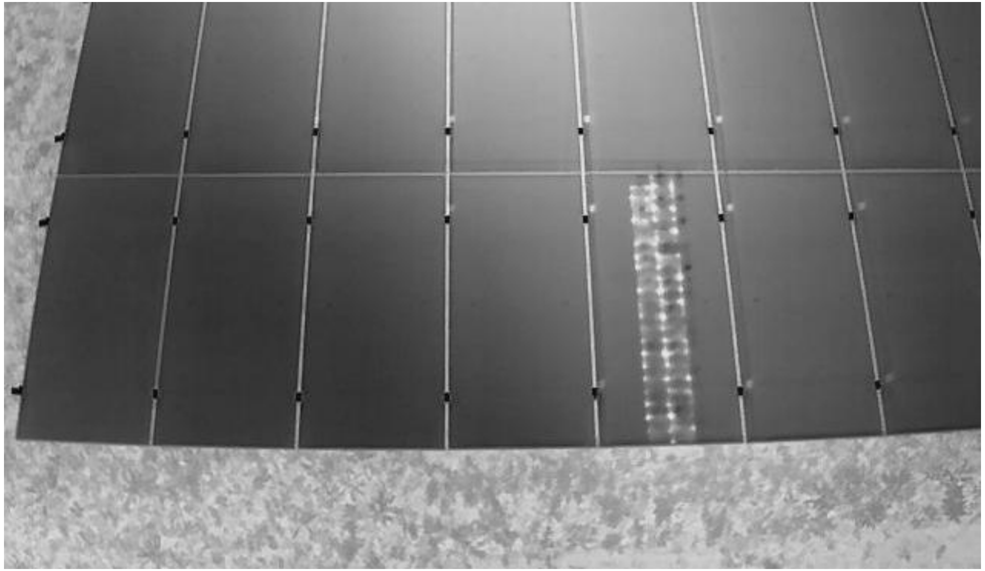


Failure in current PV systems and their relevance to find them

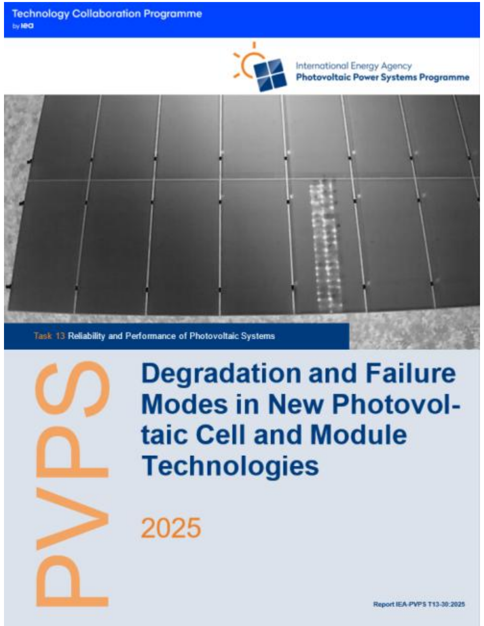
Marc Köntges

Hamelin, GER, 23rd Oct. 25, Task13 WS Characterization of Photovoltaic Systems

Degradation and Failure Modes in New PV Technologies

Introduction

- Literature, test results and current field experience are collected to access weaknesses of new module technologies such as TOPCON and HJT.
- For perovskite-based PV technologies, a comprehensive literature is conducted to identify all degradation pathways that need to be addressed for reliable use in PV applications.
- If available mitigation strategies are identified.



This report overviews currently know degradation modes and failures and their mitigations

Report IEA-PVPS T13-30:2025, February 2025

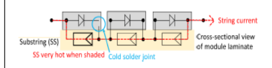
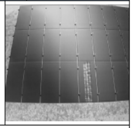
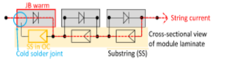
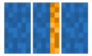
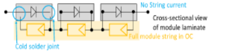
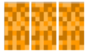
PVPS

Photovoltaic Failure Fact Sheets (PVFS) 2025

Praxis and field-oriented information for PV planners, installers, investors, inspectors, consultant or insurance companies.

- COMPONENT
- DEFECT
- APPEARANCE
- DETECTION
- ORIGIN
- IMPACT
- MITIGATION
- EXAMPLES

Component	Module		PVFS 1-14vs.02
Defect	**Junction box interconnection failure**		
Appearance	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.		
Detection	BYT, (IRT, EL, VI, IV, VOC)		
Origin	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.		
	Production ■	Installation □	Operation ■
Impact	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.		
	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, especially if the modules are installed on buildings. Regular inspections should be done to monitor the status of the not replaced modules.	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.	Testing the module bypass diodes with a mobile test centre prior to installation. Regular IRT inspections. Installation of arc detection tool.

EXAMPLES (page2)	PVFS 1-14vs.02
Example 10	 
	A cold solder joint after the diode in any junction box (either outer or inner) 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} [Köntges24].
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 [Köntges24].
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 [Köntges24].
Severity	

The original PV failure fact sheets (PVFS 2021) were reviewed to include failures occurring in new module technologies and its impact in the field:

- *Spontaneous thin glass breakage*
- *PID-p in bifacial modules*
- *Cold solder joints in new generation junction boxes*
- *Cracking and delamination in new backsheet materials*
- *Cell-cracking in MBB/multi-wire or shingled modules*

PVPS

The PVFS introduces main failures, how to detect and mitigate them, and provides information on their impact on safety and power generation, together with practical examples.

Degradation and Failure Modes in New PV Technologies

- **Impact of Innovation on Degradation**: Cell cracking issues are mitigated by multi-wire technology. LeTID is addressed by gallium-doped wafers and improved manufacturing.
- **Potential-Induced Degradation** mechanisms can be reduced through targeted tests and adjustments at cell, module, and system level. UV irradiation during testing minimize degradation in specific cell types like TOPCon and will be added in upcoming standard.
- **UV-Induced Degradation** occurs in some PV modules, but is manageable by using UV-stable designs and encapsulation materials. However, further research is required.
- **Encapsulation Material Challenges**: The degradation of polymer materials is still a major problem. New tests combining stresses like UV, humidity, and temperature are required.
- **Thin Glass Durability**: Thin glass in modern modules has shown in some cases high breakage rates, necessitating multiple-module testing under real installation conditions.
- **Junction Box Reliability**: Faulty bypass diode connections pose a safety and performance risk. It is recommended to implement tests during production and in affected installations.

But what is important to characterize in the Field?

Report IEA-PVPS T13-30:2025, February 2025

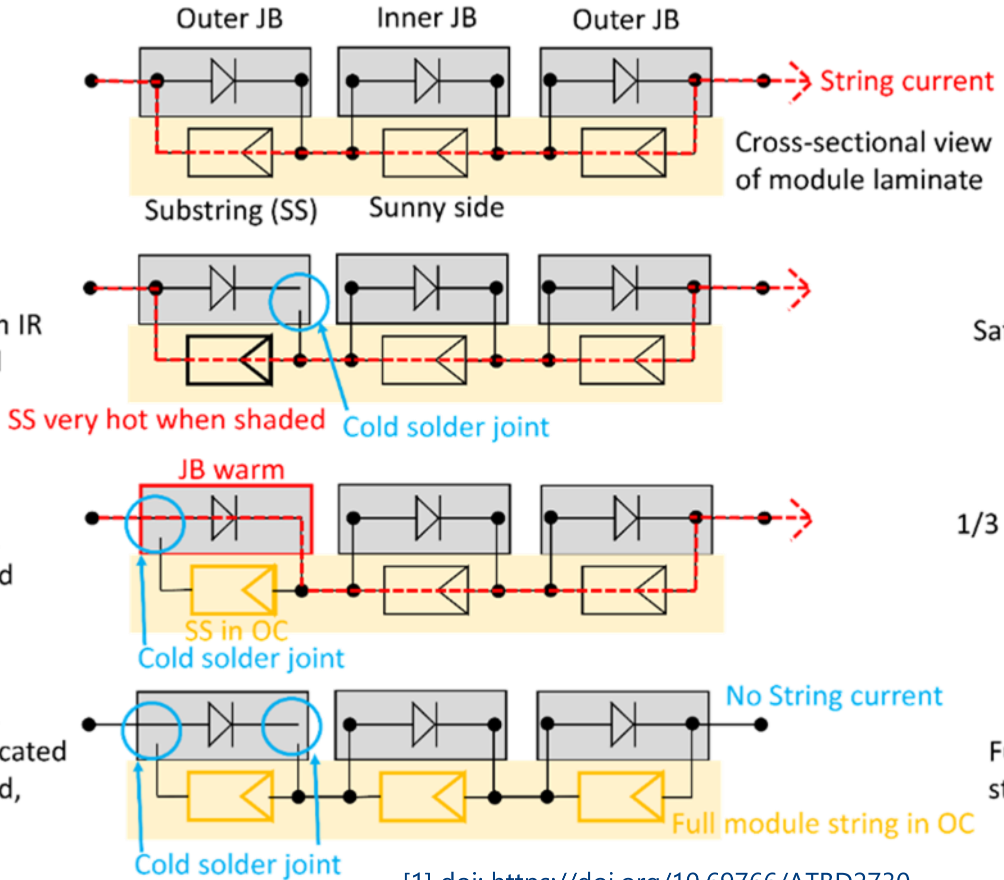
What junction box failure may happen?

Intact module — OK

Failure mode A
Cannot be found with IR
All JB can be affected — Safety failure

Failure mode B
Can be found with IR
Only outer JB affected — 1/3 power loss

Failure mode C
Can be found with IR
Module cannot be located
Only outer JB affected,
If inner JB affected
behaves like mode A — Full module string lost

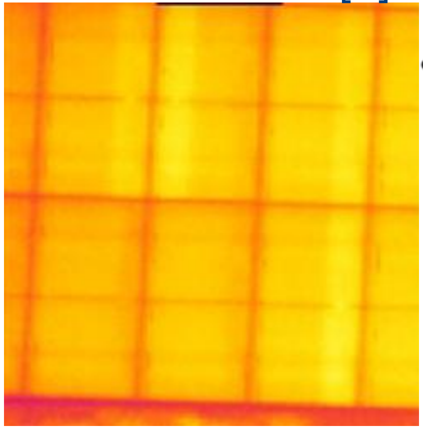


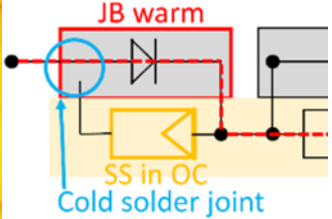
[1] doi: https://doi.org/10.69766/ATBD2730

PVPS

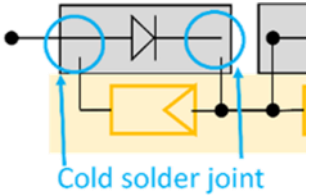
Which detection methods exist?

Failure mode B [1]





Failure mode C [1]



Failure mode B and C

- Use standard TG inspection
- Homogenious silightly hotter substrings together with hot junction box ➔ failure mode B
- Full string is not active in TG inspection ➔ failure mode C
  Visula inspection needed
  Signal transmission method

[1] doi: https://doi.org/10.69766/ATBD2730

PVPS

Which detection methods exist?

Failure mode A[1]

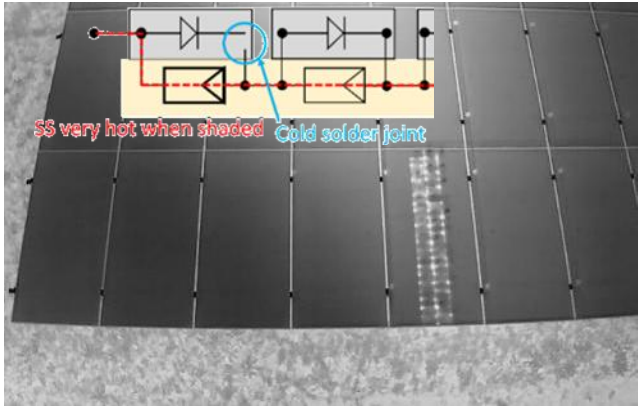


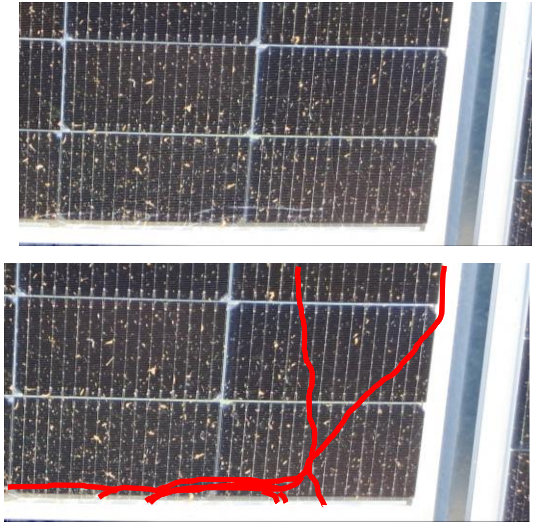
Image: photovoltaikbuero Ternus & Diehl GbR

- Failure mode A
- Reverse voltage at 3-5% of Isc in the night applied to module strings, you should get << 50 V
- Across a cell string without BPD a voltage of 15…25 V x 20…24 (cells) = 300…600 V drops
- Search for heated strings with thermographic camera in the night
- Up to two open circuit bypass diodes per string are detectable with a 1000 V power source

[1]doi: https://doi.org/10.69766/ATBD2730

PVPS

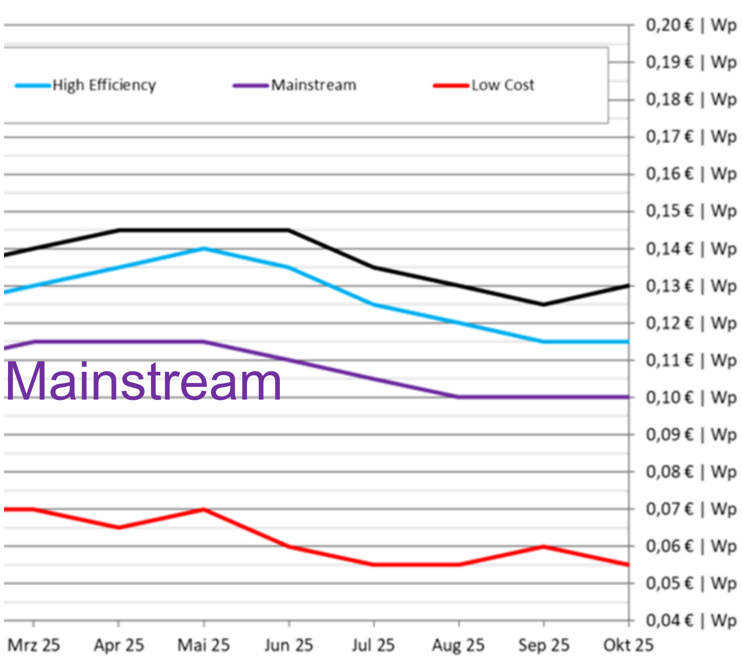
Glass breakage



- Thin glass (1.6-2.0 mm) breakage[1], often rear glass[2]
- Can cause isolation fault, loss of mechanical integrity and arcing (fire)
- Some times high failure rates (10% and more[2])
- Difficult to find with Visual Inspection (VI)
- High detection speed and reliable detection needed

[1]R. Rüther, "Make PV modules as cheap as possible, but not cheaper," PV Magazine International. [Online]. Available: https://www.pv-magazine.com/2024/01/03/make-pv-modules-as-cheap-as-possible-but-not-cheaper/
[2] M. Braga, G. X. A. Pinto, A. M. Pires, A. H. Zamboni, L. R. Nascimento, and R. Rüther, Universidade Federal de Santa Catarina, Florianópolis-SC, Brazil, https://scorecard.pvel.com/mechanical-stress-sequence/

Cost structure of module replacement

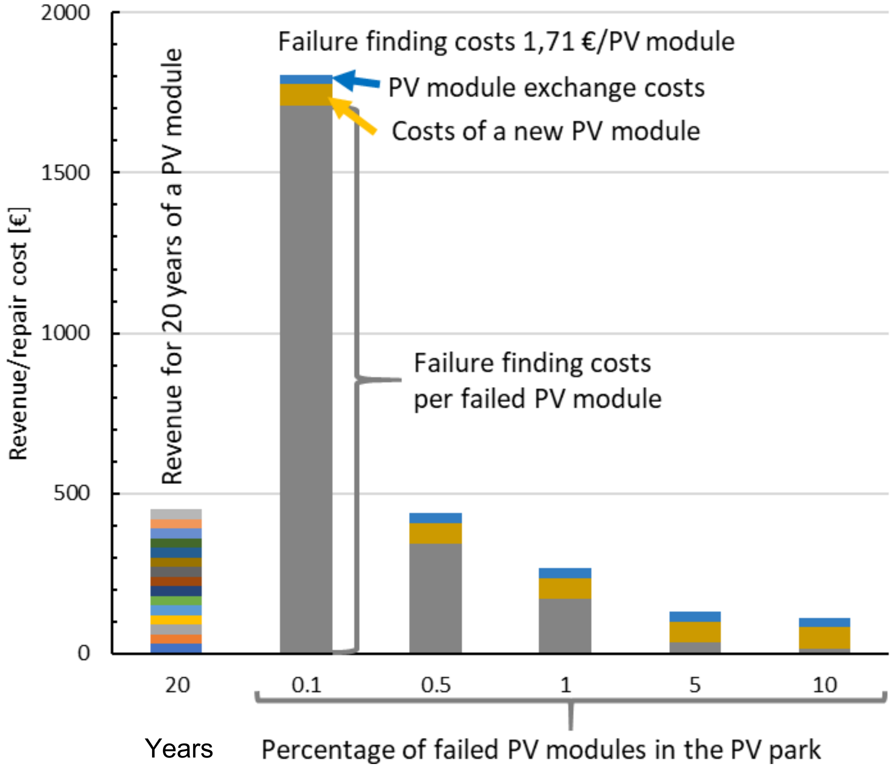


Source: PVExchange.com

- 0,10 €/Wp module costs[1]: 600 Wp PV module => 60 €
- Average yield per Wp and year: 1 kWh/Wp/a, 0,05 €/kWh[2] => 0,05 €/a/Wp => 30 €/a/module
- Assembly costs for replacing modules ~ 30 € => 0,05 €/Wp (e.g. warranty case)
- A 100% failed PV module pays for replacement in ~1 year if replaced under warranty
- A module with 10% power loss will pay for replacement in approx. 10 years if replaced under warranty

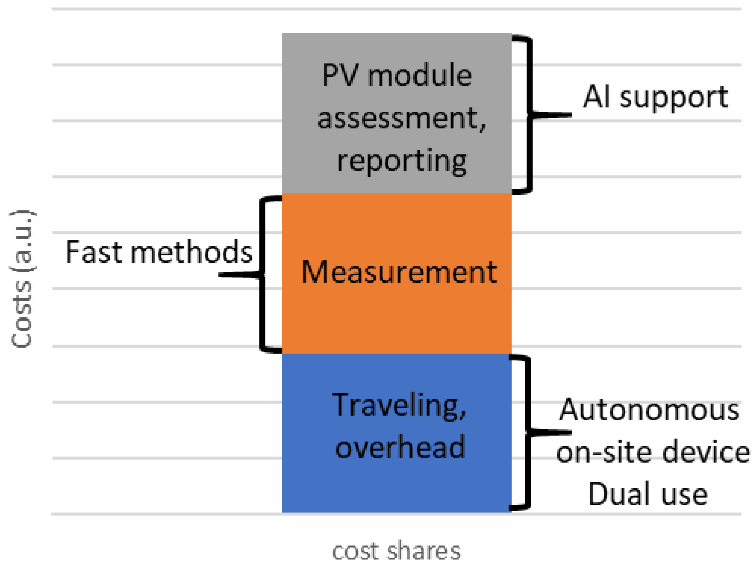
[1] https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/ErneuerbareEnergien/EEG_Foerderung/start.html
[2] https://www.pv-magazine.de/2025/10/14/photovoltaik-markt-quo-vadis/

Is finding failures financially worthwhile?



- Calculation based on assuming 100% power loss of defect PV module
- Typically only some PV modules have a high power loss
- For low defect rates in the system finding defects is not cost effective
- **Failure finding is mainly for safety**
- Find defects at system start
- Or better in the planning phase

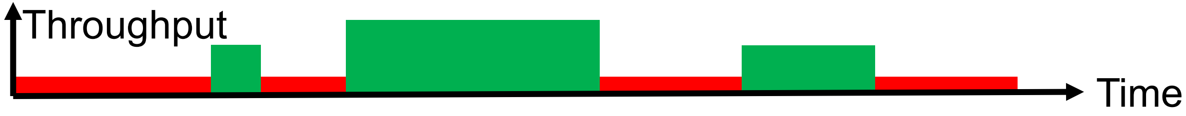
Cost structure & cost reduction of PV module characterisation



- AI analysis of measurement results can reduce assessment and reporting cost
- But: needs regular updates for new PV technologies
- No open access training dataset available for VI
- New methods must increase measurement speed
- Autonomous on site devices can reduce traveling costs. On site devices must be cheap and must have low maintenance.
- Dual use with green cutting/cleaning/theft protection may reduce traveling costs either.

Cost structure for measurement tools

- Tools with limited periods of use must have low investment costs and development costs in order to be economical (e.g. TG)



- Knowledge to increase periods of application time can also decrease over all costs

- Tools with unrestricted application periods and high analysis speed can have higher investment costs and development costs

- Tools must be able to reliably find relevant high power loss and safety failure to be economical

What methods are available?

600-1000 W/m² necessary

- TG, ITG, DPL

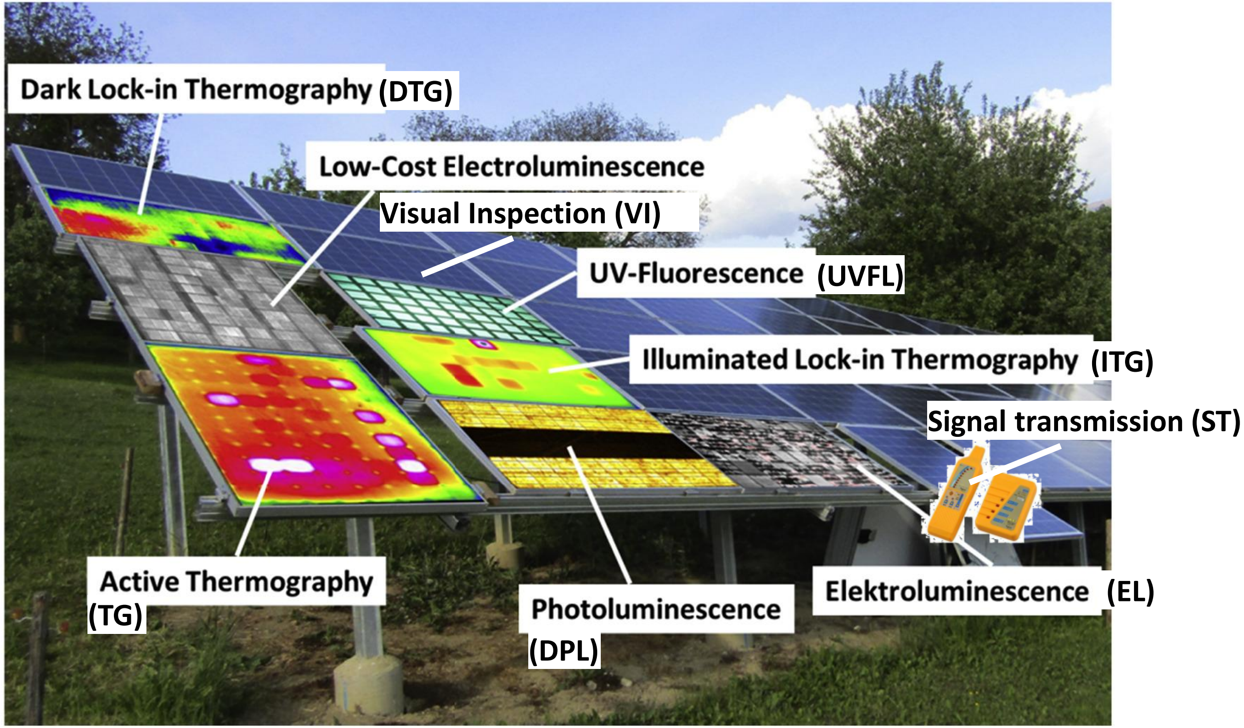
Sun shine independent

- EL, UVFL, VI, ST, ISO

No opening of the circuit

- UVFL, VI, TG, (DPL)

And many others …



Source: W. Mühleisen https://doi.org/10.1016/j.renene.2018.11.044, image modified.

Finding faults during construction acceptance

- Find faults on the first day of construction
  => Time with greatest fault finding value, as faults can be avoided for the following work

- Typical construction faults:
  screw connection NIO, wiring NIO, broken plugs, plug crimping NIO, rack imprecise, scratches/holes in back foils, cell cracks due to rough handling.

- Most defects can be found by VIS and EL/DPL

- Due to cost structure VIS and TG are mostly used for acceptance + regular inspection

Image: https://www.maz-online.de/Lokales/Havelland/Nauen/Nauen-Vattenfall-will-Hybrid-Solarpark-errichten

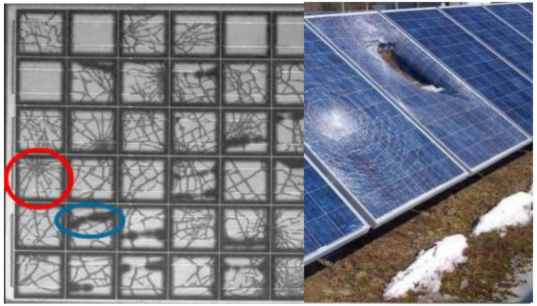
Image: https://www.pv-magazine.de/2021/10/06/gp-joule-beginnt-bau-von-90-megawatt-solarpark-in-ehemaligem-braunkohlegebiet/

Finding failure for insurance claims

- Different cost structure, as fault finding, material and working time is financed by insurer
- It is worthwhile for park operators to find almost all faults
- Typical faults and methods are:
- Hail damage (VIS, EL, UVFL, DPL)
- Snow damage (VIS, EL, UVFL, DPL)
- Storm damage (VIS, EL, UVFL, DPL)
- Water damage (VIS, ISO)
- Theft (VIS)


Source: Dr. Cedrik Zapfe


rotec GmbH Berlin


Source: https://www.wral.com/falling-ice-damages-cbc-solar-array/13396686/


Source:
Dr. Cedrik Zapfe

Conclusion

- During acceptance test highest detail of inspection should be done.
  But no more cell crack counting!
- Repeat inspection and occasion related inspection must detect only
  “high power loss & safety failure” (if no insurance case)
- Automated (AI) evaluation of inspection data has a high cost reduction potential
- Combination of regular work (green cutting/cleaning/theft protection) with inspection is possibly cost effective
- Autonomous on site inspection tools recover costs if their total cost are lower than regular traveling cost and if they need nearly no inspection/repair for it self.
- We need to detect lost bypass diodes, glass breakage and isolation faults faster&cheaper

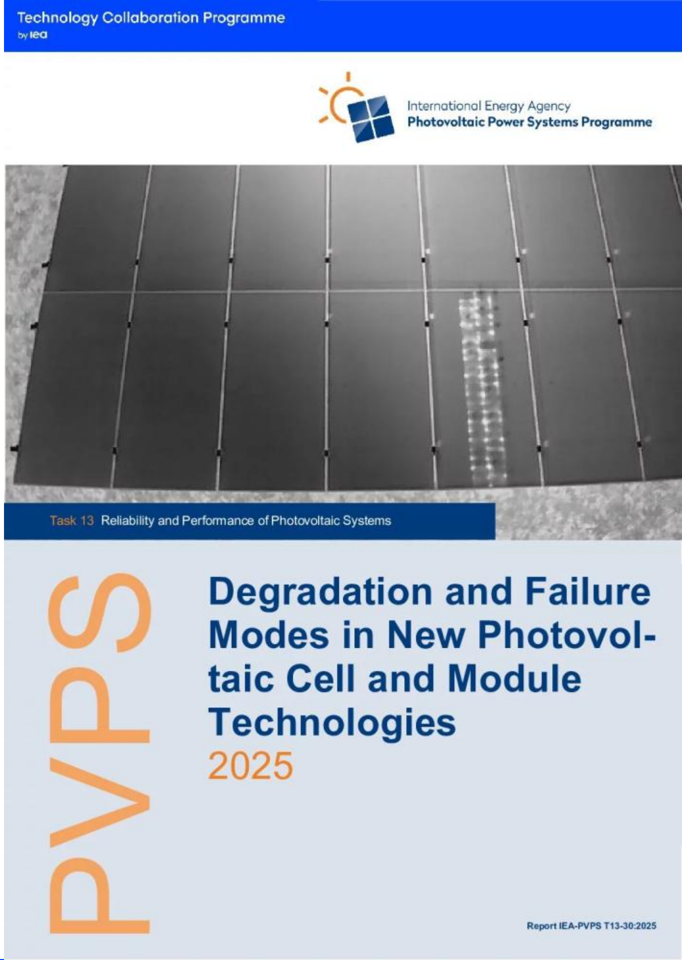
www.iea-pvps.org

New TASK13 phase starts in 2026.
Contact me if you want to be part of it!

Thank you for your attention

Marc Köntges
Marc.Koentges@ISFH.de

IEA
PVPS



https://doi.org/10.69766/ATBD2730