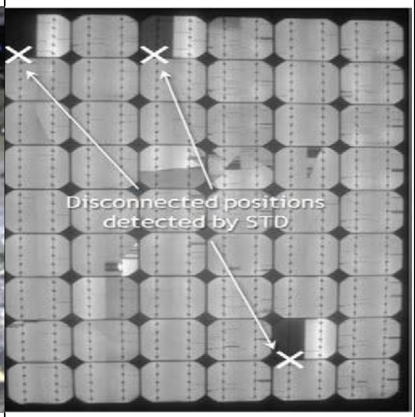
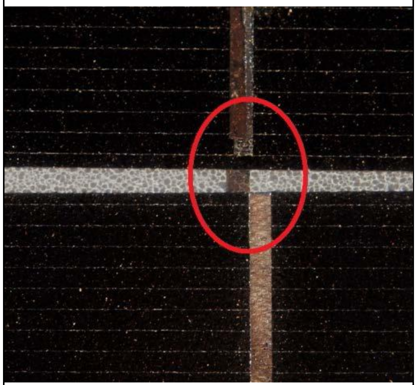
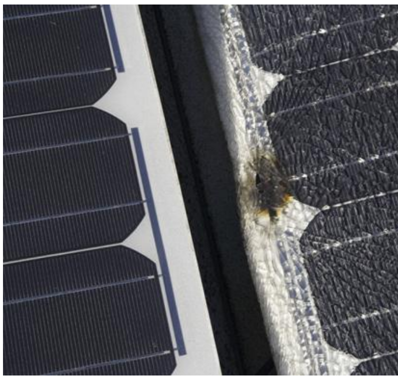
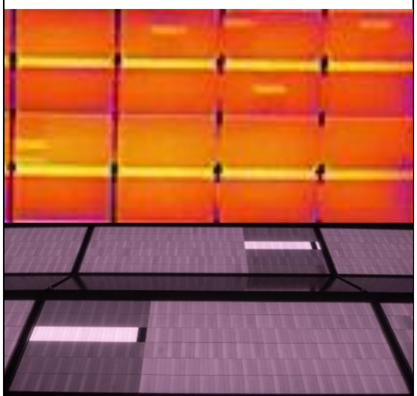
EXAMPLES (page2)			**PVFS 1-8vs.02**
Examples 10-12			
	Direct lightning stroke [Könt-ges16].	Impact damage caused by a heavy object [By the courtesy of SUPSI PVLab].	Hail damage [By the courtesy of SUPSI PVLab].
Severity	f e m / 5	f e m / 5	f e m / 5
Examples 13-15			
	Broken thin (<=2 mm) rear glass. Long (many dcm) crack lines without splitting the crack with no clear crack start.	Glass breakage on the rear side of a bifacial module caused by insufficient spacing between modules (thermal expansion of module frame is not considered).	
Severity	f e m / 2	f e m / 2 3	

<table>
<tr><td>Component
Defect</td><td colspan="4">Module
Cell interconnection failure</td><td colspan="2">PVFS 1-9vs.02</td></tr>
<tr><td>Appearance</td><td colspan="6">Weak or broken interconnection of cells or substrings is not easy to be seen by the naked eye. The failure can be identified as dark region in the electroluminescence image where the failed interconnect would not be collecting carriers and result in a hot spot in the infrared image. In a progressed stage burn marks and glass breakage can occur.
A short-circuited cell is also difficult to recognize with naked eye, while it appears as dark cell in the EL image. For parallel connected substrings the substring with short-circuited cell appears brighter in an EL image and slightly warmer in IRT than other substrings in parallel connection.</td></tr>
<tr><td>Detection</td><td colspan="6">EL, IRT, STM, (VI)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">Typically, it is caused by the manufacturing process (e.g. poor soldering, misplacement of ribbons, too intense deformation of the ribbon kink, narrow distance between the cells, incorrect conductive glue application) followed by thermomechanical stress or repetitive wind load caused by the outdoor operating environment. Electrochemical corrosion can be another cause for the degradation of interconnections. Short circuited cell occurs when the interconnection ribbon or conductive glue connects the front and rear sides of a cell.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation □</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">Poor interconnections (soldering bonds) lead to an increase of contact resistance, higher power dissipation and localized heating. Broken connections are often associated with power loss, but if redundant electrical interconnections are available, a failed connection may have negligible effect on the power output. Safety risk may be not so high until the temperature of the induced hot spot does not increase to more than around 100 °C. If all busbars of a cell are interrupted, then the current flow in that string is completely blocked and an electric arc can result if the current is not bypassed by the bypass diode and the system operates at high voltage. The safety risk depends on the durability of this bypass diode. A bypass diode, which is continuously active over days can be damaged and pass into open-circuit or short circuit state. As a result of an open circuited diode, the current goes through the failed cell string and generates heat at the disconnected position. Very high temperatures or an electric arc may cause fire, expose the electrical conducting parts to the user and destroy the mechanical integrity of the module.

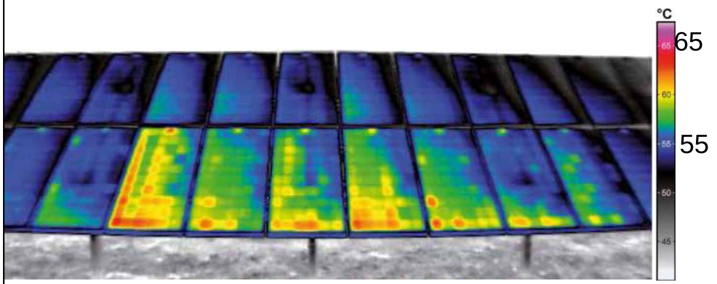
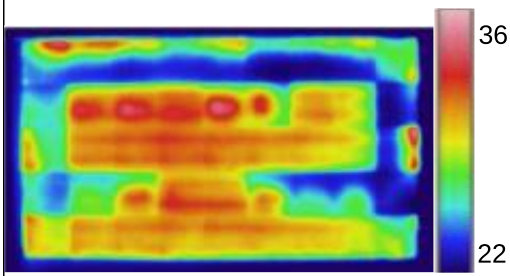
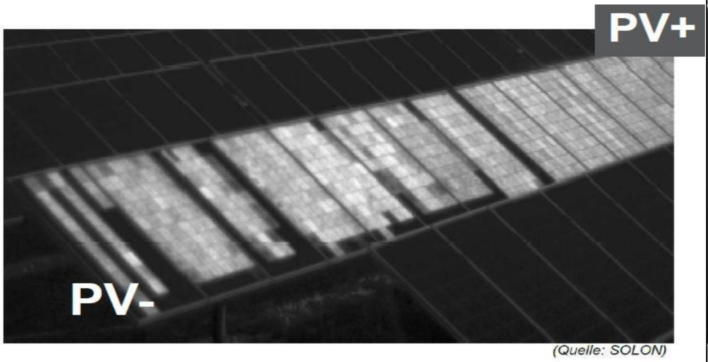
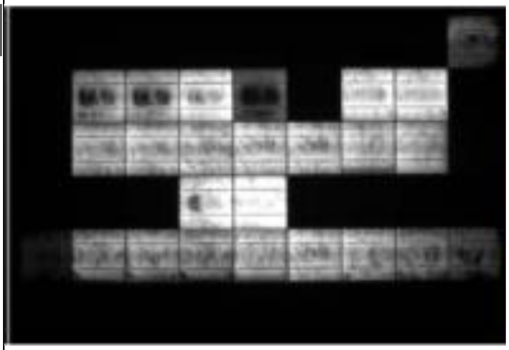
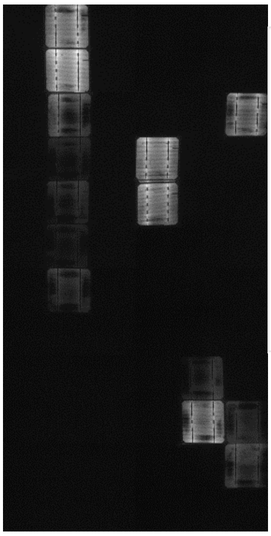
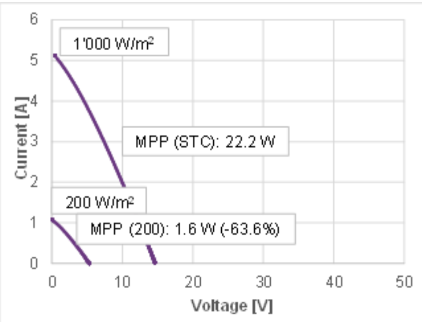
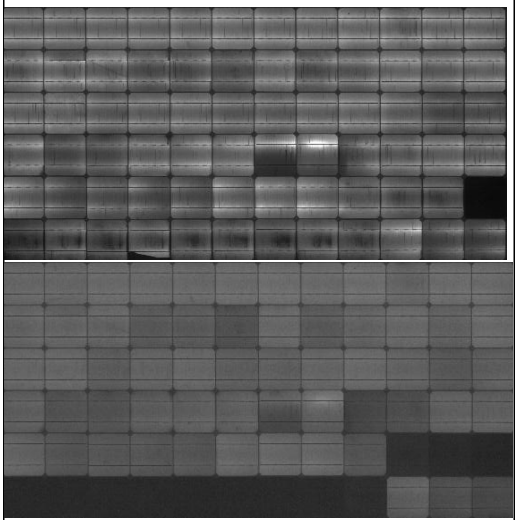
The power loss of a module with short-circuited cell depends on the interconnection profile of the module. For series connected cells in a module only the power of the short-circuited cell(s) is/are lost. The impact of short-circuited cells in a parallel connection has to be assessed in detail, but it is lower than the power of cells equivalent to the number of parallel connected cell times maximum number of shunted cells in one series connected substring. In most cases there is no safety issue for short-circuited cells.</td></tr>
<tr><td>Safety:</td><td colspan="2">f e m f e m</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Check proof of factory inspection according to IEC 62941.

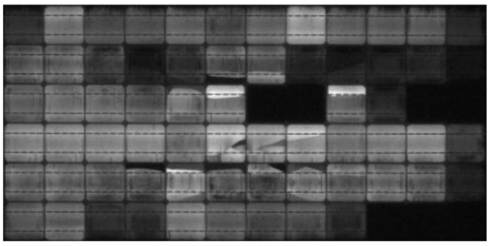
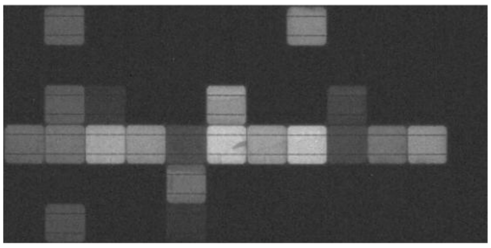
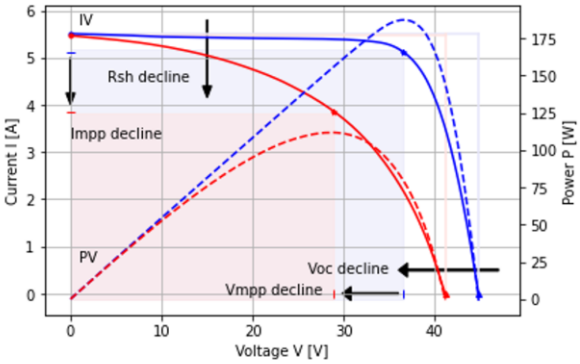
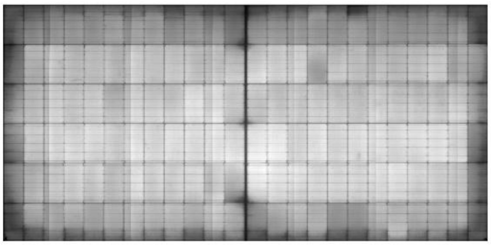
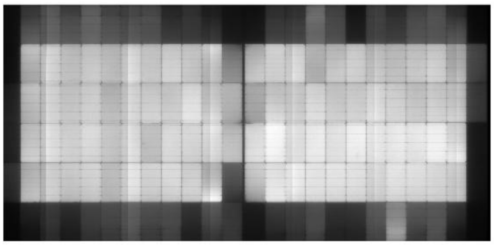
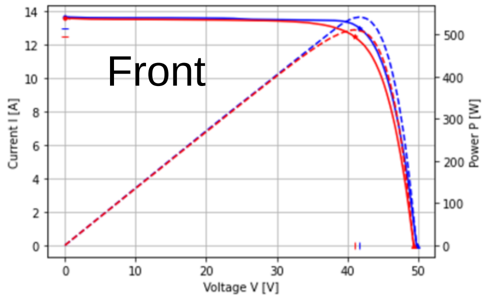
Commissioning of system with IRT.</td><td colspan="2">Pre-shipment inspection or sampling EL inspection when modules arrive the installation site.

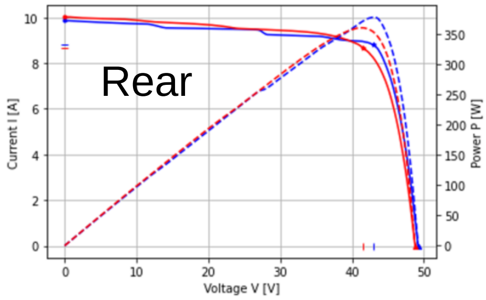
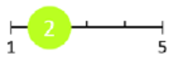
Regular system inspections.</td></tr>
</table>

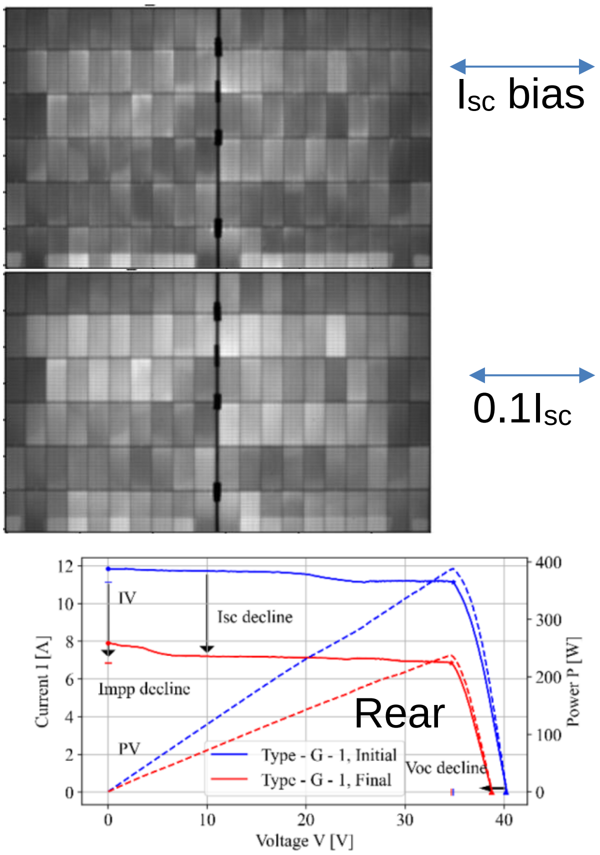
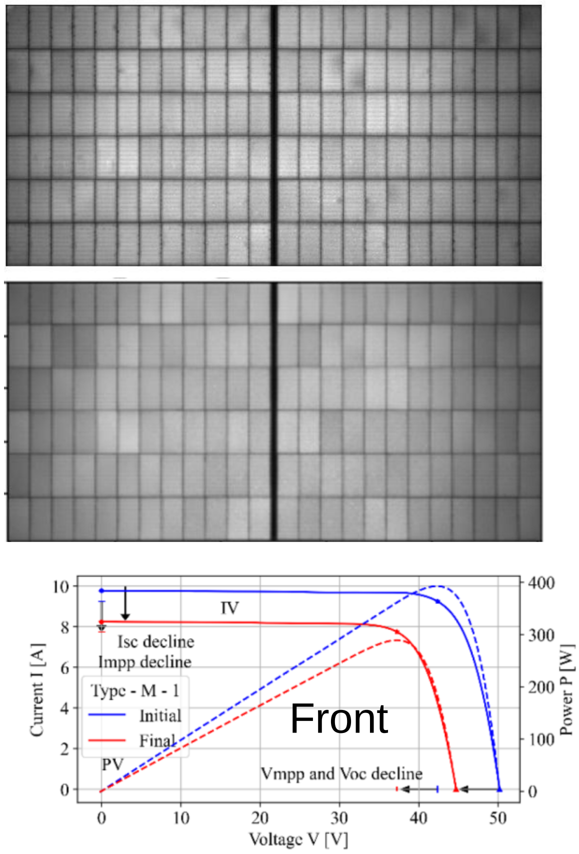
Examples 1-3			
	Zoom of a broken cell interconnect [Yang19].	EL image of a module with 3 cells with disconnected inter-connect ribbons [Köntges14].	Disconnected cell interconnect with delamination [Köntges17].
Severity	f e 2 3 4	f e 2 3 4	f e 2 3 4
Examples 4-6			
	Dislocation of interconnection ribbon [Sinclair17].	Poor soldering of string inter-connect leading to burn mark and broken glass [Yang19]. (see also PVFS 1-7 and PVFS 1-8)	Mirco arc which occur if the conductive glue on the string inter-connect has an insufficient contact [Köntges14].
Severity	f e 1 2	f e m 3 4 5	f e 2 3 4
Examples 7-9			
	IRT and EL image of short circuited shingled cells due to incorrectly applied conductive adhesive [By the courtesy of Remy Wedig, pvControl].		
Severity	2		

<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Potential induced degradation (PID)</td><td>PVFS 1-10vs.02</td></tr>
<tr><td>Appearance</td><td colspan="4">S (shunting) and p (polarization) -type PID are not optically visible; however advanced stages of c (corrosion) or d (delamination) -type PID are visible. PID causes a progressive power loss and some PID modes may also manifest in discoloration and hot spots over time. PID-s can be detected through IRT imaging of operational PV modules in direct sunlight or in the laboratory, where PID appears as warmer cells close to the bottom frame or patchwork patterns, and is more significant in PV modules positioned close to one of the poles of the PV string. PID-s is also detectable by EL imaging, especially under low current bias (1/10 rated current), where the affected cells closer to the module frame show reduced luminescence. PID-s causes a decreased shunt resistance, FF, and V_{oc} in the IV curve, and is more noticeable under low light. PID-p shows a decrease of luminescence and no low current bias dependency, being harder to detect with EL images. IV measurements can be used to confirm the presence of PID in combination with IRT or EL. PID-p causes a decrease in I_{sc} and V_{oc}, typically originating on the rear side of p-type-base cell modules (PERC) and the front of those using n-type cells (PERT, TOPCon, IBC).</td></tr>
<tr><td>Detection</td><td colspan="4">IV, EL, IRT, (MON)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="4">PID is a degradation mode induced by a high voltage stress with respect to ground. The occurrence of this failure depends on the magnitude of the voltage (number of serially connected PV modules per string) and the polarity of the electrical field build-up between the framing/glass surface and the solar cells. The last depends on the inverter typology (transformer), the grounding concept, and cell technology. Modules with p-type cells degrade in negative polarity strings whereas modules with n-type cells in strings with positive polarity. The degradation is accelerated by elevated temperature, humidity, rain (surface wetting), condensation and soiling. PID-p is caused by the build-up of surface charges on the cells, which results in a current loss. PID-s is induced by leakage currents coming from the displacement of Na+ ions from the module's front or rear glass and through the encapsulation material. The flow of Na+ ions creates shunts in the cells. For both PID types, module and cell design has a fundamental influence if and how much a module is affected by PID. There are modules on the market that are designed to be PID-resistant.</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="4">Yield losses of 20 percent and more within 1 year were observed in the past. Due to its catastrophic performance loss, PID bears a high economic risk. PID-s is to some extent a reversible polarization type and can therefore be partially reversed or stopped when detected in time. However, if detected too late, it can lead to irreversible power loss. The PID-p effect causes instead a significant reduction of I_{sc}, V_{oc} and power. PID-p is thought to be fully regenerated by reversing the polarity of the bias potential. In some cases, material degradation of the modules through corrosion and delamination occurs associated with excessive leakage current. Up to now, safety problems directly related to the PID have not been reported, but hot spots and corrosion caused by the strong cell mismatch may cause such safety issues.</td></tr>
<tr><td>Safety:</td><td></td><td>Performance:</td><td>2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Recovery of early-stage PID is possible by placing modules in non-sensitive polarity strings, applying a reverse voltage. More advanced PID cannot be fully recovered.</td><td>Modules successfully tested per IEC 62804-1 are less prone to PID. Optional for PID-resistant modules.</td><td colspan="2">Placing the modules in non-PID-sensitive DC voltage strings with one terminal grounded using an inverter with a transformer or inverters with anti-PID features.</td></tr>
</table>

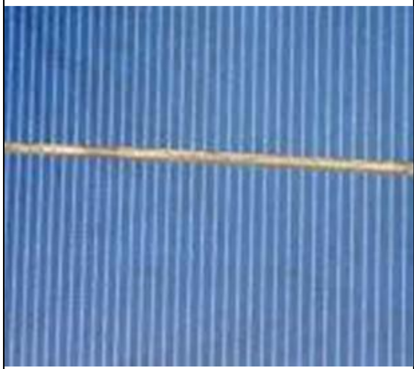
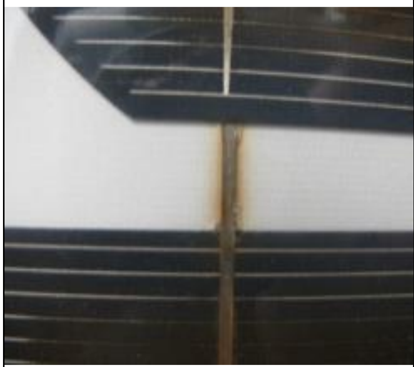
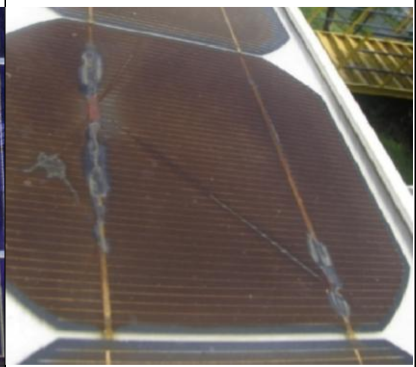
EXAMPLES (page1)		PVFS 1-10vs.02
Examples 1-2		
	Strings with PID-s, detected with IR thermography [Köntges14].	Dark IR thermography at Isc for a module affected by PID-s [Köntges14].
Severity	2 3 4 5	2 3 4 5
Examples 3-4		
	Strings with PID-s, detected with EL imaging [Köntges14].	Electroluminescence image made at Isc for a module affected by PID-s [Köntges14].
Severity	2 3 4 5	2 3 4 5
Examples 5-6	 	
	PID-s affected module with power loss of 89%, left: EL at 1.5 x I_{sc}, right: I-V curve of the same module at 1000 and 200 W/m² [Herrmann21].	PID-s affected module with power loss of 14%. top: EL at 1.5 x I_{sc}. bottom: EL of the same module at 0.2 x I_{sc} [Herrmann21].
Severity	5	3

<table>
<tr><th colspan="4">EXAMPLES (page2)</th><th>PVFS 1-10vs.02</th></tr>
<tr><td rowspan="2">Examples 7-8</td><td colspan="2">
↔ I_{SC} bias

↔ $0.1I_{SC}$

</td><td colspan="2">




</td></tr>
<tr><td colspan="2">PID-s affected Al BSF module EL imaged at I_{sc} and 0.1 I_{sc} shows chessboard pattern degradation, more visible at the lower bias current. STC IV curve shows decreased shunt resistance, FF and V_{oc} [Mahmood2024].</td><td colspan="2">PID-s affected PERC p-type bifacial module EL imaged at I_{sc} and 0.1 I_{sc} shows degradation near frame, more visible at the lower bias current. STC IV curves of front and rear show decreased FF [Mahmood2024].</td></tr>
<tr><td>Severity</td><td></td><td>
</td><td></td><td>
</td></tr>
</table>

<table>
<tr><th>EXAMPLES (page3)</th><th colspan="4">PVFS 1-10vs.02</th></tr>
<tr><td>Examples 9-10</td><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td></td><td colspan="2">PID-p affected p-type PERC bifacial module EL imaged at I_{sc} and 0.1 I_{sc} shows a decrease in minority carrier lifetime and luminescence. Rear side STC IV shows significant decrease of I_{sc}, and moderate decrease of V_{oc}. No noticeable decrease in shunt resistance [Mahmood2024].</td><td colspan="2">PID-p affected n-type TOPCON bifacial module EL imaged at I_{sc} and 0.1 I_{sc}, shows a uniform and significant decrease (~18 times less) in luminescence relative to a non-degraded module, and no noticeable current dependency of the EL image. Front side STC IV shows a significant decrease in I_{sc} and V_{oc} and no noticeable decrease in shunt resistance [Mahmood2024].</td></tr>
<tr><td>Severity</td><td></td><td>
</td><td></td><td>
</td></tr>
</table>

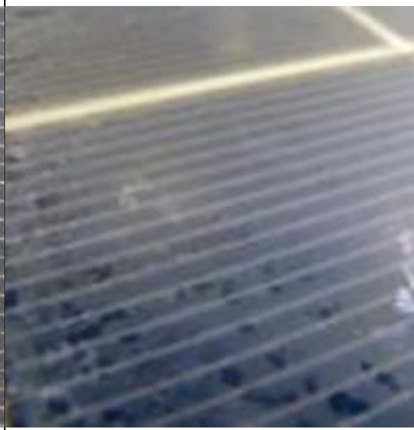
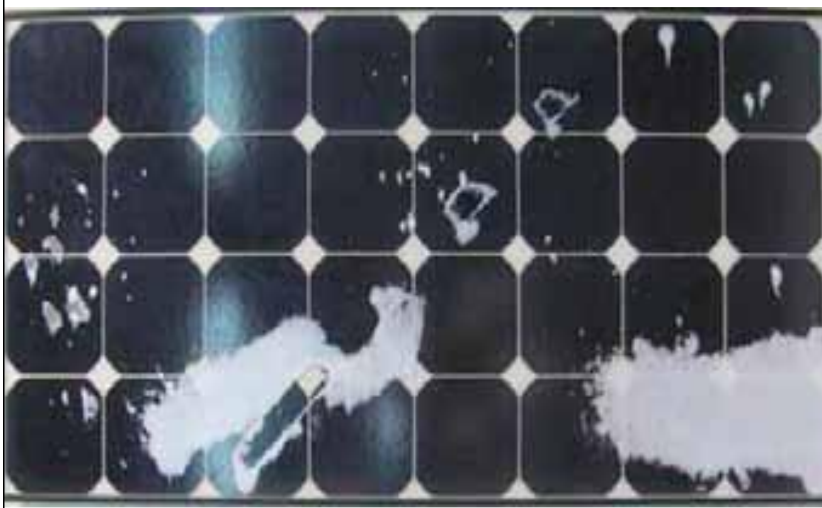
<table>
<tr><td>Component
Defect</td><td colspan="5">Module
Metallisation discolouration/corrosion</td><td>PVFS 1-11vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">The discolouration and/or corrosion of the cell metallisation and the interconnections is getting visible as a light yellow to dark brown to black discolouration of the electrical parts. Depending on the material combinations corrosion is furthermore noticeable by the presence of galvanic products that may appear powdery, white, light gray, and/or have a yellow, blue, or green tinge. The defect occurs typically at the solder bonds, on the cell gridlines/fingers or the cell/string interconnect ribbons. It is very often observed together with other failures like de-lamination and discolouration of the encapsulant and sometimes with burn marks. Under certain circumstances corrosion is more visible near cell edges. Dark areas at the cell borders of the EL images can here highlight the diffusion of moisture through the rear side of the module and the gaps between the cells and the subsequent front side cell corrosion starting from the edges.</td></tr>
<tr><td>Detection</td><td colspan="6">VI, (EL, IV)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">The corrosion/oxidation of the metallisation is caused by the presence of moisture and acidity in the encapsulant, as e.g. acetic acid, a degradation product of the mostly used encapsulant EVA or remaining crosslinker (peroxides). Acetic acid has a corrosive effect on the cell metallisation and the cell interconnect. The ingress of moisture caused by an ongoing delamination process leads together with the oxygen to a further acceleration of the corrosion. Corrosion can be caused by a poor manufacturing process (e.g residual crosslinker due to a too short lamination process; imperfections in cell soldering) or the choice of poor materials (low corrosion resistance of tin-based coating of copper ribbons, high water permeability of back sheet and/or encapsulant materials). Environmental factors can accelerate the corrosion (e.g ammonia, salt, humidity, temperature). For these reasons, corrosion is more frequent and severe under hot and humid climates or in agriculture or maritime environments. Discolouration can be also related to non-corrosive processes like a discolouration due to light-sensitive solder flux residues on the ribbon.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation □</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">The metallisation, and/or interconnect, corrosion leads to an increased series resistance and therefore losses in module performance. The power loss is less pronounced for modules with metallisation discolouration without corrosion. The defect does not automatically pose a safety issue. Locally increased series resistance leads to current mismatch. If the mismatch is getting significant, it can trigger the bypass diode and cause further power loss of the PV module.</td></tr>
<tr><td>Safety:</td><td colspan="2"></td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective action</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Check validity of IEC 61215 certification and BOM.</td><td colspan="2">Regular system inspections.</td></tr>
</table>

EXAMPLES (page1)			PVFS 1-11vs.01
Examples 1-3			
	Discolouration due to corrosion or to light-sensitive flux residues on the ribbon.	Discolouration due to corrosion on the ribbon [By the courtesy of SUPSI PVLab].	String interconnect corrosion. [Köntges17]
Severity	1	1	1 2
Examples 4-6			
	Cell interconnect corrosion [Köntges17].	Modules with light Ag finger oxidation after 5 years in the field [Yang19].	Severe oxidation/corrosion and burn marks on the Ag fingers, busbars, and interconnects of modules after 25 years [Yang19].
Severity	1 2	2	2 3 4
Examples 7-9			
	Corrosion seen as red, green and black discolouration in the string interconnect [Yang19].	Busbar corrosion and delamination at the edge [By the courtesy of SUPSI PVLab].	Glass/glass module showing delamination and subsequent corrosion [Köntges17].
Severity	2 3 4 5	3 4 5	3 4 5

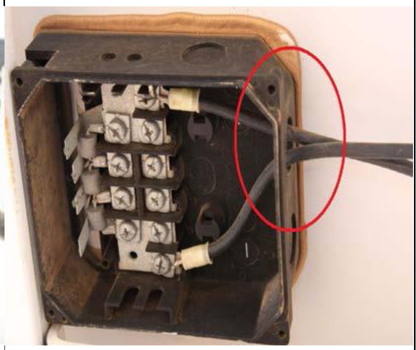
<table>
<tr><td>Component
Defect</td><td colspan="4">Module
Glass corrosion or abrasion</td><td colspan="2">PVFS 1-12vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">The degradation of the glass front layer is getting visible as a homogenous or heterogeneous change in colour and transparency of the glass. The affected glass surface can appear hazy or milky and in some cases also rougher compared to the non-degraded module/module area. Increased susceptibility to soling could be observed.</td></tr>
<tr><td>Detection</td><td colspan="6">VI, (IV)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">To optimise the efficiency and appearance of a PV module most manufacturers apply some anti-reflective coatings (ARC), anti-soiling coatings (ASC) or multilayer coatings on the front of their modules. 1-3% more power can be obtained by these techniques respect to module with uncoated glass. Corrosion or abrasion of these layers can however, reduce or vanish the effectiveness of these coatings. Glass corrosion is caused by atmospheric humidity in combination with gases or particles present in the atmosphere (e.g. pollutants, salt, ammonia) and the glass. It happens for example when water (dew) dissolves some of the sodium ions from the top of the soda lime glass, leading to the production of an alkali base that can then corrode the glass silicate. Glass abrasion or corrosion can be also caused by inappropriate cleaning techniques (mechanical removal techniques, inappropriate cleaning agents) which damage or removes the coatings. Abrasion occurs mostly in the desert, due to the combination of wind, sand and dust which causes abrasion and frosting of the glass surface.

UV or voltage induced degradation effects can further accelerate the degradation of the coatings.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ☐</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">Corrosion or abrasion of the glass front layer lowers the transmission of the glass, leading to a power loss. The power loss is generally limited to a few percent and is saturating over time except in the case where the soiling susceptibility is significantly increased and larger losses can be observed. Operating and Maintenance (O&M) costs can be affected by this.</td></tr>
<tr><td>Safety:</td><td colspan="2"></td><td>Performance:</td><td colspan="2">2 3 4</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced. Depends on the level of performance loss. For extreme environments (e.g. near to mines, cement factories), evaluate cost-effectiveness of replacing modules with lost yield.</td><td colspan="2">Check validity of IEC 61215 certification and BOM, appropriate component selection in function of intended application.</td><td colspan="2">Regular system inspections.</td></tr>
</table>

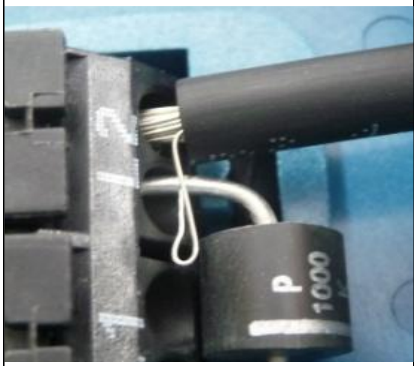
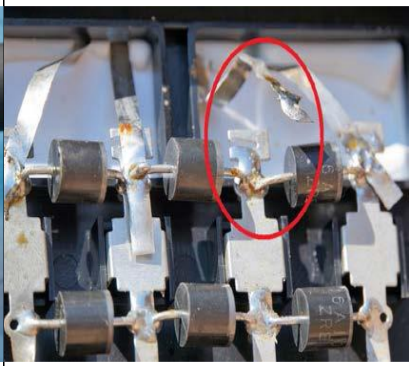
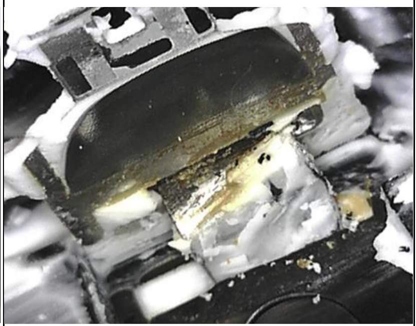
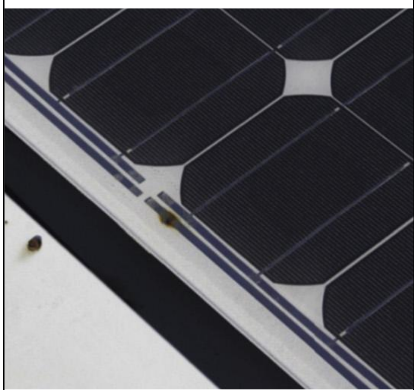
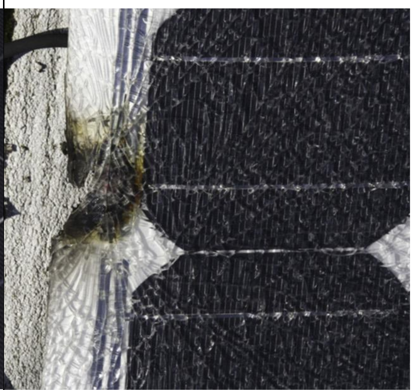
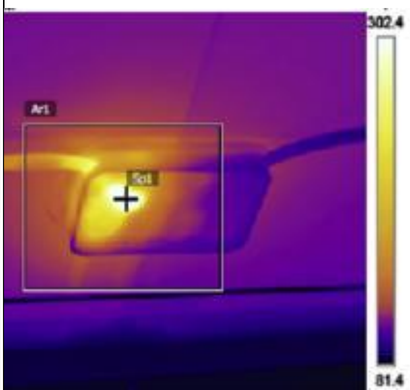
EXAMPLES (page1) — PVFS 1-12vs.01

Examples 1-3			
	Zoom of module with hazy glass (homogenous discoloration) due to surface corrosion [India13].	Zoom of module with hazy glass (heterogenous discoloration) due to surface corrosion [Petter11].	Hazy glass due to glass corrosion close to frame [India18].
Severity	2	2 3	2
Examples 4-5			
	Glass corrosion on the front of a mono-Si back-contact module after damp heat 90/90 testing [Walsh20].		Glass corrosion [Köntges16].
Severity	3		3 4

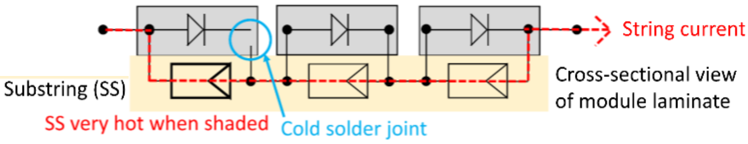
<table>
<tr><td>Component
Defect</td><td colspan="4">Module
Defect or detached junction box</td><td>PVFS 1-13vs.01</td></tr>
<tr><td>Appearance</td><td colspan="5">The junction box housing and lid appears either defect (weathered, brittle, cracked, warped, melted or burned) and/or detached (open or loose lid, shifted or detached junction box from backsheet). The sealant/adhesive material with which the junction box is attached to the back-sheet can be weathered or appear as yellowed. The sealing components/material around the wire entrance or the lid can be damaged (squeezed, broken, brittle) or completely missing.</td></tr>
<tr><td>Detection</td><td colspan="5">VI</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="5">Junction box detachment results from poor fixing of the junction box to the backsheet or use of low quality adhesive. Acrylic or PE Foam tapes were used as junction box attachment material in early years, but they frequently loss stickiness at low temperature and result in detachment. Use of inadequate IP rating junction box may cause water intrusion and subsequent failure. Opened or badly closed j-boxes may due to poor manufacturing process or air pressure caused by high temperature for boxes with no exhaust path. Delamination near a junction box can cause it to become loose. Improper handling or mounting of the modules can be also the cause of damages the j-box, like pulling modules up on the cables before mounting, or missing cable fixing or usage of too short cabling to interconnect modules to a string, causing frequent or permanent mechanical stress on the j-boxes.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="5">A defect or detached junction box is causing humidity ingress with corrosion of the interconnections, leading to performance losses and increasing risk of electrical arcing and subsequent initiation of fire. Furthermore, a loose junction box is putting mechanical stress on the contacts within the junction box, with the risk of breaking them and exposing persons to active electrical components.</td></tr>
<tr><td>Safety:</td><td>f e f e</td><td colspan="2">Performance:</td><td>1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced or repaired. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Check validity of IEC 61215 certification and BOM.
Ground fault detection by inverter or other devices at all time.</td><td>Regular system inspections.
Installation of arc detection tool.</td></tr>
</table>

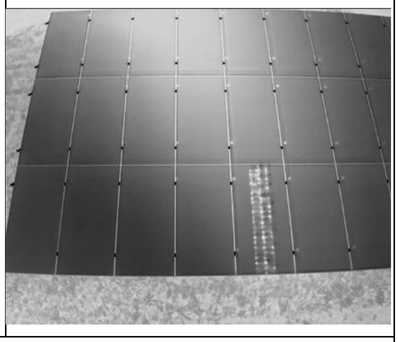
EXAMPLES (page1)			**PVFS 1-13vs.01**
Examples 1-3			
	Poorly bonded junction box on the backsheet [Köntges14].	Open junction box in the field [Yang19].	Detached junction box from backsheet [By the courtesy of SUPSI PVLab].
Severity	f e — 1	f e — 1 2 3 4 5	f e — 1 2 3 4 5
Examples 4-5			
	Left: Missing junction box lid sealing with corrosion of contacts. Right: Good junction box sealing [India13].		Missing seal or strain relive of module cables, improper cable inlet [Sinclair17].
Severity	f e	1 2 3 4 5	f e — 1 2 3 4 5
Examples 6-7			
	Melted junction box [By the courtesy of TUV Rheinland].	Burned junction box caused by corroded contacts within the junction box [By the courtesy of TUV Rheinland].	
Severity	f e — 5	f e — 5	

<table>
<tr><td>Component
Defect</td><td colspan="5">Module
Junction box interconnection failure</td><td>PVFS 1-14vs.02</td></tr>
<tr><td>Appearance</td><td colspan="6">Not connected, broken, burned, corroded or short circuited parts within the junction box. It can involve solder joints, wires, bypass diodes or tabbing ribbons. The interconnection failure itself could be hidden by the potting material in the junction box and be visible only by removing the potting material. The material can appear as degraded (yellowed, browned, burned or bubbled) due to the heat or arcing occurring in the junction box.</td></tr>
<tr><td>Detection</td><td colspan="6">BYT, (IRT, EL, VI, IV, VOC)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">Bad contacts in the junction box can be caused by cold solder joints, thermo-mechanical caused changes in contacts, wrong assembly or moisture ingress. Contacts are either soldered, screwed or inserted (mechanical spring clamping). Bad soldering contacts are caused by low soldering temperature (cold solder joint) or chemical residuals of the previous production process on the solder joints. Bad mechanical contacts are caused by loose clamping or screws. Mechanical contacts can get loose due to the thermal cycling of day and night and seasonal changes. Moisture ingress in bad or damaged junction boxes (e.g. adhesion loss, brittle, cracked, missing seal at wire entrance or junction box housing) leads to corrosion of the contacts. Delamination near the junction box can cause it to become loose, putting mechanical stress on the contacts within the junction box and breaking them.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation □</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">Depending on the position of the bad contact and its character (resistive, open circuit, short circuit or arcing) the impact on safety and performance can be very different. Resistive heating can moreover result in discolouration and burn marks in the encpasulant/backsheet behind and around the junction box and to glass breakage. In the worst-case interconnection failures cause a short circuit or internal arcing within the j-box. The heat can be detected with an IR camera (hot spot). Furthermore, connection failure could lead to equal impacts to the PV module as a diode failure if the connection to a bypass diode is lost (missing/insufficient bypass diode protection). In addition to the visual defects, interconnect failures can also lead to significant power losses or loss of shade resilience, which can both be detected by BYT of modules or strings. The measurement can be affected by changing mechanical or thermal stress conditions. Interconnect failures are particularly dangerous because the arcing can initiate fire.</td></tr>
<tr><td>Safety:</td><td colspan="2">f f e m</td><td colspan="2">Performance:</td><td>1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced, especially if the modules are installed on buildings. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Request a proof of IEC 61730-2:2023 Annex A5 a) or b) bypass diode functionality test in production. Commissioning of system with IRT or BYT. Compare VOC of parallel strings.</td><td colspan="2">Testing the module bypass diodes with a mobile test centre prior to installation. Regular IRT inspections. Installation of arc detection tool.</td></tr>
</table>

Examples 1-3			
	Junction box with poor wiring [Köntges14].	Detached tabbing ribbon due to bad soldering [Köntges14].	Corrosion failure due to water soaking of the IP65 rated Jbox [Yang19].
Severity	f — 5	f — 5	f — 2 3 4 5
Examples 4-6			
	Jbox failure due to poor electric connection [Yang19].	Evidence of loose screw connection inside Jbox with browning of pottant [Yang19].	Cold soldering of module bussing ribbon to the Jbox connection terminal pad with minor browning of pottant [Yang19].
Severity	f e m — 3 4 5	f — 2 3 4 5	f — 2 3 4 5
Examples 7-9			
	Overheating due to the poor Jbox interconnect leading to light discoloration and burn mark on front and back side [Yang19].	Overheating due to the poor Jbox interconnect leading to burn mark and glass breakage [Yang19].	IR imaging of a hotspot Jbox due to loose electric connection inside [Yang19].
Severity	f e m — 3 4 5	f e m — 3 4 5	f e m — 3 4 5

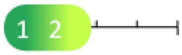
Example 10



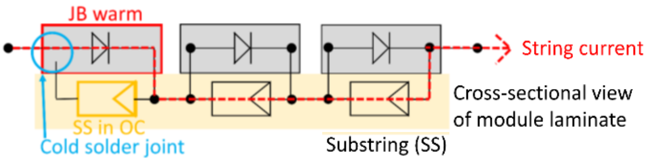


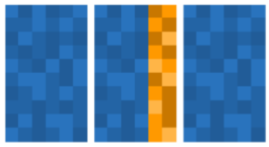
A cold solder joint after the diode in any junction box (either outer or inner) [Köntges25] can result in a safety failure that is undetectable by IRT. The not connected bypass diode is visible with night EL inspection while applying string wise reverse voltage with 3%-5% of rated I_{sc} [by courtesy of Ternus & Diehl GbR].

Severity



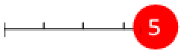
Example 11



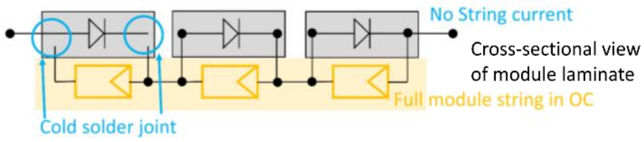


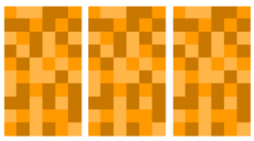
A cold solder joint before the diode in the outer junction box causes a 1/3 power loss and is detectable by IRT. However, if the inner junction box is affected, it does not cause the module sub-string to operate in open circuit [Köntges25].

Severity



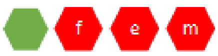
Example 12

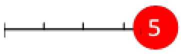




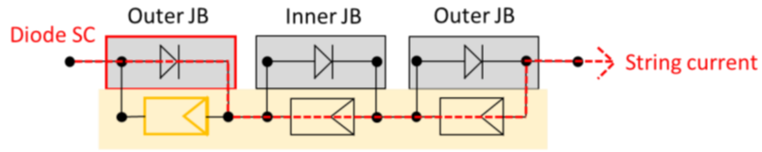
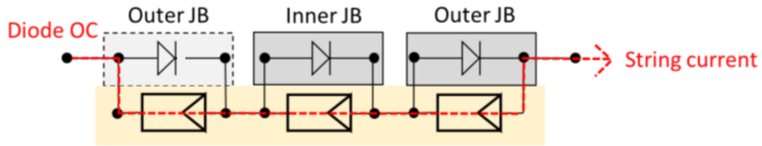
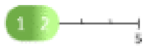
Cold solder joints before and after the diode of an outer junction box results in full string loss, which is detectable by IRT. The module location remains unidentifiable. If the inner junction box is impacted, the module continues to behave as intact [Köntges25].

Severity





<table>
<tr><td>Component
Defect</td><td colspan="5">Module
Missing or insufficient bypass diode protection</td><td>PVFS 1-15vs.02</td></tr>
<tr><td>Appearance</td><td colspan="6">Missing, disconnected, inverted, damaged, open circuited or short circuited bypass diode.</td></tr>
<tr><td>Detection</td><td colspan="6">BYT, (IV, IRT, EL, VI, VOC)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">Bypass diodes fail either because they are undersized or because they are exposed to high voltages due to lightning strikes or other high voltage events. In addition to these two reasons, the diodes have a certain ppm of failure rate, that is the nature of the component. For diodes working constantly at high temperatures this failure rate increases. This can be the case, if partial shading is frequently present. Typically, Schottky diodes are used as bypass diodes in PV modules, but they are very susceptible to static high voltage discharges and mechanical stress. Two main failure modes are observed with bypass diodes: open circuit or short circuit. Short circuit condition occurs when the bypass diode is physically shortened in the junction box, it is mounted the wrong way around or when it has been exposed to high voltages like lightning strikes or static electricity. Open circuit condition occurs when a diode is simply missing, it is not properly connected, a strong current damaged the diode, or it is undersized and not resisting to a continuous current flow. Short circuit failures are reported to be more frequent than open circuit failures. However, open circuit failures are normally not detected.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation □</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">Bypass diodes are used to avoid the reverse biasing of single solar cells higher than the allowed cell reverse bias voltage of the solar cells and to reduce the power loss caused by partial shading on the PV module. In the case of an open circuited diode no current is flowing through the bypass diode and a cell can be reversed with a higher voltage than it is designed for the cell and may evolve hotspots that may cause browning, burn marks or, in the worst case, fire. This failure is difficult to be detected until the module is exposed to these risks. A short circuited bypass diode will continuously lower the voltage and thereby the power production of the module. A short-circuited module leads to inhomogeneous heating of individual cells during operation. Also it causes mismatch losses in the case of parallel strings. Bypass diode failures sometimes cause the junction box to deform or even burnt due to heat dissipated in the junction box. When the junction box or backsheet are burnt through, the safety issues like leakage current may follow.</td></tr>
<tr><td>Safety:</td><td colspan="2">f e m</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a direct safety risk or a severity of 5 should be replaced, especially if the modules are installed on buildings. Regular inspections should be done to monitor the status of the not replaced modules.</td><td colspan="2">Request a proof of IEC 61730-2:2023 Annex A5 a) or b) bypass diode functionality test in production. Commissioning of system with IRT or BYT. Compare VOC of parallel strings.</td><td colspan="2">Testing the module bypass diodes with a mobile test centre prior to installation. Regular IRT inspections. Installation of arc detection tool.</td></tr>
</table>

<table>
<tr><th colspan="2">EXAMPLES (page1)</th><th>PVFS 1-15vs.02</th></tr>
<tr><td rowspan="2">Example 1</td><td colspan="2">
</td></tr>
<tr><td colspan="2">A short circuited bypass diode causeS a 1/3 power loss and is detectable by IRT [Köntges25].</td></tr>
<tr><td>Severity</td><td>
</td><td>
</td></tr>
<tr><td rowspan="2">Example 2</td><td colspan="2">
</td></tr>
<tr><td colspan="2">An open circuited bypass diode causes a safety failure that is undetectable by IRT [Köntges25].</td></tr>
<tr><td>Severity</td><td>
</td><td></td></tr>
</table>

Component	**Module**	
Defect	**Not conform power rating**	**PVFS 1-16vs.01**

Appearance	The STC output power of a brand new module is below a specified tolerance limit or the minimum nameplate output power is not clearly specified by the manufacturer.
Detection	IV, (MON)

Origin

Deviations of the measured power of a single module respect to the name plate power depends on the product variability, manufacturing quality, the labelling policy and the measurement uncertainty. The quality of cells (e.g. LID susceptibility) together with the binning method applied in production for the reduction of mismatch losses, has a significant impact on the product variability. The deviations in the measurement in the factory comes from several sources of uncertainty, for example the environment temperature, measured module temperature, calibration of the solar simulation, maintenance of the reference module, measurement equipment, connectors and cables. According to the international standards, the power rating has to take into account any technology related initial degradation effects (for c-Si see FS 1-17). This means that after a first exposure to light the output power of a new module has still to be within the rated power tolerance. The measurement uncertainty of the test laboratory performing the STC performance test has therefore to be taken into account. The modules have to be stabilised according the procedure described in IEC 61215-2:2021. Technology specific test requirements are described in IEC 61215-1-1:2021 to IEC 61215-1-4:2021. Depending on the technology, a maximum allowable measurement uncertainty is defined for the verification of power ratings. For c-Si modules it is specified as 3%. A PV module is considered to be conform to the IEC61215 standard, when following criterion (gate 1) is fulfilled:

$$P_{max}(Lab)\cdot\left(1+\frac{\frac{1.65}{2}|m_1|[\%]}{100}\right)\geq P_{max}(NP)\cdot\left(1-\frac{|t_1|[\%]}{100}\right)$$

P_{max} (Lab): measured maximum STC power of each module in stabilized condition
P_{max} (NP): minimum rated nameplate power of each module without rated production tolerances
m_1: measurement uncertainty in % of laboratory for P_{max} (expanded combined uncertainty (k = 2)
t_1: manufacturer's rated lower production tolerance in % for P_{max}

The minimum nameplate power rating, $P_{max}(NP)$ and tolerance t_1 has to be derived from the nameplate or data sheet values. If the $P_{max}(NP)$ derived from the datasheet is different from the nameplate value, the module can be considered to be not conform. If the tolerance is not stated on the nameplate or the datasheet, then t_1 = 0. If the tolerance is not reduced to a single value on the nameplate or data sheet (for example, if multiple tolerances or measurement uncertainty components are specified) the smallest number shall be utilized.

Production ■	Installation ☐	Operation ☐

Impact

A non-conform STC power rating is not a real module failure, as it causes no degradation or safety issue, but it has a negative impact on the lifetime energy yield and financial return. An incorrect estimation of the installed STC power has a direct impact on the energy yield predictions and investor expectations.

Safety:		Performance:	1 2 3

Mitigation

Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
Confirm underperformance through an accredited PV test laboratory. Claim for missing power.	Verify power warranties and data sheet conformity, purchase modules from trusted manufacturers.	Independent third party testing of samples at factory gate and/or arrival on site. Signature of a contractual agreements.

EXAMPLES (page1)	PVFS 1-16vs.01

Examples 1

a)

Product Z300W

Maximum power (P_{max})	300 W ±3 %
Maximum power voltage (V_{mp})	37 V
Maximum power current (I_{mp})	8,1 A
Open circuit voltage[a] (V_{oc})	45,9 V
Short circuit current[a] (I_{sc})	8,9 A
Maximum DC system voltage	1 000 V

[a] +5 % / –0 % tolerance

Product Z series
Electrical Data at STC

Peak power watts ±3 % - P_{max} (W)	300	305	310
Maximum power voltage - V_{mp} (V)	37	37,2	37,5
Maximum power current (I_{mp}) (A)	8,1	8,2	8,27
Open circuit voltage[a] - V_{oc} (V)	45,9	45,9	45,9
Short circuit current[a] - I_{sc} (A)	8,9	8,92	8,98
Module efficiency - η_m (%)	14	14,2	14,4

[a] ±5 % / –0 % tolerance on I_{sc} and V_{oc}

P_{max} (NP) = 300 W; t_1 = 3 %
V_{oc} (NP) = 45,9 V; t_2 = 5 %
I_{sc} (NP) = 8,9 A; t_3 = 5 %

b)

Product X300W

Maximum power (P_{max})	296 to 300 W
Maximum power voltage (V_{mp})	37 V
Maximum power current (I_{mp})	8,1 A
Open circuit voltage[a] (V_{oc})	45,9 V
Short circuit current[a] (I_{sc})	8,9 A
Maximum DC system voltage	1 000 V

[a] ±4 % production tolerance

Product X series
Electrical Data at STC

Peak power watts[a] - P_{max} (W)	296 to 300	301 to 305	306 to 310
Maximum power voltage - V_{mp} (V)	37	37,2	37,5
Maximum power current (I_{mp}) (A)	8,1	8,2	8,27
Open circuit voltage[a] - V_{oc} (V)	45,9	45,9	45,9
Short circuit current[a] - I_{sc} (A)	8,9	8,92	8,98
Module efficiency - η_m (%)	14	14,2	14,4

[a] ±4 % production tolerance

P_{max} (NP) = 296 W; t_1 = 0 %
V_{oc} (NP) = 45,9 V; t_2 = 4 %
I_{sc} (NP) = 8,9 A; t_3 = 4 %

If t_1 is not specified, it is taken to be 0.

c)

Product Y300W

Maximum power (P_{max})	300 W ±3 % / -0
Maximum power voltage (V_{mp})	37 V
Maximum power current (I_{mp})	8,1 A
Open circuit voltage[a,b] (V_{oc})	45,9 V
Short circuit current[a,b] (I_{sc})	8,9 A
Maximum DC system voltage	1 000 V

[a] ±2 % measurement uncertainty
[b] ±10 % tolerance on I_{sc} and V_{oc}

Product Y series
Electrical Data at STC

Peak power watts - P_{max} (W)	300	305	310
Power output tolerance (%)	-0 / +3	-0 / +3	-0 / +3
Maximum power voltage - V_{mp} (V)	37	37,2	37,5
Maximum power current (I_{mp}) (A)	8,1	8,2	8,27
Open circuit voltage[a,b] - V_{oc} (V)	45,9	45,9	45,9
Short circuit current[a,b] - I_{sc} (A)	8,9	8,92	8,98
Module efficiency - η_m (%)	14	14,2	14,4

[a] ±2 % measurement uncertainty
[b] ±10 % tolerance on I_{sc} and V_{oc}

P_{max} (NP) = 300 W; t_1 = 0 %
V_{oc} (NP) = 45,9 V; t_2 = 2 %
I_{sc} (NP) = 8,9 A; t_3 = 2 %

t_2 is not reduced to a single value. Thus, the smaller value is chosen. The same situation exists for t_3.

d)

Product T300W

Maximum power (P_{max}) Power selection (±5 W)	300 W
Maximum power voltage (V_{mp})	37 V
Maximum power current (I_{mp})	8,1 A
Open circuit voltage (V_{oc})	45,9 V
Short circuit current (I_{sc})	8,9 A
Maximum DC system voltage	1 000 V

±3 % tolerance on P_{max}, I_{sc}, V_{oc}

Product T series
Electrical Data at STC

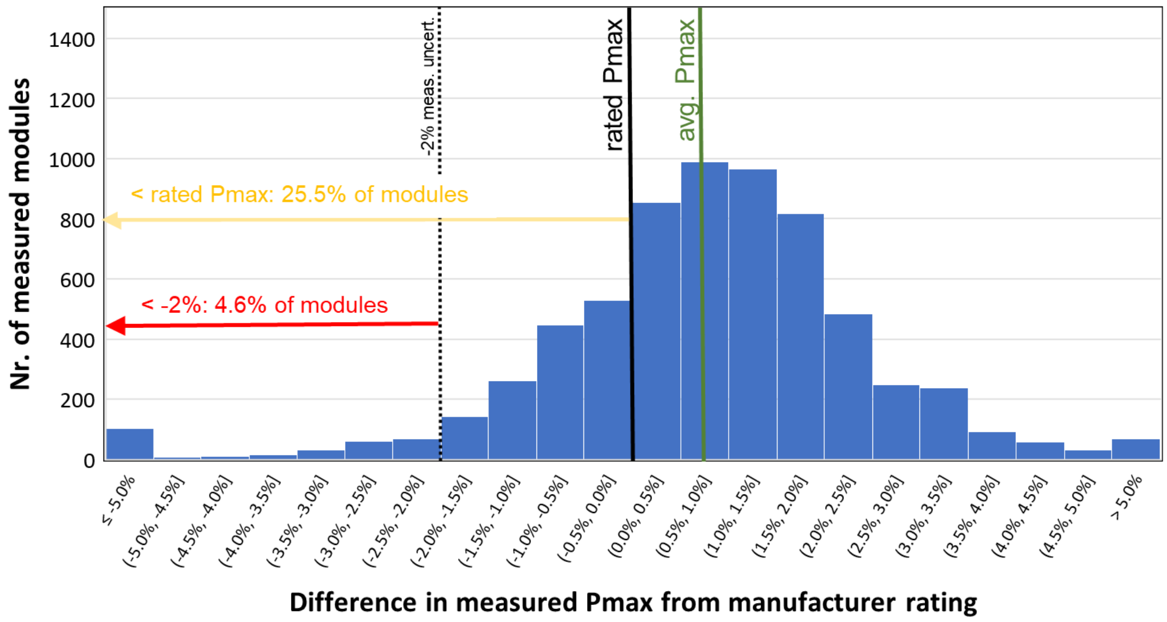
Peak power watts[a] - P_{max} (W)	300	310
Maximum power voltage - V_{mp} (V)	37	37,5
Maximum power current (I_{mp}) (A)	8,1	8,27
Open circuit voltage[a] - V_{oc} (V)	45,9	45,9
Short circuit current[a] - I_{sc} (A)	8,9	8,98
Module efficiency - η_m (%)	14	14,4

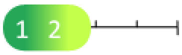
[a] ±3 % tolerance on P_{max}, I_{sc}, V_{oc}

Fails to meet requirements of IEC 61215-1 5.2.2. Lower edge of power bin is 295 W on nameplate, but is 300 W on datasheet.

Example of a hypothetical conform (a-c) name plate and datasheet values with on the right the accord. IEC 61215-1:2021 derived rated values and tolerances in comparison to a hypothetical example of a not conform STC rating (d) [IEC 61215-1:2021].

Severity		NA

<table>
<tr><th>EXAMPLES (page2)</th><th colspan="2">PVFS 1-16vs.01</th></tr>
<tr><td>Examples
2</td><td colspan="2">
</td></tr>
<tr><td></td><td colspan="2">Statistical analysis done by Eternalsun on around 6500 new modules with 96 different PV module types from 29 different manufacturers. [Herrmann21] Considering the measurement uncertainty of +/-2% a total of 4.6% of the modules are below the gate 1 limit defined by the IEC 61215 standard [IEC 61215-1:2021].

Note: In case of a measurement uncertainty of +/-5% none of the PV modules would fail, but it would be not conform to the IEC 61215 standard prescribing a maximum measurement uncertainty for c-Si modules of +/-3%.</td></tr>
<tr><td>Severity</td><td></td><td>
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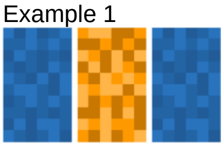
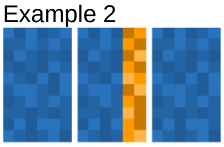
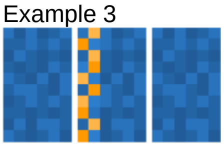
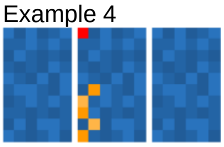
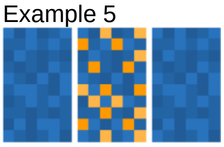
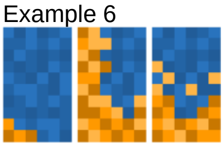
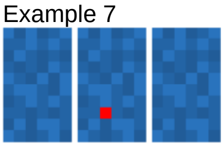
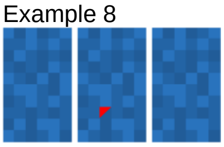
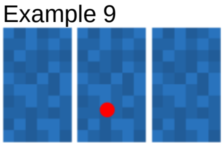
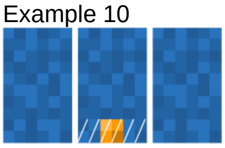
<table>
<tr><th>Component
Defect</th><th colspan="2">Module
Light induced degradation in c-Si modules (LID/LeTID)</th><th>PVFS 1-17vs.02</th></tr>
<tr><td>Appearance</td><td colspan="3">Light induced degradation in crystalline silicon modules is recognisable mainly as a drop in STC output power, but also short circuit current and open circuit voltage, within the initial lifetime of a PV system. It isn't correlated with any visual defect or other failure modes. Increasing non-uniformity of electroluminescence images (patchwork pattern) can in some cases highlight an ongoing degradation process.</td></tr>
<tr><td>Detection</td><td colspan="3">IV, (EL, IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="3">Two different light induced degradation effects are known: LID (light induced degradation) and LeTID (light and elevated temperature induced degradation). Both degradation modes occur at cell level, but the physical mechanism staying behind them are different. The first is related to the concentration of boron and oxygen in the cells, whereas the second one is probably correlated to the concentration of hydrogen in the cell, but the mechanisms are still not fully understood. Mainly p-type boron-doped multi and mono crystalline silicon modules are affected. Gallium-doped and high-efficiency cell technologies that use n-type wafers, such as n-type PERC, HJT, or n-PERT seem to be much less or not at all concerned by these two degradation effects. LID occurs only within the first days of exposure to the sun and is limited to 1-3%, whereas LeTID is in a more severe and long-term light induced degradation mechanism. LeTID was observed for the first time with the introduction of PERC modules on the market. The degradation can reach up to 10% and sum-up with the LID loss. It occurs only at elevated temperatures above 50°C. The speed with which the degradation occurs depends on the average module temperature and is therefore strongly site dependent. The time frame in which it occurs is in the order of magnitude of years. Once the full degradation is reached the modules can regenerate, recovering the lost power. This process is however very slow and also climate-dependent. The lost power may even not recover over the typically expected 25-year lifetime of a module. There exist approaches of accelerated regeneration of LeTID-sensitive modules in the field, but they are typically costly and not very user-friendly. Over the last years most manufacturers adapted their cell production process to stabilise the cells in-line.</td></tr>
<tr><td>Production ■</td><td>Installation ☐</td><td>Operation ☐</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="3">LID or LETID causes no safety problems, but it has a negative impact on the lifetime energy yield and financial return. An under-estimation of the initial degradation has a direct impact on the energy yield predictions and investor expectations. LID is less critical for the investors, because it is generally less severe and it is taken into account by the manufacturers when labelling the modules and defining the first year warranty, whereas a high LeTID degradation rate and the difficulty to predict the trend over time is much more critical for manufacturers' warranties and system owners. The sensitivity of PV modules to LeTID can be tested in the laboratory.</td></tr>
<tr><td>Safety:</td><td colspan="2">Performance: 2 3</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td>Confirm underperformance through an accredited PV test laboratory. Claim for missing power.</td><td>Verify power warranties. Verify the use of LeTID stable cells by module manufacturer.</td><td>Request test reports with % power loss for realistic estimations. Stipulate a contractual agreement on tolerated loss. Test individual modules. Verify BOM (cell type).</td></tr>
</table>

<table>
<tr><td>Component
Defect</td><td colspan="3">Module
Insulation failure</td><td>PVFS 1-18vs.01</td></tr>
<tr><td>Appearance</td><td colspan="4">A module with bad insulation between its current carrying parts and the frame (or the outside world) are not directly visible by eye. An unequivocally detection is only possible through a measurement of the insulation resistance of the module under dry (≥40 Mohm/m²) or better humid/wet conditions. It can be sometimes deduced by the presence of visual defects which can potentially lead to insulation problems. Under certain circumstances like after a rain fall or in the early morning when the PV modules are covered by dew, this kind of defect is detected by the inverter (low insulation fault) or the inverter is switching off when the resistance value falls below a certain limit.</td></tr>
<tr><td>Detection</td><td colspan="4">INS, (MON)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="4">Insulation failures can have different causes. It can occur in the design/production phase of a module, due to solar cells too closely positioned to the frame or to material weaknesses like the use of inadequate encapsulation or backsheet materials or a poor lamination process. In the installation phase it can be caused by mechanical damages of the module, whereas in the operational phase it is generally caused by catastrophic events or due to a delamination process close to the edge of the module or water ingress or condensation in the junction box. Modules with failed or skipped insulation test in production due to an insufficient quality assurance could be also the origin of the problem. Various module failures are at the origin of an insulation failure: backsheet and encapsulant delamination, backsheet damages, burn marks, glass breakage.</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="4">A low insulation resistance at module level itself does not lead to a performance loss, until an inverter failure occurs. The presence of an electrical leakage current to the frame can become a safety hazard exposing persons to a potential electric shock hazard. Touching non-insulated parts of the string or frame can cause severe injury, without the use of safety gear and safe measuring instruments.</td></tr>
<tr><td>Safety:</td><td>e</td><td>Performance:</td><td>1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Modules with a direct safety risk or a severity of 5 should be replaced. Regular inspections should be done to monitor the status of the not replaced modules. In case of individual module testing all modules which failed the insulation and/or wet-leakage test should be replaced.</td><td>Check validity of IEC 61215 certification and BOM, commissioning of system with IRT, ground fault detection by inverter or other devices at all time.</td><td colspan="2">Regular system inspections, Insulation testing of modules with mobile test centre before installation.</td></tr>
</table>

<table>
<tr><td>Component
Defect</td><td colspan="2">Module
Hot spot (thermal patterns)</td><td>PVFS 1-19vs.02</td></tr>
<tr><td>Appearance</td><td colspan="3">A hot spot is a thermal abnormality such as a local overheating or a thermal pattern which deviates from the normal behaviour of a module. It can be detected only by imaging techniques such as e.g. infrared thermography (IRT). Hot spots are not visible by the naked eye until they lead to irreversible hot spot damages like e.g. local yellowing, burn marks, glass or cell breakage. The position, size, intensity and pattern of the hot spot/s depends on the origin and progress of the failure, but also under which conditions the module is operating (shading, load and irradiance level).</td></tr>
<tr><td>Detection</td><td colspan="3">IRT, (VI)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="3">A hot spot can be triggered by various factors, including (i) previous failures, like damaged cells (see PVFS 1-01), glass breakage (see PVFS 1-08), poor electrical connections (see PVFS 1-09 and 1-14), insufficient bypass diode protection (see PVFS 1-15) and potential-induced degradation (PID) (see PVFS 1-10), (ii) production-related issues, like severe cell mismatch, low-quality solar cells, or poor module manufacturing processes, or (iii) non-ideal operating conditions like shading or soiling (see PVFS 1-20). When shading condition occurs, the affected cell or group of cells is forced into reverse bias, causing it to dissipate power, which can lead to overheating. If the power dissipation is high or localised, the reverse biased cell(s) can overheat, potentially resulting in melting of solder joints, deterioration of the encapsulant and/or backsheet, and even glass breakage. To reduce the effects of hot spots, bypass diodes are connected in parallel with cells. Properly designed and functioning bypass diodes help in reducing hot spot damages from occurring.</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="3">Hot spot formation does not always result in significant power loss. Due to normal tolerances in cell sorting and PV module production, thermal abnormalities under 10% of the inspected modules usually do not indicate quality issues. Most modules with a single hot cell have an insignificant power loss. Power reduction becomes significant when a bypass diode is permanently activated and consequently the cell string is cut off from power production of the PV module. The impact on system performance is only noticeable in its energy yield when multiple PV modules are affected. Severe losses can occur if PID is the origin of the abnormal cell heating. Module safety can be compromised when overheating leads to critical module damages or to a fire. Temperature differences of 10 K to 20 K (at approximately 800 W/m^2) should be further controlled to prevent temperature increases during PV system operation, as they may indicate damaged bypass diodes or junction box failures, posing direct safety risks (see PVFS 1-14 and 1-15). Differences over 20 K (at approximately 800 W/m^2) are critical, risking accelerated degradation of polymer materials and loss of insulation properties. If affected modules aren’t replaced, temperature differences may rise further. Lack of regular cleaning and maintenance can also lead to high temperatures due to bird droppings or power mismatches, resulting in module damage. In such cases, it may be challenging to identify whether the cause was a quality issue or insufficient maintenance.</td></tr>
<tr><td>Safety: N/A</td><td colspan="2">Performance: N/A</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td>Modules with a direct safety risk or a severity of 5 should be replaced or repaired. If more than 10% modules show thermal abnormalities, the reason for that behaviour should be evaluated and corrective actions implemented.</td><td>Commissioning of system with IRT or BYT.</td><td>Regular system inspections (i.e. IRT).</td></tr>
</table>

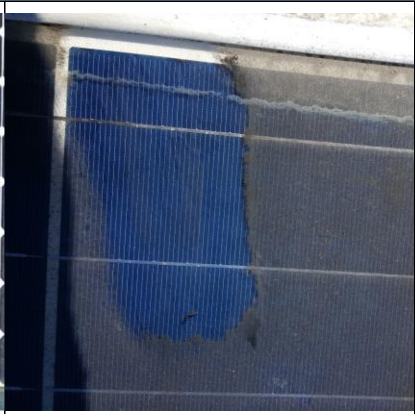
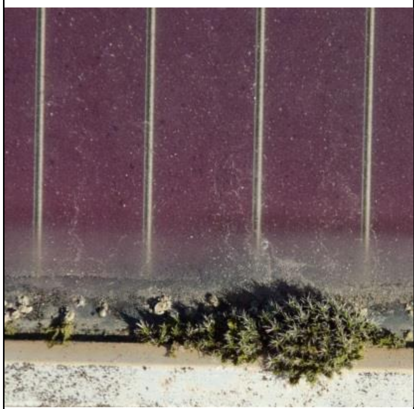
EXAMPLES (page1)					**PVFS 1-19vs.02**
Pattern	**Description**	**Origin**	**Performance**	**Remarks**	**Safety**
Example 1 	One module warmer than others	Module could be open circuited - not connected to the system	Module normally fully functional,	Check wiring	
Example 2 	One sub-string of serially connected cells is warmer than others in the module	Open circuited sub-string - Disconnection in junction box or sub-string	Sub-string power lost, reduction of V_{oc}	May have burned spot at the module. Replace PV module.	
Example 3 	One substring overheated with irregular pattern	Short circuited bypass diode or short-circuited substring	Sub-string power lost, reduction of V_{oc}	Replace module	
Example 4 	A single cell appears warmer, while there are multiple warmer cells with an irregular pattern in the parallel-connected sub-string.	Shaded or defected cell (bypass diode activation)	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch).	
Example 5 	Single cells are warmer, not any pattern (patchwork pattern) is recognized	Whole module is short circuited - All bypass diodes short circuited - Array wiring failure	Module power drastically reduced (almost zero), strong reduction of V_{oc}	Check wiring (see PVFS 1-15)	
Example 6 	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 (see PVFS 1-10)	
Example 7 	One cell clearly warmer than the others	- Low I_{sc} performance of cell - Shaded or defected cell	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen	Visual inspection needed, cleaning (cell mismatch) (see also PVFS 1-1, 1-3, 3-3)	
Example 8 	Part of a cell is warmer	- Low I_{sc} performance of cell - Shaded or defected cell - Disconnected string interconnect	Power decrease not necessarily permanent, e.g. shadowing leaf or lichen, *FF* reduction	Visual inspection needed, cleaning (cell mismatch). Replace PV module (see also PVFS 1-1, 1-7, 1-9)	

EXAMPLES (page2) | **PVFS 1-19vs.02**

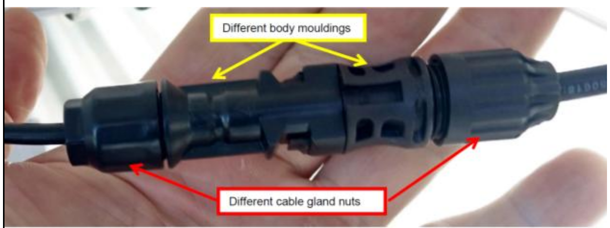
Pattern	Description	Origin	Performance	Remarks	Safety
Example 9 	Point heating	- Formation of micro-arc in the interconnection circuit - Junction breakdown at cell caused by shading	Power reduction	Crack detection after detailed visual inspection of the cell possible. Replace PV module (see also PVFS 1-1, 1-7, 1-9)	
Example 10 	Sub-string part remarkably hotter than others when equally shaded	Sub-string with missing or open-circuit bypass diode	Massive I_{sc} and power reduction when part of this sub-string is shaded	May cause severe fire hazard when hot spot is in this sub-string (see also PVFS 1-15, 3-3)	 

Reviewed typical IR image patterns observed in outdoor measurements [Köntges14].

Component Defect	**Module** **Soiling**		**PVFS 1-20vs.01**
Appearance	Soiling is visible as a deposition of dust, dirt or other contaminants on the surface of a PV module. The deposition can be uniform or non-uniform and vary in thickness. Due to the presence of hot-spots caused by non-uniform soiling, it can be also seen through IRT imaging.		
Detection	VI, (IRT, MON)		
Origin	Soiling of PV modules can have various origins such as dust accumulation, air pollution, bird droppings or growth of moss, lichens or algae. It can be due to natural sources, as sand in desert areas, seasonal pollen or volcanic emissions, or due to human activities, as near mining, industry, high ways, railways, urban or agricultural surroundings. The soiling level and its persistence over time depends on the exposure time, the chemical composition and particle size as well as the local climate conditions. Whereas rainfalls and wind can lead to a natural cleaning of modules, humidity can have a contrary effect by increasing adhesion and cementation of dust on the module. The module design (e.g glass coating, frame, distance of cells from the edge), the orientation (e.g tilt angle, azimuth, landscape/portrait) and mounting conditions (e.g clamps, height above ground, stringing) of the modules plays an important role. Typically soiling increases as tilt angles decreases. The direction of the wind or obstacles can influence the soiling process, leading to non-uniform patterns on system and module level.		
	Production ☐	Installation ■	Operation ■
Impact	The deposited soiling layer causes optical losses, reducing the amount of light that reaches the solar cells, with a consequential performance drop. Soiling is not a real module failure, as it is reversible when the module is cleaned, but it has a negative impact on the lifetime energy yield and financial return. Soiling is a site-specific issue. In arid regions with seasonal dry periods and dust, extreme soiling losses of up to 25%/a are reported, if modules are not cleaned. In temperate regions with year-round rain, the annual soiling losses typically ranges between 0% to 4%. In case of specific soiling sources (e.g. railway, farming, etc.) and/or constraints of the natural cleaning effect due to unfavourable mounting conditions (e.g low tilt angle) much higher losses can be observed. Non-uniform soiling leads to current mismatch losses which further increases the power loss and to hot-spots which in extreme cases can permanently damage a PV module. In modules affected by **potential induced degradation (PID)**, soiling can further accelerate the ongoing degradation effect. Soiling can be mitigated by cleaning the modules or preventing excessive soiling. The cleaning approach has to be appropriate to the type of soiling and site specific conditions (e.g. accessibility and water availability). The cleaning schedule should take into account that natural agents, such as rain-falls, wind or dew can have a natural cleaning effect at no cost. Anti-soiling coatings (ASC) can help in reducing soiling and stretch the cleaning frequency, but only if the coating is adequate for the type of soiling present on the system and if adequate cleaning processes are followed, which do not damage the coating. Moreover, it has to be considered that some ASC can also increase transmission losses by themselves.		
	Safety:	e	Performance: 2 3 4 5
Mitigation	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Cleaning by qualified persons is recommended when the revenue lost because of the missed energy production is higher than the cleaning cost. A best time to clean should be defined.	Preliminary site inspections for the assessment of the soiling risk. Cost estimation for the implementation of mitigation measures. Regular visual inspections to control the soiling level.	Estimation or measurement of soiling losses prior to installation. Installation of soiling sensors to determine the most profitable time to clean.

Examples 1-3			
	Uniform light soiling, which in ideal conditions is self-cleaning when raining [By the courtesy of SUPSI PVLab].	Uniform heavy soiling caused by rail way station [By the courtesy of SUPSI PVLab].	Non-uniform soiling caused by low inclination and close mounting to roof [By the courtesy of SUPSI PVLab].
Severity	2	3 4	2 3
Examples 4-6			
	Moss growing on the edge of a module combined with edge soiling [Köntges17].	Soiling pattern on a system in the Atacama desert [By the courtesy of ISE FhG].	Soiling pattern demonstrating dominant wind direction on a test site in Atacama desert [By the courtesy of ISE FhG].
Severity	e 2 3	3 4	3 4
Examples 7			
	Heavy biofilm soiling [Köntges16].		
Severity	4 5		

<table>
<tr><td>Component
Defect</td><td colspan="5">Cables and Interconnectors
DC connector mismatch</td><td>PVFS 2-1vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">Combination of male and female DC-connectors of two different manufacturers or types (cross-mating) between modules, strings, arrays or to the inverter.</td></tr>
<tr><td>Detection</td><td colspan="6">VI, (IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">There is yet no standard for PV connectors prescribing dimensions and tolerances. Therefore, it is possible to find very similar-looking and even apparently fitting connectors on the market, advertised as ‘compatible’. Slight differences in the design of the connector can lead to reduced water and vapour tightness. Problems may also occur due to incompatibilities of materials (chemical incompatibility or different thermal expansion parameters) of the metal contact, gaskets or sealings. Most of the time the mismatch of connectors occurs at the string end where extension cables are used or when connecting an inverter or a string combiner box, which has been delivered with incompatible connectors.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">The interconnection of connectors from different manufacturers may significantly increase the risk of loss of performance and defects which cause hazards for human and environment [IEC TR 63225:2019]. The consequences are e.g. contact corrosion, burnt connectors, electrical arcing and in the worth case a fire. One of the most common failures is that no current will flow through the connection at all. The problems do not manifest themselves right away, but only over time with increasing contact resistance and/or degradation of the connector/s. At humid weather conditions mismatching connectors can also lead to a partial failure of the inverter or a ground fault. The fire risk is further increased when the connectors are not properly positioned and are close to flammable material such as wooden roof beams or heat-insulation materials. Often connectors are at least partly installed at position where they cannot be inspected during normal visual inspections (e.g. within profiles, underneath roof parallel modules or even in BIPV). In combination with the unclear compatibility issue, the interconnection of different brand or type of connectors may result in high risks.</td></tr>
<tr><td>Safety:</td><td colspan="2">f e</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">All not matching connectors should be replaced.</td><td colspan="2">Ask supplier or check module/inverter spec sheets for the type/manufacturer of connector, only connectors from the same manufacturer and certified as compatible should be mated together.</td><td colspan="2">Verify that both modules and inverters are delivered with the same connectors. Provision of spare connectors and string cables with connectors of the same type as the module connectors.</td></tr>
</table>

EXAMPLES (page1)			PVFS 2-1vs.01
Examples 1-2			
	Connectors (male of female) are of different brand or type and obviously do not match [Moser17].	Connectors (male of female) are of different brand or type and obviously do not match [Moser17]	
Severity	f e | 1 2 3 4 5	f e | 1	
Examples 3-5			
	Corroded connector due to cross-mating [By the courtesy of Stäubli].	Melted connector due to cross-mating [By the courtesy of Stäubli].	Burned connector due to cross-mating [By the courtesy of Stäubli].
Severity	f e | 3 4 5	f e | 5	f e | 5
Examples 6-7		 Red 'O' ring · Black 'O' ring · Logo 'TUV' · Logo MC4 brand	
	Different types of connectors recognisable by different body mouldings and cable gland nuts [ESV guide].	Different types of connectors recognisable by different 'O' rings or logos [ESV guide].	
Severity	f e | 1	f e | 1	

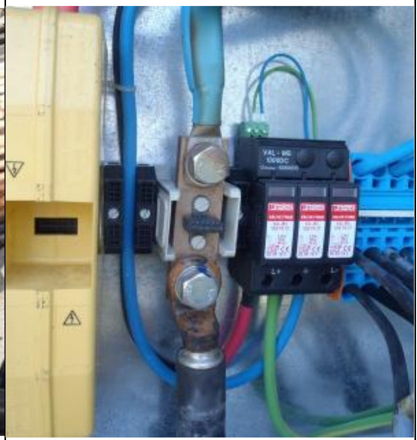
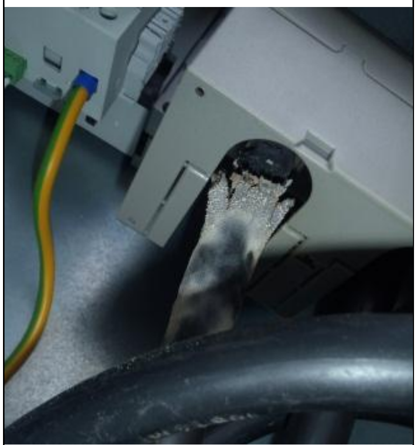
<table>
<tr><td>Component
Defect</td><td colspan="2">Cables and Interconnectors
Defect DC connector/cable</td><td>PVFS 2-2vs.01</td></tr>
<tr><td>Appearance</td><td colspan="3">A damaged connector or cable appear as melted, burned, brittle, broken, cracked or whitened. Opened connectors can demonstrate corrosion. Affected connectors show very often overheating or hot spots in an early state if a thermography check is performed.</td></tr>
<tr><td>Detection</td><td colspan="3">VI, (IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="3">One of the major causes of damaged connectors are the combination of incompatible components (DC connector mismatch), a low quality connector or a bad installation. In the last case the connectors are either not installed according the instructions (e.g. bad crimping or connection, exposure to rain or polluted before installation, installation of damaged connectors) or the connectors are not fixed correctly exposing them over longer times to humidity or dirt without allowing the connector to dry completely. In case of damaged cables the major causes are the use of low quality material in production (e.g. insulation material or cupper wires), an inadequate selection of components within the design phase (e.g. undersized cables, too large cable glands, inadequate IP classification or UV protection) or an improper handling or fixing of the cables in the installation phase (e.g. cable routing over sharp or abrading edges, hanging cables close to connections, overly tight bending, missing or not correctly installed cable glands or exposure to direct UV radiation).</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="3">Damaged connectors or cables constitute a high safety risk and may lead to the power loss of the whole string. The continuity of the circuit isn’t any more guaranteed and inverter failures can occur (low insulation faults or inverter switch off), leading to partial or complete power losses. In the worst case damaged cables or not well-connected connectors may cause electric arcs. In many cases, the connectors and cables are much closer to flammable material such as wooden roof beams or heat-insulation materials than the PV module laminate, increasing the risk of fire.</td></tr>
<tr><td>Safety: f e f e</td><td colspan="2">Performance: 1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td>Components constituting a direct safety risk should be replaced. Regular inspections should be done to monitor the status of the not replaced components.</td><td>Protection of connectors and cables from humidity during installation. Use of adequate crimping tools. Installation should be done by trained personal.</td><td>Signature of a contractual agreement for maintenance of the warranty when connectors are substituted by the installer, perform regular system inspections.</td></tr>
</table>

Examples 1-3			
	Weathered connector [Köntges17].	Cracked connector [Köntges17].	Corroded connector [Köntges17].
Severity	f e / 2 3	f e / 5	f f e / 3 4
Examples 4-6			
	Not fully inserted or interlocked connecter [Yang19].	Melted connector [Köntges17].	Cracked/disintegrated cable insulation [Köntges17].
Severity	f e / 2 3	f e / 4 5	f f e / 3 4 5
Examples 7	   		
	Incorrect crimping (right) versus correct crimping (left) [PVSurvey19].		
Severity	f e	2 3	

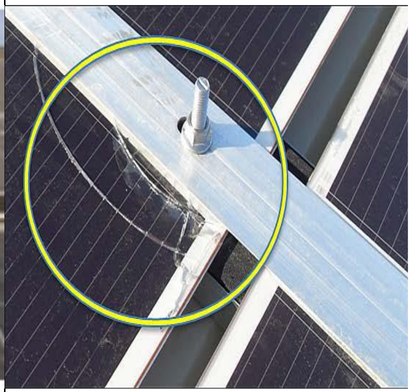
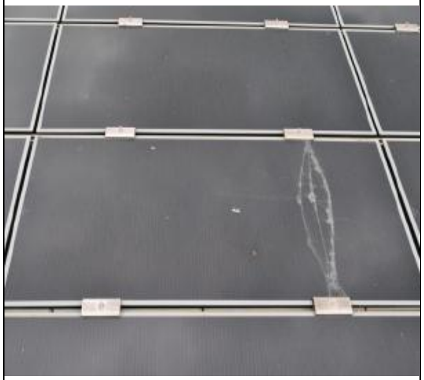
EXAMPLES (page2)			**PVFS 2-2vs.01**
Examples 8-10			
	Burned connector [Köntges17].	Corroded Cable [Köntges17].	Animal bite on cable [Köntges17].
Severity	f e — 5	f e — 1 2 3	f f e — 3 4 5

<table>
<tr><td>Component
Defect</td><td colspan="3">Cables and Interconnectors
Insulation failure</td><td>PVFS 2-3vs.01</td></tr>
<tr><td>Appearance</td><td colspan="4">A bad isolation of cables is not always visible by eye. An unequivocally detection is only possible through the measurement of the insulation resistance under dry or humid/wet conditions. It can be sometimes deduced by the presence of degraded or damaged cables and/or connectors. Under certain circumstances like after a rain fall or in the early morning when the cables or connectors are exposed to humidity, this kind of defect can lead to inverter failures (low insulation fault or inverter switch off).</td></tr>
<tr><td>Detection</td><td colspan="4">VI, (INS, MON)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="4">Isolation failures occurs as a result of a short-circuit. It is usually the result of a combination of humidity and damaged or degraded DC cables or connectors.</td></tr>
<tr><td>Production ■</td><td>Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="4">A low insulation resistance due to the cables or a connector does not lead to a performance loss itself, until an inverter failure occurs. An isolation fault can however cause potentially fatal voltages in the conducting parts of the system potentially exposing persons to an electric shock hazard. Touching of non-insulated parts may cause severe injury, without the use of safety gear and safe measuring instruments. In the worst case damaged cables or connectors may cause electric arcs and initiate a fire.</td></tr>
<tr><td>Safety:</td><td>f e f e</td><td>Performance:</td><td>2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td>Cables or connectors constituting a direct safety risk should be replaced. Regular inspections should be done to monitor the status of the not replaced components.</td><td>Ground fault detection by inverter or other devices at all time.</td><td colspan="2">Regular system inspections.</td></tr>
</table>

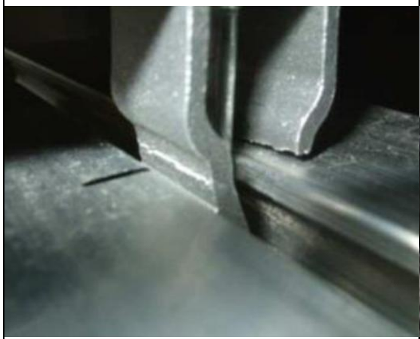
<table>
<tr><td>Component
Defect</td><td colspan="5">Cables and Interconnectors
Thermal damage in combiner box</td><td>FS 2-4vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">Defects appearing in the combiner box as discoloured or burned cable interconnections or fuses. Damaged parts can be found by visual inspection or infrared thermography (IRT).</td></tr>
<tr><td>Detection</td><td colspan="6">VI, IRT, (MON)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">Thermal damages in the combiner box can be due to the selection of inadequate components (e.g underrated fuses or fuse holders), a not proper connection of DC cables (e.g improper wire torqueing, missing fuses) or a wrong wiring of the modules/strings in the field or on-roof.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">This damage is caused by the excess heat generated in fuse holder and defect DC connectors/cables. The partial or complete thermal damage of the combiner box leads to performance losses, electrical shock hazards and risk of fire. Actions must be taken immediately by qualified personnel to prevent further damage.</td></tr>
<tr><td>Safety:</td><td>f e m f e m</td><td colspan="2">Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Replace the components with defect or abnormal temperature.</td><td colspan="2">Use IRT to check the components and connection to find poor connection or defect components.</td><td colspan="2"></td></tr>
</table>

EXAMPLES (page1)						FS 2-4vs.01
Examples 1-3						
	Burned terminal block of the combiner box [TUV Rheinland].		Improper wire torqueing causes a fire [Köntges16].		Connection show signs of corro-sion [TUV Rheinland].	
Severity	f e m	5	f e m	5	f e m	1 2
Examples 4						
	Connecting terminals show signs of burning, have melted or charred [TUV Rheinland].					
Severity	f e m	5				

<table>
<tr><td>Component
Defect</td><td colspan="5">Mounting
Bad module clamping</td><td>PVFS 3-1vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">Inadequate fastening or damage of the module or frame by the clamp.</td></tr>
<tr><td>Detection</td><td colspan="6">VI</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">The installation instructions of the module and mounting structure from the manufacturer are not followed. Typical errors at the planning and installation stage are: (a) use of inadequate clamps for the selected module and/or mounting structure, e.g. sharp edges damaging glass/glass modules, wrong combination of clamps and modules or mounting structure (b) too short and too narrow clamps or (c) the positions, kind or number of the clamps on the module not being chosen in accordance with the manufacturer's manual. Other errors are too excessively or insufficiently tightened screws during the mounting phase.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">An improperly installed clamp compromises the integrity of the mounting system and the ability of the module to stay in place under high wind or load conditions. The detachment of modules can happen as series effect because the modules share the clamps with the module next to it. Once one module is detached, the clamp immediately loses fixing force on the next module and result in series detachment. The detachment of the module/s from the mounting structure is posing a serious hazard to persons and the risk of damaging the rest of the system and/or the property in the vicinity of the installation site. Problems such as frame damage, glass breakage or cell cracks can occur compromising on the long term the performance and the electrical safety.</td></tr>
<tr><td>Safety:</td><td colspan="2">f e m e m</td><td>Performance:</td><td colspan="2">1 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Modules with a safety risk or a severity of 5 should be replaced.</td><td colspan="2">Use only compatible clamps (mounting structure/ modules/ clamps) and follow manufacturer mounting instructions. Check local wind and snow loads.</td><td colspan="2">Testing of non-standard mounting configurations by an accredited test laboratory (eg. facade mounting), perform regular system inspections</td></tr>
</table>

EXAMPLES (page1)			**PVFS 3-1vs.01**
Examples 1-3			
	Improper installation of clamp [By courtesy of SUPSI PVLab].	Wrong combination of clamps and modules [Moser17].	Glass breakage caused by too tight screws [Herrmann21]. (see also PVFS 1-8)
Severity	f e e — 1	f e e — 1	f m e m — 2 3 4
Examples 4			
	Glass breakage caused by poor clamp design [Moser17]. (see also PVFS 1-8)		
Severity	f m e m — 2 3 4		

Component Defect	**Mounting** **Inappropriate/defect mounting structure**		**PVFS 3-2vs.01**
Appearance	Mechanical damages (e.g cracking, bending) or other visual defects (e.g. corrosion of frame or mounting holes) observable on the mounting structure.		
Detection	VI		
Origin	Typically, this failure occurs when the mounting structure is not designed to withstand the wind or snow loads which are typical for the site in which the system is installed (e.g. mounting structure does not comply with static calculations, underestimation of the environmental conditions), or if the anchorage of the mounting structure to the ground or roof is weak (e.g. ground conditions are not considered sufficiently when choosing the mounting structure). The roof strength, to withstand the added load of the PV system and include allowance for O&M activities, is not verified. Another reason for the failure of a mounting structure is the use of inappropriate materials (e.g use of corrosive materials in a corrosive environment, insufficient galvanisation, poor quality material due to a bad or missing quality assurance in production), leading to a premature degradation or mechanical failure of the mounting structure. Installation errors (e.g. missing/non-original components, excessively or insufficiently tightened screws) can be the origin of a failure of the mounting structure.		
	Production ■	Installation ■	Operation ■
Impact	An inappropriate or damaged mounting structure compromises the integrity of the modules mounted on it and in some cases also the substructure (e.g roof insulation). In the worst case this leads to the detachment of single modules or the whole mounting structure from the roof or ground, or roof collapses, posing a serious hazard to persons and the risk of damaging the rest of the system and/or the property in the vicinity of the installation site. Performance losses are to be expected, depending on the damage on module level (number of disconnected modules/strings, **glass breakage, cell cracks**, **back sheet damages**, **damaged or detached junction box**) and the time and labour needed to repair the system. Galvanic corrosion is important for the installation with two different metals in contact, for example aluminium frame fixed on steel structure, especially in humid or costal area. Direct contact of different metals generates galvanic corrosion which frequently happens around the fastening screws. Therefore insulation between two different metals is required in humid and costal area.		
	Safety: f e m	Performance: 1 2 3 4 5	
Mitigation	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Mounting structures with a direct safety risk should be replaced or repaired.	Use only compatible mounting structures (ground/mounting structure/modules) and follow manufacturer mounting instructions. Check local load (conditions (wind, snow, other).	Regular system inspections. Testing of non-standard mounting configurations by an accredited test laboratory (e.g. facade mounting), perform regular system inspections.

EXAMPLES (page1)			PVFS 3-2vs.01
Examples 1-3			
	Corrosion due to salt water [Köntges16].	Cracks in mounting structure due to mechanical stress [Köntges16].	Screw canal bends due to mechanical stress [Köntges16].
Severity	f e m / 1 2	m / 1	m / 1
Examples 4-6			
	Bracket fractured due to mechanical stress [Köntges16].	Undersized mounting structure for local snow load conditions [Köntges16].	Undersized mounting structure for local wind conditions [India13].
Severity	m / 1	m / 5	m / 5

<table>
<tr><td>Component
Defect</td><td colspan="2">Mounting
Module shading</td><td>PVFS 3-3vs.01</td></tr>
<tr><td>Appearance</td><td colspan="3">Depending on the position of the sun (day and time), shading can be seen either by eye when performing a visual inspection, or by comparing monitoring data of unshaded and shaded strings or by running shading simulations. The shade can have different patterns and change/move over the day and season.</td></tr>
<tr><td>Detection</td><td colspan="3">VI, (MON, IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="3">The choice of the mounting structure and the position in which the modules are mounted influences the shading conditions. Shading can be caused by different factors or obstacles e.g trees, antennas, poles, chimneys, satellite dishes, roof or façade protrusions, near buildings, cables, or by self-shading (inter array or row-to-row shading) or soiling. Shading conditions can change over the lifetime of a PV system due to growing vegetation, new constructions or construction elements. It can be distinguished between different types of shades: direct shades hindering the direct light to reach the module or diffuse shades.</td></tr>
<tr><td>Production ☐</td><td>Installation ■</td><td>Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="3">A cell or module which does not receives or receives less sunlight due to a shading obstacle, lowers the performance of a PV system. Typically, the cumulative annual shading loss of PV systems is between 1-5%, but energy losses up to 20-30% can be observed for roof top or façade systems. Due to series connection of cells and modules, the power loss is significantly higher than the shaded area. The final loss depends on the on-site implementation or shading mitigation measures like optimised string and module arrangements (landscape mounting), use of module-level power electronics (MLPEs), inverter characteristics (MPPT search algorithms, string control) or the use of shading tolerant module technologies (e.g half-cut cells, back contact cells). Shading itself does not pose a safety issue, but the hot-spots caused by prolonged shading can lead to follow-up failures (e.g burn marks, bypass diode failures, glass breakage, arcing or fire). It further can result in an acceleration of the aging process resulting into higher degradation rates. The right time to consider the impact of shading is at the system planning phase, later it is usually too late. The use of MLPEs such as micro-inverters and DC optimizers for individual modules can potentially increase performance under shading conditions, but the gain achieved by these devices do not always exceeds the loss caused by the MPLE device itself (lower efficiency), and the shading still activates the bypass diode and result in hot spot on the shaded cell, which increases the risk of reliability issues. The choice of using them only in the area where shading occurs should be considered an alternative to install them for all modules. A cost benefit analysis should be done in any case.</td></tr>
<tr><td>Safety: f e m</td><td colspan="2">Performance: 2 3 4 5</td></tr>
<tr><td rowspan="2">Mitigation</td><td>Corrective actions</td><td>Preventive actions (recommended)</td><td>Preventive actions (optional)</td></tr>
<tr><td>Indirectly damaged modules with a safety or severity risk of 5 should be replaced or repaired. Eventual trees or vegetation responsible for the increased shading loss should be cut.</td><td>A basic shading analysis (full year solar/shade data) is recommended to identify areas and periods of major shading. Areas exposed to shading within the central part of the day or sunny season should be avoided or appropriate/cost-effective shading mitigation measure should be implemented.</td><td>A detailed shading loss analysis should be done which estimates and compares different system configurations and shading mitigation measures. Perform regular system inspections.</td></tr>
</table>

EXAMPLES (page1)			PVFS 3-3vs.01
Examples 1-3			
	Shading by pole-and-wire (poor design: too close to nearby shading objects) [Jahn18].	Shading due to bad planning or coverage by afterwards build construction element. [Moser17].	Shading by tree with seasonal changes due to foliage [Moser17].
Severity	2 3 4	5	3 4
Examples 4-6			
	Missing maintenance on flat green roof [By courtesy of SUPSI PVLab].	Vertical shading of a standard module with 3 bypass diodes [By courtesy of J.Lin PV Guider].	Shading by balustrade [By courtesy of J.Lin PV Guider].
Severity	f e m 5	3 4 5	2 3 4
Examples 7			
	Continuous shading caused by chimney [By courtesy of SUPSI PVLab].		
Severity	f e m 3 4 5		

<table>
<tr><td>Component
Defect</td><td colspan="4">Inverter
Overheating</td><td colspan="2">PVFS 4-1vs.01</td></tr>
<tr><td>Appearance</td><td colspan="6">The inverter reduces its power or switches off to protect components from overheating (temperature derating). Inverters do not always deliver a corresponding status message "power reduction" or "derating". For this reason, it is recommended to check the inverter behaviour by determining and analysing performance curves (Power vs Irradiance).</td></tr>
<tr><td>Detection</td><td colspan="6">MON, (IV, IRT)</td></tr>
<tr><td rowspan="2">Origin</td><td colspan="6">Temperature derating of the inverter can occur for various reasons, e.g. improper installation of the inverter, fan failure, dust blocking heat dissipation or an incorrect programming of the inverters.</td></tr>
<tr><td colspan="2">Production ■</td><td colspan="2">Installation ■</td><td colspan="2">Operation ■</td></tr>
<tr><td rowspan="2">Impact</td><td colspan="6">When the monitored components in the inverter reach the maximum operating temperature, the inverter shifts its operating point to a lower power. During this process, power is reduced step-by-step. In the extreme case, the inverter switches off completely. As soon as the temperature of the threatened components falls below the critical value, the inverter returns to the optimal operating point. The partial or complete failure of the inverter leads to performance losses, which will get worse if the problem is not solved. In the worst case inverter will switch off. Inverter overheating do not affect module safety.</td></tr>
<tr><td>Safety:</td><td colspan="2"></td><td>Performance:</td><td colspan="2">3 4 5</td></tr>
<tr><td rowspan="2">Action</td><td colspan="2">Corrective actions</td><td colspan="2">Preventive actions (recommended)</td><td colspan="2">Preventive actions (optional)</td></tr>
<tr><td colspan="2">Once identified the origin of the temperature derating the failure should be repaired. The filters and in general heat dissipation path should be cleared of obstruction.</td><td colspan="2">Follow the given installation procedure, use of adequate cooling technology, perform regular inspections of the ventilation units.</td><td colspan="2">Monitoring of inverter temperature</td></tr>
</table>

<table>
<tr><td colspan="6">EXAMPLES (page1)</td><td>PVFS 4-1vs.01</td></tr>
<tr><td rowspan="2">Examples 1-3</td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">Dust blocking heat dissipation [By courtesy of TUV Rheinland].</td><td colspan="2">A soiled air filter causes overheating [By courtesy of TUV Rheinland].</td><td colspan="2">Installation not appropriate (direct exposition to sun) [By courtesy of TUV Rheinland].</td></tr>
<tr><td>Severity</td><td></td><td>3</td><td></td><td>3</td><td></td><td>3</td></tr>
</table>

Component	**Inverter**		**PVFS 4-2vs.01**
Defect	**Incorrect installation**		
Appearance	The inverter must be installed according to the installation instruction. A common failures is the installation near flammable, explosive, corrosive or humid sources. Also the minimum distances to bottom, top or to the sides are not always fulfilled. If the input cables are not fixed properly, increased temperatures can occur at the loose contact point which lead to lower performance or risk of fire. Inverters must always be accessible for operation and maintenance and properly secured to an appropriate base.		
Detection	VI (MON)		
Origin	Violating instruction manual, e.g. installed nearby flammable materials as wood or in direct sun light. Minimum distance to adjacent components not maintained.		
	Production ☐	Installation ■	Operation ☐
Impact	Incorrect installation of the inverter can cause danger to users and hazardous conditions and can result in **overheating** of the inverter. The use of the inverter in the presence of flammable vapours or gases can lead to explosions. The inverter housing can become very hot under operation. Follow the instruction to provide gaps from both sides and top for adequate cooling. Direct sunlight on the inverters must be avoided. The inverter must be safely accessible to avoid accidents during maintenance work.		
	Safety: f e m	Performance: 1 2 3 4 5	
Action	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Dismount the component and follow the installation procedure.	Follow the given installation procedure, use of adequate cooling technology, perform regular inspections of the ventilation units.	Monitoring of inverter temperature.

EXAMPLES (page1)			PVFS 4-2vs.01
Examples 1-3			
	Installation in direct sun light [By courtesy of TUV Rheinland].	Inverters are not or difficult accessible for operation and maintenance [By courtesy of TUV Rheinland].	Distance to bottom, top or to the sides too low [By courtesy of TUV Rheinland].
Severity	3	e m 2	f 3
Examples 4-5			
	Housing not appropriate [By courtesy of TUV Rheinland].	Presence of inflammable material [By courtesy of SUPSI PVLab].	
Severity	1	f 1	

Component Defect	**Inverter** **Not operating (complete failure)**		**PVFS 4-3vs.01**
Appearance	If the inverter does not work despite good production conditions, common problems are the lack of restart after grid faults or **isolation faults**. The inverter may show fault codes to help understanding the problem. This can be observed by checking the display or the data log of the monitoring system. Examples for hardware defects in the inverter are discoloured or burned cable interconnections or fuses. Damaged parts can be found by visual inspection or infrared thermography (IRT).		
Detection	MON, (VI, I-V, VOC)		
Origin	A complete failure of the inverter occurs due one or more malfunctions of single hardware or software component of the inverter or faults due to grounding issues, e.g. high humidity inside the inverter, or a firmware issue.		
	Production ■	Installation ■	Operation ■
Impact	The complete failure of the inverter leads to significant performance losses and immediate actions must be taken. When the restart does not work or the fault occurs recurrently the origin must be identified in most cases by a service team. Software issues can be solved by updating the firmware for technical reasons or to update the system to new standards/grid technical requirements. While damaged hardware components of central inverters are usually repaired, string inverter are replaced more often for economic reasons. Damaged hardware can cause fire and electric shock hazards and must be repaired by qualified personnel.		
	Safety: f e f e	Performance: 3 4 5	
Action	Corrective actions	Preventive actions (recommended)	Preventive actions (optional)
	Restart the inverter. Replace the components with defect or abnormal temperature. Update the software.	Use IRT and VOC to check the components and connection to find poor connection or defect components.	

EXAMPLES (page1)			PVFS 4-3vs.01
Examples 1-3			
	Insulation failure [TUV Rheinland]	Not operating inverter [TUV Rheinland].	Damaged hardware component [Sinclair17].
Severity	e — 3 4 5	3	f e — 5

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