PV Module forensics

Characterization of module materials in the field

Dr. Gernot Oreski

Polymer Competence Center Leoben GmbH,
Roseggerstraße 12, 8700 Leoben
+43 664 88679331
gernot.oreski@pccl.at

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Introduction

- Introduction
  - Materials in PV modules
  - Role of material interactions in PV module failure modes
  - Module forensics
- Use Case #1: **Backsheet cracking**
- Use Case #2: **Adhesive failure - detachment of junction boxes**
- Practical exercise: **Identification of polymers in PV modules**

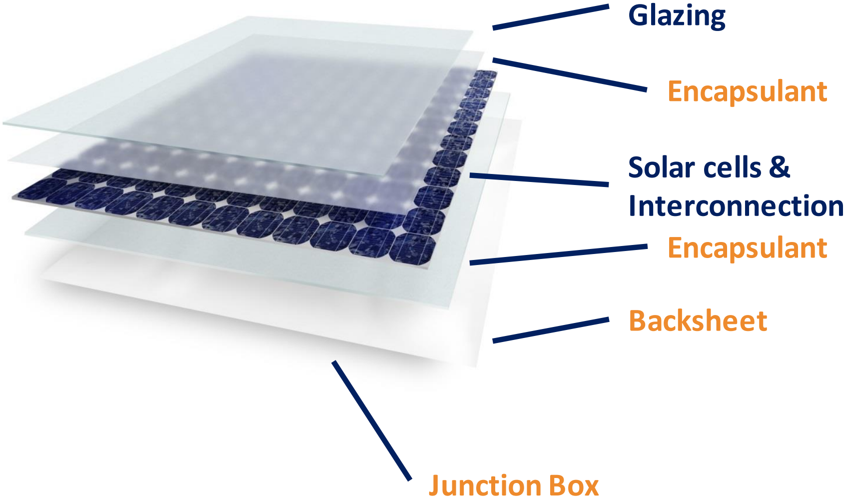
[1] European Comission, PV Status Report 2019,
https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/pv-status-report-2019

Polymers in PV systems

PV system in South Styria (Austria)

PV system in the Atacama desert (Chile)

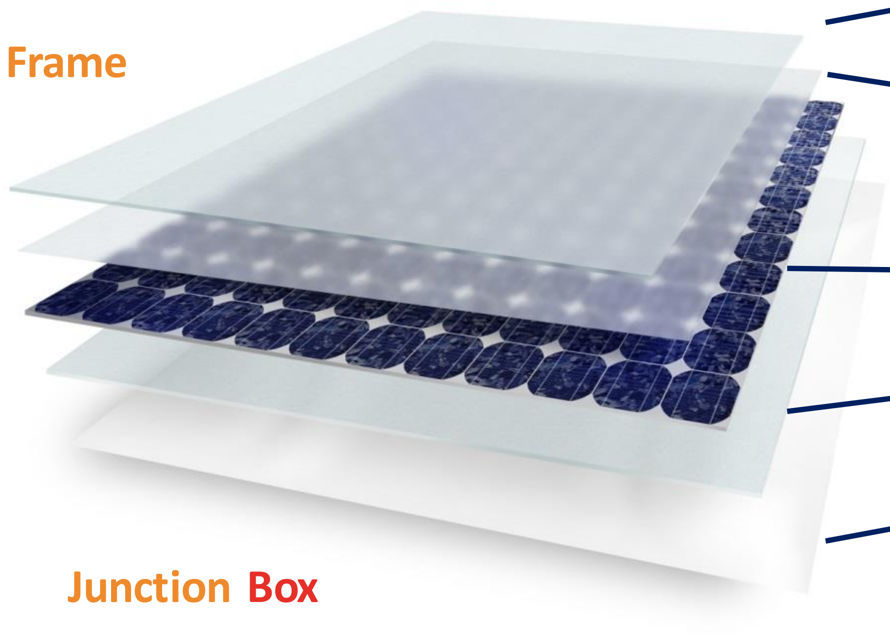
PV modules
- ✓ *Encapsulants*
- ✓ *Backsheets*
- ✓ *Frontsheets*
- ✓ *Junction box (casing; mold)*
- ✓ *Adhesives for frame and Junction Box*



Balance of System
- ✓ *Cables & Cable ties*
- ✓ *Adhesive tapes*
- ✓ *Inverter (casings)*
- ✓ *Floating bodies (Floating PV)*

Introduction

Photovoltaic modules



Multi-material composite containing glass, polymers, semiconductors and metal

Encapsulant: Requirements

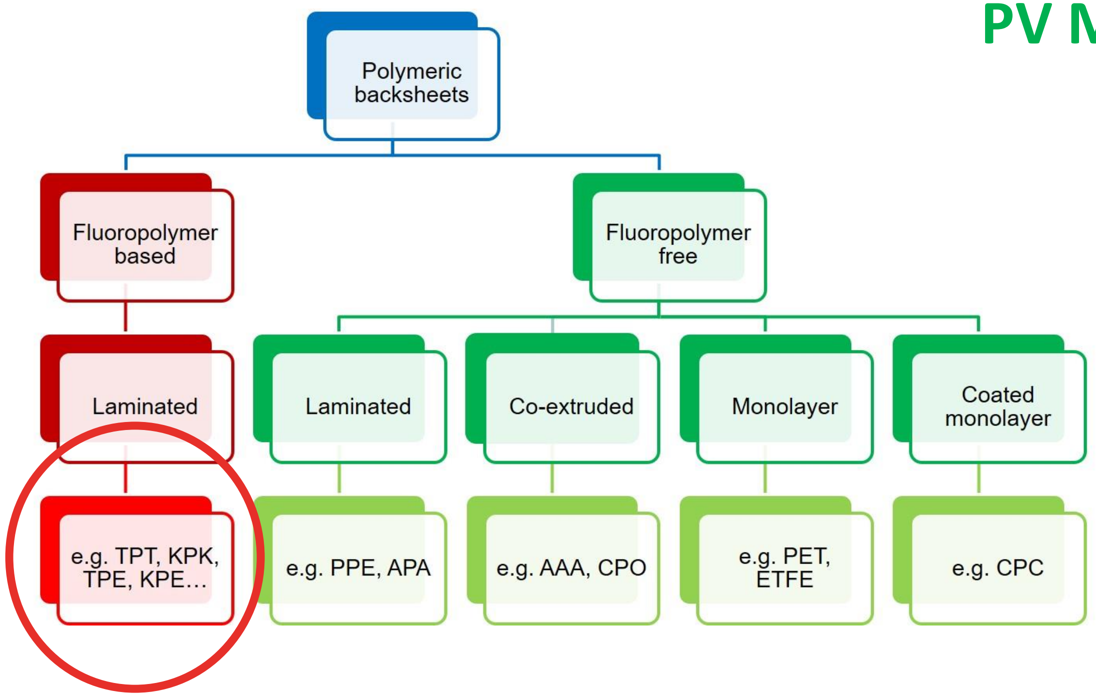
- Mechanical protection, structural support and physical isolation of the solar cell
- Optical coupling: Refractive index between glass and anti-reflective coating of solar cell
- Transparency in solar region of wavelength (300-2500nm)

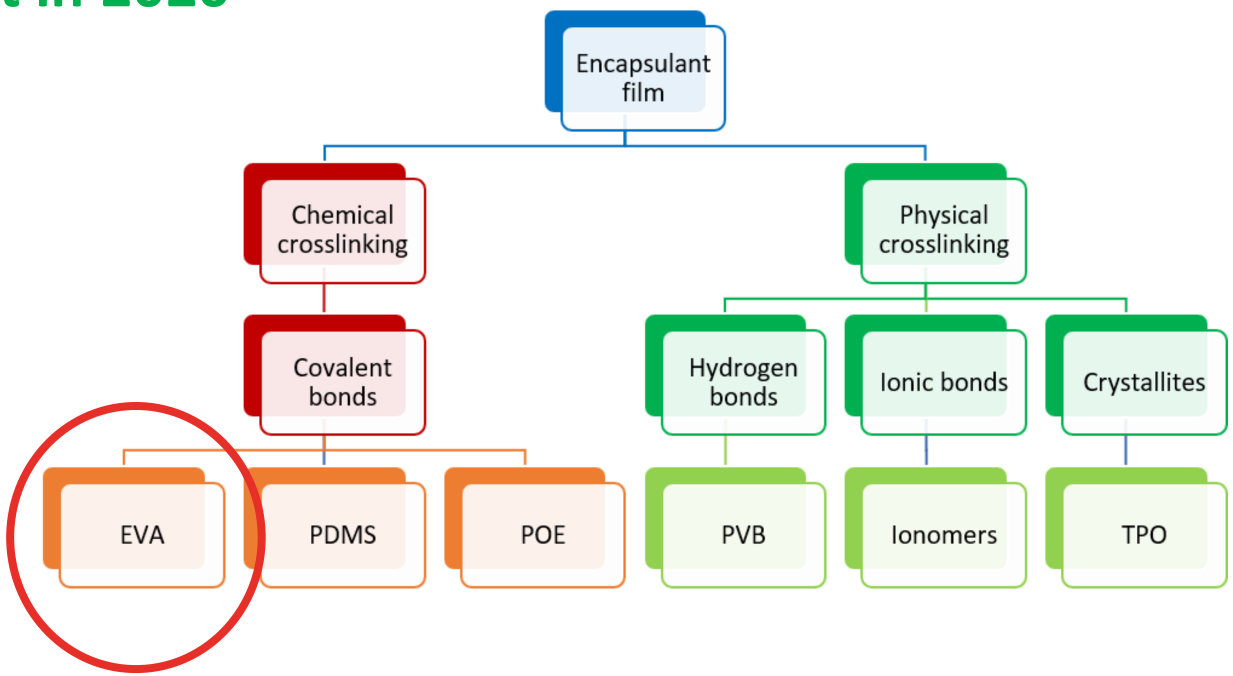
Backsheet: Requirements

- Electrical isolation
- Protection against weathering
- Barrier (humidity, oxygen)
- Mechanical stability

Introduction

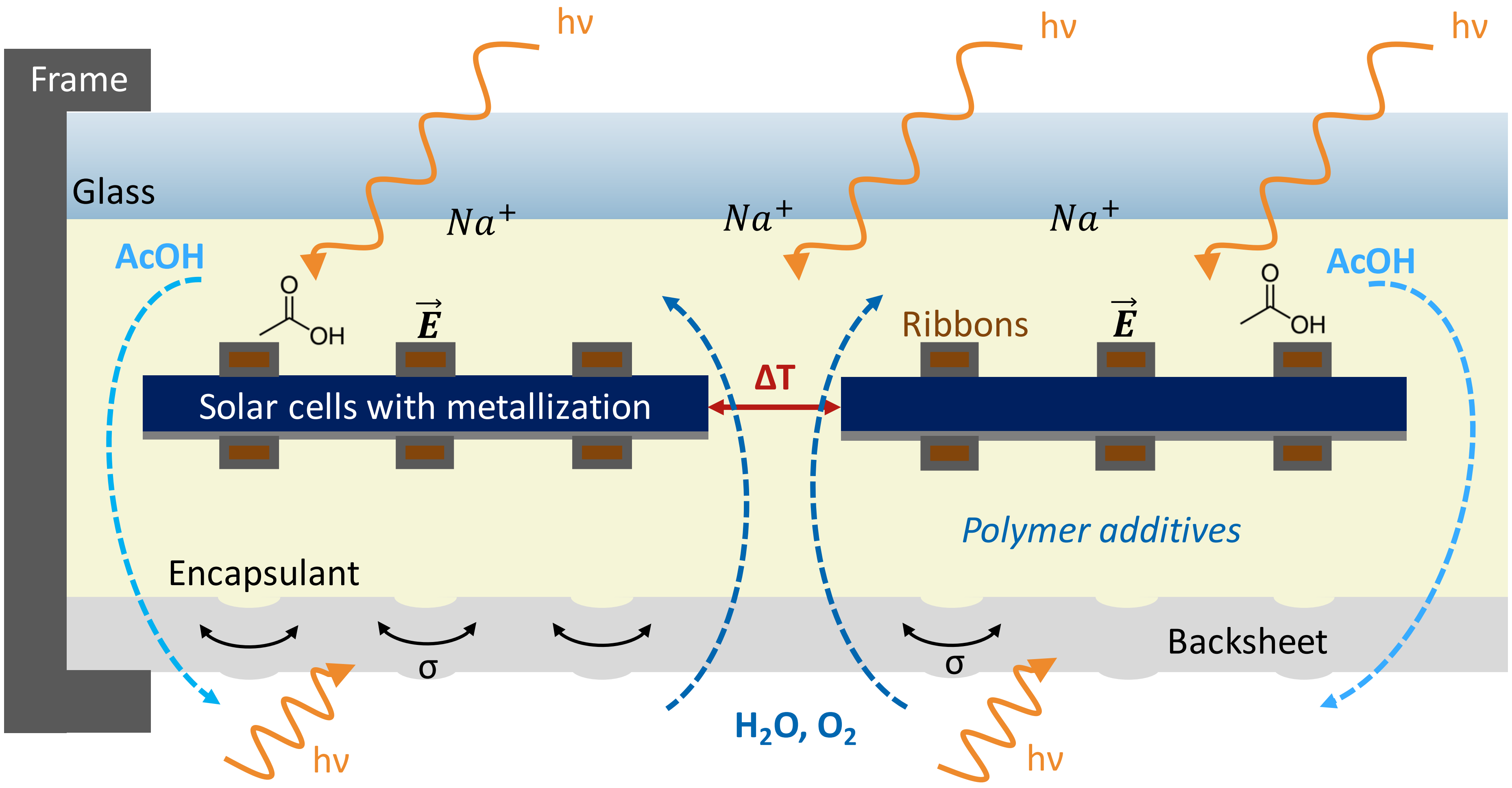
PV Market in 2020





- Backsheet & encapsulant market offers a broad variety of material and layer configurations
- Reduction of LCOE is the main driving factor for new developments
  - ✓ *Replacement of expensive materials with more economic ones*
  - ✓ *Increase of quality and reliability*
  - ✓ *Addition of new features (e.g. enhanced optical properties, selective permeability etc.)*
- Dominating materials: EVA encapsulants and PET/PVDF or PET/PVF laminates as backsheets with still more than 90% market share [2]

Stress factors during operation



External factors

Environmental conditions

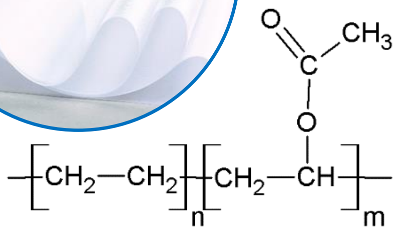
- Irradiation
- Temperature
- Humidity
- Atmospheric gases
- Mechanical loads (Wind, snow)

Internal factors

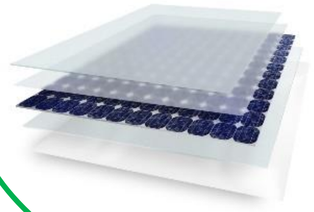
- Bill of material
- Processing effects

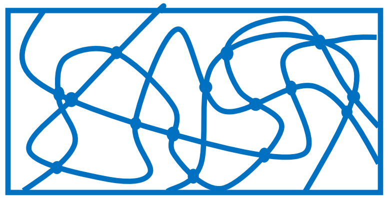
- **External and internal stress factors influence performance and long-term reliability of PV modules**
- **The materials in PV modules have to withstand extremely challenging micro-climatic conditions**

PV module degradation modes - Material interactions



Module lamination

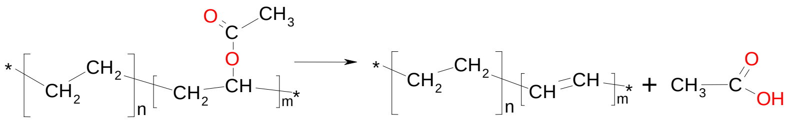




Peroxide induced chemical crosslinking

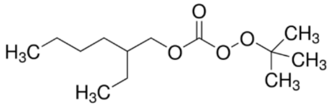
Degree of crosslinking after module lamination: 70-90%

Formation of acetic acid

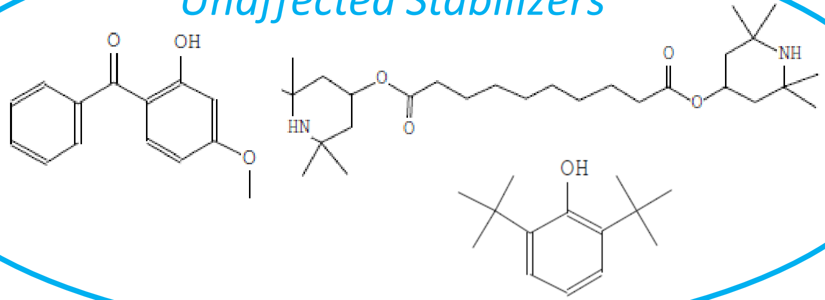


UV, T, RH

Remaining reactive peroxides [6]



Unaffected Stabilizers



Polymer encapsulants are the key component for quality and reliability of PV modules

Interactions may lead to unintended degradation effects

ation modes - Material interactions

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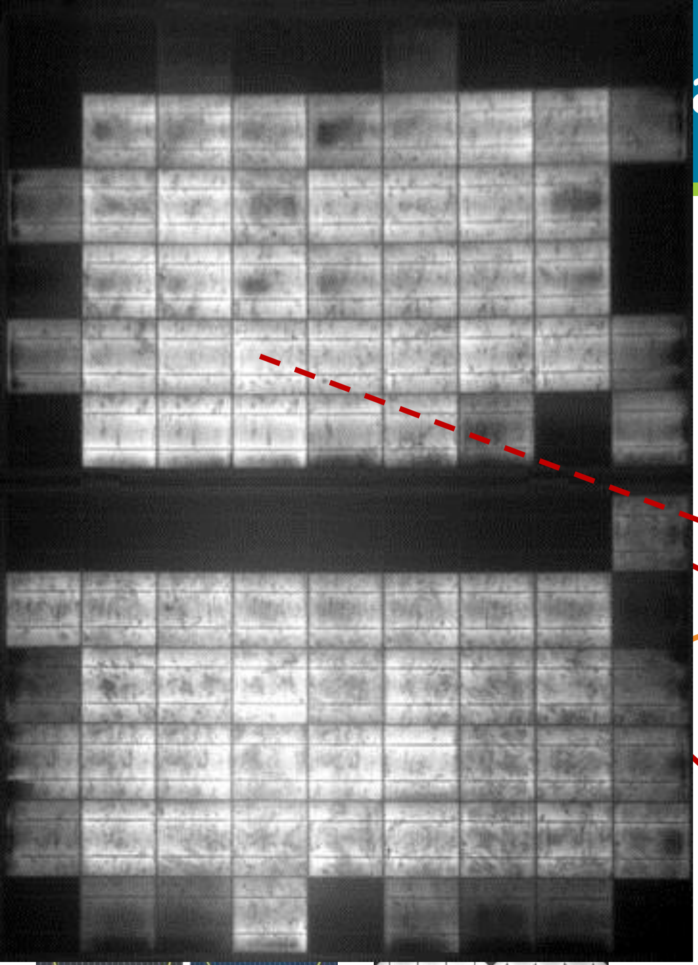
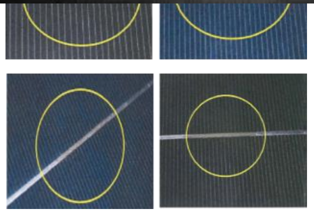
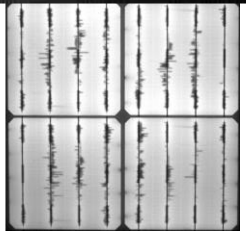
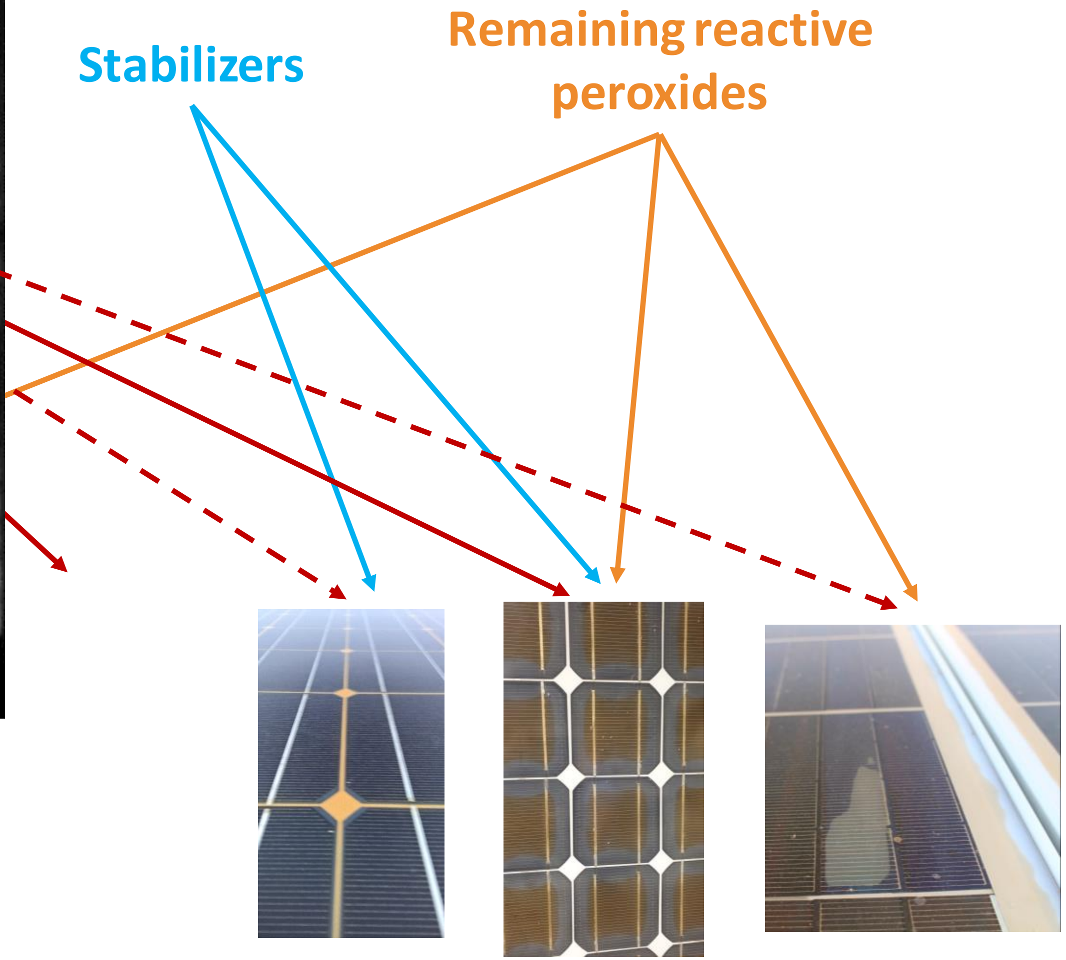






https://doi.org/10.1002/pip.3323



Ribbon corrosion

Silver grid corrosion

Potential induced degradation

Backsheet yellowing

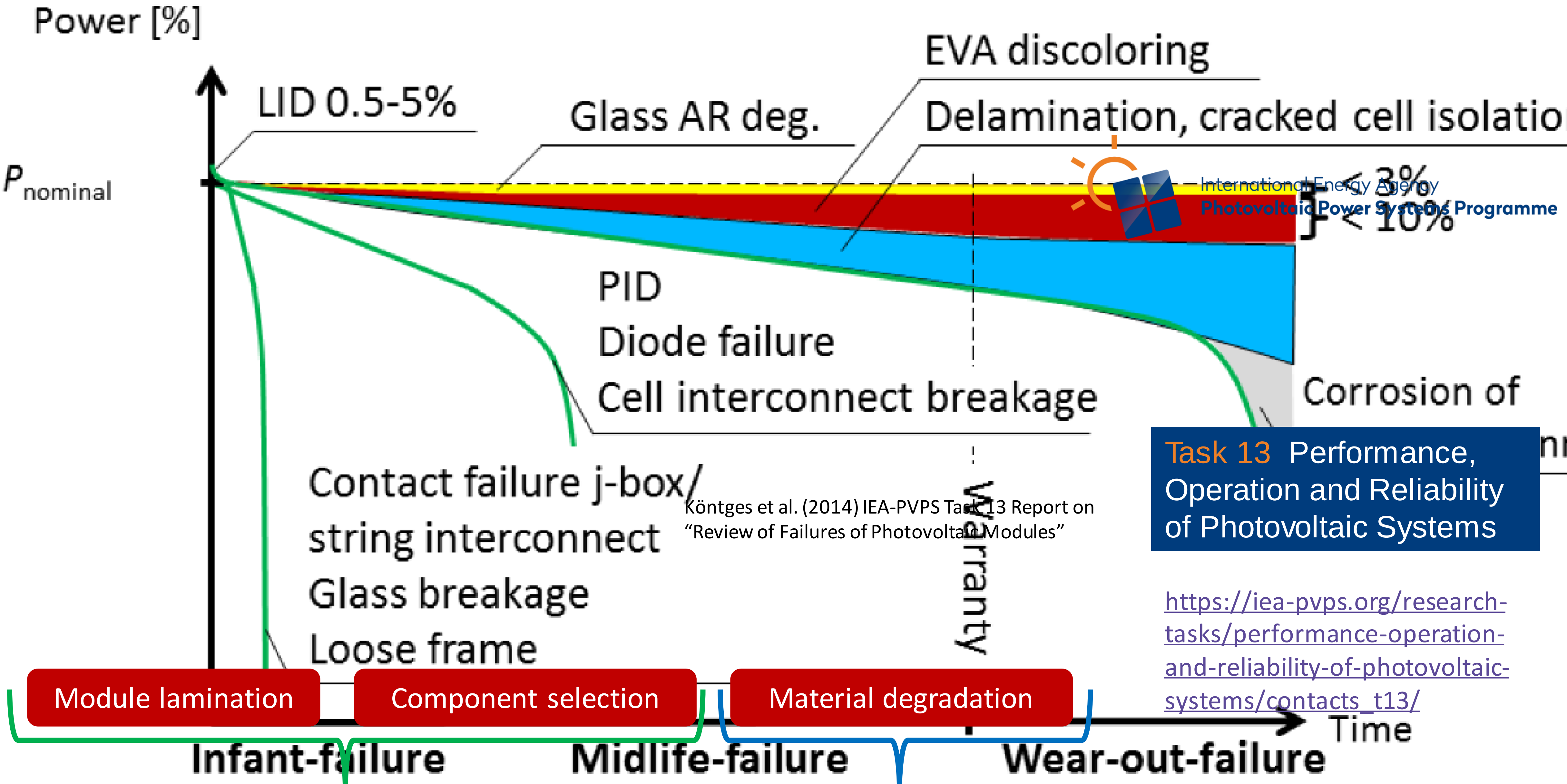
EVA Yellowing

Delamination

doi: 10.1002/app.44912

- PV module degradation modes Influenced or driven by permeation processes of O_2, H_2O and corrosive degradation products
- Polymeric materials (E+BS) play major role in PV module degradation
- Any new PV module component may introduce new material interactions and new degradation modes

New components have to be tested thoroughly to avoid unintended degradation effects



International Energy Agency
Photovoltaic Power Systems Programme

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

Task 13 Performance, Operation and Reliability of Photovoltaic Systems

https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/contacts_t13/

Mostly avoidable: Extensive R&D, quality and reliability testing needed

Can be delayed to some extent with proper stabilization

Introduction

What is the aim of PV module forensics?

- Root cause analysis of PV failure modes
  - ✓ *Identification of internal and external stress factors*
  - ✓ *Analysis of chemical and physical aging mechanisms*
  - ✓ *Derivation of degradation pathways*

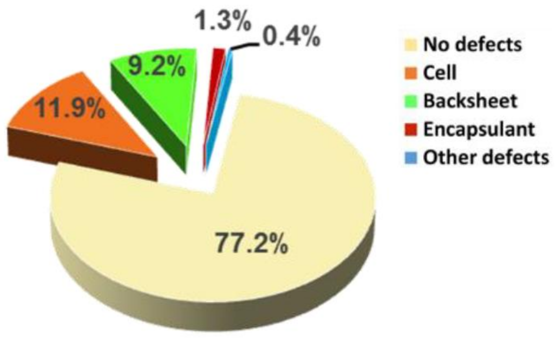
Power loss → Visual Inspection → Module characterization (IV, EL, IR…) → Material extraction → Material characterization (chem., phys.) → Degradation mechanisms

Use Case #1: Backsheet cracking

Backsheet cracking

Depending on the type and severity of crack formation,

- Defective backsheets (BS) primarily impose a **safety risk** due to failing wet leakage insulation
- BS cracks may accelerate various PV module **degradation modes** or polymer hydrolysis by providing gateways of moisture ingress into the modules
- **Results in a performance loss over time and/or need for repair or replacement of the modules**



Ground mounted: 206 installations (1028 MW)

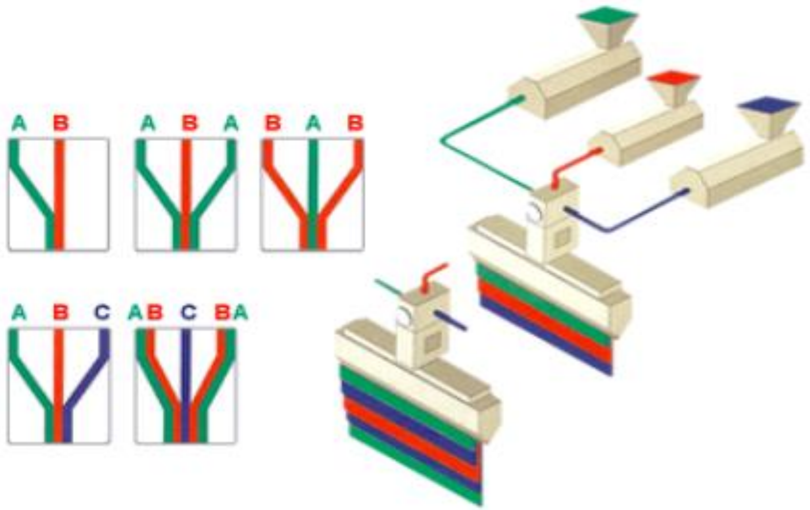
Table I: Defect rate by backsheet types

Material	Averaged Age (yrs)	Fields/MW	Defect rate (MW basis)
PA	6.1	19/121	45.7%
Glass	8.3	9/9	12.8%
PVDF	3.4	47/240	10.6%
PET	5.1	46/251	3.4%
FEVE	3.4	26/155	2.3%
Tedlar®	9.7	99/111	0.05%

PA = Polyamide
PVDF = PolyVinylidene DiFluoride
PET = PolyEthylene Terephthalate
FEVE – FluoroEthylene VinylEther

PA and PVDF backsheets show most cracking [1]

[1] Field Analysis and Degradation of Modules and Components in Distributed PV Applications
H. Hu, W.J. Gambogi, K. Roy-Choudhury, L. Garreau-Iles, T. Felder, S. MacMaster, O. Fu, T.-J. Trout ; 35th EU PVSEC, 2018; 5BO.12.1;



eets

c)

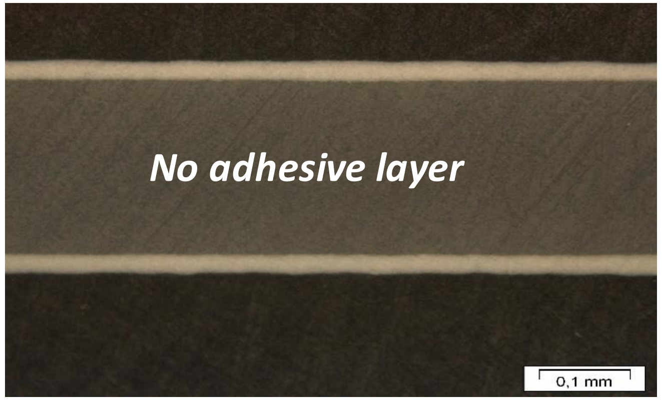
- ✓ 2017: Polypropylene (Isovoltaic/Borealis; Renolit; Bischof&Klein)
- ✓ 2018: PA-Polyolefin (DSM; Tomark Worthen)

- *Several advantages compared to laminated backsheets*
  - ✓ *Full back integration: easy material modifications are possible regarding additive formulation, fillers and geometry*
  - ✓ *Less production steps*
  - ✓ *Reduced processing induced material degradation*
  - ✓ *No delamination*
  - ✓ *Increased sustainability*

C. Thellen et al.: "Co-extrusion of a novel multilayer photovoltaic backsheet based on polyamide-ionomer alloy skin layers" in PVSEC, Amsterdam 2017.

Polymers used (PA, PP, PE) are usually cheaper than fluoropolymers and easier to produce than PET films

3 layer co-extruded PP backsheet



Polyamide backsheet failure

2010

Market introduction of co-extruded polyamide based backsheets (AAA)

2010-2015

Around 12 GW of PV was sold with AAA backsheets

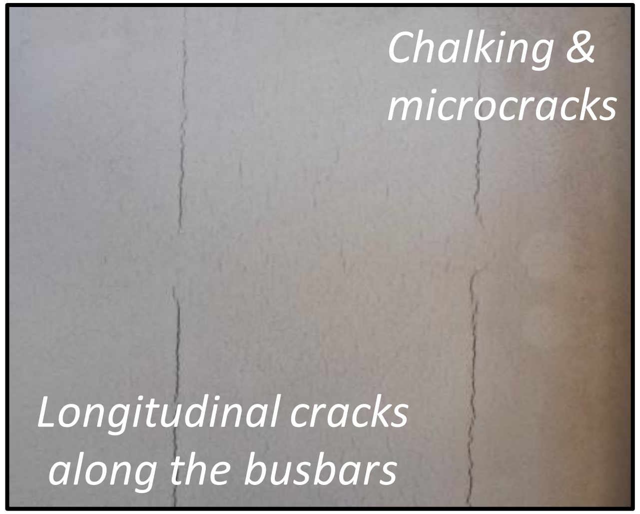
~ 70 mio m²
(1.5m² module size; 250W per module)

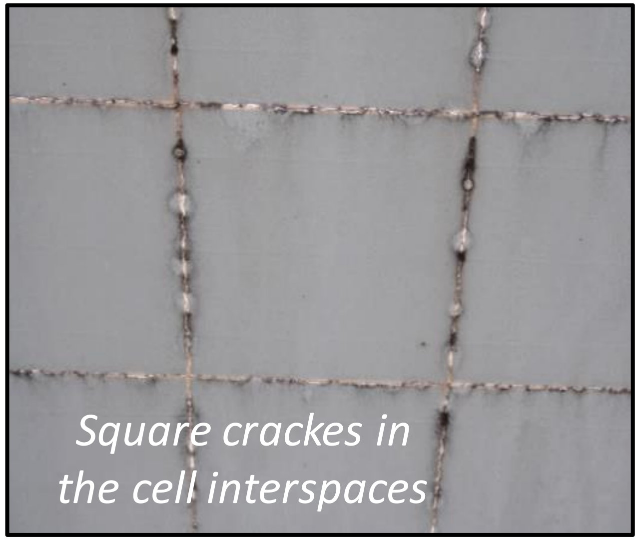
2015 -

Unforeseen cracking of AAA backsheets after some years in the field

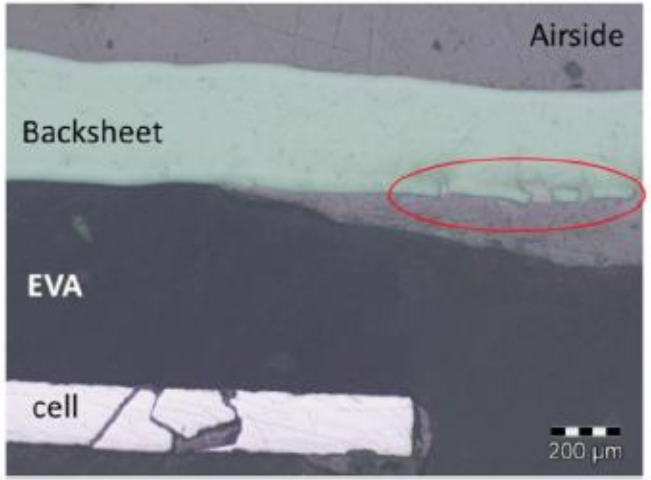
Major motivation for backsheet development: Improved raw material supply

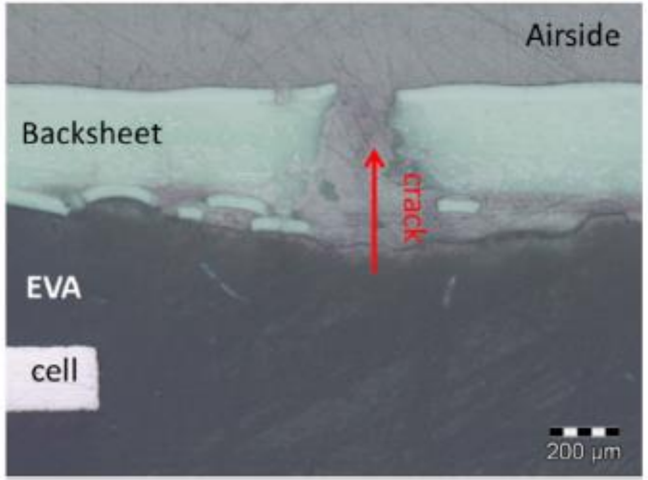
- *TPT backsheet dependent on supply of PVF*
- *Strong demand growth could not be met with PVF supply*

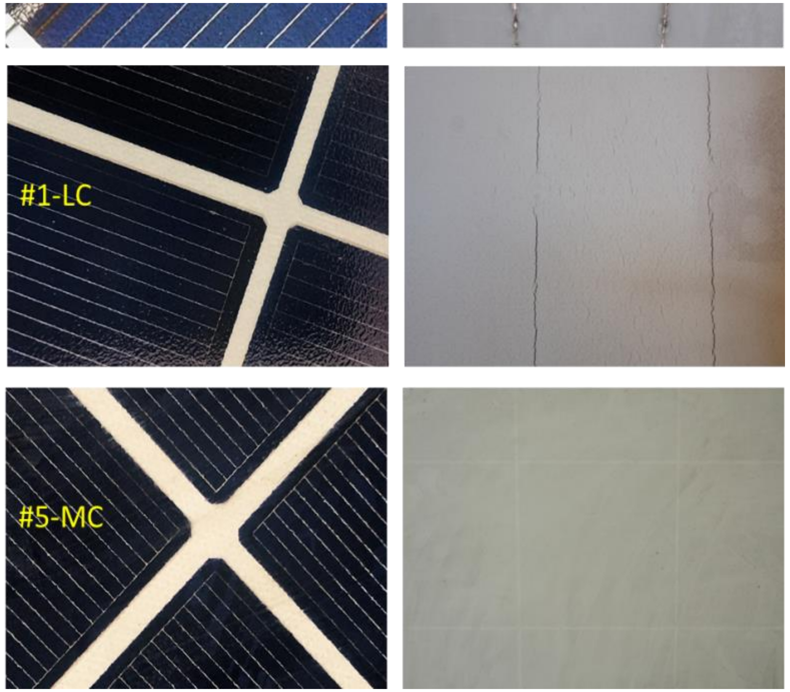




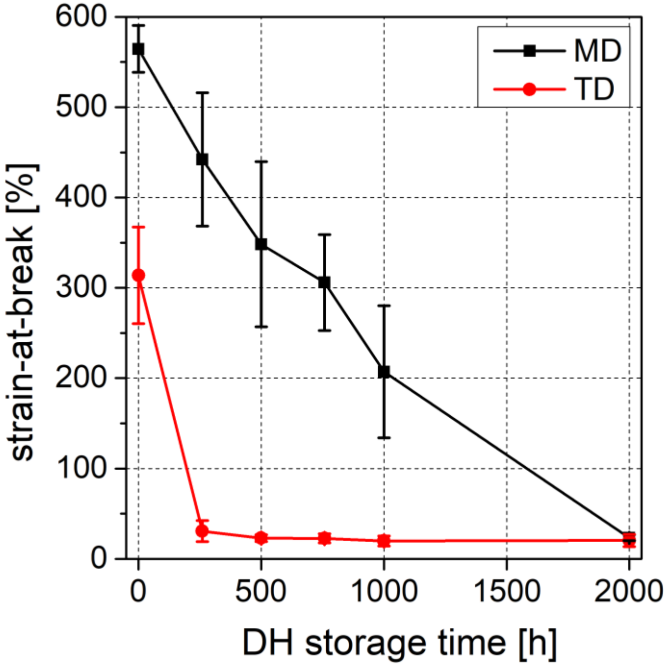
G. Eder, Y. Voronko, G. Oreski, W. Mühleisen, M. Knausz, A. Omazic, A. Rainer, C. Hirschl, H. Sonnleitner (2019) „Error analysis of aged modules with cracked polyamide backsheets“, Solar Energy Materials and Solar Cells 203, https://doi.org/10.1016/j.solmat.2019.110194







Starting point



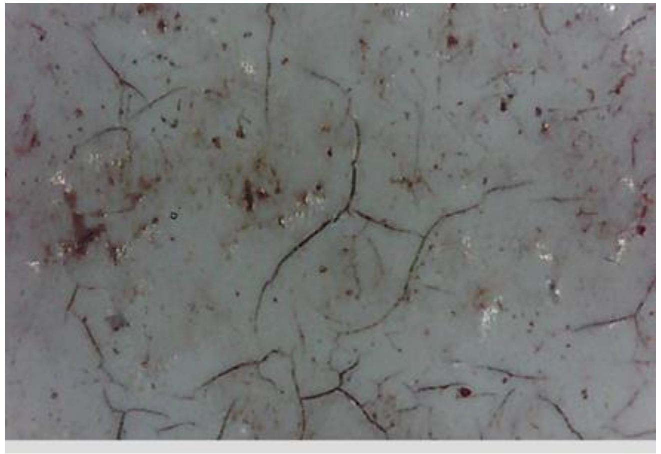
Physical aging process of PA12 significantly reduces the ability for plastic deformation of the backsheet

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

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

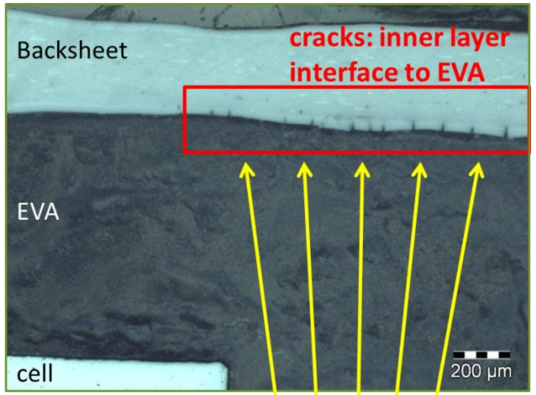
Polyamide backsheet failure

Material aging → Crack initiation → Crack propagation



✓ *Formation of micro-cracks at local stress concentrations*

→ *Daily and seasonal temperature changes in combination with different thermal expansion coefficients of PV materials cause thermo-mechanical stresses*



UV radiation in the cell interspaces

- ✓ *Cracking of strongly oxidized inner PA layer*
  → **Square cracks**
- ✓ *Height of ribbons impose additional tensile stress*
  → **Longitudinal cracks**
- ✓ *Chalking does not have an impact on crack formation*

Additional effect in combination with certain EVA types

✓ *Strong photo-oxidation and cracking of inner PA layer due only in combination with* ***high acetic acid concentration*** *and a* ***phosphor additive***

Weak chemical resistance of PA12 towards acetic acid and weak to moderate resistance towards phosphoric acid compounds [12]

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

Polyamide backsheet failure

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So why have the failure mechanisms of AAA not been observed in the lab?

Formation of cracks is a two-step process

- *Reduction of fracture toughness due to long term exposure at high temperatures or UV irradiation*
- *Continuously occurring mechanical and thermo-mechanical loads → internal stresses due to constrained thermal expansion of the backsheet*

Strain at break reduction was observed very early, but consequences of this behavior were totally underestimated

What was done?

DH

UV

TC / DML

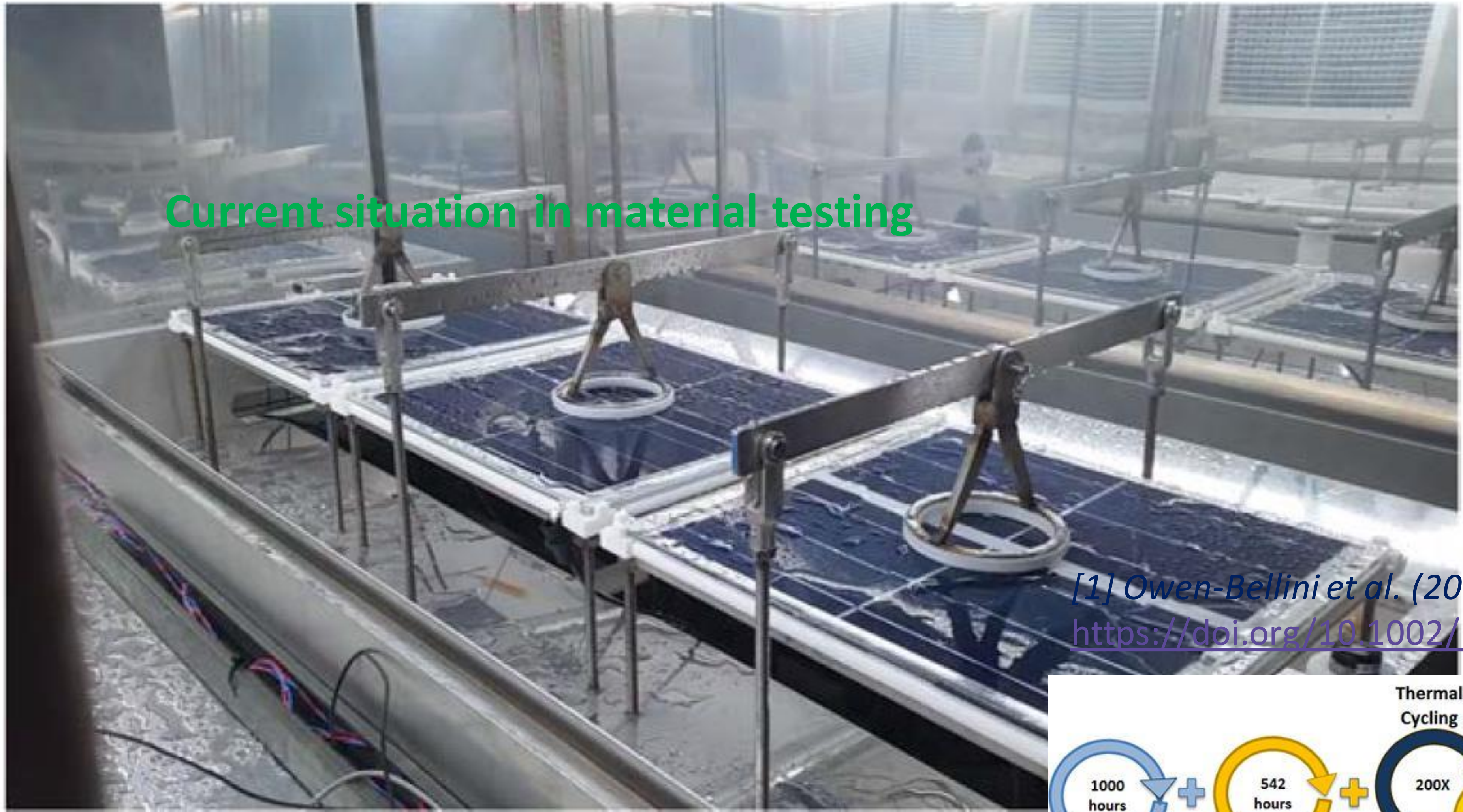
Single stress testing

- *Loss in strain-at-break was observed after DH and UV exposure of the film, but no cracking due to missing thermo-mechanical loads*
- *Thermal load of TC too low to induce the physical aging effect of the PA backsheet*

What should have been done?

DH + UV + TC / DML = Crack

Sequential / combined stress testing

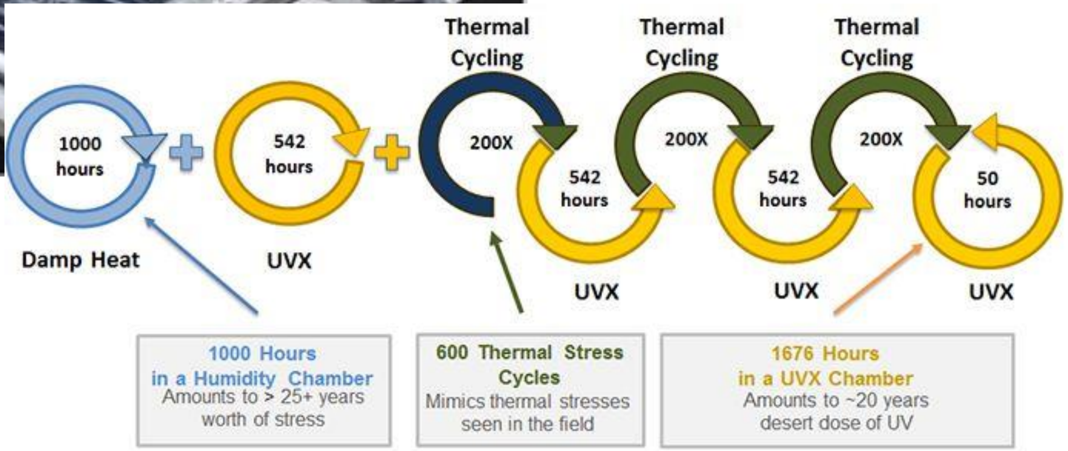


Current situation in material testing

thermo-mechanical load) lead to crack formation

- ✓ *NREL - C-AST*
- ✓ *DuPont - MAST*

[1] Owen-Bellini et al. (2020) https://doi.org/10.1002/pip.3342



[2] Gambogi et al. (2018, DuPont), doi: 10.1109/PVSC.2018.8547260.

Use case #2: Adhesive failure - detachment of junction boxes

G. Oreski, C. Barretta, L. Castillon, P. Christöfl and M. Köntges, *Importance of bill of material (BOM) control and IEC 61215 scope of application*, 37th European Photovoltaic Solar Energy Conference, 2020

Details of show case

Starting point

- ✓ *Identical PV modules that were installed on several sites in a tropical climate for 8 years*

Problem

- ✓ *Randomly the junction box (JB) was either detached or missing*
- ✓ *Systems with identical modules have also been installed for the same time in other climate zones (Germany, Greece, Italy, Czech Republic), but no detached or missing junction boxes have been observed*
- ✓ *All modules underwent IEC 61215 certification*

Auxiliary means

- ✓ *Known Bill of Materials (BOM)*
- ✓ *Reference module that was stored in the dark was made available*

Overall objective

Root cause analysis of JB damage

Approach

- Comprehensive failure analysis of 4 selected PV modules
  - ✓ *M1: Reference module*
  - ✓ *M2: Module exposed in Germany*
  - ✓ *M3: Module exposed in the Caribbean with detached junction box*
  - ✓ *M4: Module exposed in the Caribbean*
- Analysis of junction box adhesive
  - ✓ *175 samples from modules exposed in the Caribbean, Czech Republic, Greece and Italy*

nction box (JB)

JB adhesive failure at backsheet surface

Possible root causes

- ✓ *Processing: Surface cleaning and incomplete crosslinking of adhesive*
- ✓ *Degradation (adhesive; backsheet)*
- ✓ *Different Bill of Materials*

Additional observations: *Snail trails, bubbles, cell framing, burn marks, scratches and punctures*

Corrosion

Brown discoloration and corrosion of busbars and fingers

Possible root causes

- ✓ *Formation of acetic acid*
- ✓ *High water vapour saturation*

Power losses between 30% and 70% compared to nameplate values

- *Drop in the fill factor from ~73% to a range between 40 and 55%*
- *Reduction in the short circuit current between 30 and 40%*

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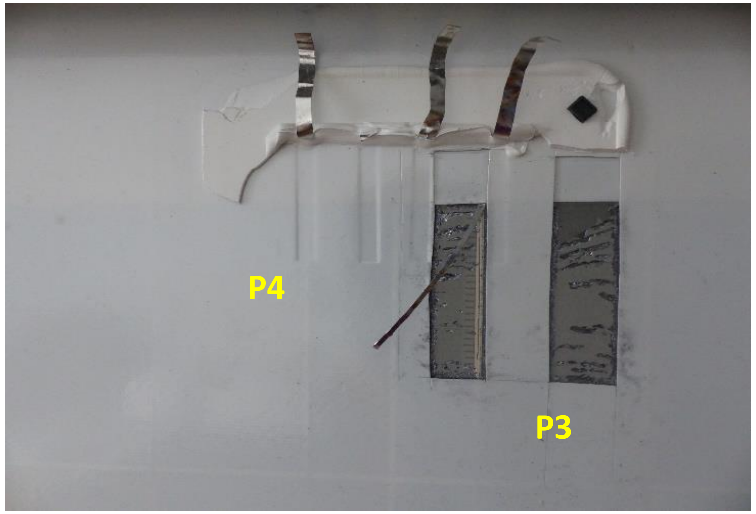
G. Oreski, C. Barretta, L. Castillon, P. Christöfl and M. Köntges, *Importance of bill of material (BOM) control and IEC 61215 scope of application*, 37th European Photovoltaic Solar Energy Conference, 2020

Results
Material extraction

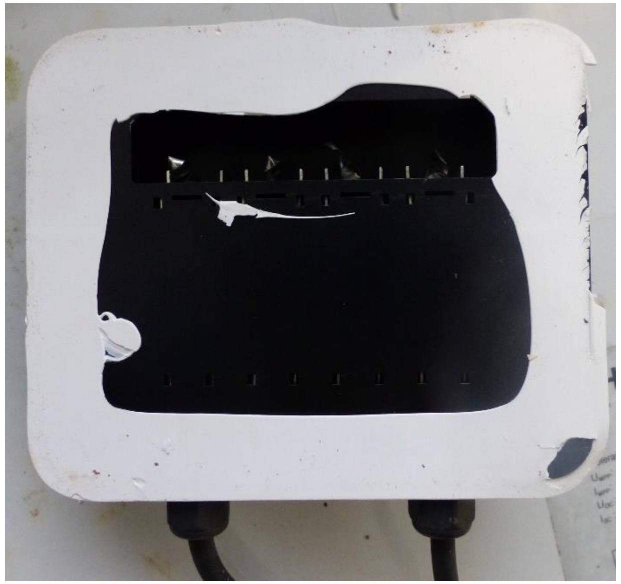
- ✓ *Polymer materials have been extracted by cutting a rectangular section and then pulling the obtained stripe*
- ✓ *Backsheets have been separated from rear EVA*



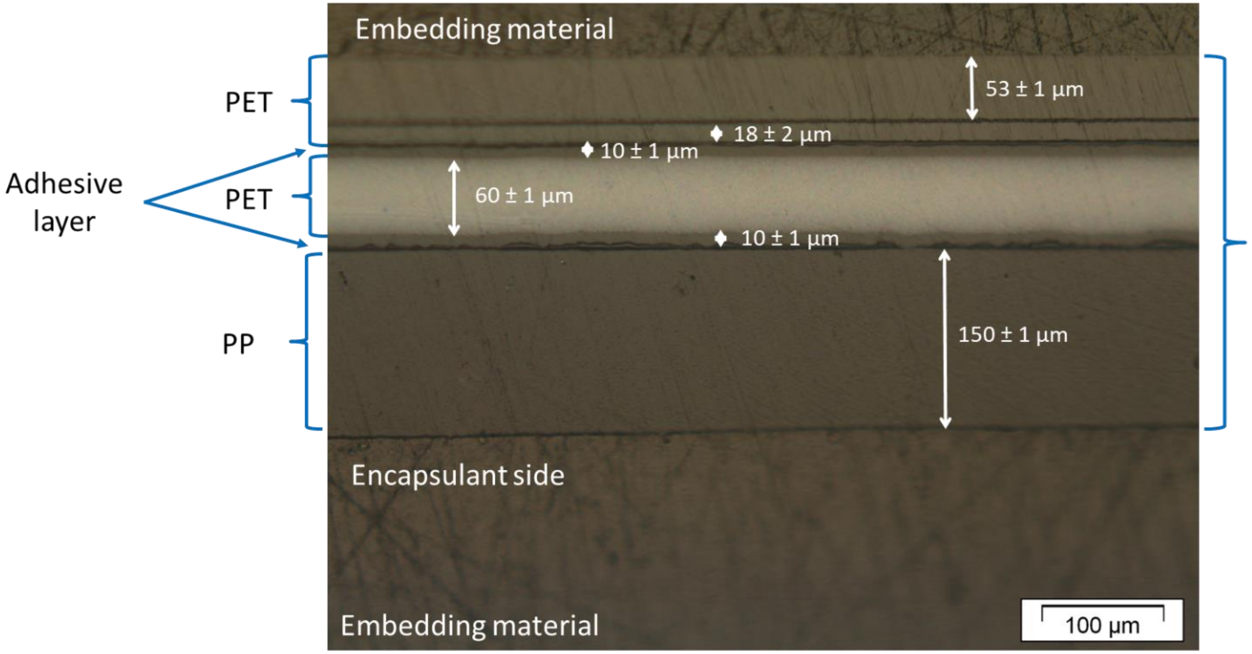
Samples have been taken at 4 different positions

- ✓ **P1**: *Central area of the module*
- ✓ **P2**: *Bottom area of the module*
- ✓ **P3**: *Beneath the adhesive connecting junction box and backsheet (after removing the junction box)*
- ✓ **P4**: *Area of the module covered by the junction box*

- ✓ Part of the glue from the junction box adhesive is removed for further material characterization



Results
Backsheet



Overall thickness: ~300 µm

- **Identical backsheet configuration found for all investigated modules**

uncovered

below JB

Backsheets from modules exposed to tropical climate show similar degradation behavior
→ *Assumption: Backsheet has no or only minor influence on adhesion loss of junction boxes*

- ✓ *Crystallization peak temperature of outer PET layer increases due to hydrolysis*
- ✓ *Reduced degradation of the outer PET layer in areas covered by junction box*

Results
JB adhesive

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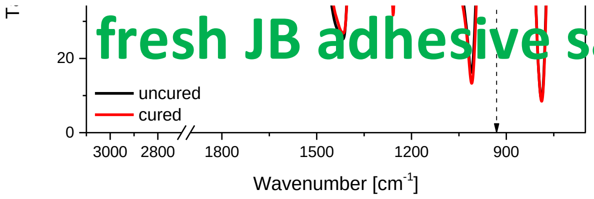
Infrared spectroscopy: Analysis of chemical composition of fresh JB adhesive samples – uncured and cured



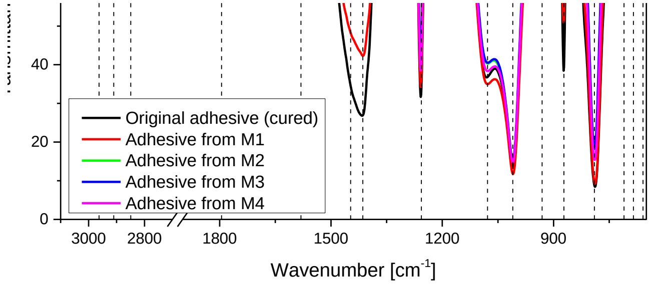
Silicone based JB adhesives

Wavenumber [cm-1]	Comment
2963	C-CH_3 stretching
2910	C-CH_3 stretching
2849	C-CH_3 stretching
1795	Anhydride, Lactone
1581	C=C stretching vibration
1447	CH_3 deformation vibration
1414	CH_3 deformation vibration
1256	CH_3-Si symmetric deformation vibration
1078	Si-O-Si stretching vibration
1010	Si-O-Si stretching vibration
931	CH_2 out-of-plane deformation vibration
872	Si-O stretching vibration
790	CH_3-Si deformation vibration

Curing parameters: 50°C for 16 hours

A difference can be seen at 931 cm^{-1}, which probably corresponds to the vinyl group of the crosslinking agent (Vinyl oximino silane)

Results
JB adhesive



- ✓ *Two different types of silicone based JB adhesives are identified*
- ✓ *The main differences between the two categories are the intensities of the peaks at around 1447, 1414, 870 cm^{-1}, as well as in the region below 710 cm^{-1}*
- ✓ *No peak or shoulder at 931 cm^{-1} visible*

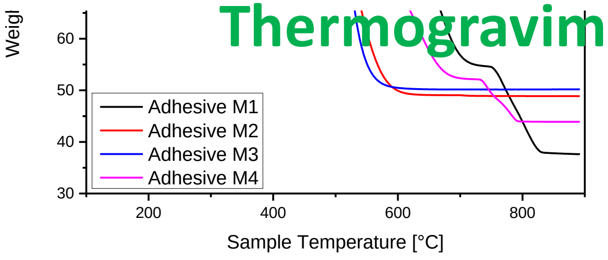
  → **JB adhesives fully crosslinked**
- ✓ *JB adhesives belonging to M1 and M4 show the same characteristic peaks as the original adhesive, whereas for M2 and M3 an alternative adhesive was used*
- ✓ *Module M3 with detached junction box has alternative adhesive*

- ✓ **M1:** *Reference module*
- ✓ **M2:** *Module exposed in Germany*
- ✓ **M3:** *Module exposed in the Caribbean (with loose junction box)*
- ✓ **M4:** *Module exposed in the Caribbean*

Different type of adhesive may be main cause for adhesion failure of junction boxes

Results
JB adhesive

Thermogravimetric analysis: Investigation of thermal decomposition process



- ✓ **M1:** *Reference module*
- ✓ **M2:** *Module exposed in Germany*
- ✓ **M3:** *Module exposed in the Caribbean (with loose junction box)*
- ✓ **M4:** *Module exposed in the Caribbean*

Not combustible residue: Inorganic fillers

Two different types of JB adhesives are identified

- ✓ *Adhesives from M1 and M4 correspond to the original adhesives*
- ✓ *An alternative adhesive for M2 and M3*

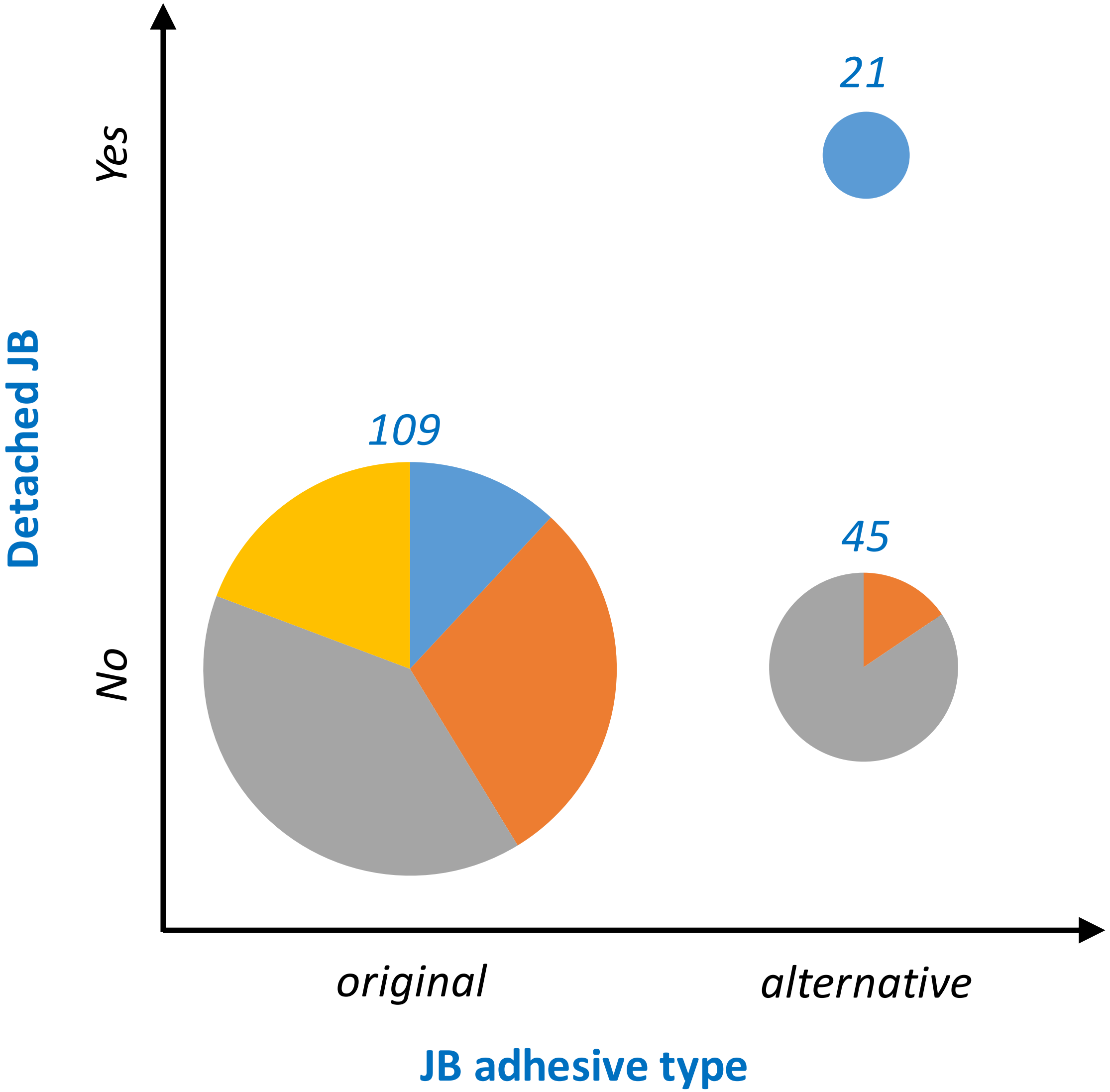
Different filler contents

- ✓ *About 37 – 44% for original adhesive*
- ✓ *Around 50% for alternative adhesive*

Good agreement with results from IR spectroscopy

Results
JB adhesive

Identification of adhesives from modules in different locations and climate zones



Summary: 175 samples	Original	Alternative	Total
Carribean	13	21	34
Greece	32	7	39
Italy	21	0	21
Czech Republic	43	38	81

- ✓ *Random use of alternative adhesive for junction boxes*
- ✓ *BOM states only one adhesive for all modules*
- ✓ **Adhesion failure is just observed for modules from the Caribbean using alternative adhesive**

Open question:
Will the alternative adhesive also fail in moderate and Mediterranean climate?

Summary

PCCL
Polymer Competence Center Leoben

- **As expected, tropical climate was found to be harsher than moderate climate**
  - ✓ *AAC and backsheet degradation is found in tropical climates*
  - ✓ *Power losses between 30% and 70% caused by AAC*
  - ✓ *No significant degradation in moderate climate zone*
- **Adhesion loss between junction box and backsheet is attributed to an unspecified alternative adhesive**
  - ✓ *JB adhesive specified in BOM works fine*
  - ✓ *Backsheet degradation and insufficient curing is ruled out as root cause*
- **Results confirm importance of an incoming inspection of PV modules before installation with respect to its BOM**
  - ✓ *The use of a non-qualified adhesive would have been detected in advance*
- **Results also shows the limits of the “one module type fits all” approach**
  - ✓ *Either PV modules are overengineered to endure in all climates*
  - ✓ *Or modules inadvertently fail under certain climatic conditions, as observed in this work, but work without any power loss in moderate climates*

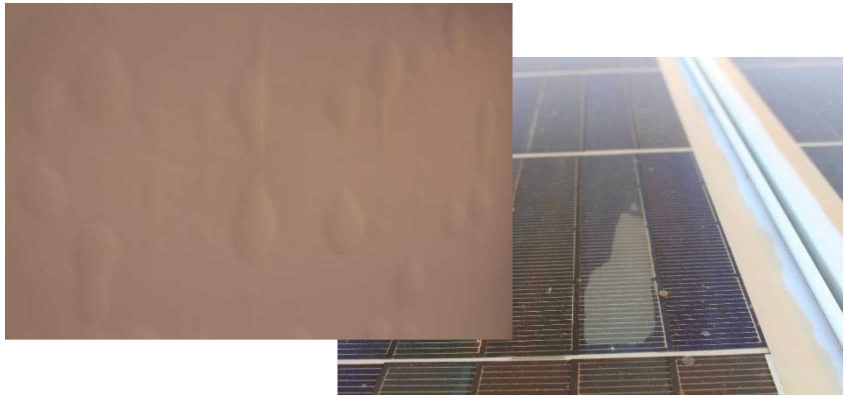
Polymers in photovoltaics

- **Role of the polymers in photovoltaic energy generation has generally been underestimated**
  - ✓ *No active role in power generation*
- **Choice of polymers has distinctive impact on PV modules attributes such as**
  1) ***Efficiency,*** *as the optical properties of encapsulant (transmittance) and backsheet (reflectance, back scattering) define the number of photons arriving at the solar cell*
  2) ***Quality,*** *as the main infant failures are caused by bad processing parameters, which are defined by the encapsulant properties, and material incompatibilities*
  3) ***Reliability,*** *as most PV module degradation modes are directly linked to polymer degradation and material interactions with polymer components*

→ Better understanding of material properties of polymers in PV modules and their influence degradation processes is a precondition for a successful development of new components and reliable PV module designs

Future challenges: Compatibility issues

- Check of compatibility of PV module components will get more and more important in the future, as the variety on materials and components will grow
- **Emergence of new degradation modes** (e.g. LeTid, PID....)



Adhesion - delamination

✓ Adhesion to glass and solar cell strongly dependent of lamination parameters

✓ Surface treatment of backsheets usually optimized for adhesion to EVA but not alternative encapsulants

Backsheet yellowing: Migration of additives into backsheet-encapsulant interface are main cause for backsheet yellowing

Corrosion: Broad variety of new ribbon materials, interconnection technologies and encapsulant films

Unexpected failure modes?

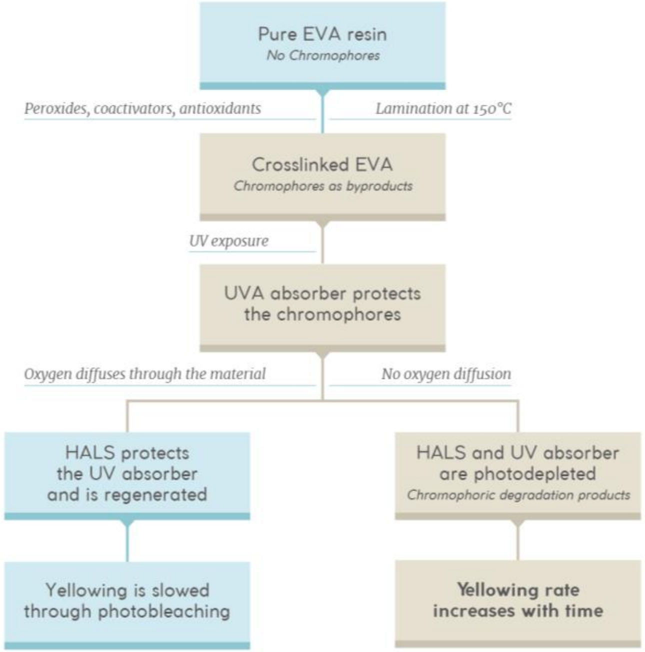
Constant need for adaption of test methods and standards

Practical exercise: Polymer identification in PV modules

Polymer identification

What happened here?

Polymer identification



G. Oreski, B. Ottersböck, A. Omazic, 6 - Degradation Processes and Mechanisms of Encapsulants, Editor(s): H. E. Yang, R. French, L. Bruckman, In Plastics Design Library, Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules, William Andrew Publishing, 2019, Pages 135-152, https://doi.org/10.1016/B978-0-12-811545-9.00006-9

Backsheet or encapsulant yellowing?

Yellowing at backsheet - encapsulant interface:
Formation of oxidized antioxidants with conjugated double bonds

G. Oreski, G.C. Eder, Y. Voronko, A. Omazic, L. Neumaier, W. Mühleisen, G. Ujvari, R. Ebner, M. Edler, Performance of PV modules using co-extruded backsheets based on polypropylene, Solar Energy Materials and Solar Cells 223, 2021, 110976 https://doi.org/10.1016/j.solmat.2021.110976

Polymer identification

- Control of module Bill of Materials (BOM), especially the polymers, is relevant for the following value chain segments and stakeholders

Testing & Certification

- **BOM control / Material ID**
- **Field Audits**
- **Stakeholder: Test institutes; certification bodies**

System installation

- **Quality control of delivered modules**
- **Stakeholder: EPC contractors, investors, banks, assurance companies**

Operation & Maintenance

- **BOM control / Material ID**
- **Damage analysis**
- **Evaluation of repair actions**
- **Stakeholder: O&M companies; system owner**

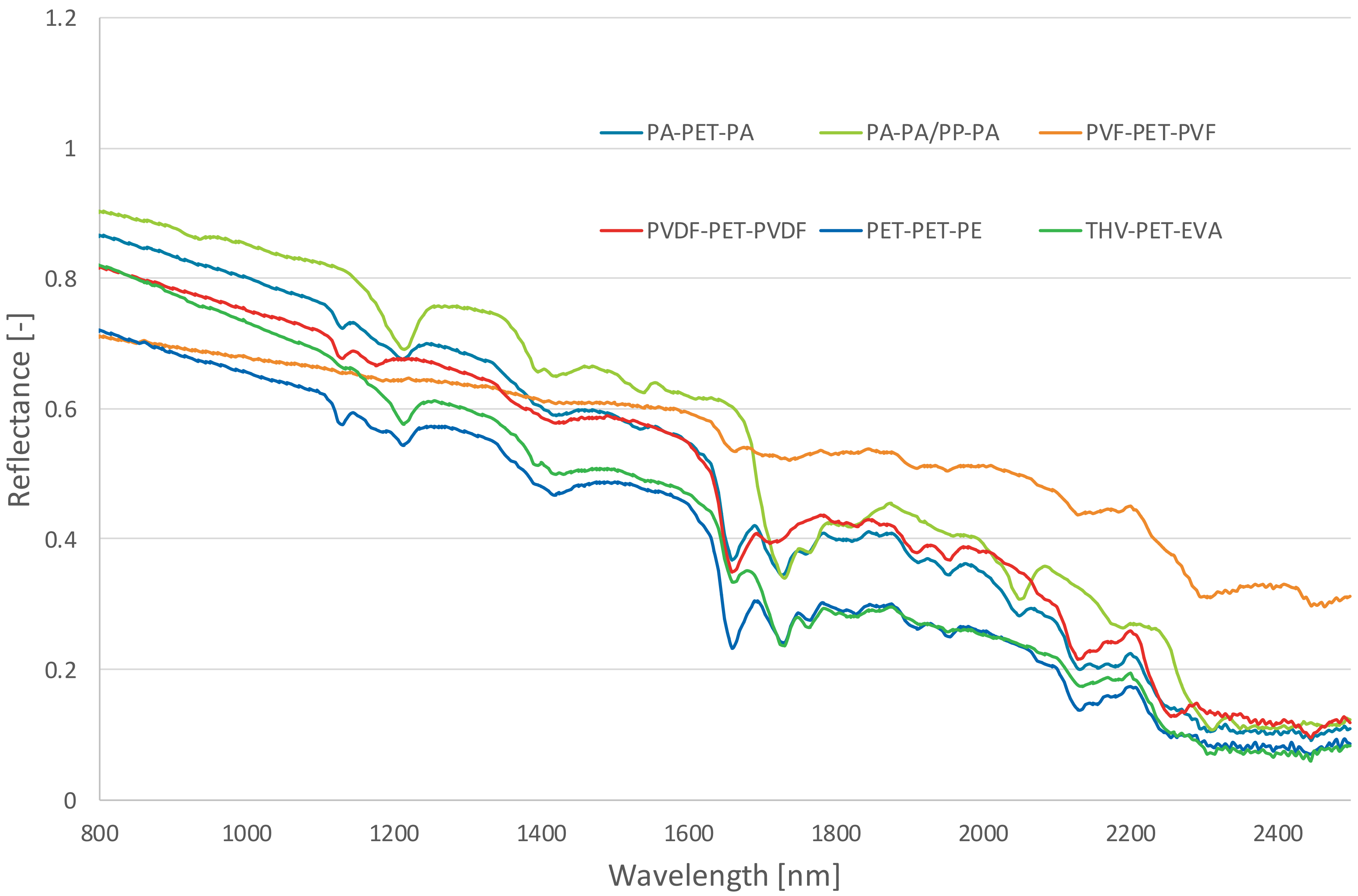
Recycling

- **Identification of fluorine containing polymers**
- **Stakeholder: O&M companies; recycling plants**

BOM as given in documentation and/ore IEC61215 certificate

Combustion of fluoropolymers requires special equipment regarding corrosion resistance and exhaust gas filtration

Polymer identification



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https://iea-pvps.org/research-tasks/performance-operation-and-reliability-of-photovoltaic-systems/contacts_t13/

https://orcid.org/0000-0003-4223-9047