Reliability Challenges for new PV designs

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Introduction

I. What is the motivation for new PV module materials and PV module designs?

II. What are the main challenges for new designs and materials?

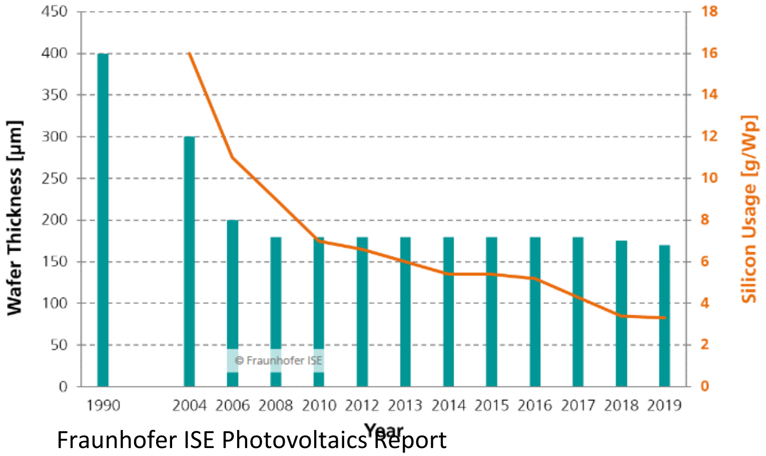
III. What are potential root causes for unexpected degradation and failure mechanisms?

IV. What can we do to mitigate potential damages?

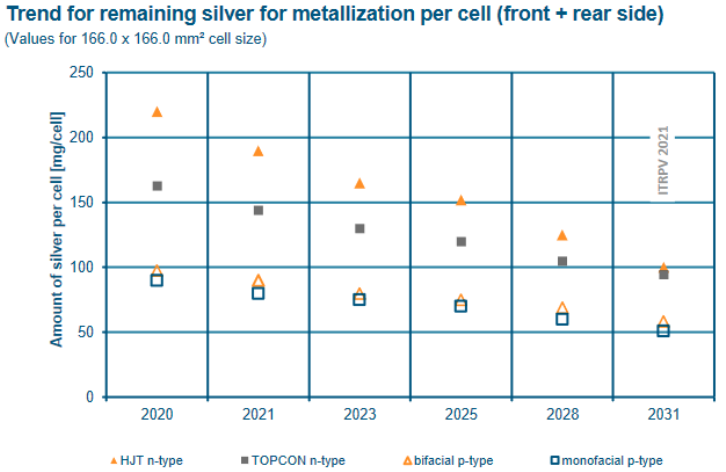
Motivation for new materials and module designs

Decrease of LCOE: Cost reduction and performance improvement

- Reduction and replacement of expensive materials
  - ✓ *Solar cell thickness*
  - ✓ *Silver content*
  - ✓ *Glass thickness*
  - ✓ *Replacement of Fluoropolymers*
- Acceleration of manufacturing process
  - ✓ *Ultra Fast curing EVA*
  - ✓ *Thermoplastic encapsulants*
- Performance increase
  - ✓ *Interconnection: Reduction of resistive losses and cell shadowing*
  - ✓ *Encapsulants and backsheets with enhanced optical properties*
- Production related cost decrease
  - ✓ *Wafer size*



Fraunhofer ISE Photovoltaics Report
https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html



International Technology Roadmap for Photovoltaic (ITRPV) (https://itrpv.vdma.org/en/)

G Oreski *et al* 2022 *Prog. Energy* **4** 032003, https://www.doi.org/10.1088/2516-1083/ac6f3f

Motivation for new materials and module designs

- **Sustainability and legal regulations**
  - ✓ *Ecodesign*
  - ✓ *Recyclability*
  - ✓ *Replacement of rare or harmful materials*
- **New technological requirements**
  - ✓ *Wafer technology*
  - ✓ *New cell and interconnection technologies*
  - ✓ *New module designs*
- **PV systems designed for specific environmental conditions**
  - ✓ *Bulding and infrastructure integration*
  - ✓ *Floating PV*
  - ✓ *Vehicle integration*
  - ✓ *Agri PV*
  - ✓ *Desert PV*

G Oreski *et al* 2022 *Prog. Energy* **4** 032003,
https://www.doi.org/10.1088/2516-1083/ac6f3f

What is a major challenge of new PV module materials and designs?

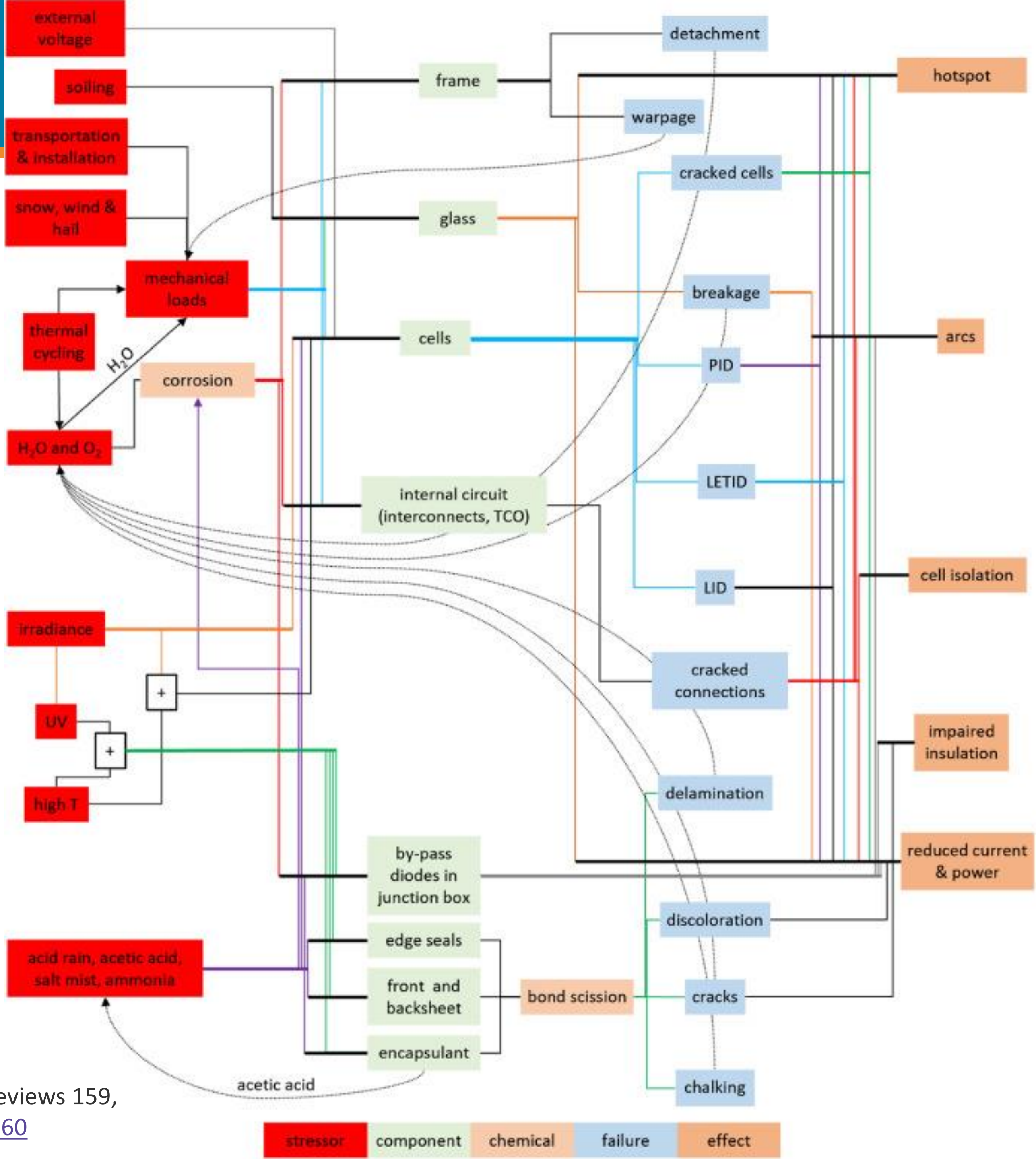
Lack of knowledge of the bill of materials and its interactions may lead to unintended failure and degradation modes

Importance of bill of materials

Flow diagram representing the relationships between stressor, component, failure and effect

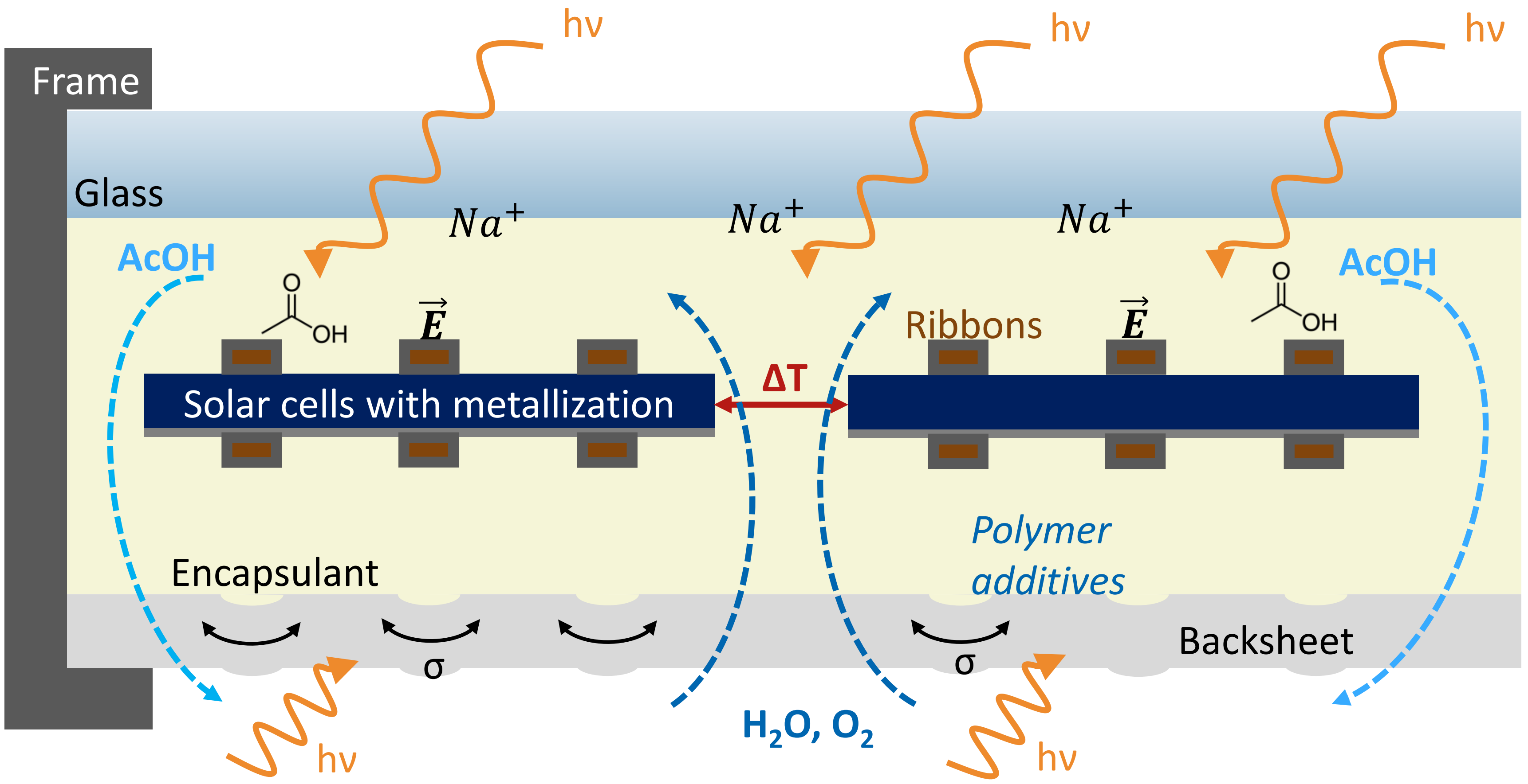
- Lines are coloured to discern line crossings
- Thick black lines to the left of the "component" and "effect" are there to indicate the termination of the connector from the previous point in the flow diagram
- Thick coloured lines to the right indicate branching
- Dotted lines indicate when failure results in a new stressor

Change of one component/material may affect the noted relationships



M. Aghaei *et al* 2022 Renewable and Sustainable Energy Reviews 159, 112160, https://doi.org/10.1016/j.rser.2022.112160

Stress factors during operation



External factors

Environmental conditions

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

Internal factors

- Bill of material
- Processing effects

A change of manufacturing process, material, component or module design can lead to

✓ *different microclimate causing varying reaction rates*

✓ *different chemical and physical processes*

✓ *new material interactions*

Some examples for BOM intransparency and its effects

Example 1: Detached junction box

Starting point

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

Problem

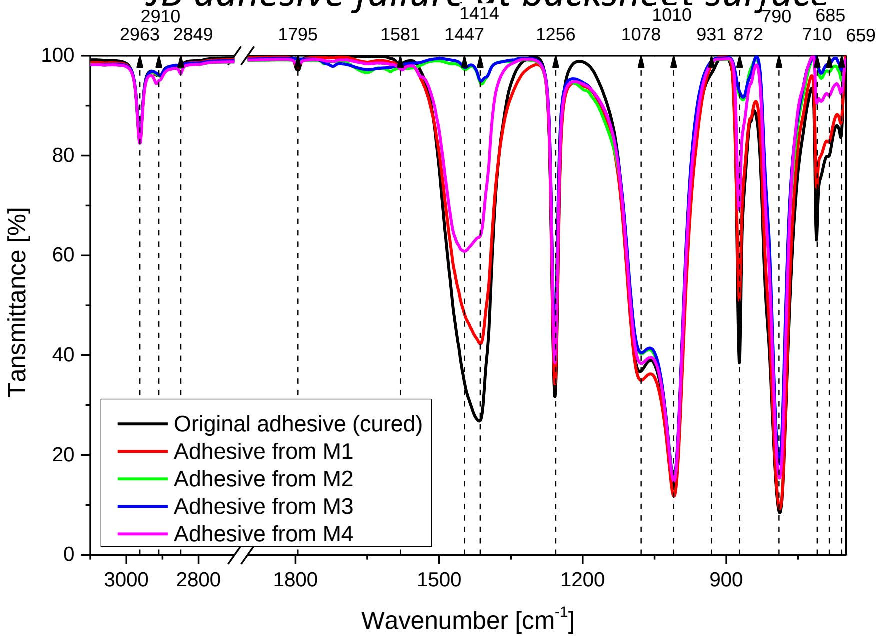
- ✓ *Randomly the junction box (JB) was either detached or missing*
- ✓ *Systems with identical modules have also been installed for the same time in other climate zones (Germany, Greece, Italy, Czech Republic), but no detached or missing junction boxes have been observed*
- ✓ *All modules underwent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

Auxiliary means

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

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

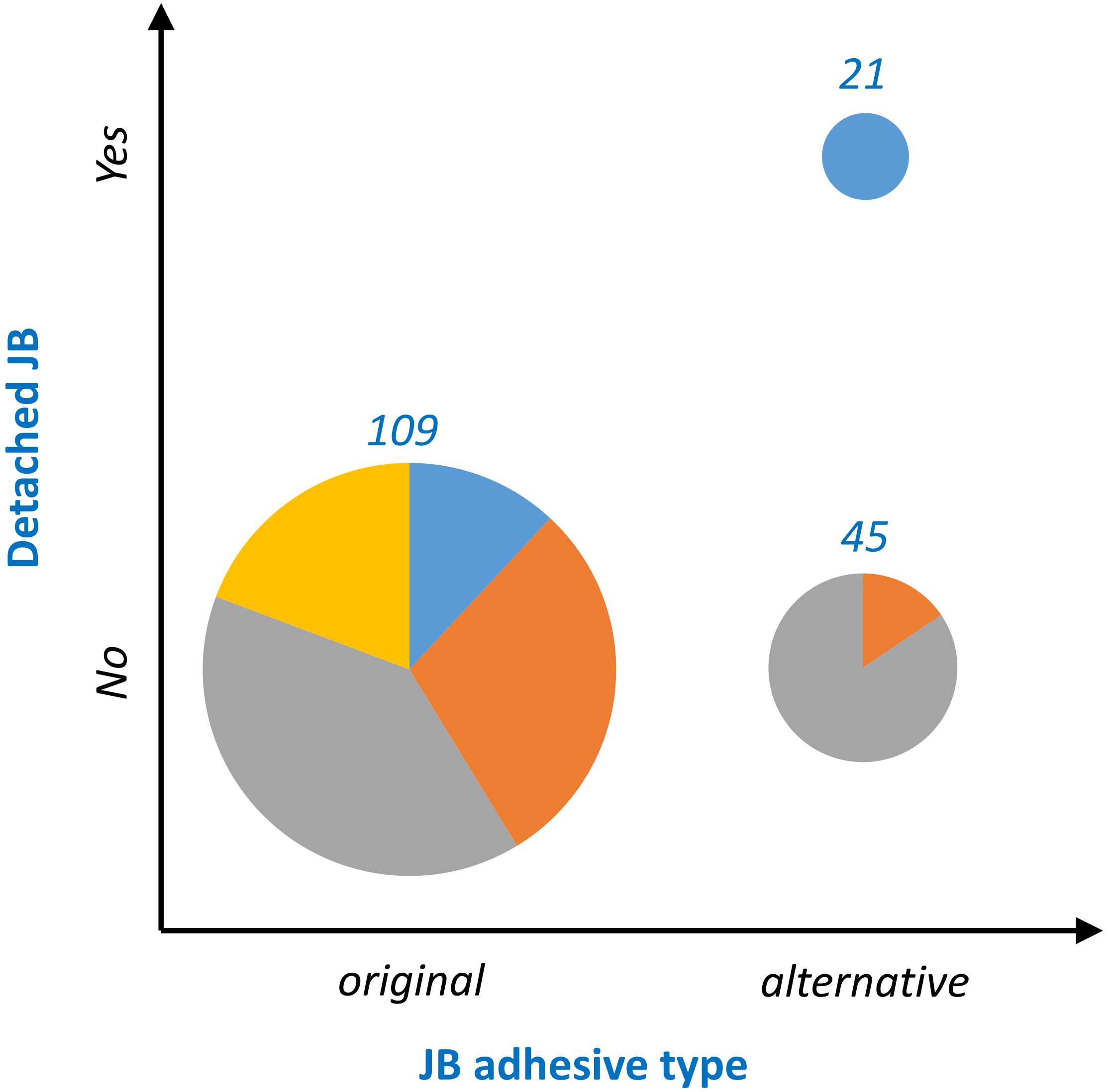
JB adhesive failure at backsheet surface



Different type of adhesive was found to be main cause for adhesion failure of junction boxes

Example 1: Detached junction box

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?

Example 2: Backsheet yellowing

What happened here?

Cost pressure from purchasing

Re-certification is expensive

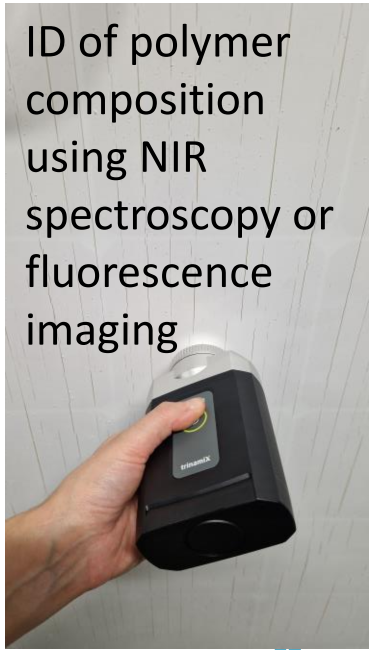
Difficult to prove during installation

Reasons for BOM variations within same module type that are not communicated properly

Different suppliers

Supply chain issues

Changes due to temporary shortages in production

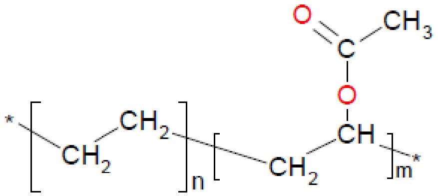


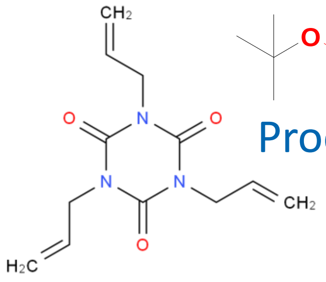
Potential future issues

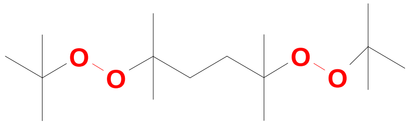
Chemical structure of encapsulants

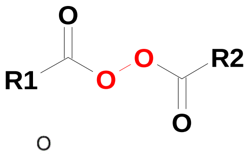
What are EVA encapsulants made of?

Function	Type	Weight%	Common examples
Base polymer	Ethylene Vinyl Acetate	96-98	
Curing agent	Peroxides	1-2	Luperox TBEC, Luperox
Curing co-agents (initiators)	Triallylisocyanurate Triallylcyanurate	n.a	Taicros
Adhesion promoter	Trialkoxy silanes	0.2-1	Silane A 174, Dynasylan
UV absorber	Benzophenones, benzoltriazoles	0.2-0.35	Tinuvin 234, Cyasorb 531, Chimasorb 81
UV stabilizer – primary antioxidant	Hindered amine light stabilizers (HALS)	0.1-0.2	Tinuvin 123, Tinuvin 770
Primary antioxidants	Sterically hindered phenols	n.a	BHT
Secondary antioxidants	Phenolic phosphonites	0-0.2	Irgafos 168, Naugard P

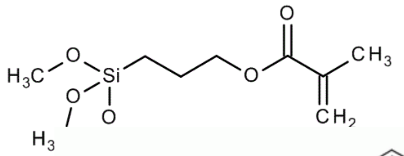


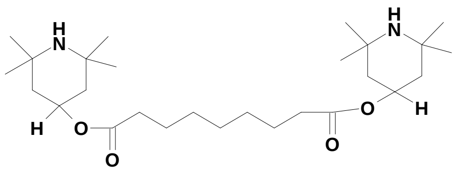


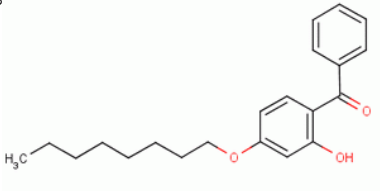




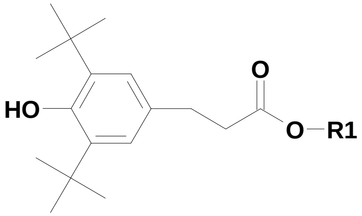
Processing additives

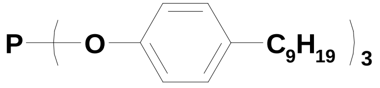






Stabilizers





G. Oreski, B. Ottersböck, A. Omazic, 6 - Degradation Processes and Mechanisms of Encapsulants, In: Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules, https://doi.org/10.1016/B978-0-12-811545-9.00006-9

Chemical structure of encapsulants

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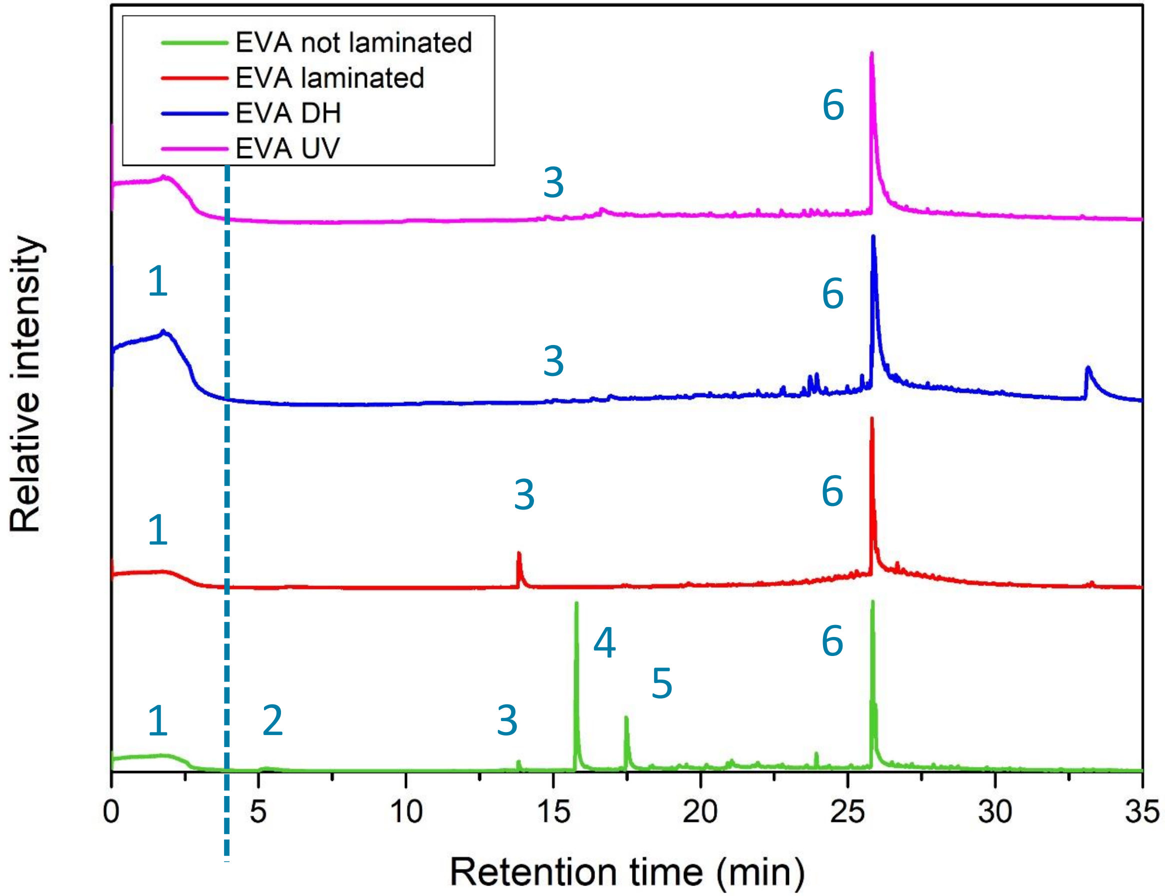
Additive analysis of EVA from PV modules

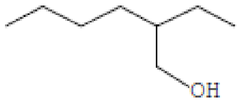


Thermal Desorption - Gas chromatography coupled with mass spectrometry

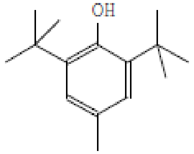
Ageing tests:

- DH (85°C/85% R.H.), 3000 hours
- UV exposure ~85 kWh/m^2 (ISO 4892-3 Cycle 1)
- Single layers of cured encapsulant

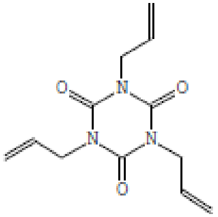
1) Acetic acid
2) Fragment of peroxide



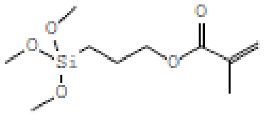
3) Antioxidant



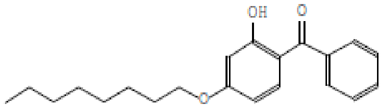
4) Crosslinking agent



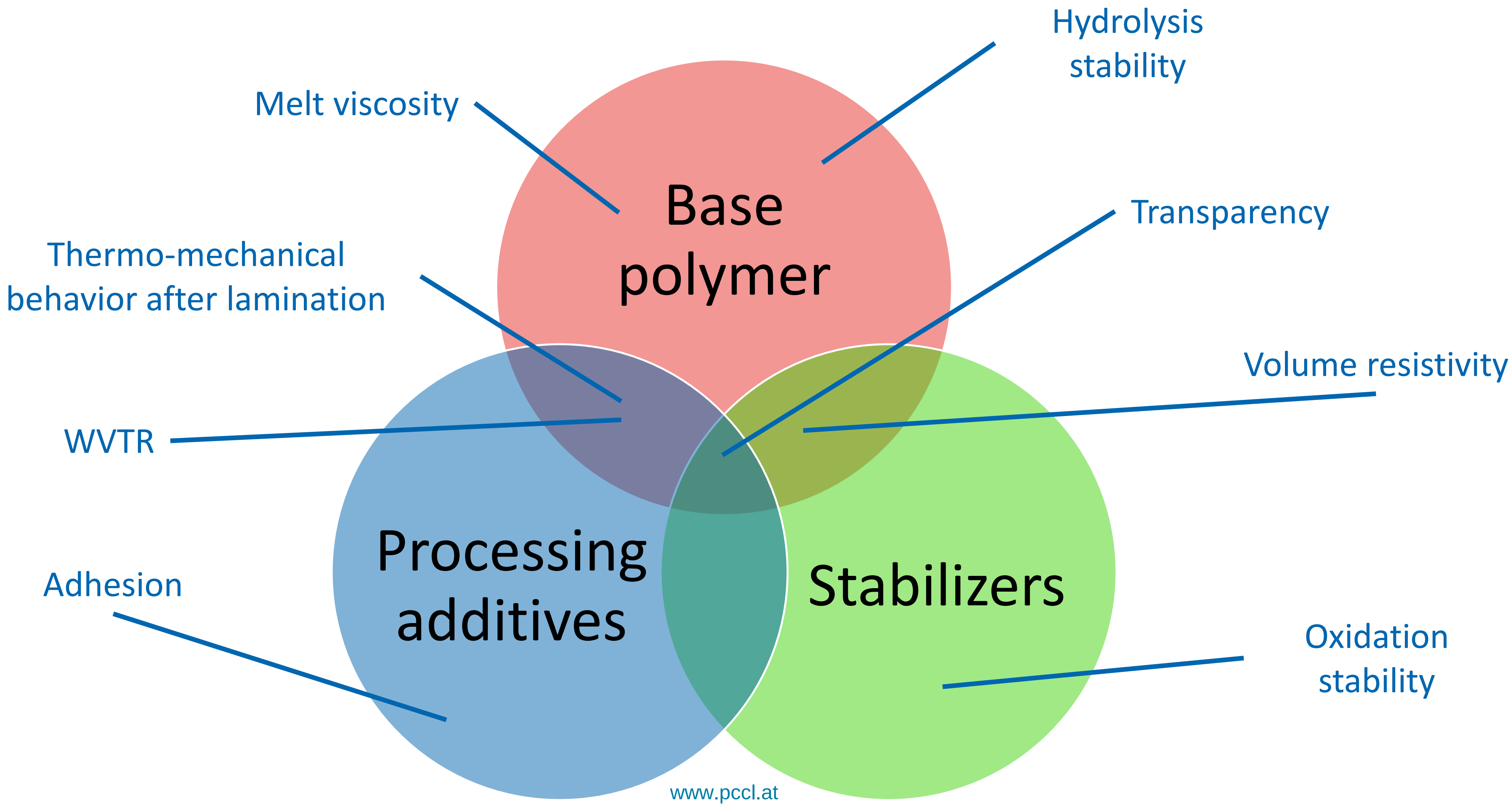
5) Adhesion promotor



6) UV absorber



Which component defines encapsulant properties?



The polyolefin misconception

Why shouldn´t we call "polyolefin" encapsulants that way?

- ✓ Do these objects have something in common?
- ✓ What would you call them?
- ✓ How would you compare them?
- ✓ Knowing one of them, would you be able to draw conclusions on all the others?

*"A **polyolefin** is any of a class of polymers produced from a simple **olefin** (also called an **alkene** with the general formula C_nH_{2n}) as a monomer"*

- ✓ Thermoplastic polyolefins: Polyethylene (PE), polypropylene (PP), polymethylpentene (PMP), polybutene-1 (PB-1)
- ✓ Polyolefin elastomers (POE): Polyisobutylene (PIB), ethylene propylene rubber (EPR), ethylene propylene diene monomer (M-class) rubber (EPDM rubber)

→ Term „Polyolefin" has different meaning in PV industry

The polyolefin misconception

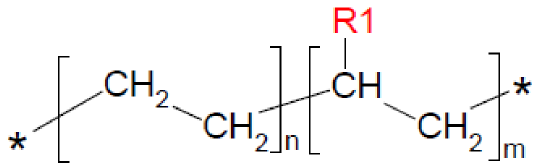
What are "polyolefin" encapsulants made of?

Ethylene *can be copolymerized with*

- *(i) other monomers like α-olefins*
- *(ii) a wide range of other un-saturated monomers*
- *(iii) ionic composition that creates ionized free radicals*

*→ **Ethylene Copolymers***

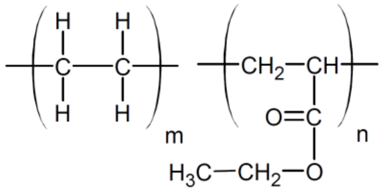
- *Ethylene α-olefin copolymer*
- *Ethylene acrylate copolymers*
- *Ethylene acrylic acid copolymers (Ionomers)*
- *[Ethylene vinyl acetate (EVA)]*



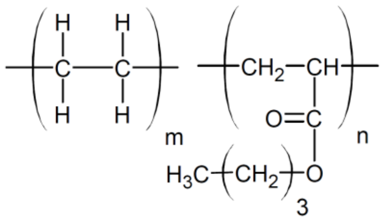
Market inventory (done with help from NREL, CWRU, ISE, EPFL, CSEM, IP-Fab, Dow) - Paper coming in Summer 2023

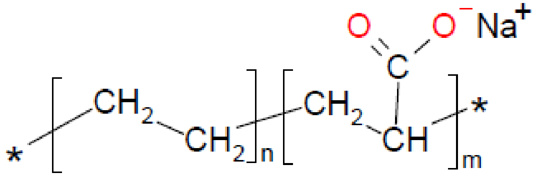
- ✓ > 30 different types from > 20 manufacturers
- ✓ Production dates ranging from 2006 to 2022
- ✓ 4 different base polymers
- ✓ 3 different curing chemistries
- ✓ Melting temperatures ranging from 54°C to 113°C

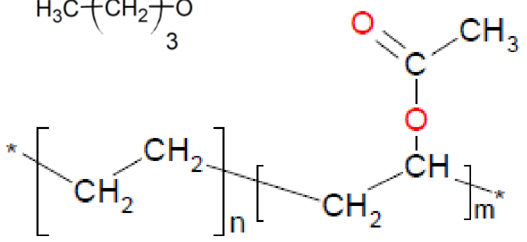
Ethylene-ethyl acrylate (EEA)



Ethylene-butyl acrylate (EBA)





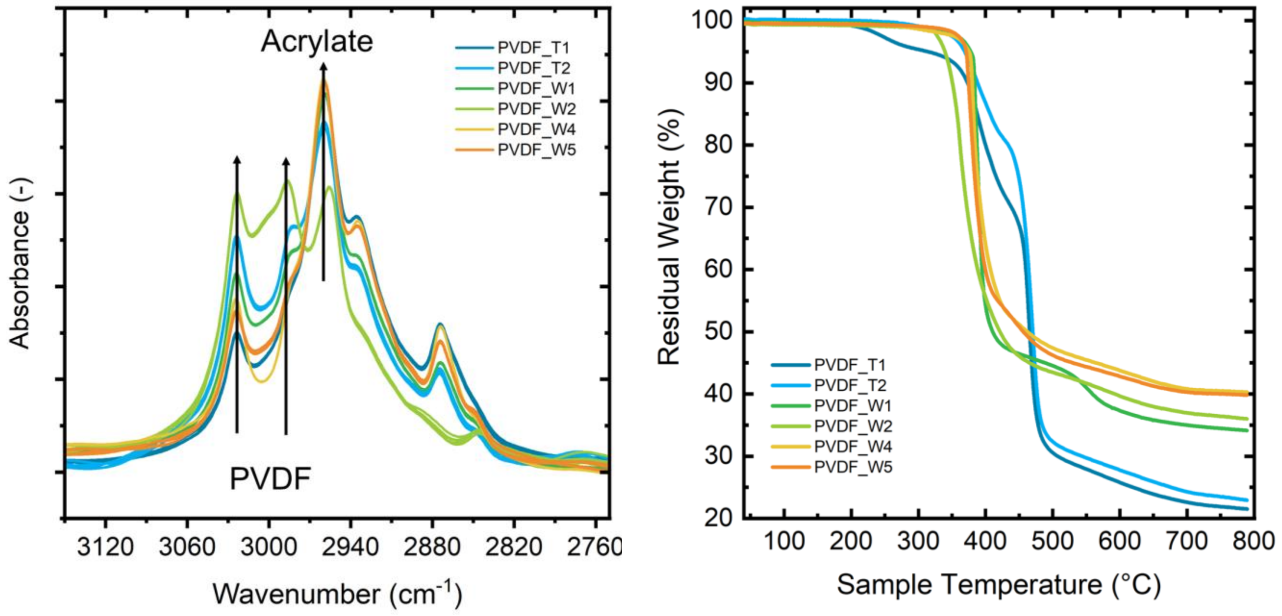


www

PVDF backsheets

What about PVDF backsheets?

- PVDF based backsheet have currently the highest market share
- Significant backsheet cracking also found for PVDF
- Cracking was found consistently in machine direction of backsheet - possible correlation with anisotropic mechanical properties
- PVDF shows strong physical aging effects (changes in crystallinity & crystalline phase, shrinkage) upon exposure to elevated temperature



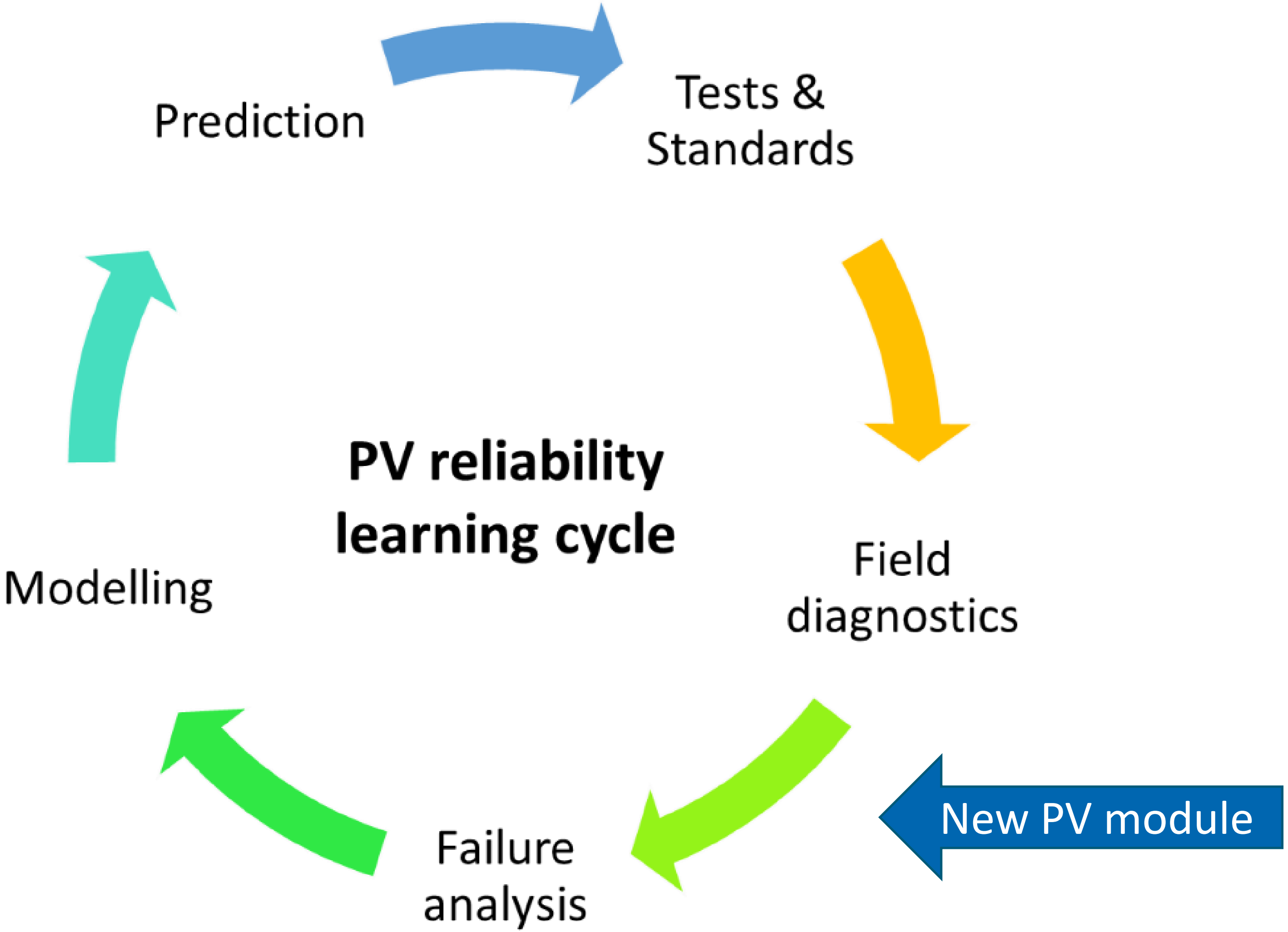
C. Barretta et al. (2022), Chemical and morphological characterization of PVDF films used for photovoltaic backsheets, 8-WCPEC, Milano (I)

- Exact composition of PVDF for backsheets often not known / not given
  - ✓ *PVDF / PMMA / TiO_2 compound*
  - ✓ *Different PVDF copolymers*
  - ✓ *Multilayer structures*

Mitigation measures?

Reliability learning cycle

- **Main issue:** It takes up to several years from installation to first occurrence of failure mode to understanding of failure modes
- **Additional complication:** Every single change or variation in BOM potentially changes the outcome

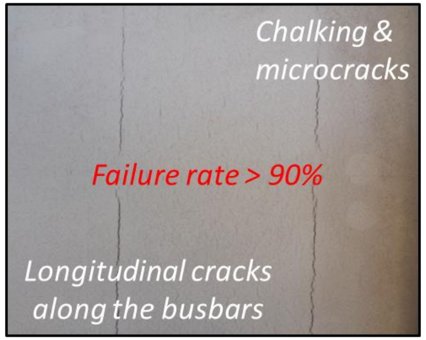


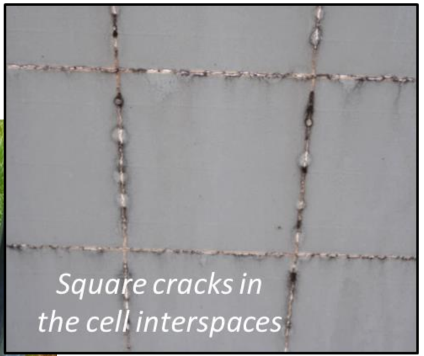
Reliability learning cycle: PA backsheet cracking

Market introduction → First anomalies and concerns → First failure reports → Failure mode analysis → Test development → Test standard

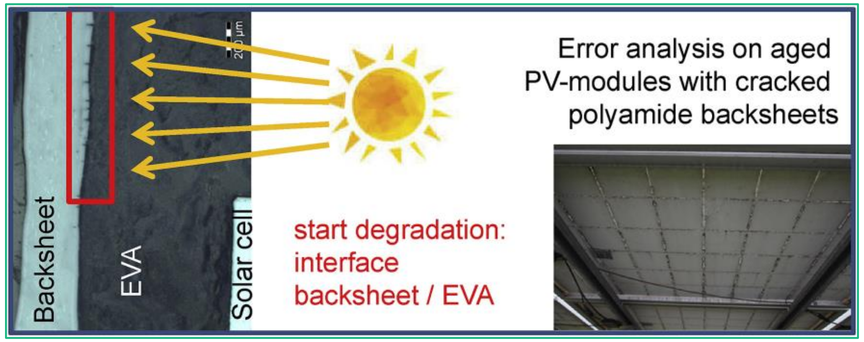
- *Market introduction of co-extruded polyamide based backsheets (AAA)*
- *~15GW of PV with AAA backsheets was sold between 2010 and 2015*

From 2015 on: Observation of chalking and microcracks



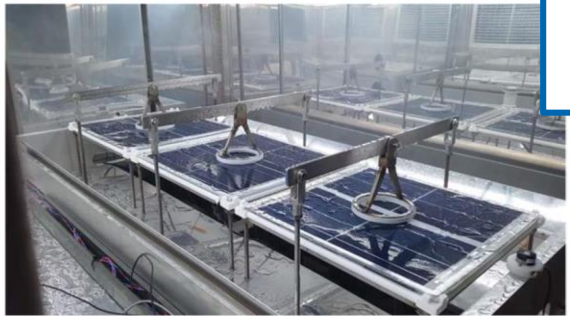


From 2016 on: First reports of cracking



https://doi.org/10.1016/j.solmat.2019.110194

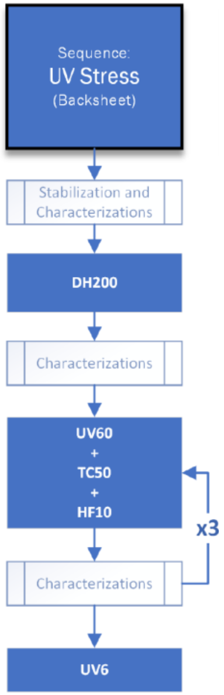
2019: First failure mode analysis papers published



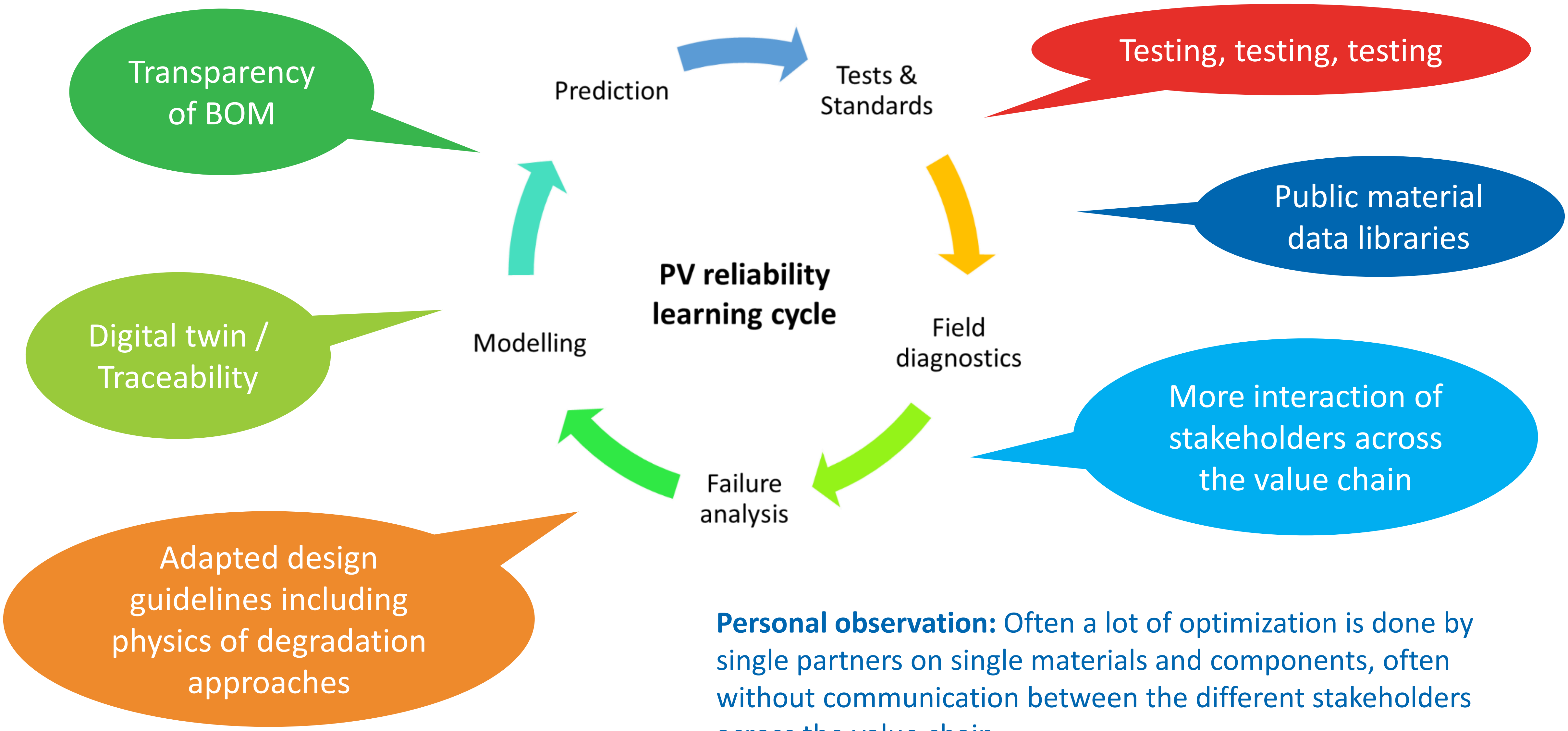
Owen-Bellini et al. (2020)
https://doi.org/10.1002/pip.3342

2020: First replication of backsheet cracking with combined accelerated stress test

2021: New standard on extended stress testing IEC TS 63209-1



Mitigation measures



Personal observation: Often a lot of optimization is done by single partners on single materials and components, often without communication between the different stakeholders across the value chain

Summary & Conclusion

- 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

Mention NIR Trinamix

Outlook

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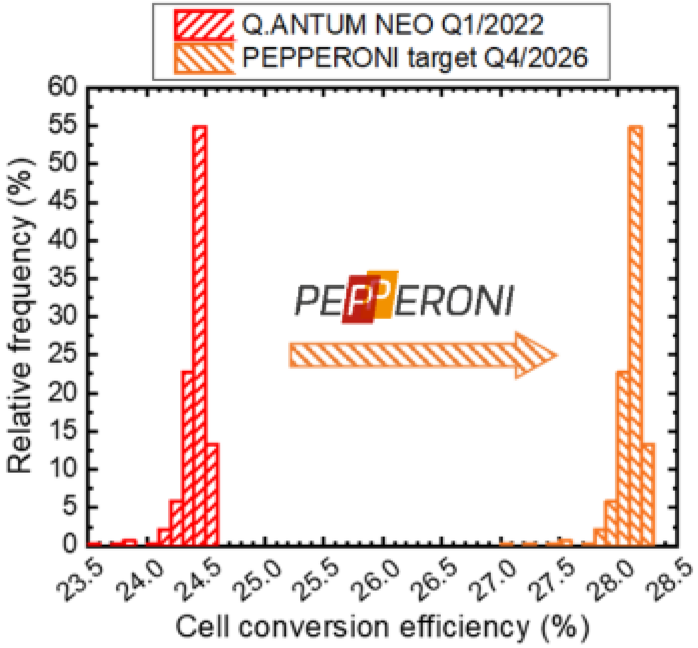
4-year project

Results (by 2026, TRL7)

- ✓ **Pilot line** for perovskite/Si tandem modules established at QC facilities in Germany with target capacity of **200 MW/year**
- ✓ **Production equipment** allowing high production yields >90%, qualified for industrial scale production
- ✓ **New materials** defined, characterised and validated
- ✓ New knowledge on **socio-economic aspects and recycling potential**
- ✓ **Improved stability** (potential lifetime >30 years) and **performance** (>28% cell efficiency on full area M10 industrial wafers) of PK/Si tandem cells



- **Long-term outdoor behavior or perowskite top cell in double glass module simply not known**
- **Short term tests mainly focus on damp heat tests / stability towards humidity**
- **Thermo-mechanical loads will be a major challenge for the reliability of the top cell**
- **What will happen if the perovskite top cell stops working?**

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Thank you for your attention!

Project funding

solartrain

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PVRe²

Energy Research Programm -, FFG No. **867267**, Klima- und Energiefonds

klima energie fonds

INFINITY

Energy Research Programm -, FFG No. **850414**, Klima- und Energiefonds

FFG

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International Energy Agency
Photovoltaic Power Systems Programme

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