This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

goPV

Jun. 21st

Solar PV Modules

Testing, reliability, lifetime

Alejandro Borja Block - EPFL

co-organized with Università di Catania

(14:00-15:00)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

Outline

1. Introduction
2. Factors impacting module reliability over lifetime
3. Quality in manufacturing
4. Accelerated-aging testing
5. Do PV modules make it to 35 years?

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Reliability Engineering: Definitions

Brand new PV module

Durability

Perform as required, under given conditions of use and maintenance, until the end of lifetime

Lifetime

- User requirements are not longer met

- 80% of initial power for PV

Reliability

Perform as required, without failure, for a given time interval, under given conditions

Failure

Loss of ability to perform as required

Warranty: is a written promise by a company that, if you find a fault in something they have sold you within a certain time, they will repair it or replace it free of charge.

PV modules's typical warranty: 25 yrs with 80% of initial performance.

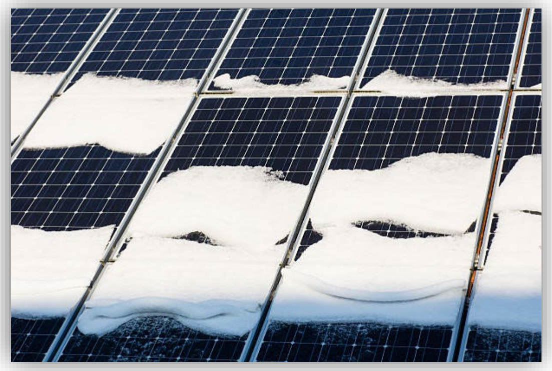
Operation of PV modules

Electrical Stress
High voltages, shadows

Temperature
heat, frost, night-day cycles

Irradiance
light, UV

Mechanical Stress
wind, snow, hail



Atmosphere
salt mist, dust, sand, pollution

Moisture
rain, dew, frost

Testing and certifications

Why do we need them?

- Give certainty to manufacturers and customers that the PV modules will perform as required
- Improve module design
- Investigate new technologies and materials

Outline

Factors impacting PV module reliability over lifetime

Components →

- R&D
- Process parameters
- Process stability
- Quality inspection

Modules →

- R&D
- Component selection
- Processing parameters and stability
- Quality inspection

Installation →

- Transport
- Handling
- Mounting

Operation

- Climate
- Micro-climate
- O&M

Factors impacting PV module reliability over lifetime

Components
- R&D
- Process parameters
- Process stability
- Quality inspection

→

Modules
- R&D
- Component selection
- Processing parameters and stability
- Quality inspection

→

Installation
- Transport
- Handling
- Mounting

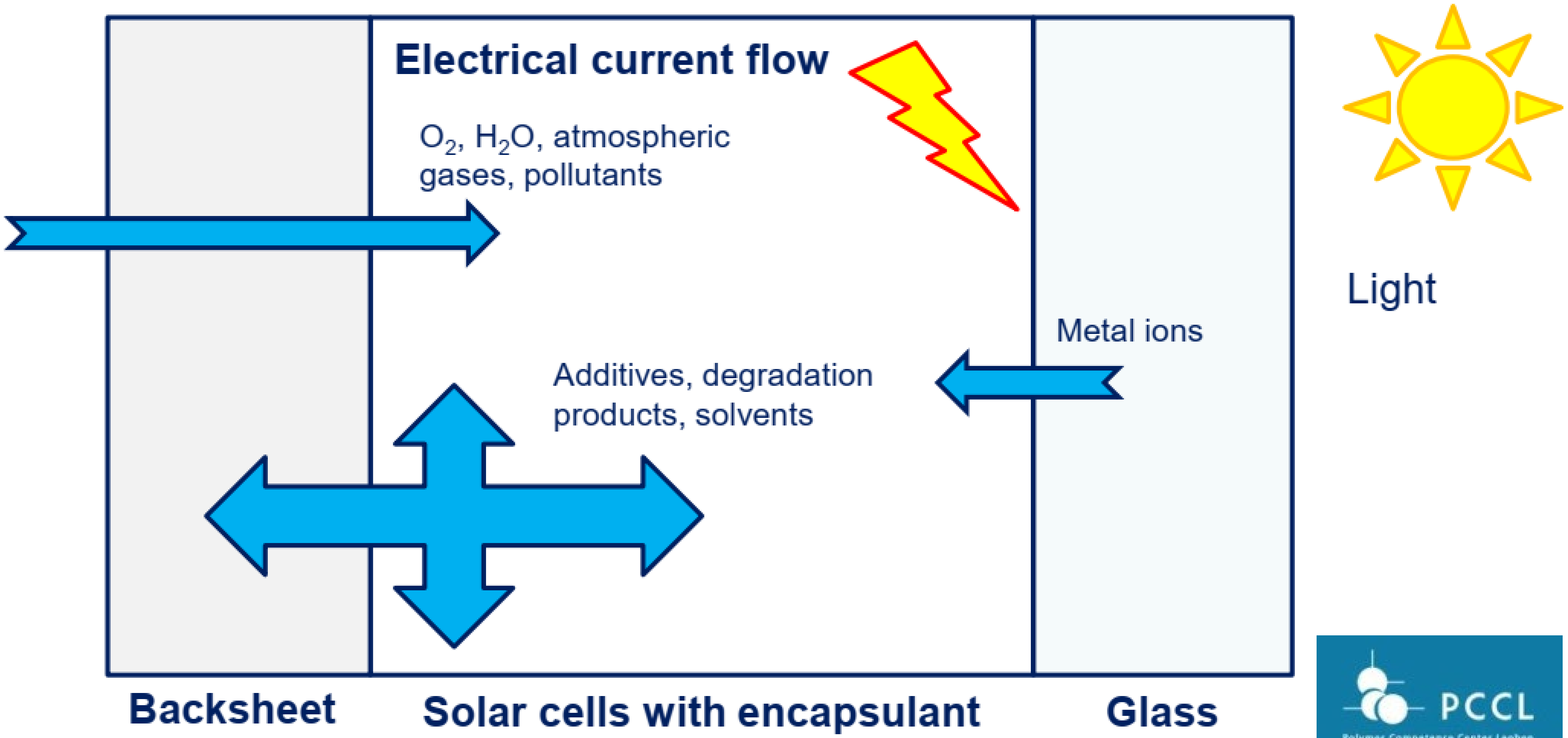
→

Operation
- Climate
- Micro-climate
- Operation
- Maintenance

Components/material interactions

Components

Modules



→ Interactions may lead to unintended degradation effects:
Yellowing, corrosion, potential induced degradation, snail trails

Factors impacting PV module reliability over lifetime

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Modules
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- Climate
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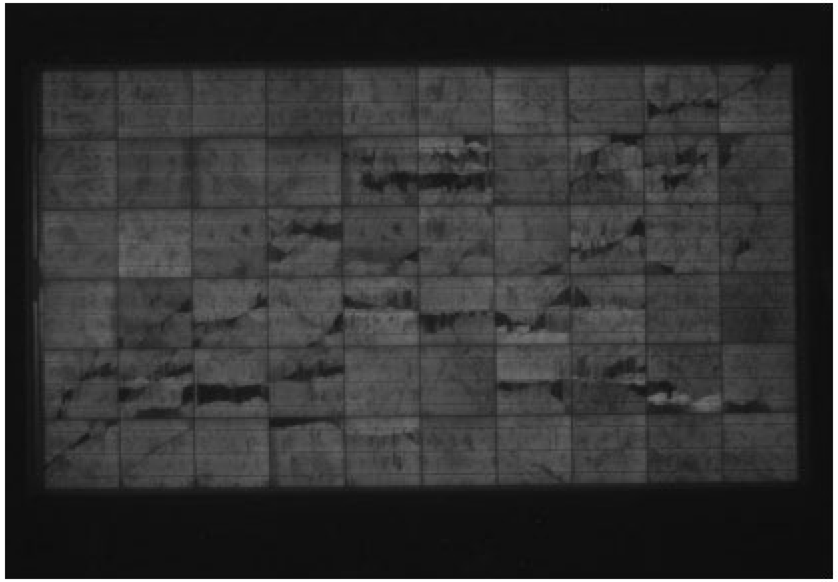
- Maintenance

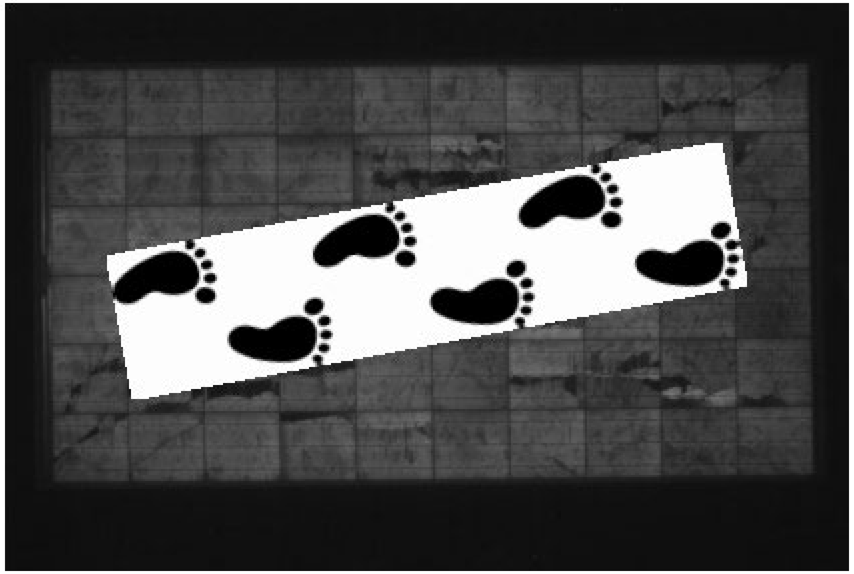
Factors impacting PV module reliability

Installation

- Transport
- Handling
- Mounting

Electro-luminescence (EL) imaging:
makes visible defects not visible to the human eye





Switzerland, 5 kW plant, 2013

Handling

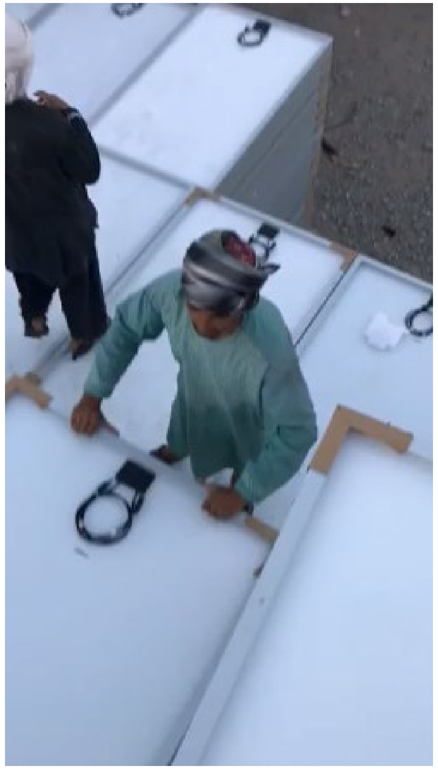
Installation

- Transport
- Handling
- Mounting

Stepping on solar modules….

Old habits die hard!

Lagos, Nigeria, 2016



Virtuani & Agostinelli, EUPVSEC Brussels 2018

Factors impacting PV module reliability over lifetime

Components
- R&D
- Process parameters
- Process stability
- Quality inspection

Modules
- R&D
- Component selection
- Processing parameters and stability
- Quality inspection

Installation
- Transport
- Handling
- Mounting

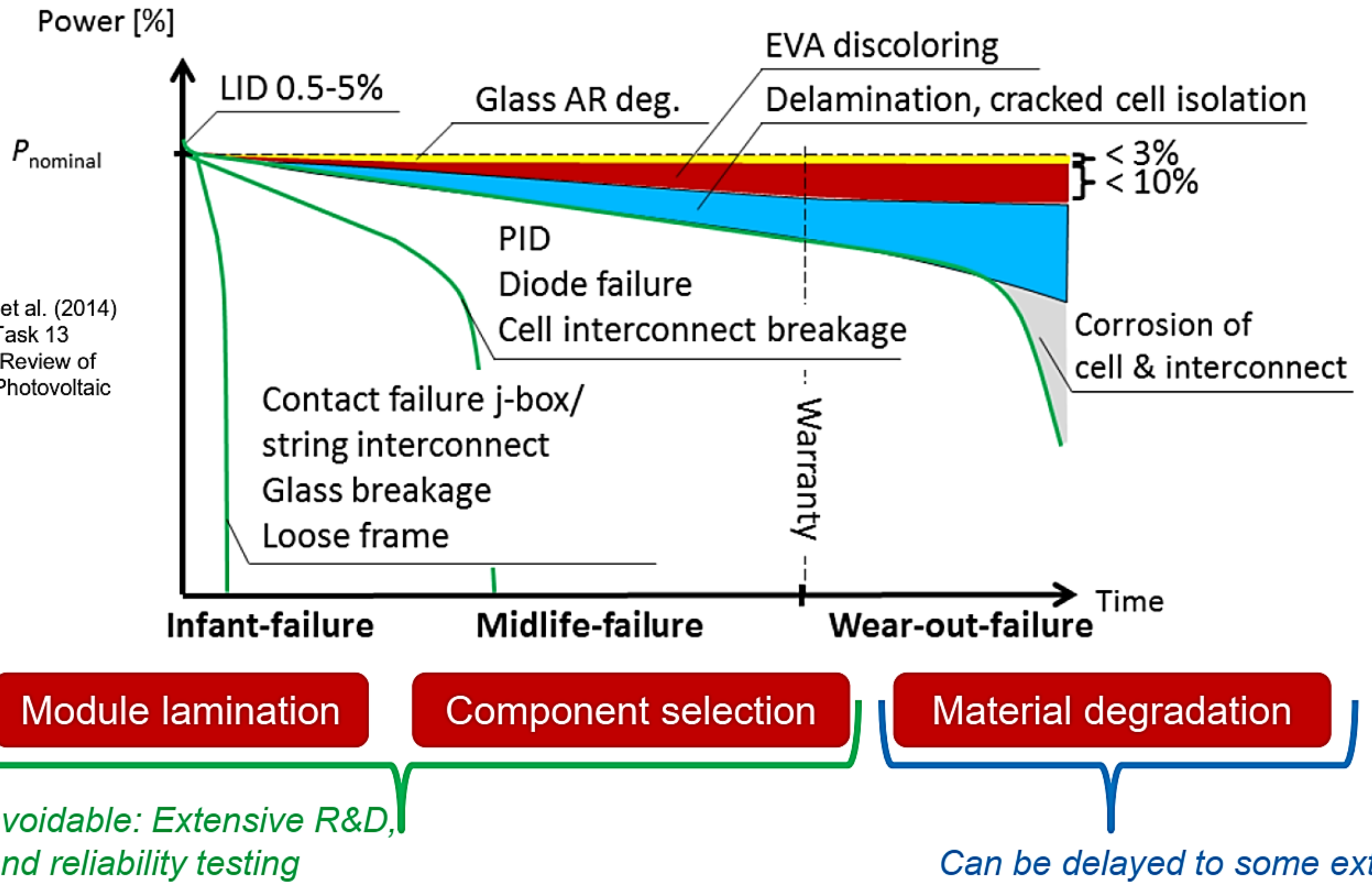
Operation
- Climate
- Micro-climate
- Operation
- Maintenance

Degradation modes in c-Si PV Modules [1]

Operation

- Climate
- Micro-climate
- Operation
- Maintenance

[1] Köntges et al. (2014) IEA-PVPS Task 13 Report on "Review of Failures of Photovoltaic Modules"

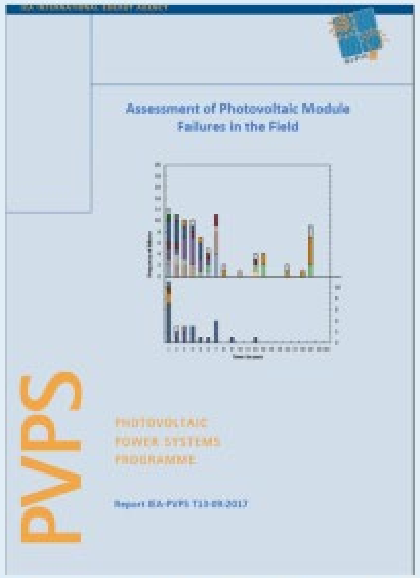


Overview of module degradation modes

IEA INTERNATIONAL ENERGY AGENCY

PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

IEA- PVPS Task 13 Report: Performance and Reliability of Photovoltaic Systems



PVPS

[1] Report IEA-PVPS T13-01:2014 "Review of Failures of Photovoltaic Modules"

[2] Report IEA-PVPS T13-09:2017 "Assessment of Photovoltaic Module Failures in the Field"

Download @ http://www.iea-pvps.org/

Outline

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Quality of PV modules in manufacturing

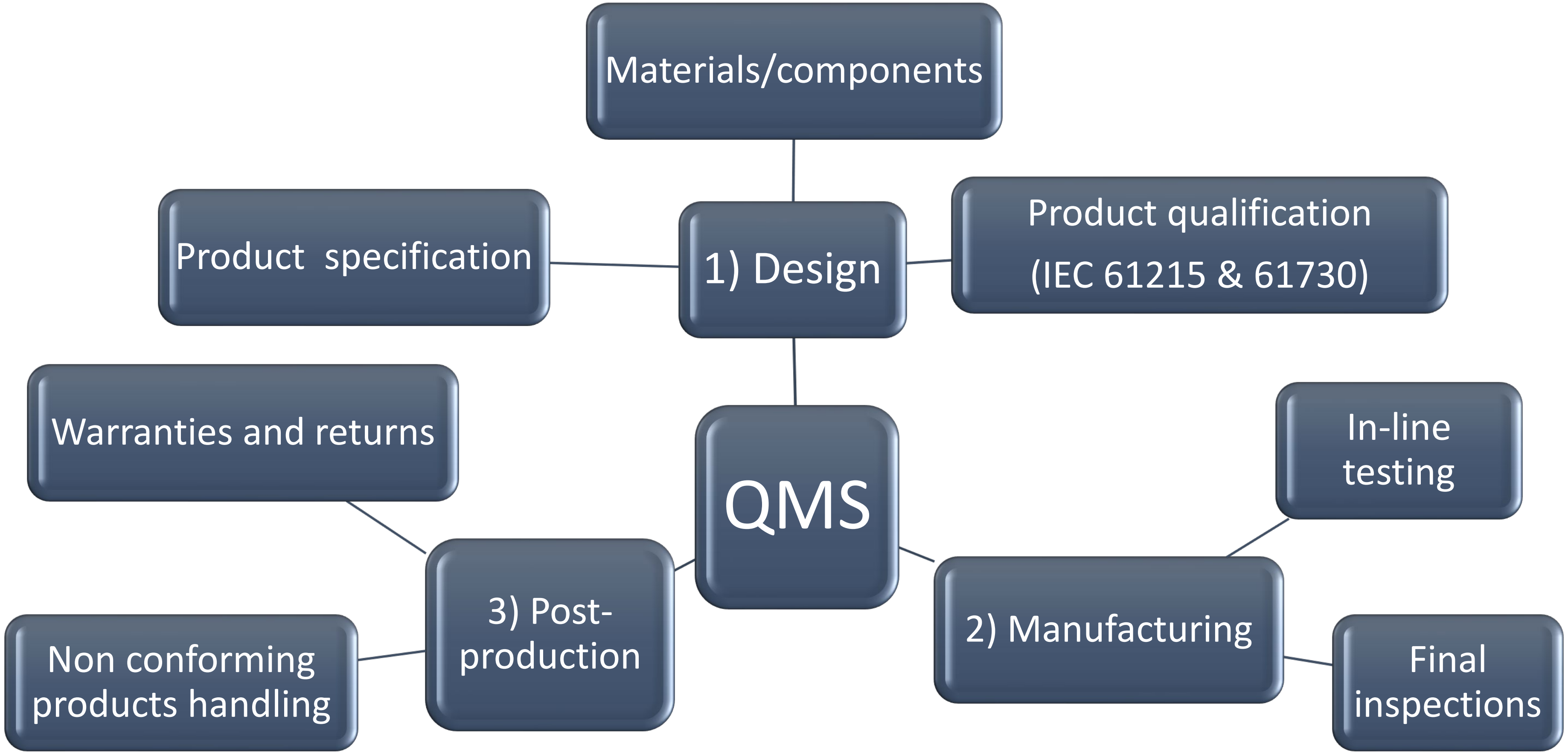
Good materials selections, optimal design and **manufacturing quality** are needed to ensure long-term module performance and reliability .

How do we ensure quality in manufacturing?

→ An effective **Quality Management System (QMS)** is required.

Quality Management System (QMS)

An effective QMS in manufacturing should manage properly:

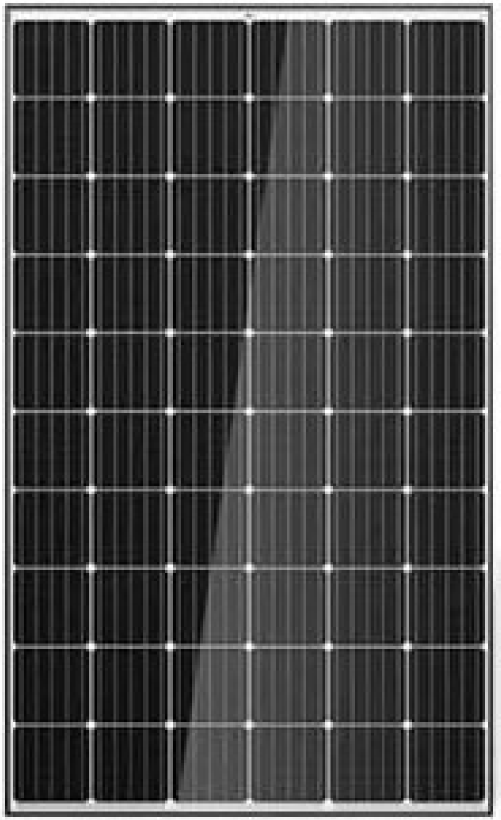


Testing in the production line

Visual Inspection	Electroluminescence
I-V	Electrical stress

Testing in the production line

Visual Inspection



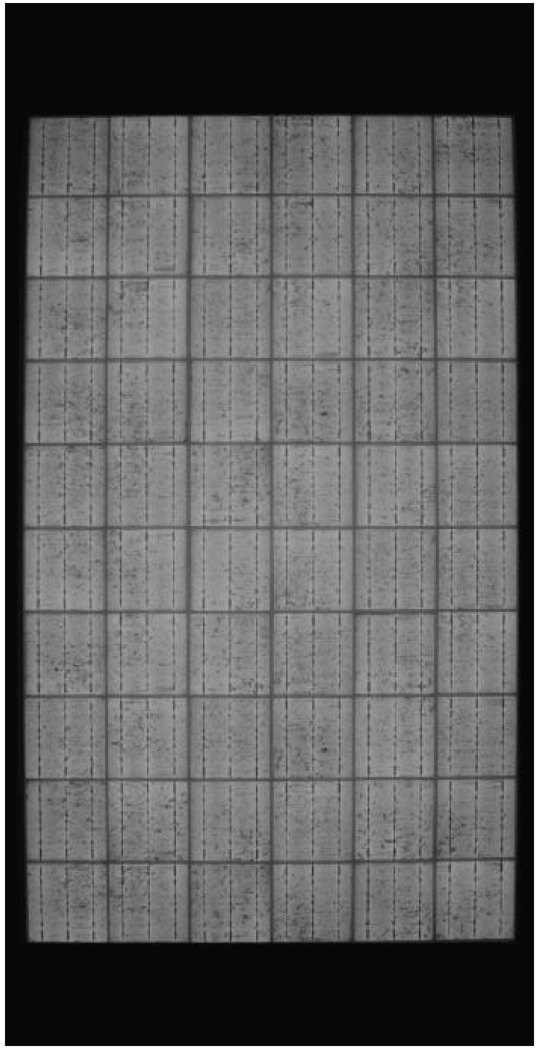
Method:
- Operator → Camera and software
- Good illumination

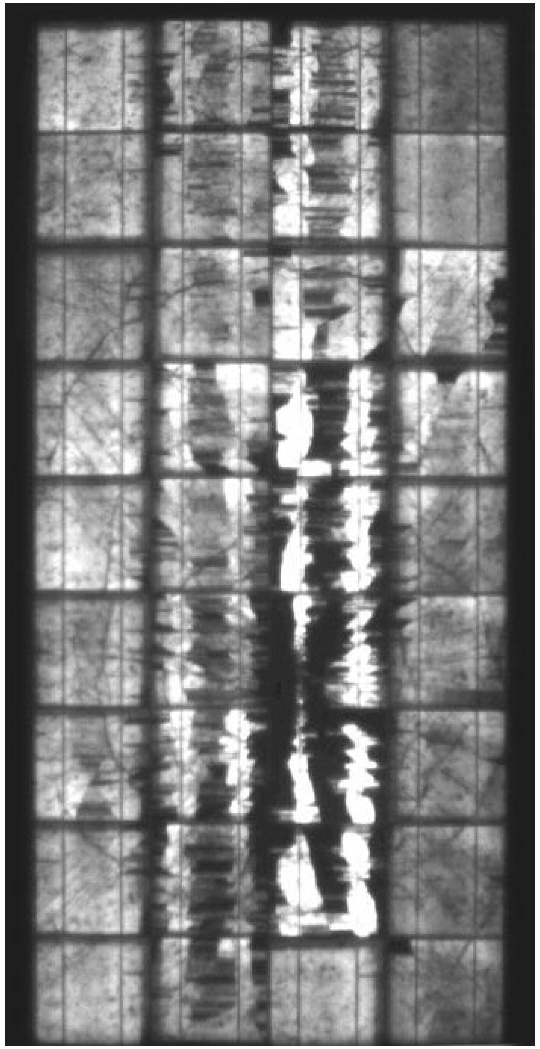
Common defects:
- Bubbles
- Metallic ribbon shift
- Solar cell misalignment
- Dirtiness

Testing in the production line

EL

Pre and post lamination





https://russia.kyocera.com/products/solar_electric_systems/service/test_methods/

Method:

- Current injection
- Darkness
- IR camera (900nm-1100nm)

Results:

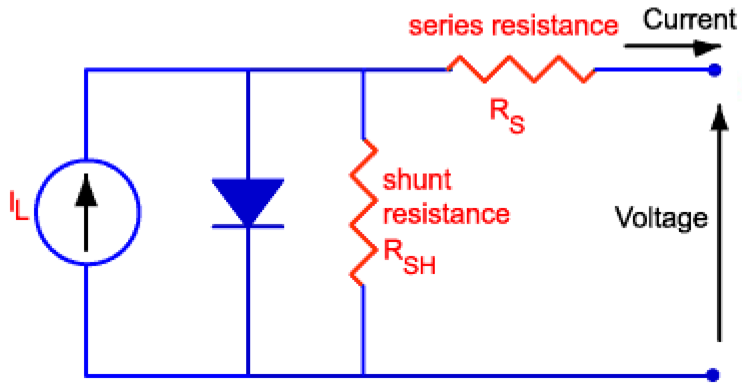
- Bright area: photovoltaic active
- Dark area: defects, shadows

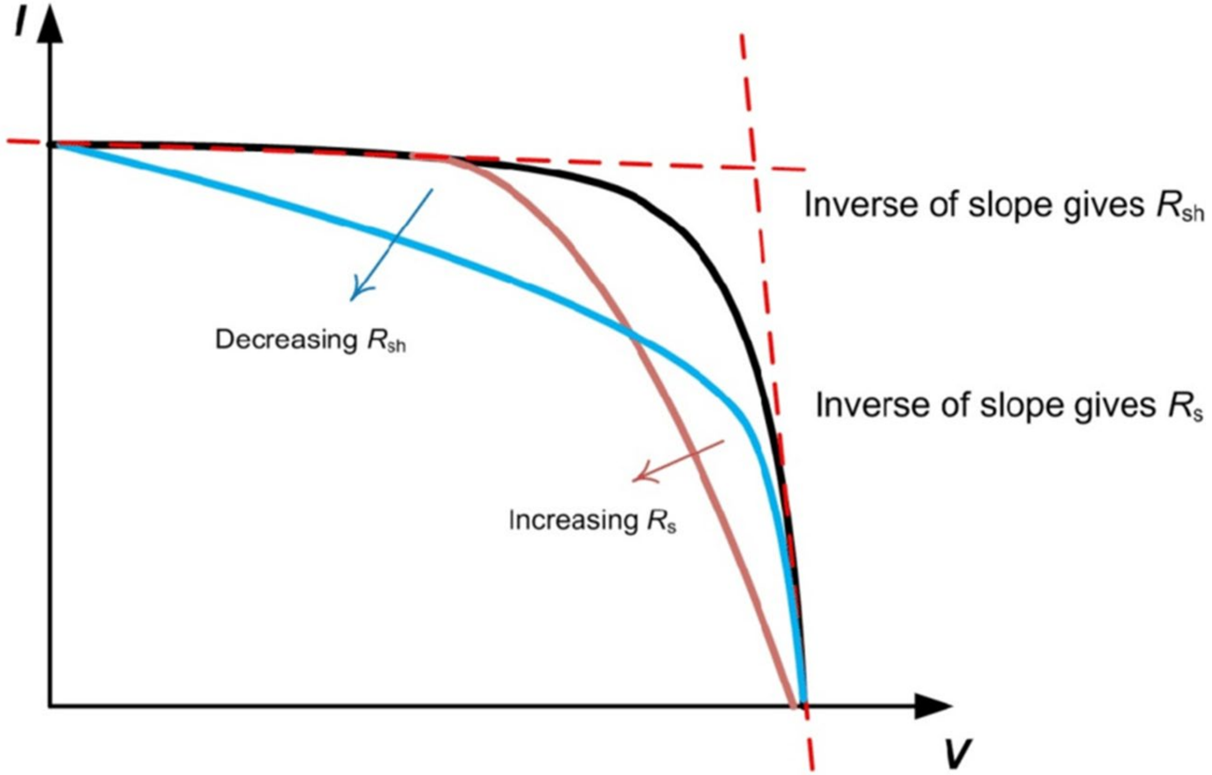
Common defects:

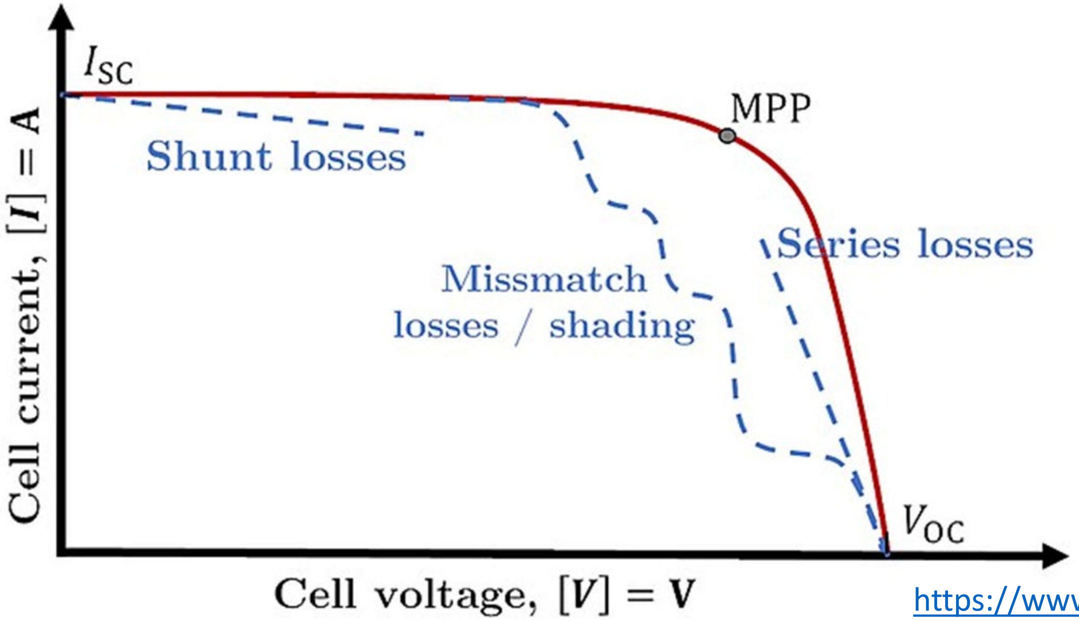
- Cracks
- Solar cell degradation (PID, DH, etc…)

Testing in the production line

IV







Ideal solar cell:

- Series resistance (R_s) $\longrightarrow$ 0
- Shunt resistance (R_{sh}) $\longrightarrow \infty$

https://www.pveducation.org/pvcdrom/solar-cell-operation/series-resistance
https://www.pveducation.org/pvcdrom/solar-cell-operation/shunt-resistance

Testing in the production line

IV

https://www.nmtronics.com/solar/hspv.html

Solar simulator:

- Connect J-box
- 1000 W/m^2
- A few seconds
- Classify modules according to power generation

Testing in the production line

Electrical stress

Source : Dongguan Hong, TU instrument Ltd

HIPOT /WET LEAKAGE TEST → insulation of internal electrical circuit

HIPOT

- Done for every module (dry)

WET LEAKAGE TEST

- Some modules
- Module covered with water
- Max. system voltage x2 applied to cells
- Isolation resistance times module area ≥ 40 MΩ/m2

Factory inspections & audits

PIB – White paper: results of 250+ factory audits (120+ manufacturers)

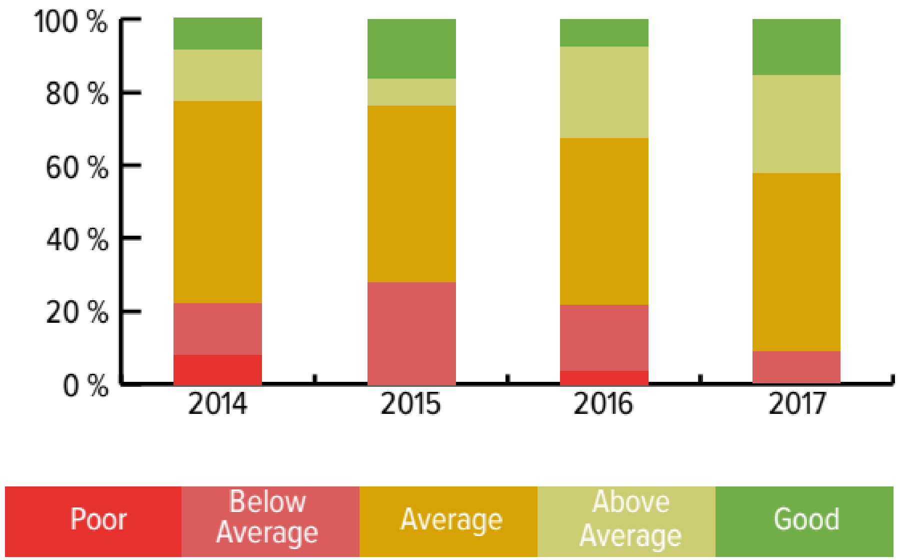


Figure 5: Quality rating trends from 2014 to 2017 normalized over all manufacturers audited each year

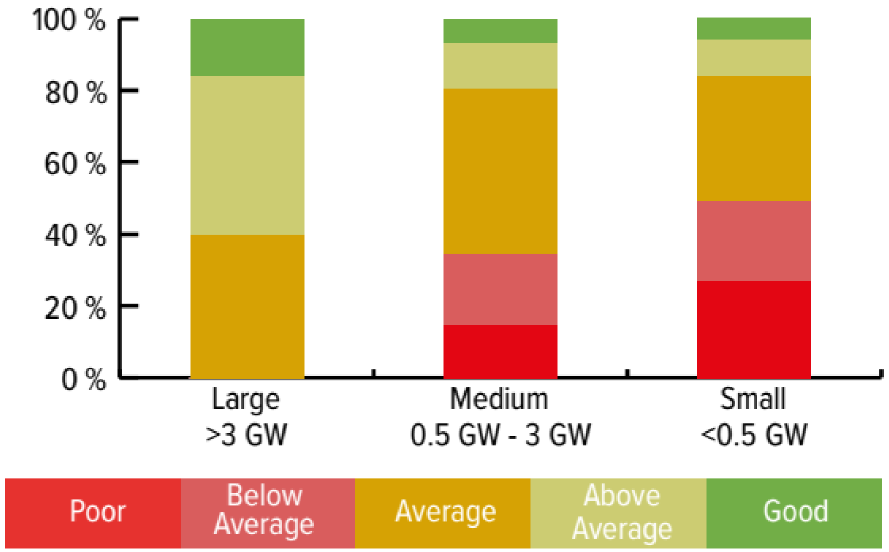


Figure 8: Quality ratings compared to factory size (based on 2017 industry-wide audit results).

PV module quality, in general, has been improving over the past years.

Larger capacity can be leveraged to obtain better products at a lower cost and ensure more consistent manufacturing quality with higher levels of automation.

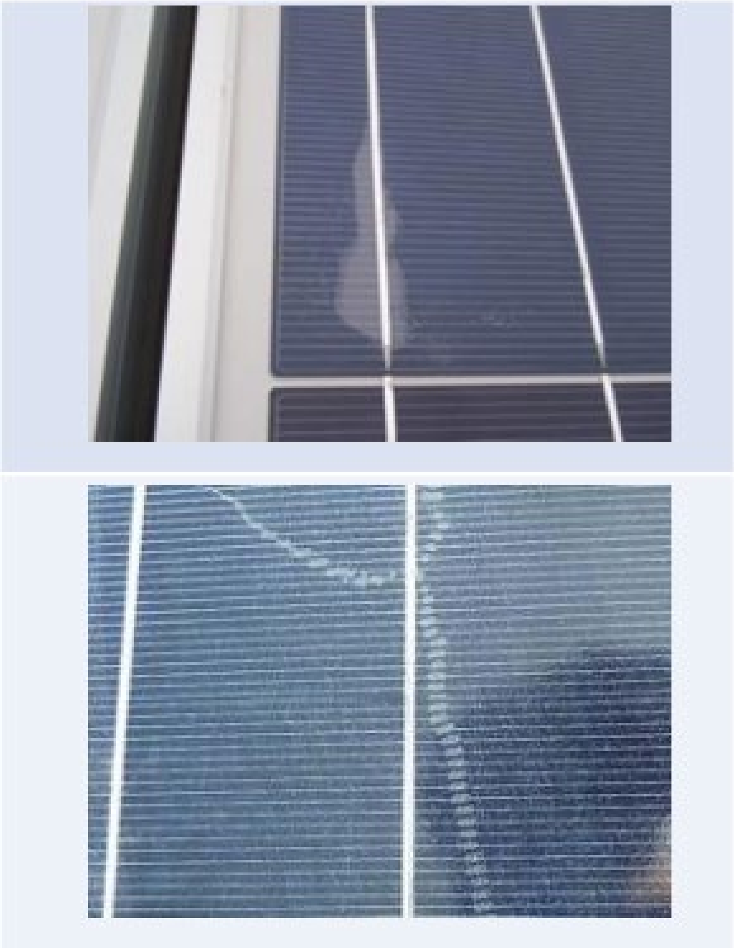
Detection methods in the field

Typical inspection methods for failure analysis and quality assurance

- Visual inspection (VI)
- Array I-V curve measurement
- **Infrared (IR) analysis**
- Electroluminescence (EL) analysis

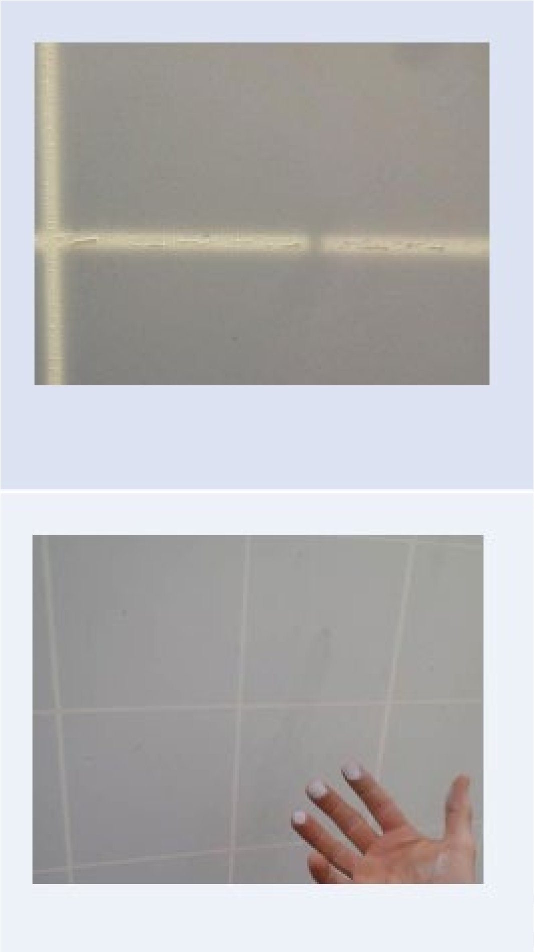
Detection methods in the field: Visual inspection

Delamination effects



Discolouration effects

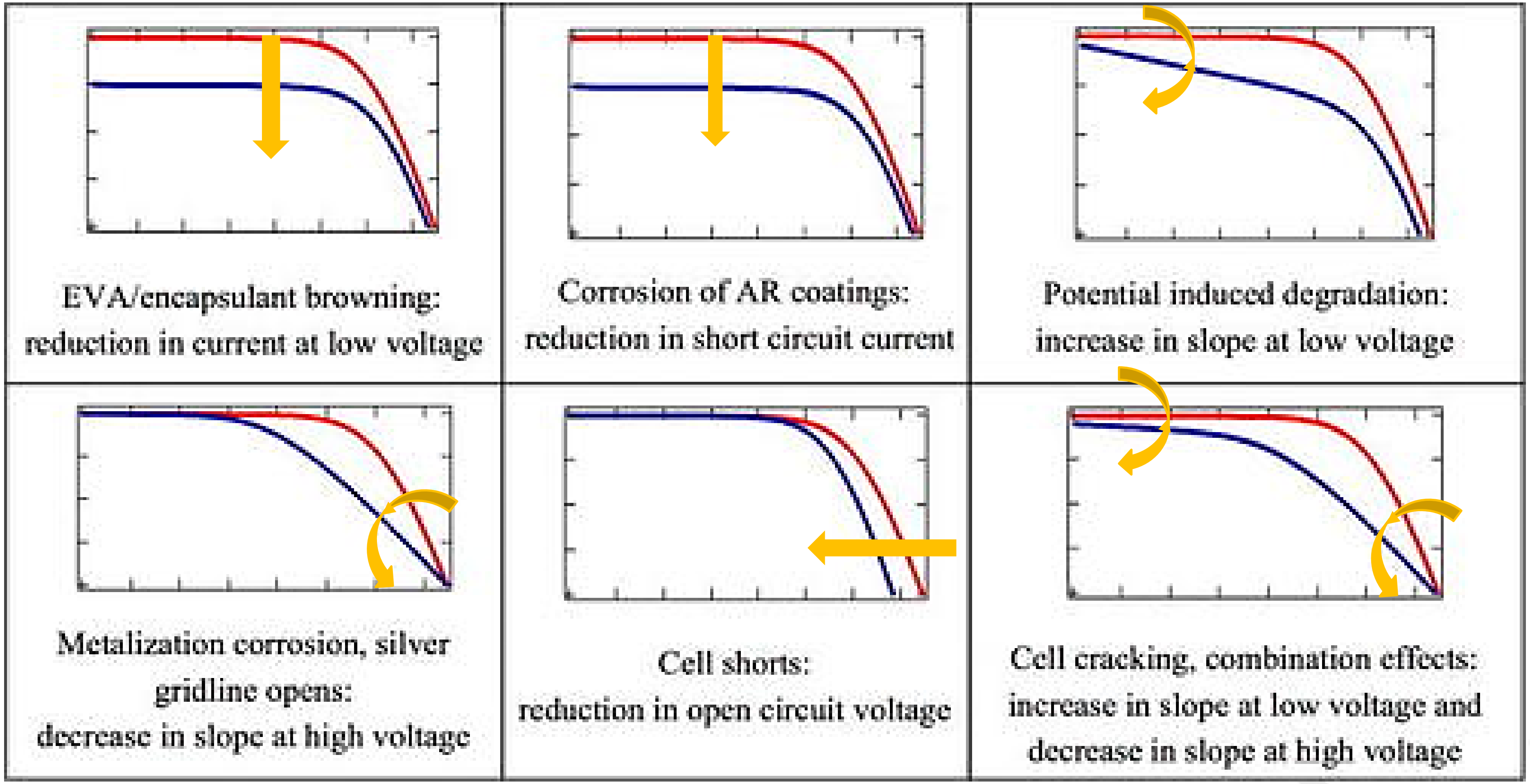
Backsheet failure



Ulrike Jahn, Failure Detection in the Field, 2019

Detection methods in the field: IV

- **Electrical** performance

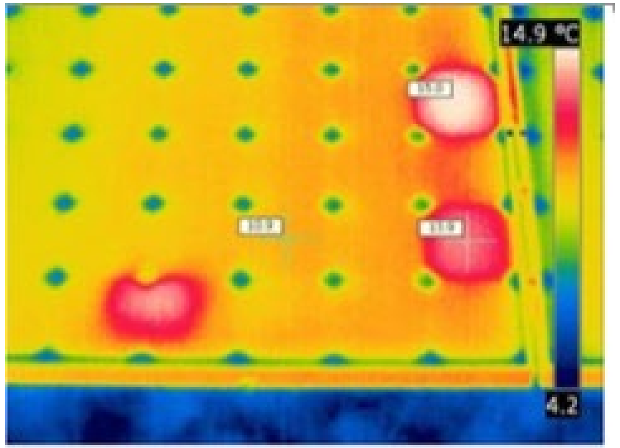


Insights into metastability of photovoltaic materials at the mesoscale through massive *I–V* analytics, 2016.

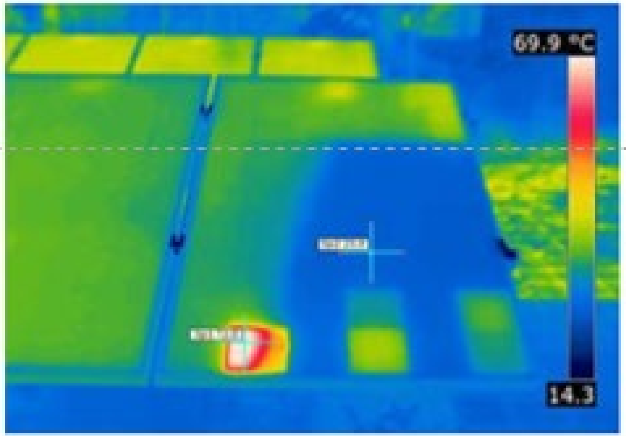
Detection methods in the field: IR

- Localization of array interconnection failures
- Localization of **failures causing heat generation**

Electrical mismatch of cells



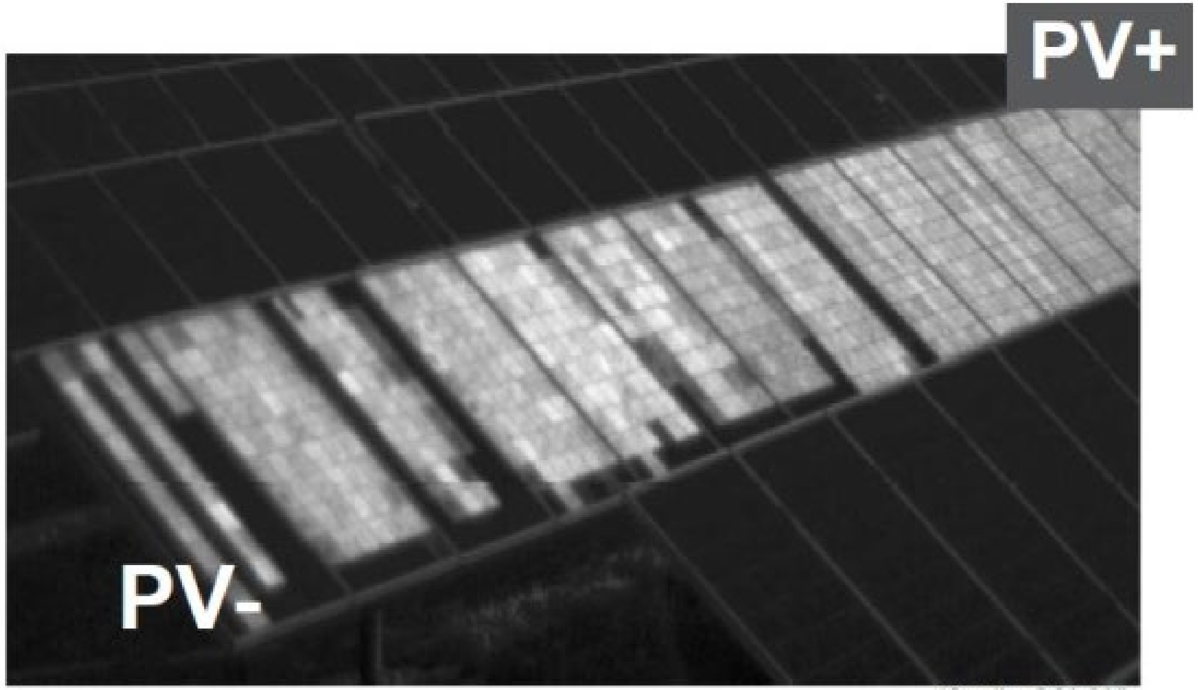
Cell cracks/burn marks



Active bypass diode

Detection methods in the field: EL

- Localization of **cracked cells** and **interconnects**
- Potential induced degradation



(Quelle: SOLON)

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Accelerated-aging (or qualification) testing

We cannot wait 35+ years for a product feedback !

→ The industry makes use of **accelerated-aging testing**.

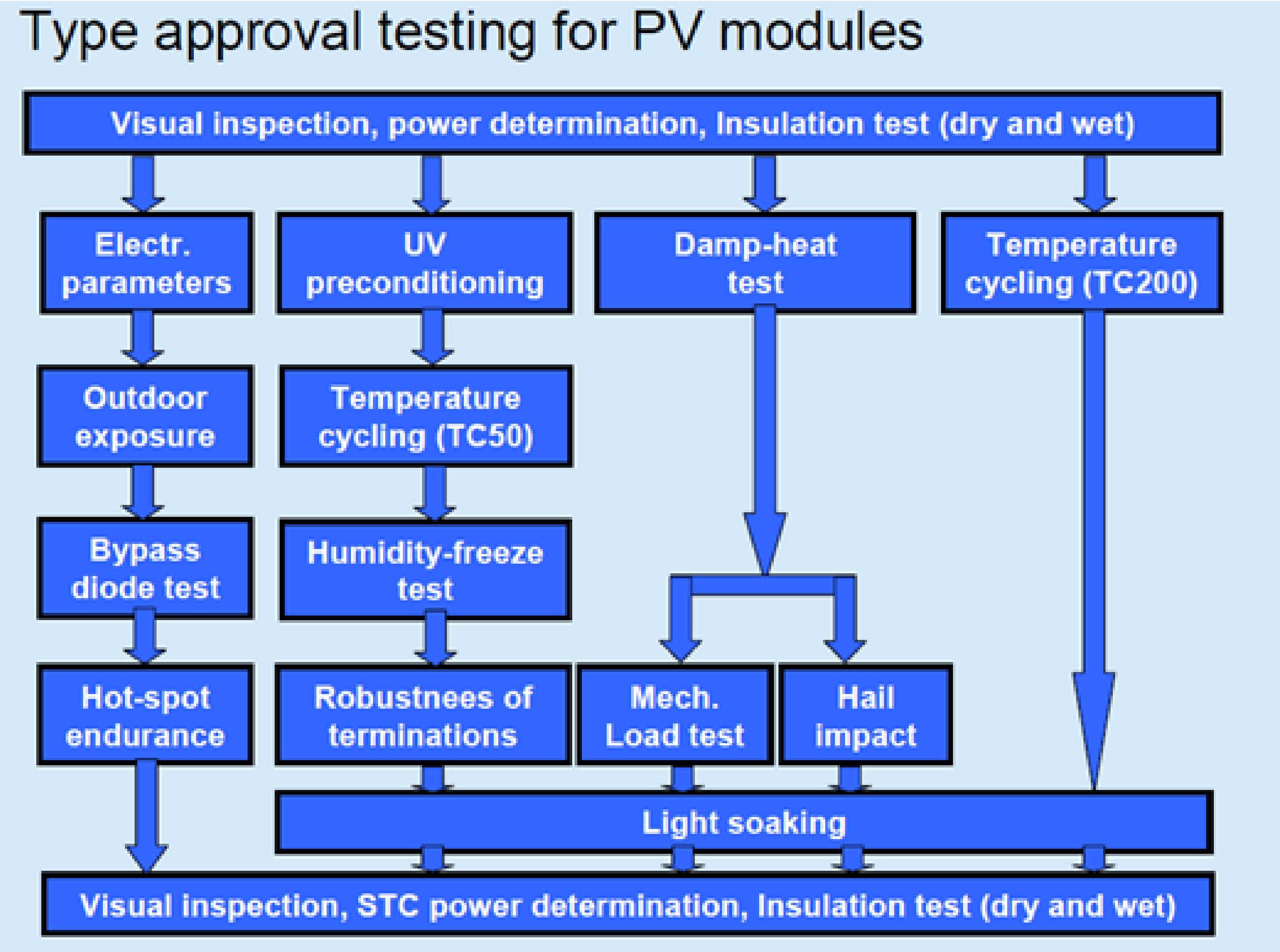
Industry standards to qualify PV modules:

- **IEC 61215** (performance)
- **IEC 61730** (safety standards)

IEC 61215/61730
→ Increased product quality

But…

Old/simplified testing sequence →



Limits of existing qualification standards

Main limits in IEC 61215/61730 are:

- Evidence that products qualified according to this standard fail later in the field exist
  E.g. modules made with Polyamide backsheets
  →minimum level of quality is **not a guarantee for durability** !

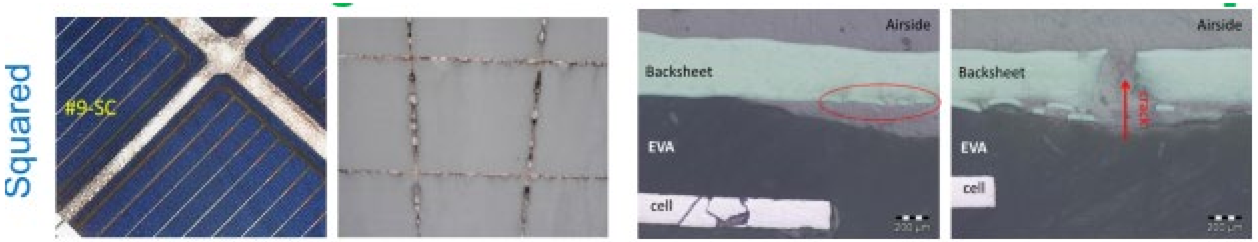
Virtuani & Agostinelli, EUPVSEC Brussels 2018

- It is **not a lifetime standard** (no info about lifetime)

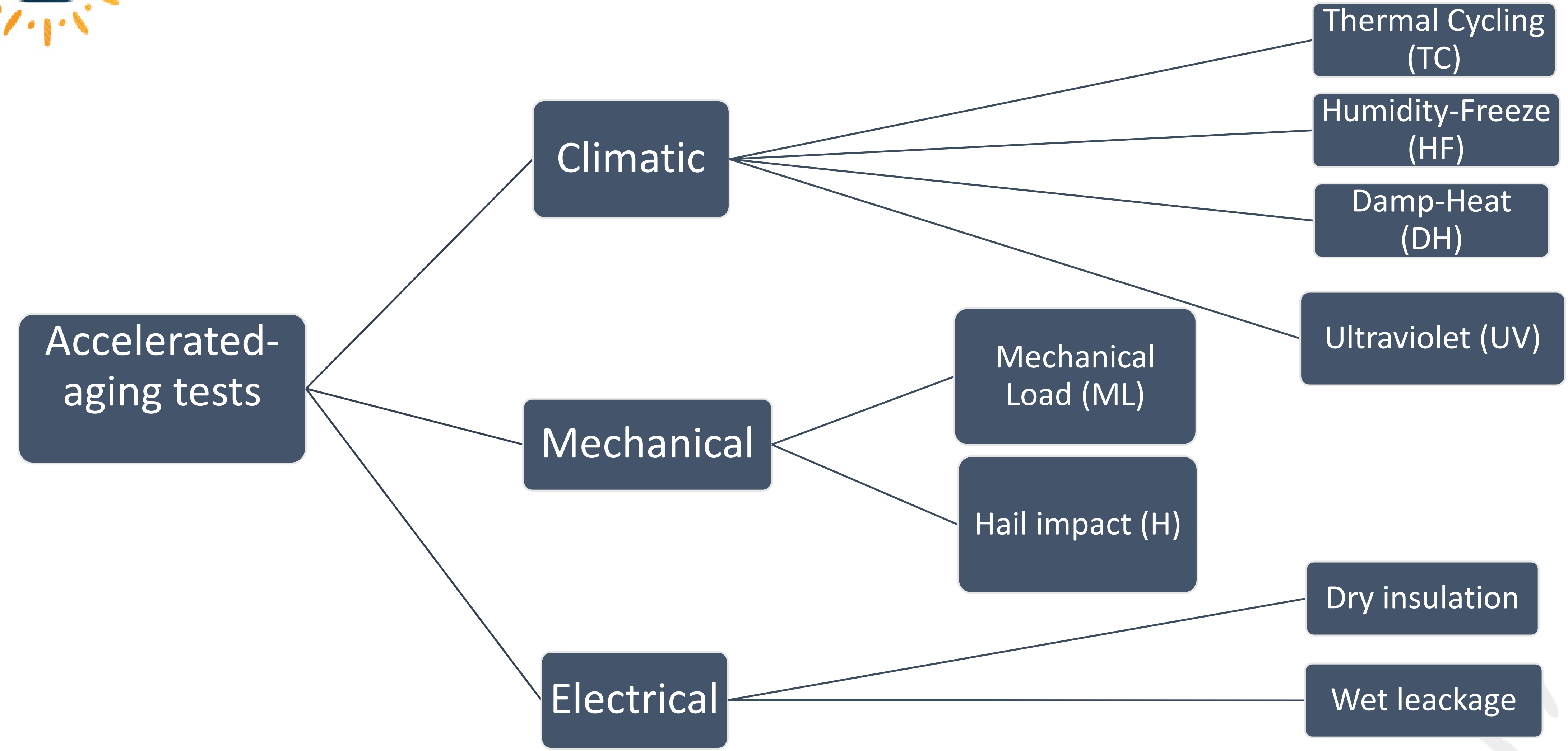
- It is **explicitly refering to temperate climates**:
  → What about more challenging climates?

- Cracking of PA backsheets after 5-8 years in operation
- No cracking during accelerating indoor testing

[7] G. Eder, Y. Voronko, G. Oreski, W. Mühleisen, M. Knausz, A. Omazic, A. Rainer, C. Hirschl, H. Sonnleitner (2019) „Error analysis of aged modules with cracked polyamide backsheets", Solar Energy Materials and Solar Cells 203, https://doi.org/10.1016/j.solmat.2019.110194



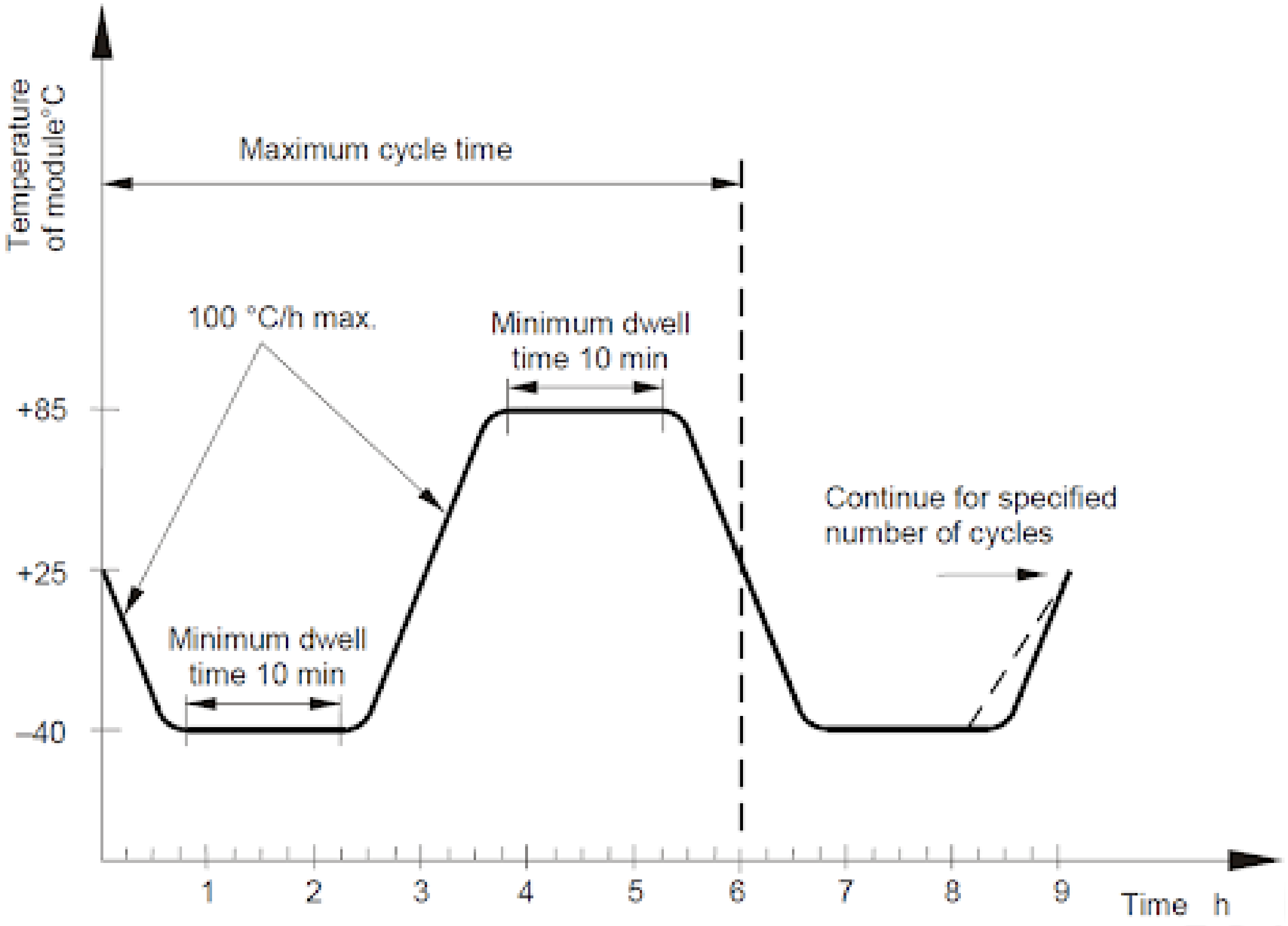
Accelerated-aging (or qualification) testing



Climatic: Thermal cycling

Test conditions
- 50/200 cycles
- -40°C to 85°C

Failure modes
- Broken interconnect
- Broken cell
- Solder bond failures
- Junction box adhesion
- Module connection open circuits
- Open circuits leading to arcing



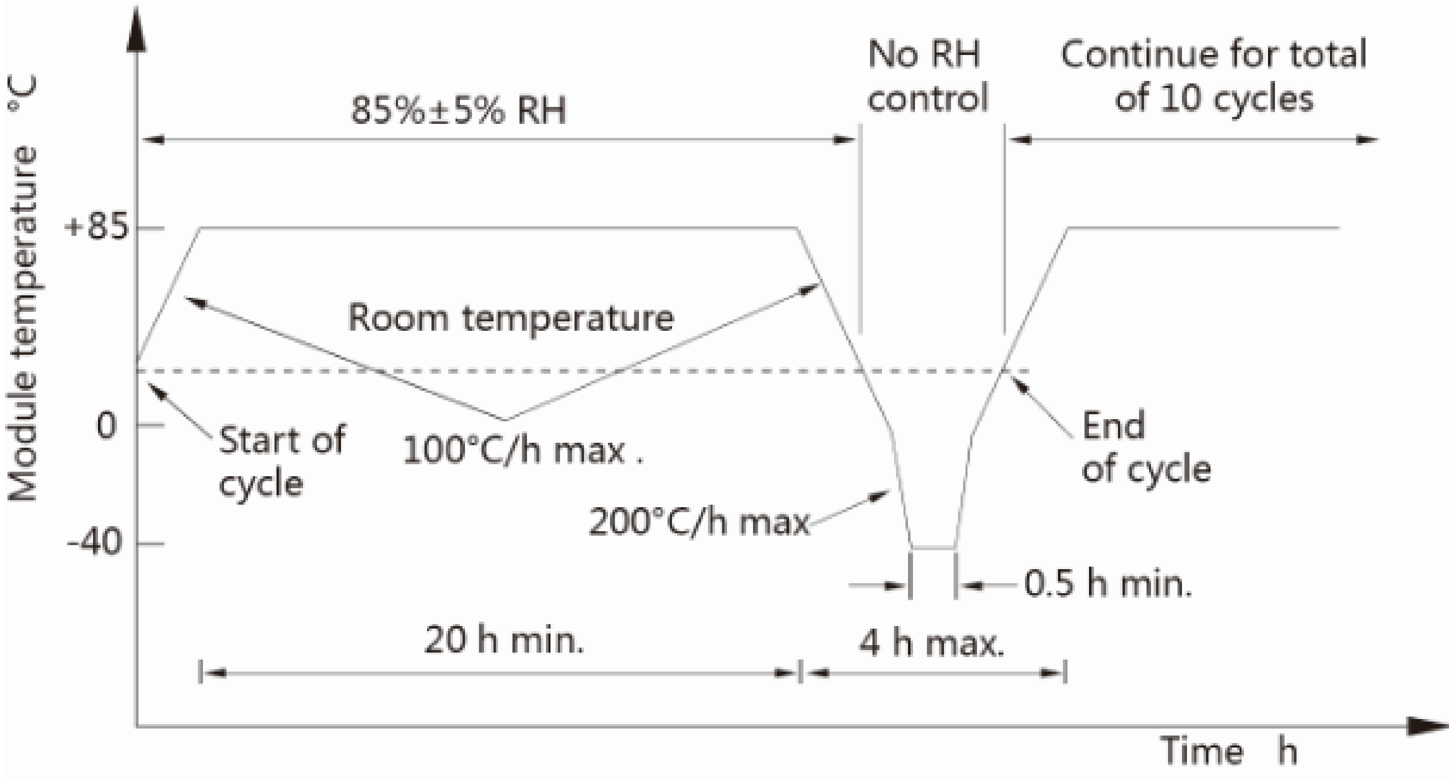
Climatic: Humidity freeze

Test conditions

- 10 cycles
- -40°C to 85°C

Failure modes

- Delamination of encapsulant
- Junction box adhesion



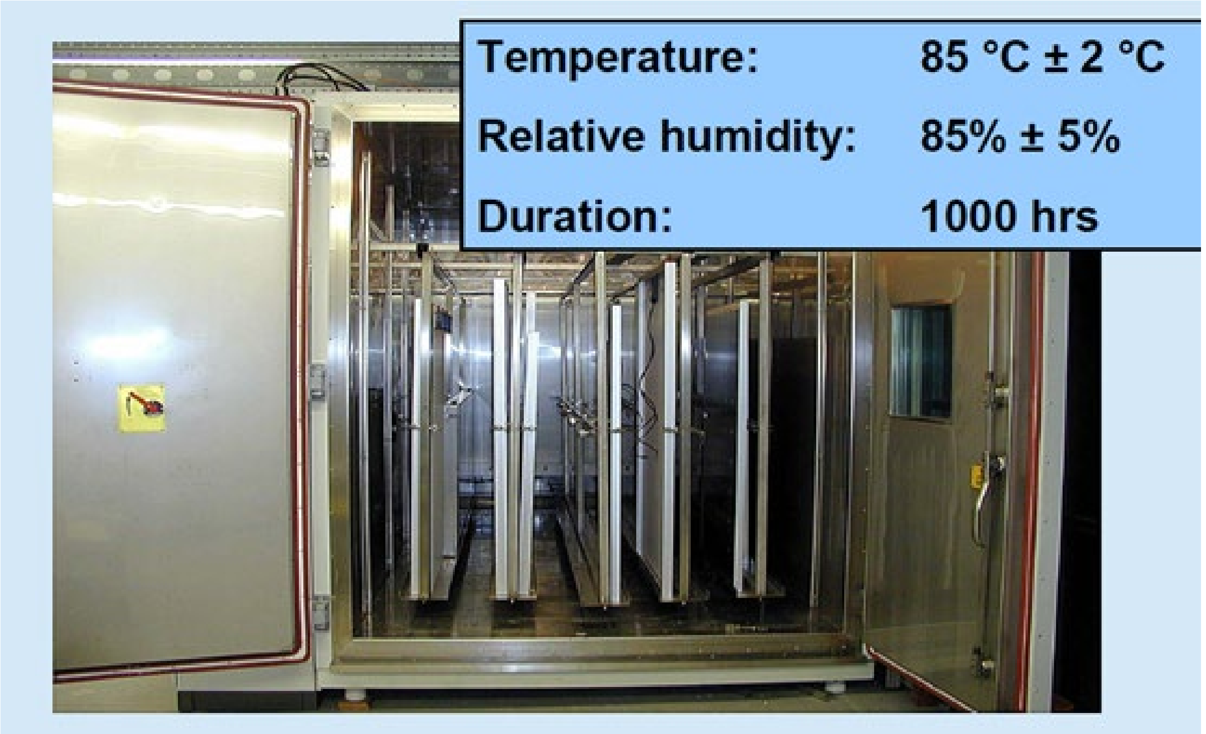
Climatic: Damp Heat

Test conditions

- 1000h
- 85%RH, 85°C

Failure modes

- Corrosion
- Delamination of encapsulant
- Encapsulant loss of adhesion and elasticity
- Junction box adhesion



Climatic: UV

Test conditions
- 15 kWh/m2 (61215)
- 2x60 kWh/m2 (61730)

Failure modes
- Delamination of encapsulant
- Encapsulant loss of adhesion and elasticity
- Encapsulant discoloration
- Ground fault due to backsheet degradation

Mechanical: Load

Test conditions
- 3 cycles
- +/- 2.4 MPa

Failure modes
- Glass and cell brakeage
- Loss of electrical continuity
- Solder joint failures
- Frame deformation

Mechanical: Hail test

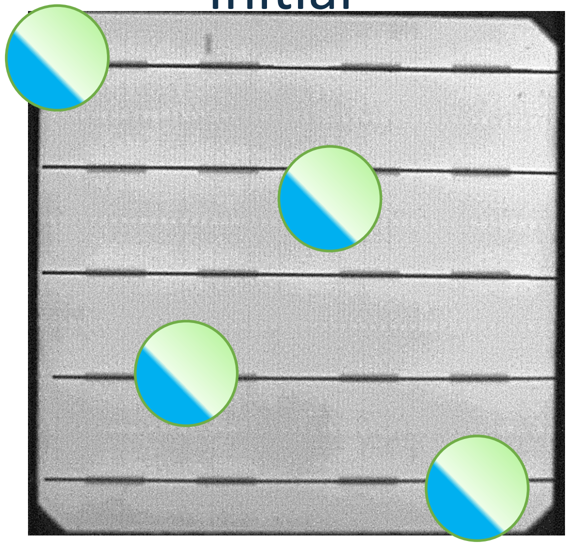
Test conditions

- Hail-stone:(∅: ≥25 mm)
- Velocity: ≥23 m/s;

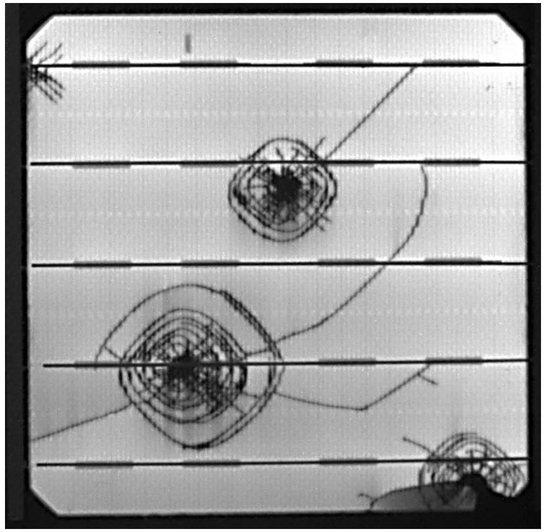
Failure modes

- Glass and cell breakage

Initial



After hail test



Electrical: dry and wet

Already mentioned

Source : Dongguan Hong, TU instrument Ltd

HIPOT /WET LEAKAGE TEST → insulation of internal electrical circuit

HIPOT

- Done for every module (dry)

WET LEAKAGE TEST

- Some modules
- Module covered with water
- Max. system voltage x2 applied to cells
- Isolation resistance times module area ≥ 40 MΩ/m2

Extended testing (1)

Module manufacturers compliment the basic IEC 61215/61730 qualification testing with **additional testing sequences.** E.g.

IEC 61215/61730

+

- IEC 61701 [30] for salt-mist corrosion testing (maritime environment)
- IEC 62716 [31] for ammonia-corrosion testing (rural or farm environment)
- IEC 60068 -2-68 (sand abrasion: Dust and sand →desert)
- Newly designed standards (TS)
- IEC TS 62782:2016 - dynamic mechanical load
- IEC TS 63126:2020 - operation at high temperatures

Extended durability testing (based on IEC) have been designed and proposed by several research groups and certification bodies.

Extended testing (2)

Extended durability testing include:

a. Increasing **stress levels** and **duration** (time periods and number of cycles);
   E.g. Thermal Cycling (200 → 400 → 800 cycles) or Damp Heat (1000 → 3000 hours)

b. Multiple combined stress factors (e.g. humidity and UV or humidity and high applied voltage)

Two major **problems with the "do it yourself" approach** to product qualification:

(1) it may require module manufacturers to do **more testing than is necessary**.
(2) it may force module manufacturers to make **costly but unnecessary changes** to their products to pass tests that do not predict module performance.

As of today, **no consensus** on the effectiveness of such extended testing sequences exist.

Outline

Track-record of PV system/module lifetimes

EPFL

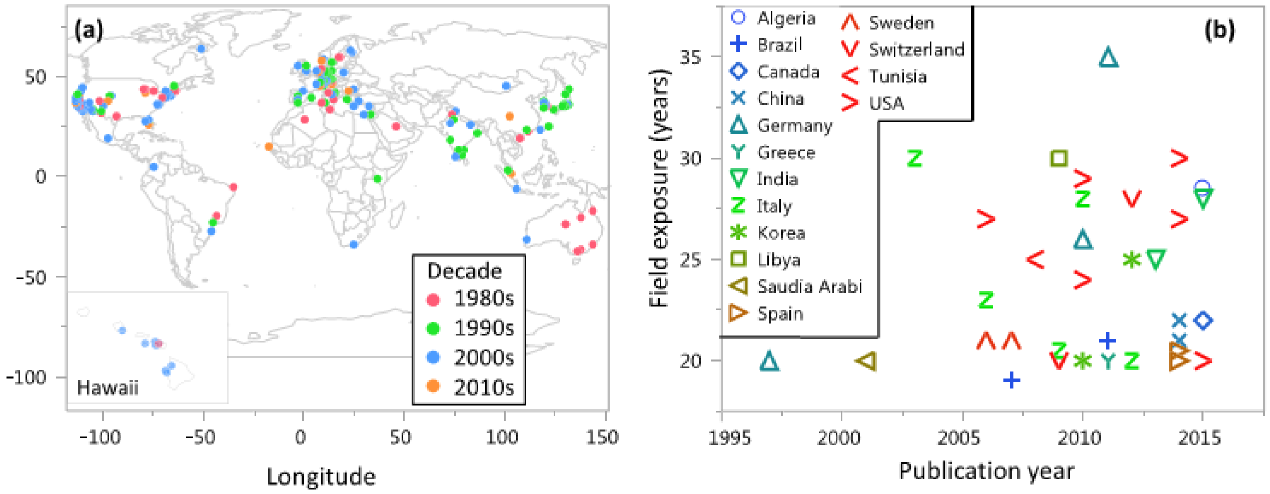


Figure 1. Worldwide reported degradation rates colored by the decade of installation (a) and system reports exceeding 20 years by publication year (b).

D. Jordan et al., 2016 *cited*

35 years of PV
The Tiso-10-kW Solar Plant: Lessons Learned In Safety And Performance

Alessandro Virtuani[1], Eleonora Annigoni[1] & Christophe Ballif[1]
Mauro Caccivio[2], Gabi Friesen[2] & Domenico Chianese[2]
Tony Sample[3]

École Polytechnique Fédérale de Lausanne (EPFL), Neuchatel, Switzerland
SUPSI, Lugano, switzerland
Joint Research Centre (JRC), Ispra, Italy
c

35th EU PVSEC 2018
35th European Photovoltaic Solar Energy Conference and Exhibition

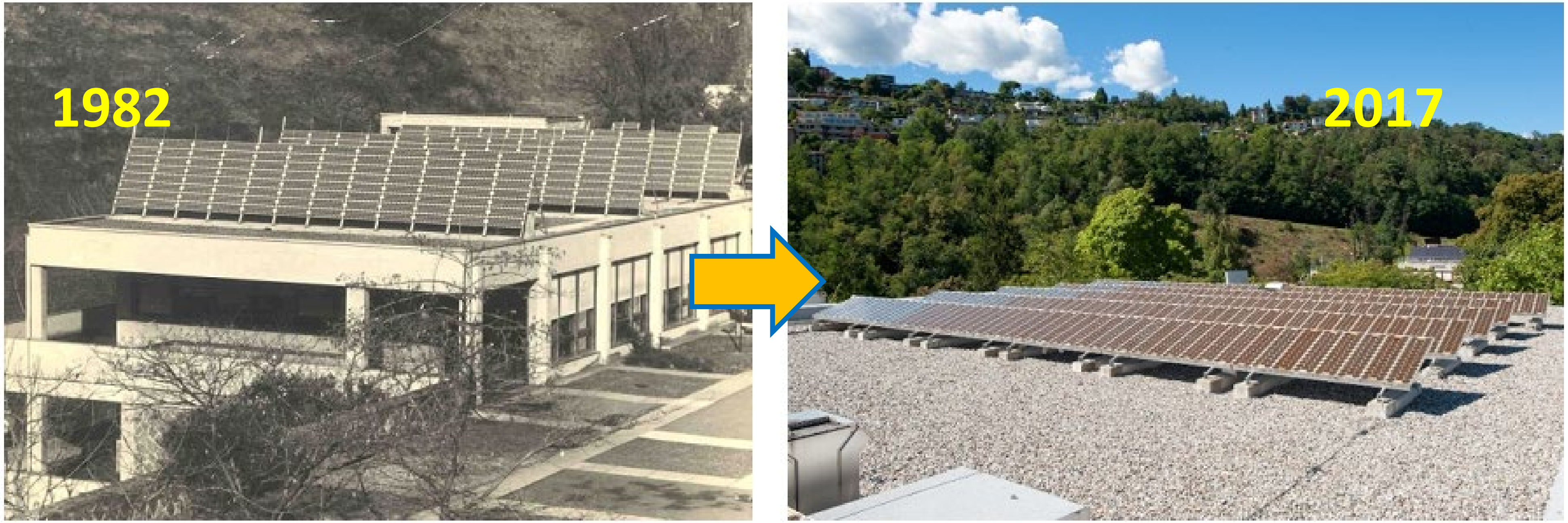
35 years of PV: the TISO-10-kW plant 1/3

RESEARCH ARTICLE

WILEY PROGRESS IN PHOTOVOLTAICS

35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—Part 1

Alessandro Virtuani[1] | Mauro Caccivio[2] | Eleonora Annigoni[1] | Gabi Friesen[2] | Domenico Chianese[2] | Christophe Ballif[1] | Tony Sample[3]



70% of modules experience a degradation of ≤ 20% and would still be covered by a 35-yrs-long warranty set at 80% of initial power.

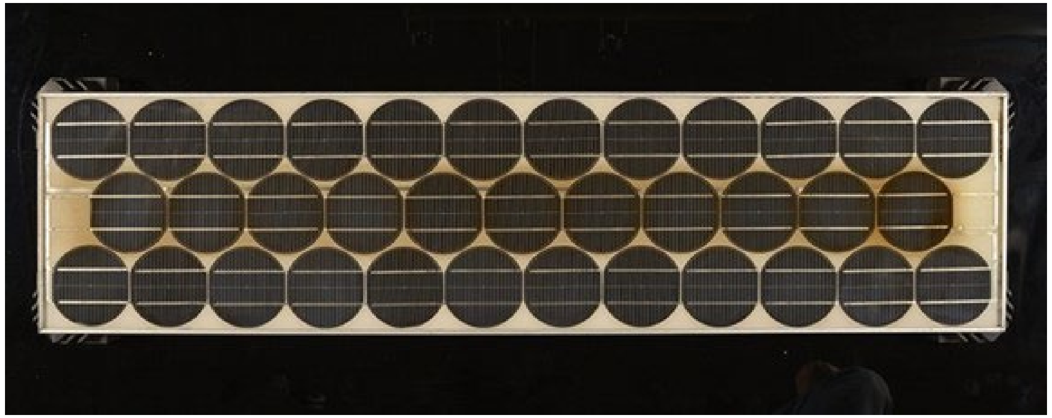
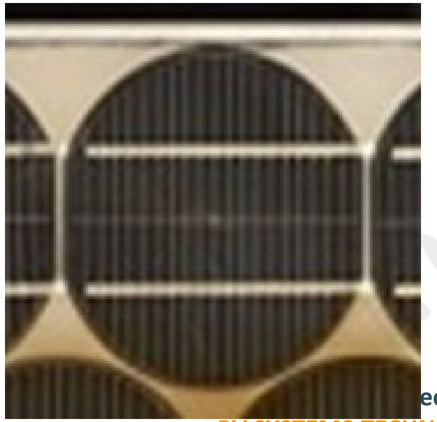
35 years of PV: the TISO-10-kW plant 2/3

The **TISO (Ticino Solare) PV plant**: first grid-connected plant of Europe (May 1982);

- Installed in Lugano (46°N, 8°57'E), **temperate climate**:
  insol. 1243 kWh/m²/y, min/max air T 1.1-20.8 °C, min/max RH 57-80 °C (avg)
- The history of the plant (**35+ years**) is very well documented

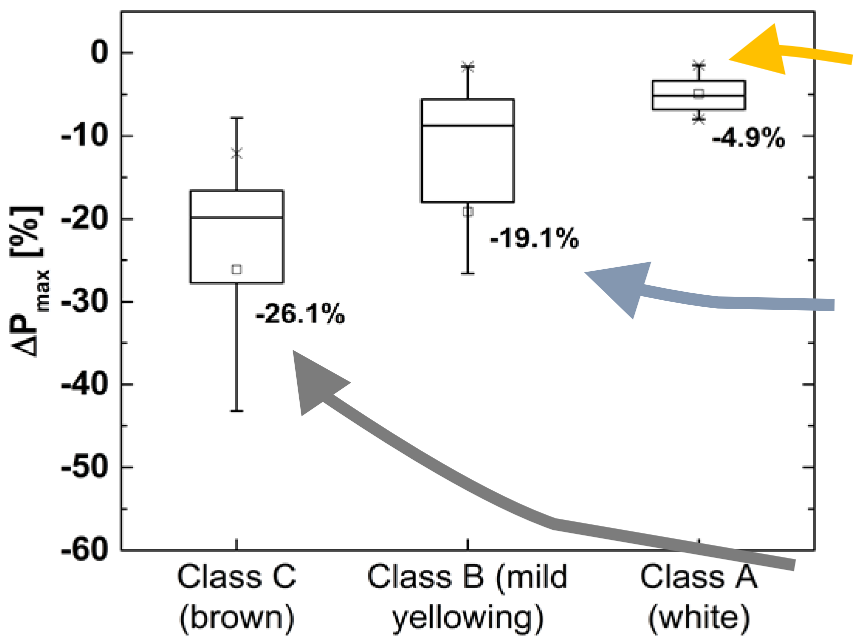
Modules (35 cells) manufactured in **1981**: ARCO-Solar ASI 2600

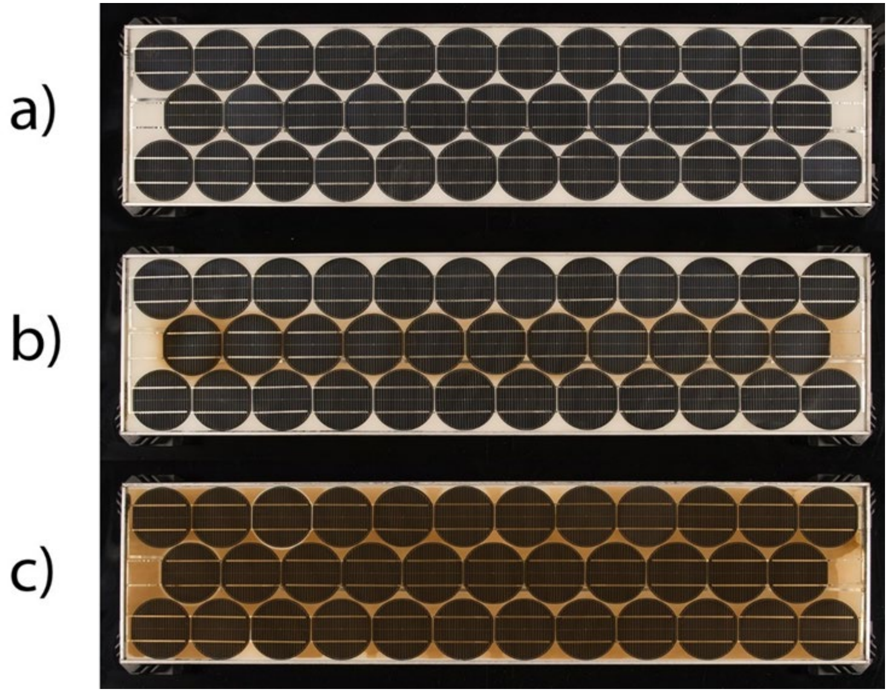
- **Cells**: c-Si (mono), 4'' wafers, thickness 320-330 μm, 2 ribbons
- **Encapsulant**: PVB (we exclude presence of EVA, even if manufacturing soon swithched to EVA)
- Module **sealing** is **quite solid**:
  3-mm glass, backsheet: Tedlar/steel/Tedlar, edge seal, J-box closed on all sides

35 years of PV: the TISO-10-kW plant 3/3

Discoloration of encapsulant: yellowing & browning





Power variation (2017 vs 1982) for modules belonging to the three different classes based on different encapsulant discoloration levels.

Long-term performance of modules strongly depends on the quality of the encapsulants!

More details?

RESEARCH ARTICLE

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35 years of photovoltaics: Analysis of the TISO-10-kW solar plant, lessons learnt in safety and performance—Part 1

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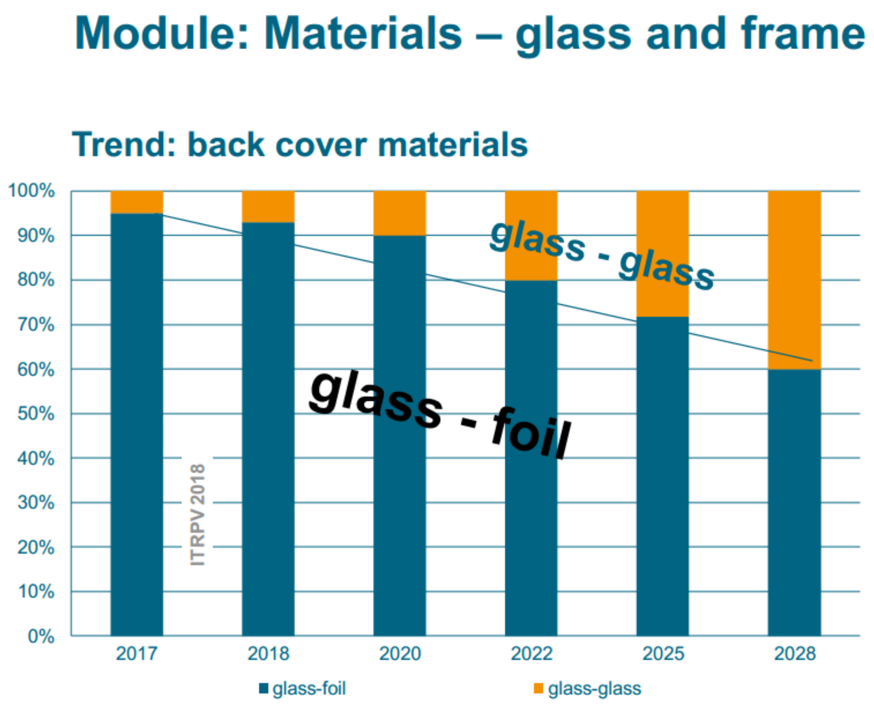
Part 1: Prog Photovolt Res Appl. 2019;27:328–339

Part 2: Prog Photovolt Res Appl. 2019;27:760–778

What can we learn from a 35 yrs-old technology ?



ITRPV Report 2018

- **Packaging** structure of Arco Solar modules is quite solid
  (glass + PVF/steel/PVF BS + edge seal >>> no EVA).

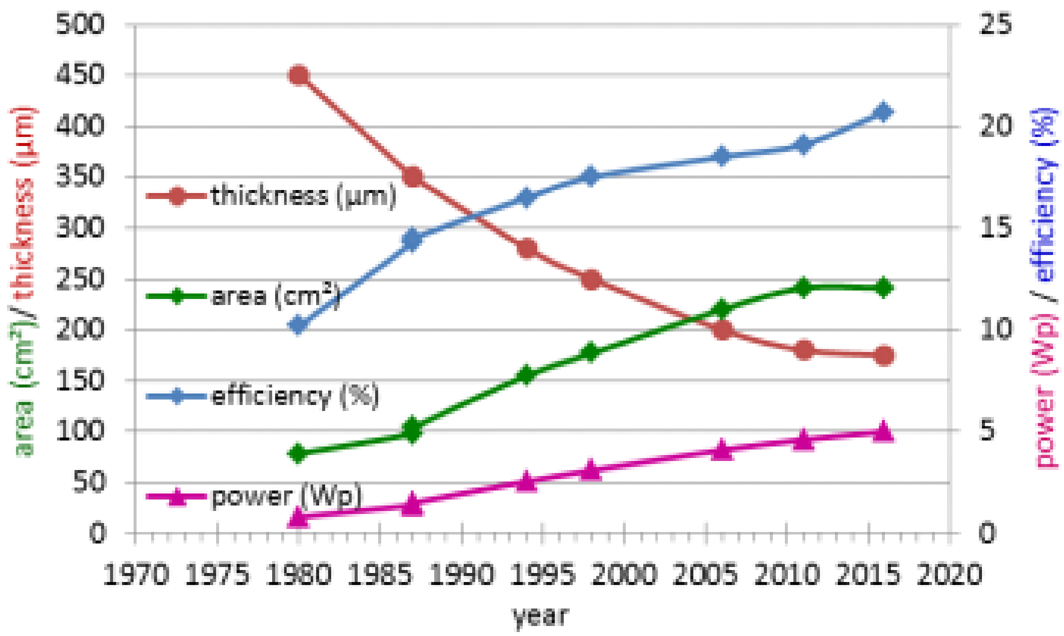
- **Closer to glass/glass** rather than to conventional glass/foil structures, used in the vast majority of modules deployed so far.

What do we learn from a 35-years-old technology?

The *great leap forward*……..

Dramatic evolution in technologies in the last 35+ years

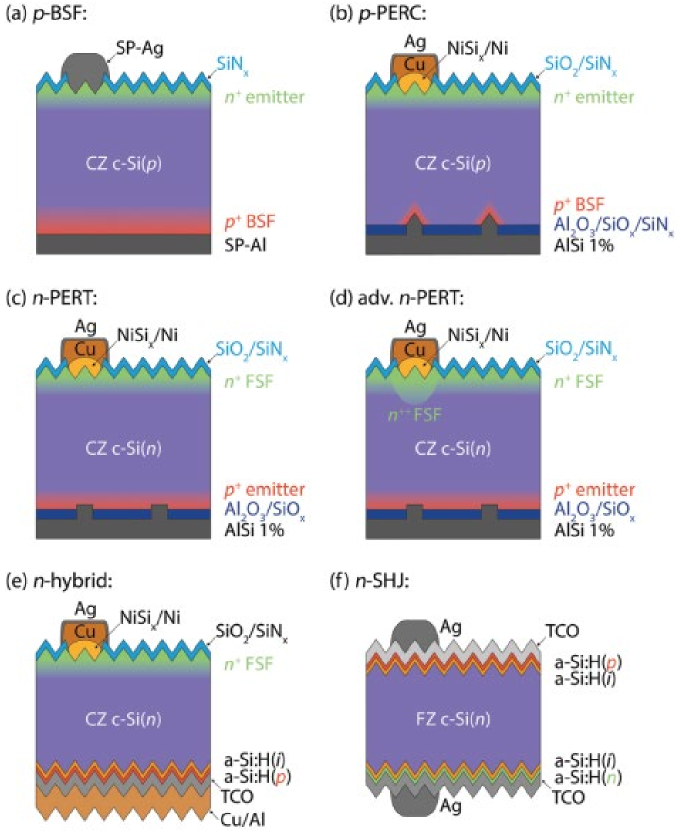
- Cell size, power, thickness



E. Cunow,
33rd EUPVSEC 2017

- Cell technologies

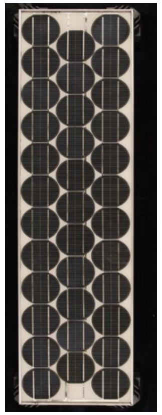
J. Hascke et al.
En. Env. Sci. 2017



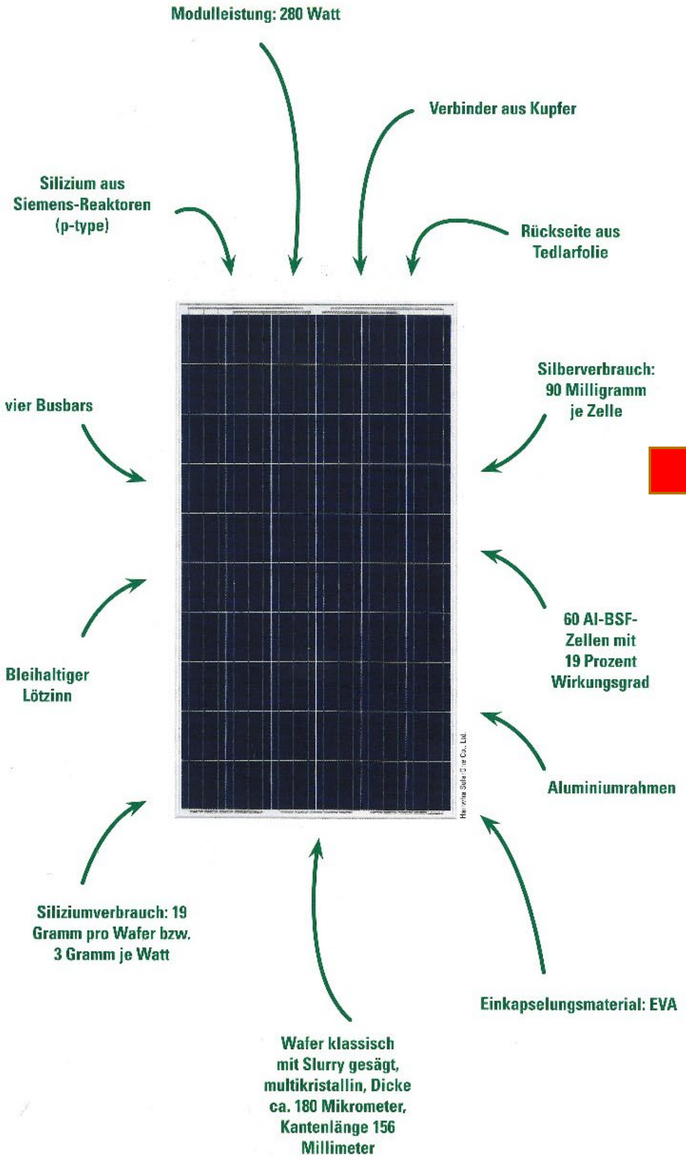
- Modules: busbar/ribbon number, size, materials, structures
- Systems: trasformerless inverters (no grounding required), higher system voltages (1500+ V), …

Technology evolution: c-Si modules

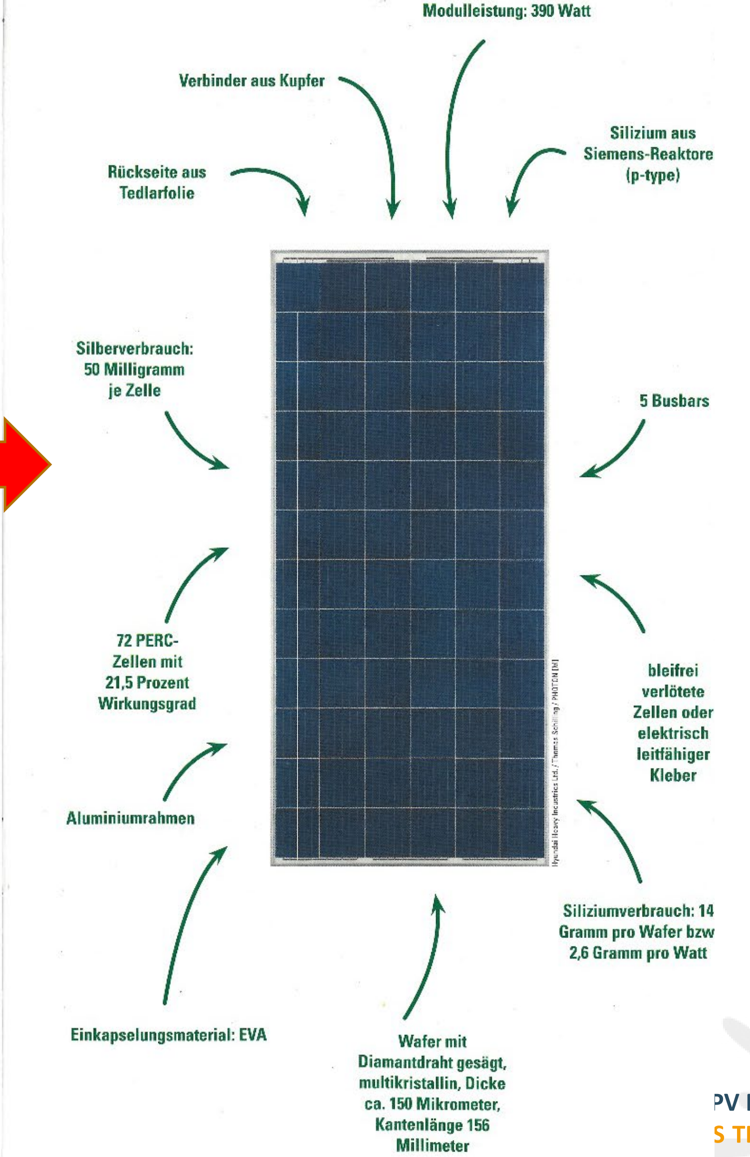
1982



2018

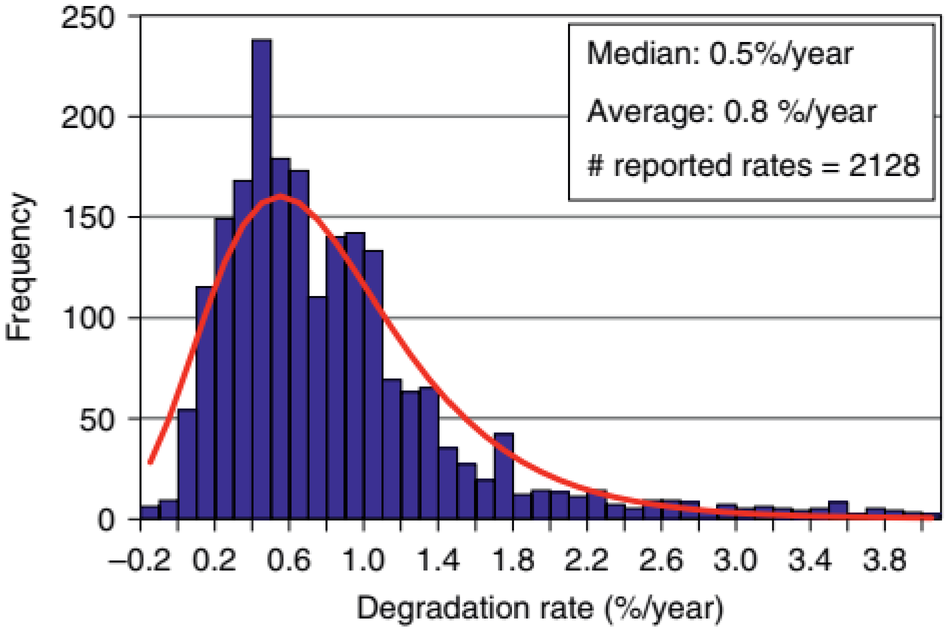


2028

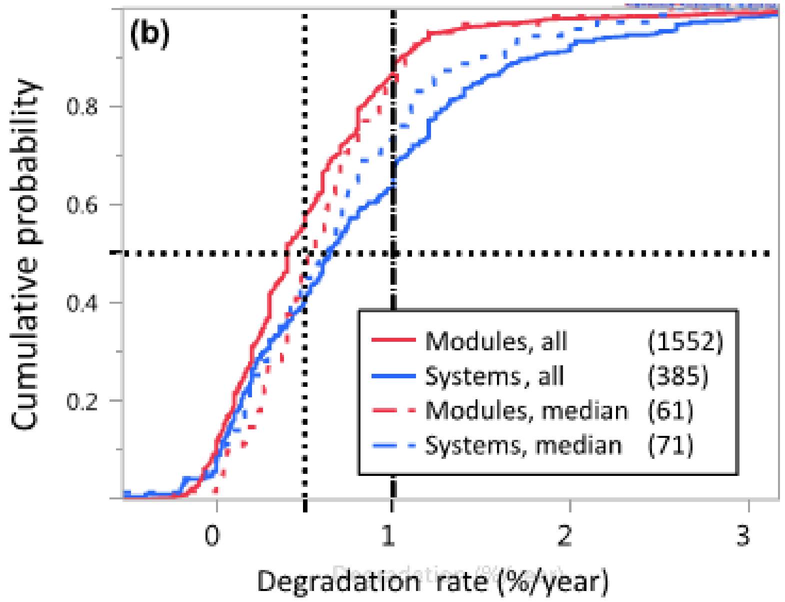


Photon 6/2018
& ITRPV Report 2017

Degradation rates for c-Si (crystalline silicon) modules



D. Jordan, S. Kurtz, Prog.Photov. 2013; 21: 12-29



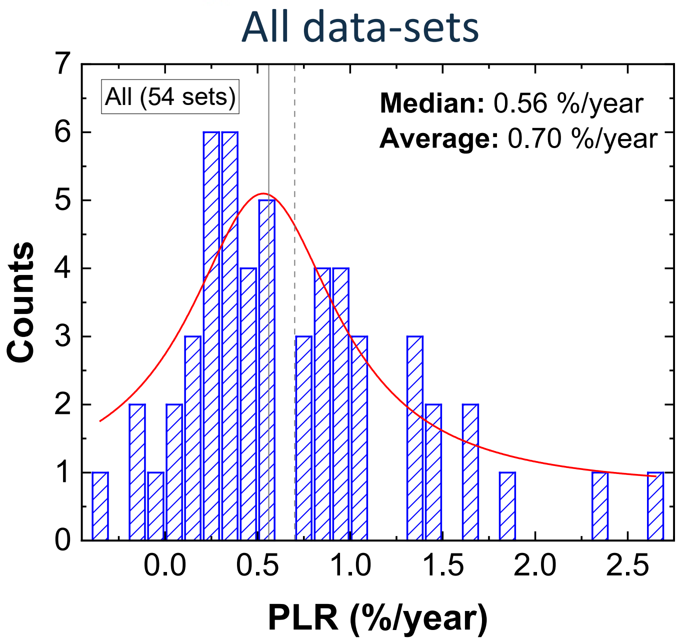
D. Jordan et al., Prog.Photov. 2016; 24: 978-989

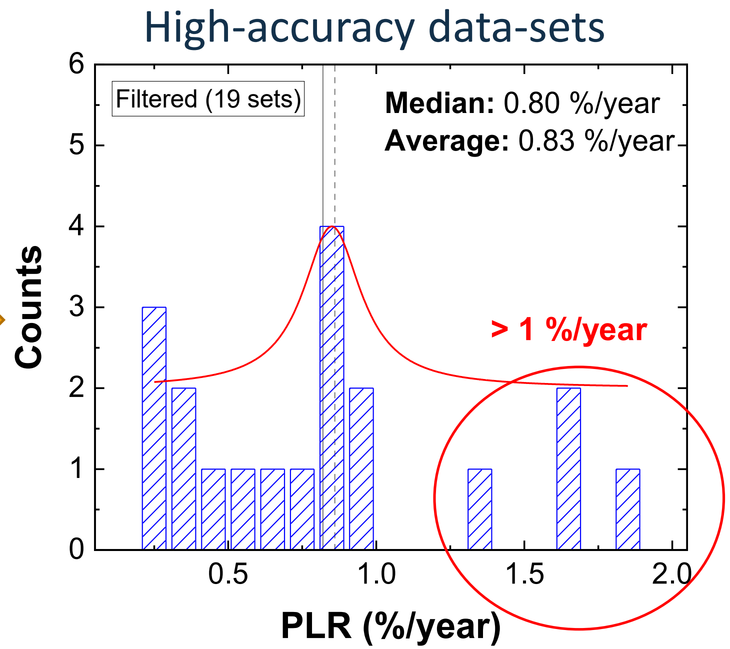
Dirk C. Jordan, NREL 2013 & 2016
'Compendium of photovoltaic degradation rates' & related works.

Data for PV systems/modules from an extensive literature survey

Degradation rates of Silicon Heterojunction Technology

O. Arriaga Arruti et al., *pending for submission* (2022)





Not a clear climate dependence trend

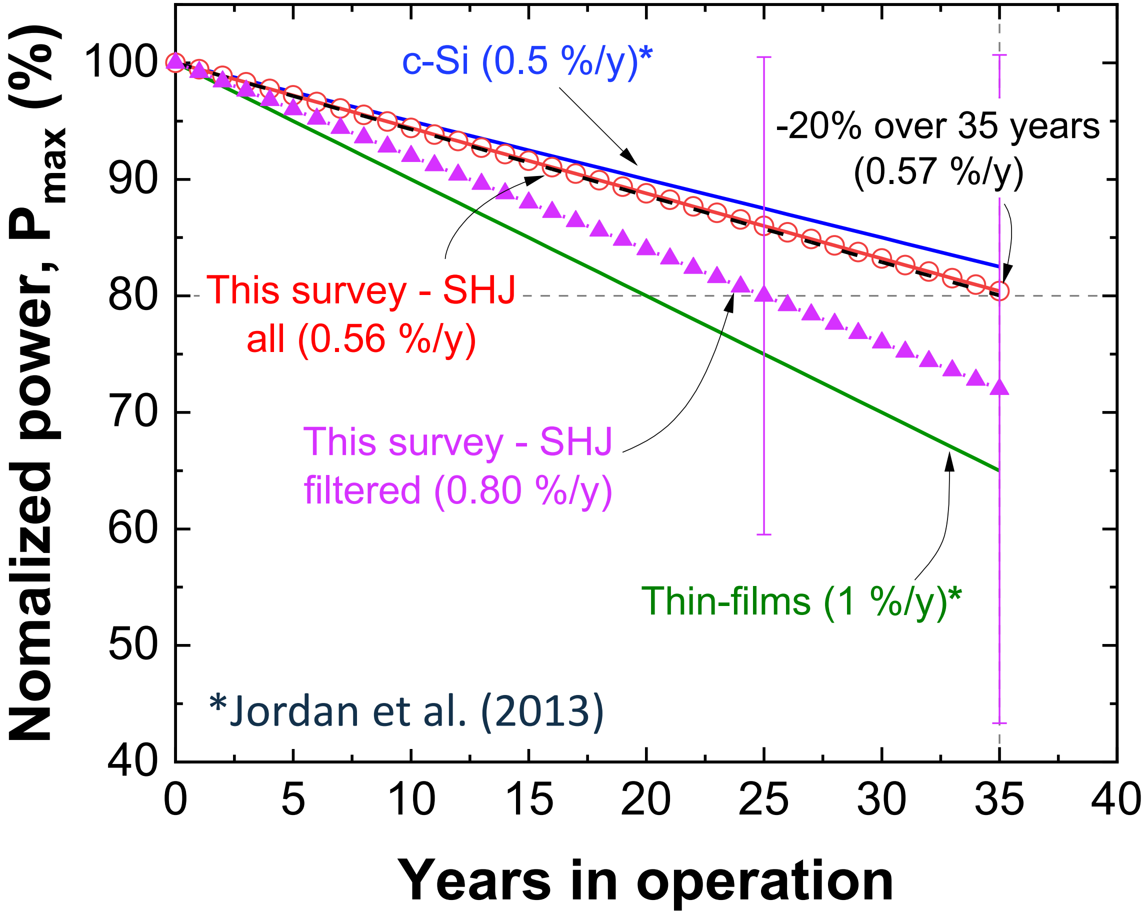
Main failure modes

- Often not studied.
- Loss in V_{OC} (several climates).
- **Encapsulant browning** ⟶ not particular to the SHJ technology.

Caveats particular to this survey

- Mainly **Sanyo/Panasonic** technology
  - G/BS module configuration
  - Front-emitter
- **Limited statistics** and temporal horizon (max. 10-15 years).

How do we ensure the 35+ years of operation of SHJ modules?



Main issues of SHJ technology

Sensitivity to:

1. Moisture ingress
2. PID
3. UV exposure

We can solve them!

Solutions:

- Use of **high volume resistivity encapsulants** (ionomer, PO)
- Prevent moisture ingress by applying an **edge sealant**.
- Using encapsulants with **UV cut-off** or a cut-off **no lower than 353 nm**.

Other applications

BIPV

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

One of the Terra-cotta Tones, with ISSOL, Solstis Userhuus, SFOE

VIPV

Taken from: ISFH

Higher stresses and new materials

Conclusions (1)

- **Do PV modules reach 35 years of service lifetime? → YES**!!!
  Example the Tiso-10 solar plant.
  Important: different technology & temperate climate.

- PV technology has evolved considerably over the last decades:
  PROS: know-how, better material/process/design quality control, track record, etc.

  CONS: increased requirements (e.g. system voltages), new cells/materials entering the market for which no track record exist

- A note of caution: deployment in non-temperate climates (hot-humid, hot-arid, maritime...) for which little experience exist

Conclusions (2)

- Consistent manufacturing as one of the key enablers:
  Quality Management Systems (QMS)

- Accelerated-aging testing → beyond qualification testing → limits & potential

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

Thank you for your attention!

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