Reliability testing of new Polyolefin Encapsulants and Backsheets

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Outline

- Overview polymeric encapsulants & backsheets for PV-modules

- Polyolefin PV-components
- Reliability testing (according to standards and climate specific)

- Experimental / analytical and electrical results
    - materials / modules under test
    - material stability / material compatibility
    - electrical performance

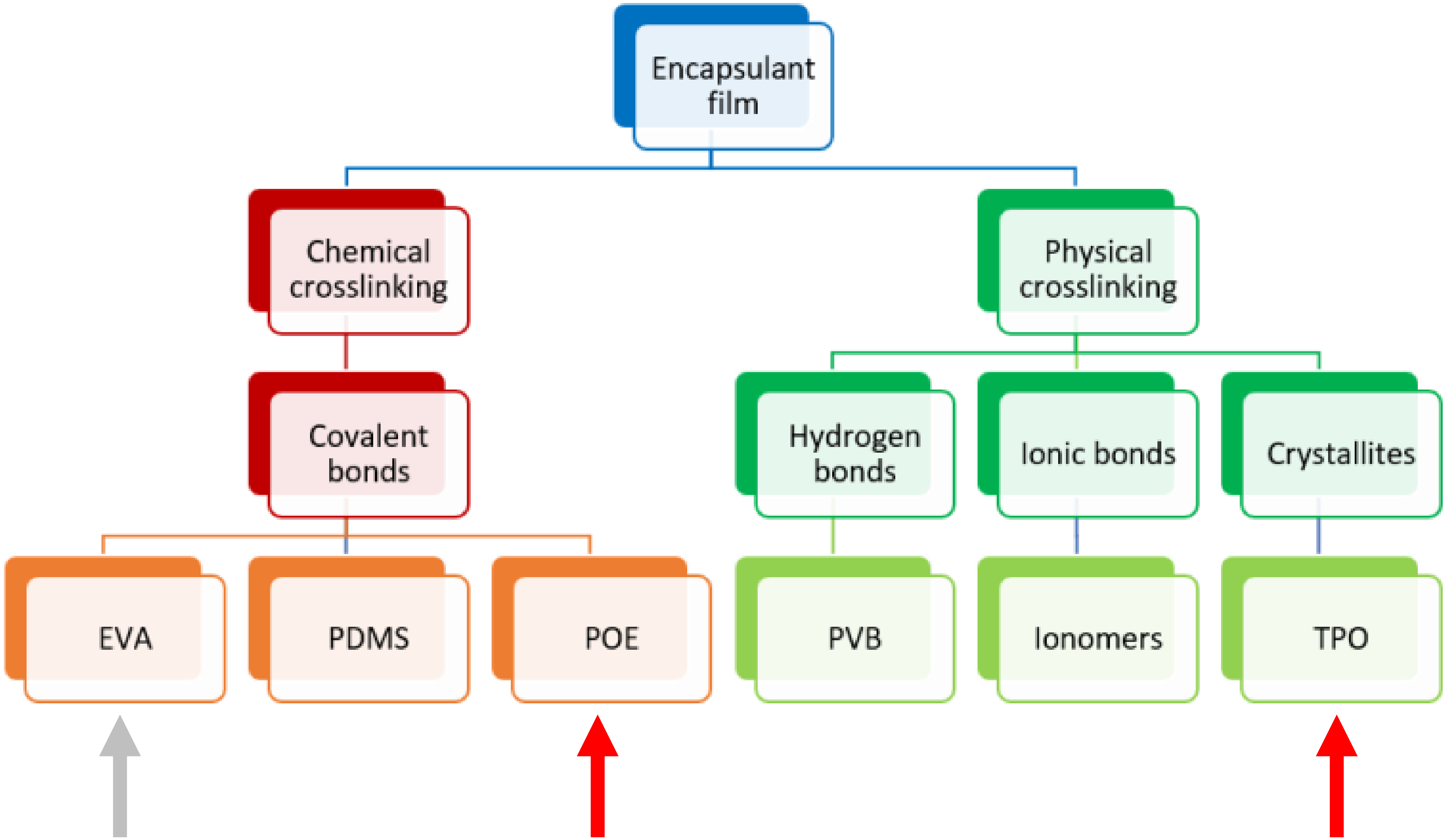
- Results – performance degradation modelling:

  Analysis of electrical performance /degradation by backsheet and encapsulant

  analysis of variance

  mixed effects models
- Conclusions and summary

Encapsulants for PV-Modules



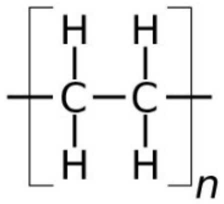
https://iea-pvps.org/wp-content/uploads/2021/04/IEA-PVPS-T13-13_2021_Designing-new-materials-for-photovoltaics-report.pdf

Polyolefin Encapsulants

.....are developed as **replacement of EVA**

→ polyethylene PE or PE copolymers (PE backbone with different side groups e.g. acrylates, acrylic acids or n-alkanes)

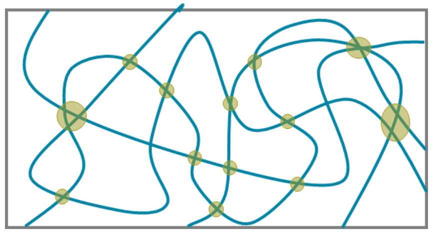
Polyethylene



- **ThermoPlastic Olefins (TPO)**

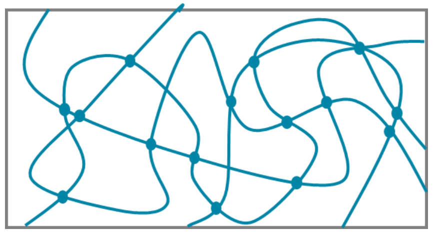
  thermo-reversible physical crosslinks like ion bonds, hydrogen bonds or via crystallites

  -> thermoplastic material -> lamination process: only melting - no crosslinking -> allows for processing times < 10min



- **PolyOlefin Elastomers (POE)**

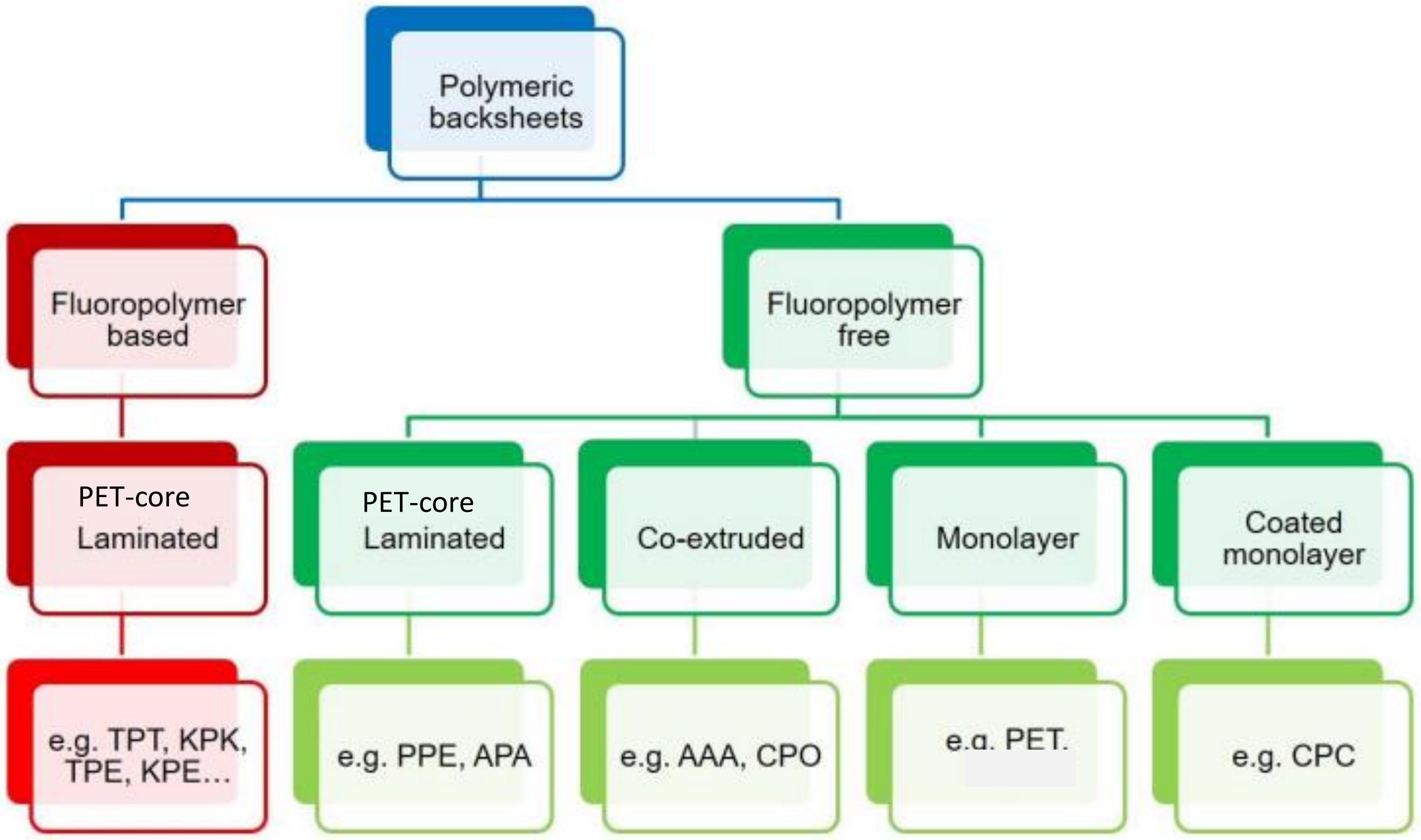
  POE films contain crosslinking agents, which form a 3-dimensional network in the lamination process (as EVA); chemical crosslinking -> elastomer material



- higher volume resistivity and lower WVTR than EVA
- higher transmittance and higher chemical inertness than EVA (no hydrolysis; no acetic acid formation)

Properties and degradation behaviour of polyolefin encapsulants for photovoltaic modules; Prog Photovolt Res Appl.2020;28:1277–1288; G.Oreski, A. Omazic, G.Eder; https://doi.org/10.1002/pip.3323

Backsheets for PV-Modules



3-layer architecture

Mono-layer

https://iea-pvps.org/wp-content/uploads/2021/04/IEA-PVPS-T13-13_2021_Designing-new-materials-for-photovoltaics-report.pdf
and Prog. Energy 4 032003: https://doi.org/10.1088/2516-1083/ac6f3f

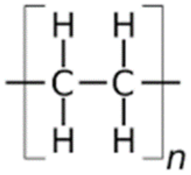
Polyolefin Backsheets

….. are developed for the replacement of PET, F-Polymer and PA-based backsheets

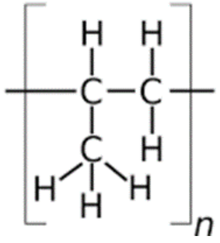
→ use of polypropylene PP, polyolefin blends (PE and PP) or mod. PP

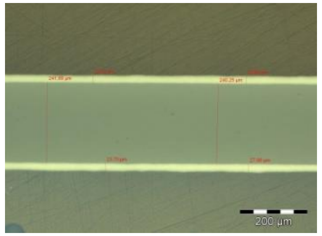
→ 3-layer backsheets are available; fluor-polymer free, sustainable material

Polyethylene

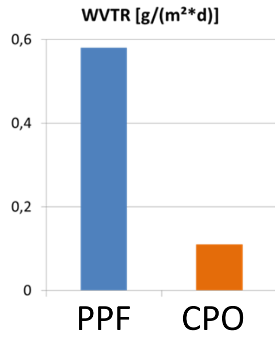


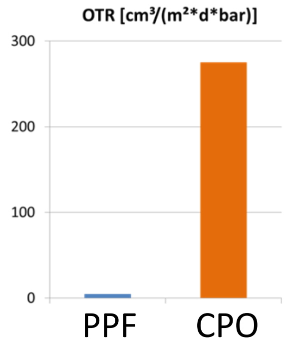
Polypropylene





- **Coextruded PolyOlefins (CPO)**
  - Co-extruded PP backsheets have lower stiffness and higher flexibility than laminated backsheets with a PET core
  - more simplified manufacturing, lower moisture permeability and better hydrolytic stability (generally: good chemical stability)
  - Polymers used (PP, PE) are usually cheaper than fluor-polymers and easier to produce than PET films





Performance of PV modules using co-extruded backsheets based on polypropylene, Solar Energy Materials and Solar Cells,223,2021,110976; G. Oreski, G.C. Eder;
https://doi.org/10.1016/j.solmat.2021.110976

Reliability testing: Modules / Components - Standards

According to standards

IEC 61215-1:2021 and -2

Terrestrial photovoltaic (PV) modules - Design qualification and type approval

Part 1: Test requirements

Part 2: Test procedures

IEC 62788-2:2017 – Series

Measurement procedures for materials used in photovoltaic modules

Part 1: Polymeric materials - Encapsulants

Part 2: Polymeric materials - Frontsheets and backsheets

Part 7-2: Environmental exposures - Accelerated weathering tests of polymeric materials

IEC TS 63209-1:2021 Photovoltaic modules - Extended-stress testing - Part 1: Modules

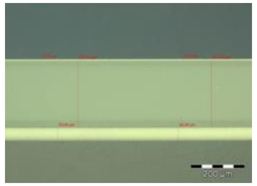
Climate specific Reliability Testing

Aging action	Duration		Temperature T Module	Chamber	Rel. Humidity H Module	Chamber	Irradiance I	DML	Salt	TC	Intervalls
Reference	1000h	1	-	85°C	-	0,85	-	-	-	-	constant
Moderate 1	1000h	1	113°C	85°C	0,304	0,85	1000 W/m²	-	-	-	constant
Moderate 2	1000h	1	78 °C	60°C	0,181	0,4	1000 W/m²	-	-	-	48h
	= 7 cycles	2	-	85°C	-	0,85	-	-	-	-	96h
Moderate 3	1000h	1	78°C	60°C	0,181	0,4	1000 W/m²	-	-	-	48h
	= 7 cycles	2	-	85°C	-	0,85	-	-	-	-	96h
		3	-	-	-	-	-	1000 c	-	-	24h
Moderate 4	1000h	1	78°C	60°C	0,181	0,4	1000 W/m²	-	-	-	48h
	= 7 cycles	2	-	85°C	-	0,85	-	-	-	-	96h
		3	-	60°C	-	-	-	-	Salt-mist	-	24h
Moderate 5	3000h	1	78°C	60°C	0,181	0,4	1000 W/m²	-	-	-	48h
	= 7 cycles	2	-	85°C	-	0,85	-	-	-	-	96h
		3	-	-40/+85°	-	-	-	-	-	50 c	300h
Alpin 1	2000h	1	-	85°C	-	0,85	-	-	-	-	250h
	= 4 cycles	2	119°C	85°C	0,249	0,85	1200 W/m²	-	-	-	250h
		3	-	-	-	-	-	1000 c	-	-	24h
Tropical 1	3000h	1	-	85°C	-	0,85	-	-	-	-	constant
Tropical 2	3000h	1	-	90°C	-	0,9	-	-	-	-	constant
Arid 1	1000h	1	129°C	95°C	0,157	0,5	1200 W/m²	-	-	-	constant

Experimental &
analytical and electrical Results

Modules under test - Materials

Type	Material composition	Thickness [µm]	Remark
EVA	Ethylene Vinyl Acetate	480	crosslinking
POE	Ethylene Acrylate Copolymer	400	crosslinking
TPO	Polyethylene based	Front: 445 Back: 460	non-crosslinking
CPO	Polypropylene	285	co-extruded
PPF	Polyester based with inner F-coating	310	laminated



Investigation of the degradation behaviour with respect to

(i) potential material incompatibilities

(ii) the module performance

in dependence of the encapsulant and backsheet type used;

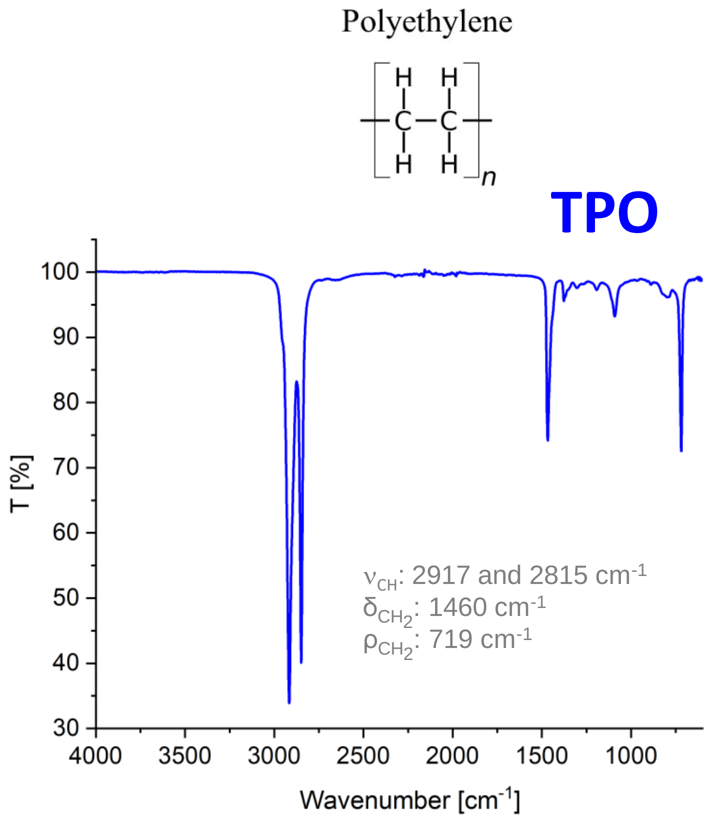
Framed 6-cell test modules:

- structured front glass (3.2 mm)
- encapsulant (EVA or TPO or POE)
- m-crystalline and mono-facial Si-cells
- standard SnPb-coated Cu-ribbons
- backsheet (PPF or CPO)

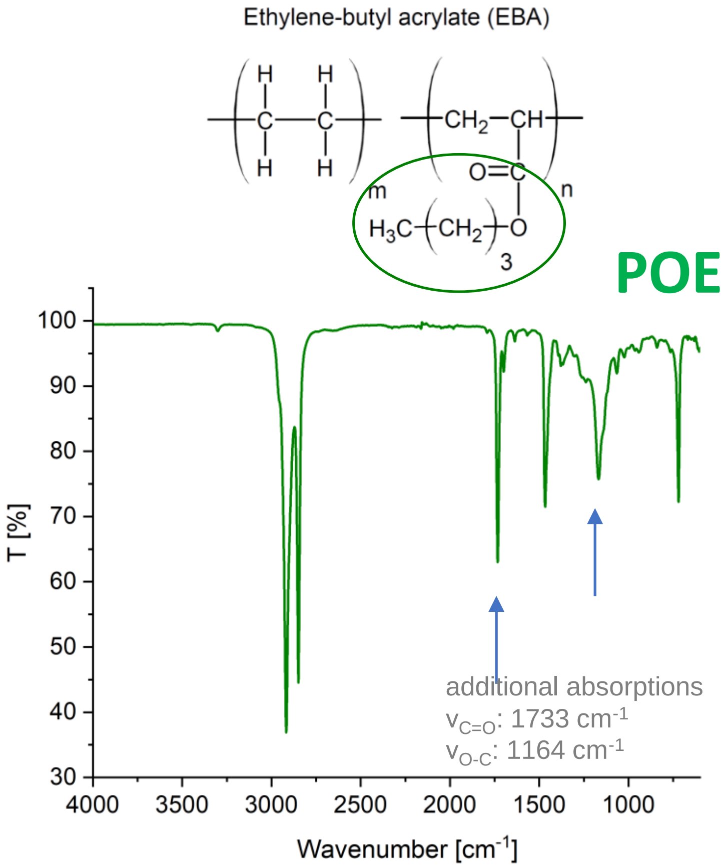
At minimum, 3 identical modules were manufactured for each module type/composition

Encapsulants – Material Characterisation / IR

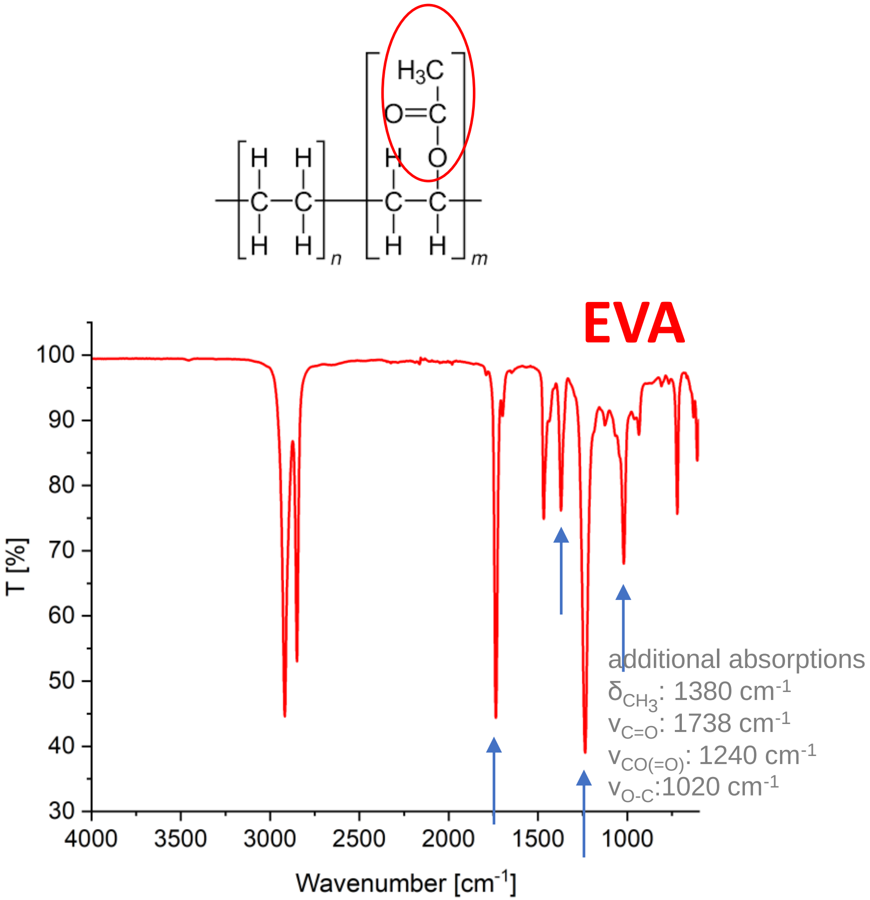
- All have polyethylene backbone



PE



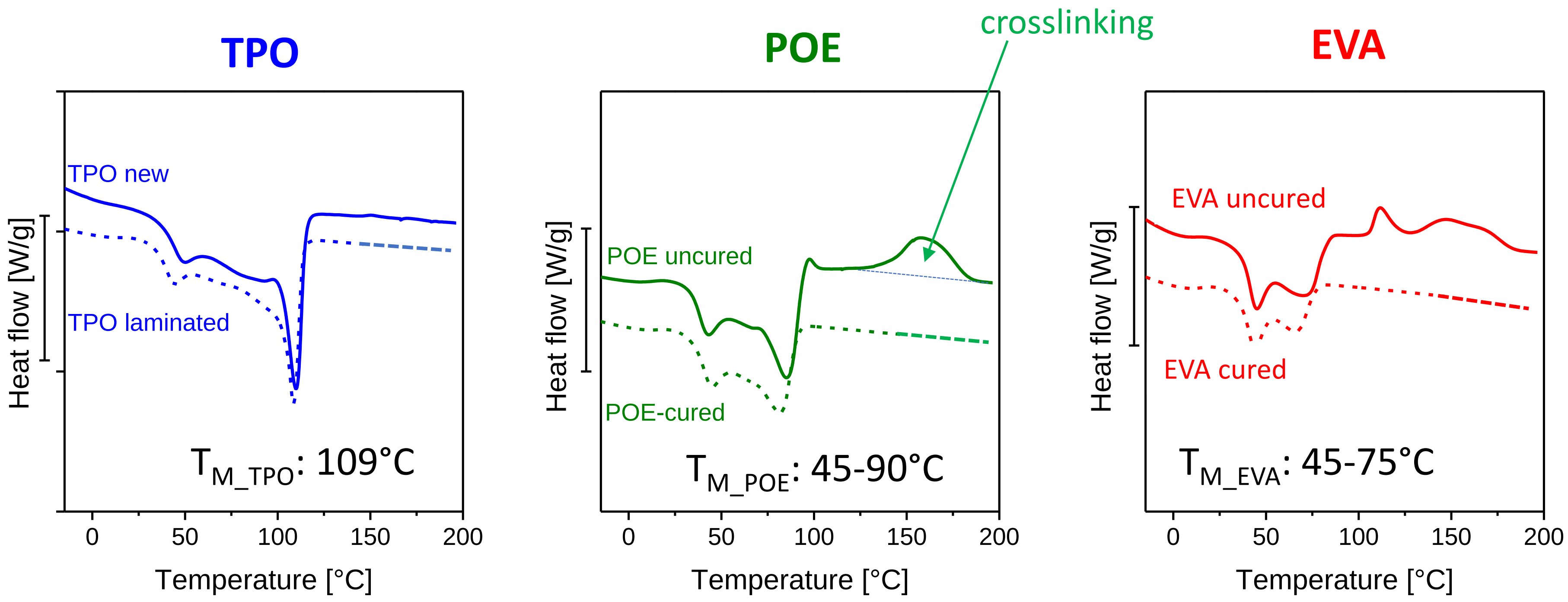
PE + acrylate-modification



PE + acetate-groups

Encapsulants – Material Characterisation / DSC

- Different thermal behaviour



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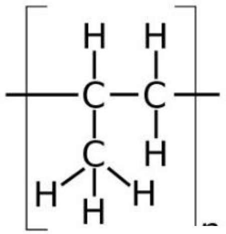
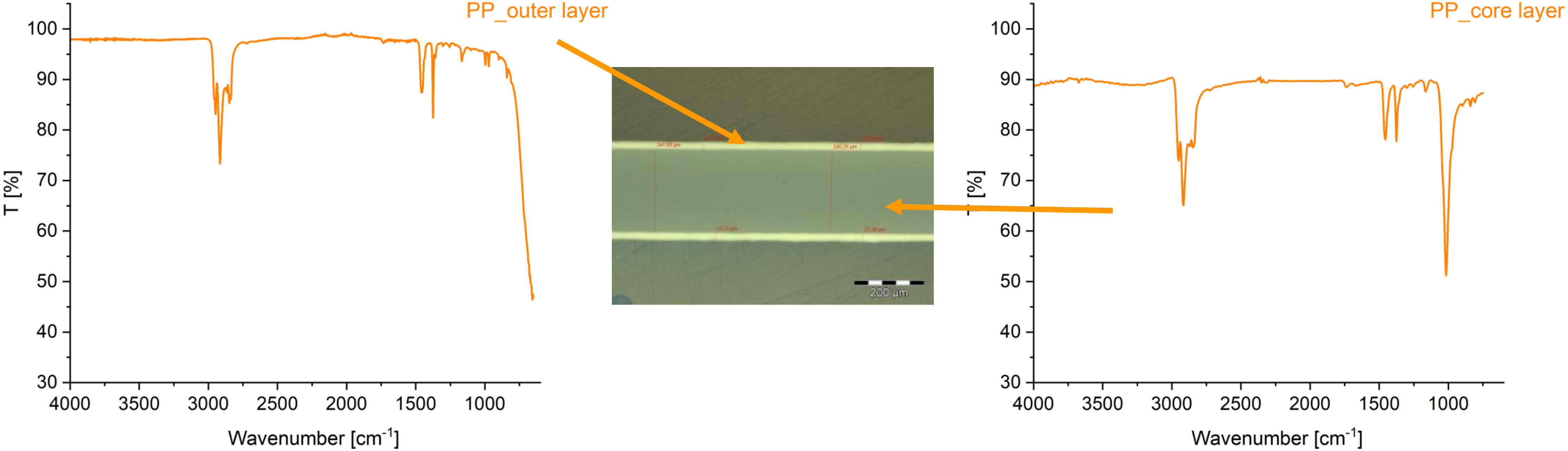
Polyolefin Backsheet – Material Characterisation / IR

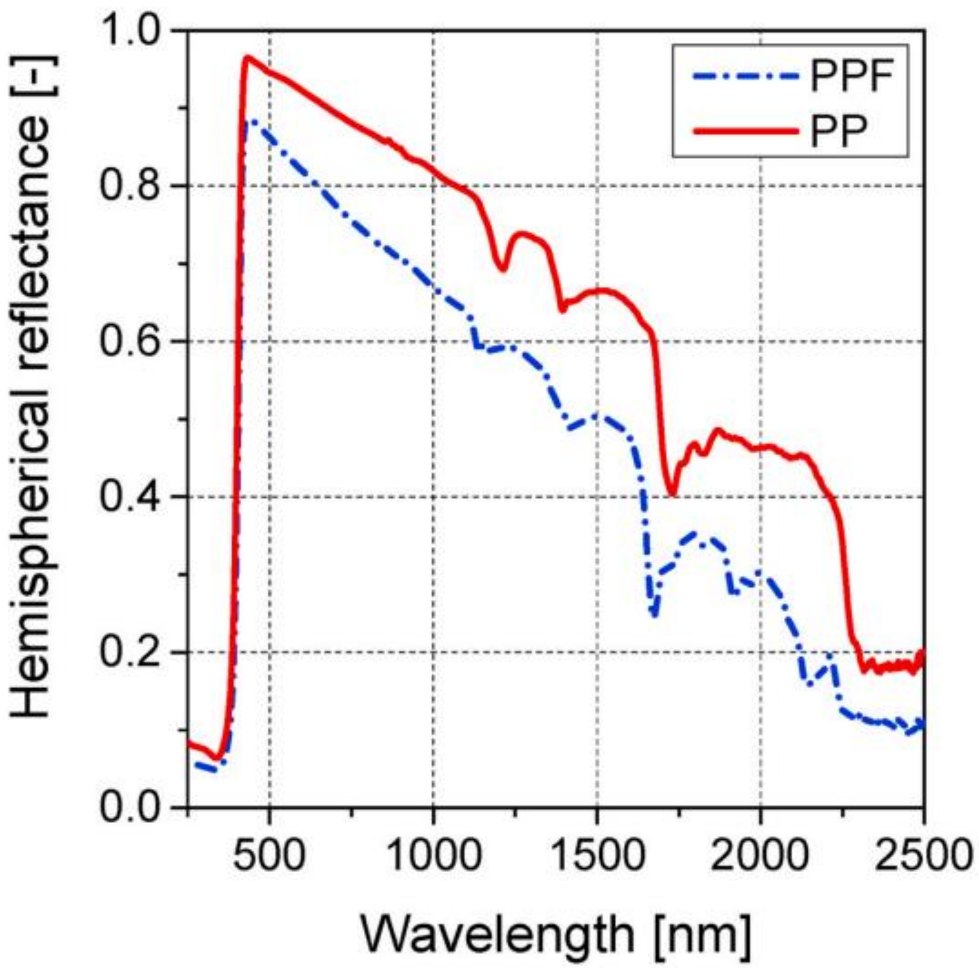
- CPO based on polypropylene / 3 layers:
  1. PP + TiO_2
  2. PP + Talcum
  3. PP + TiO_2

Polypropylene





Polyolefin Backsheet –
Material Characterisation / Reflectance



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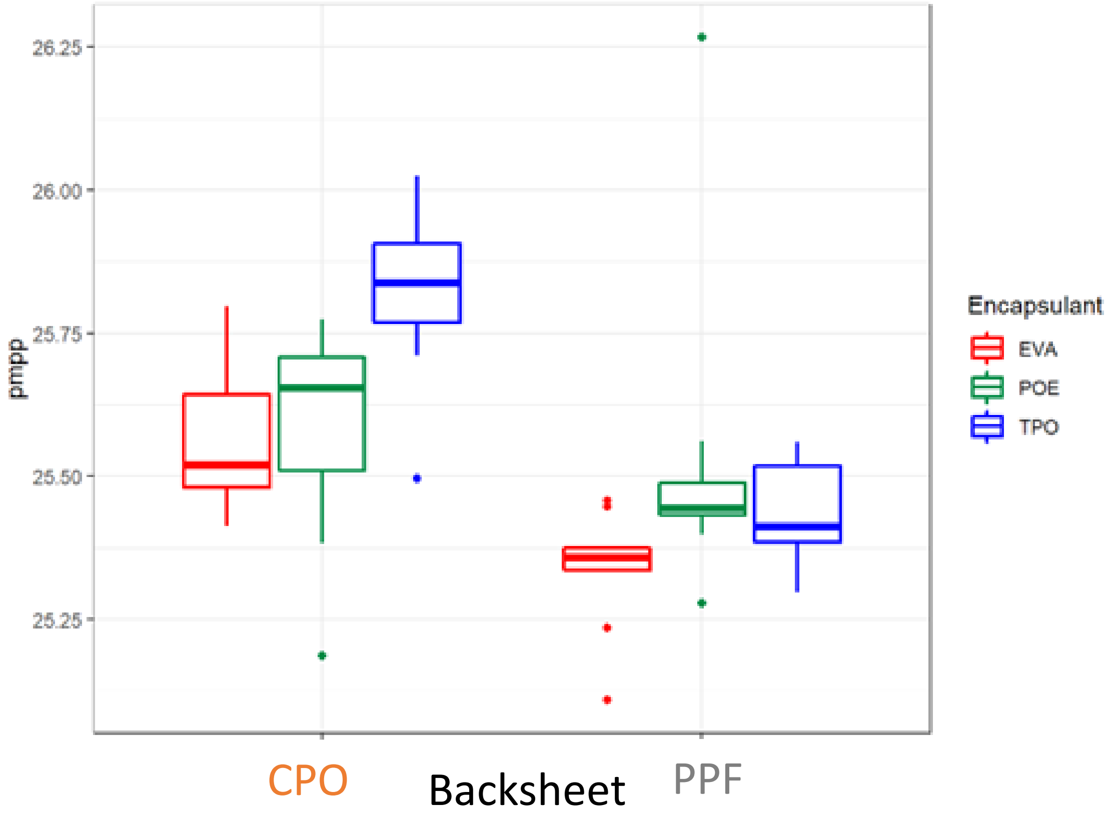
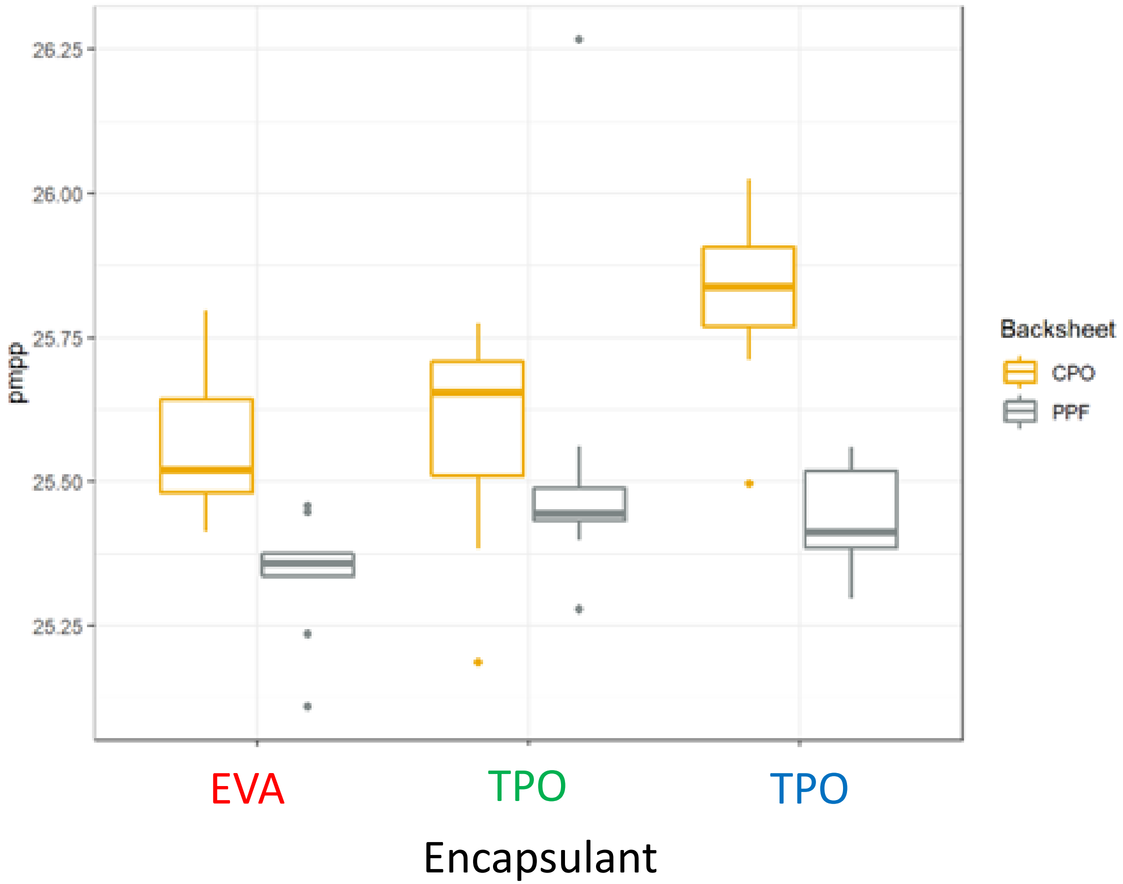
Analysis of electrical performance (P_{mpp}) - by Backsheet and Encapsulant – Original state





Test modules with Polyolefin PV-Components – Reliability testing

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Type	Duration	Temperature	Humidity	Irradiation	Remarks
Damp Heat (DH)	1000h 2000h 3000h →6000h	85°C	85% r.H.	no	constant
Irradiation (I)	1000h 2000h	50°C	< 50% r.H	1000W/m² (300-2500nm) metal halide lamps	constant
Sequential (DH-I-H)	S1: 330h S2: 8h S3: 8h	85°C 50°C 30°C	85% r.H < 50r.H. 85% r.H	no 1000W/m² (300-2500nm) no	sequential test procedure: S1 + 40x (S2 + S3)

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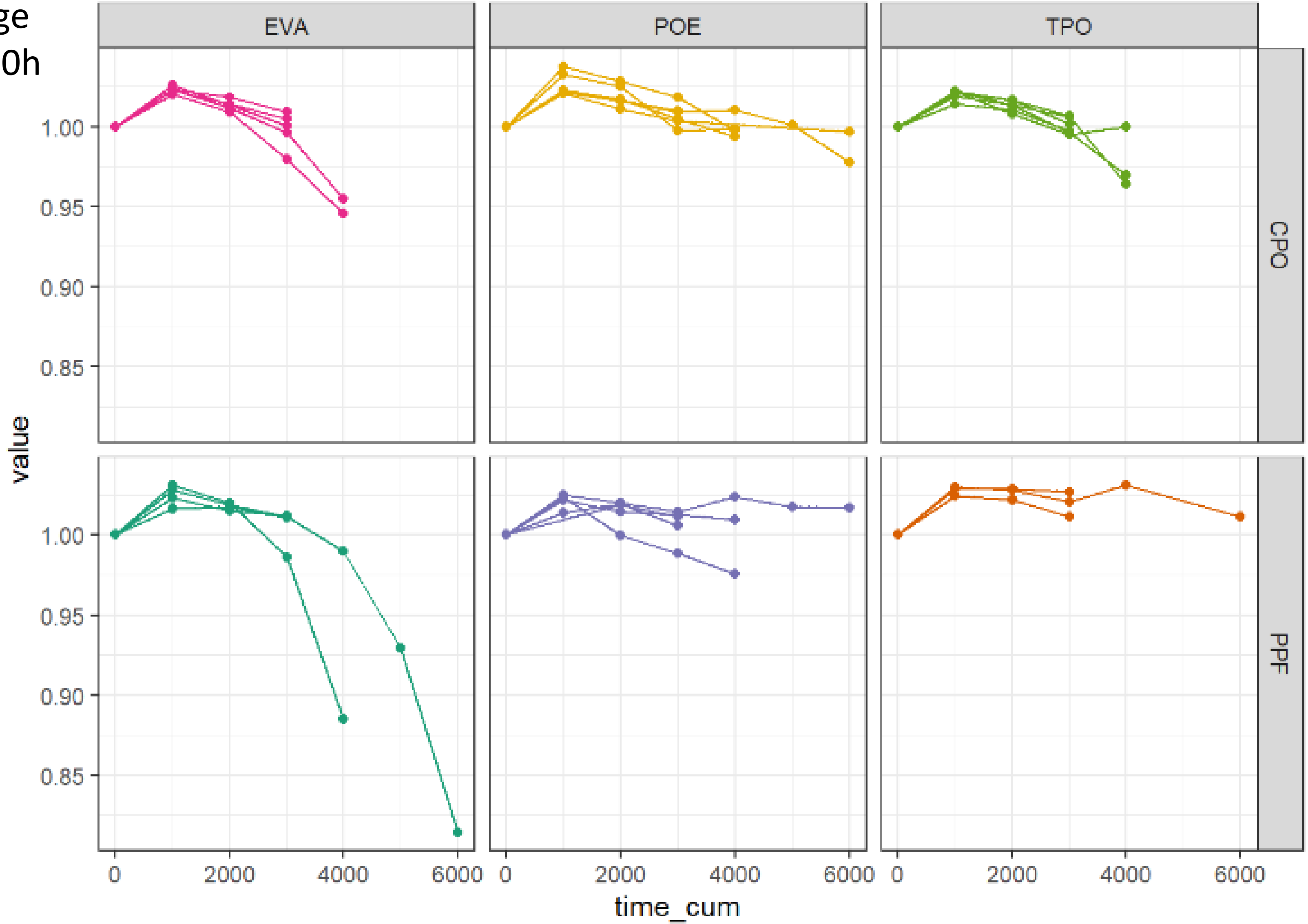
Analysis of electrical performance (norm. Pmpp) - by Backsheet and Encapsulant / DH-Storage

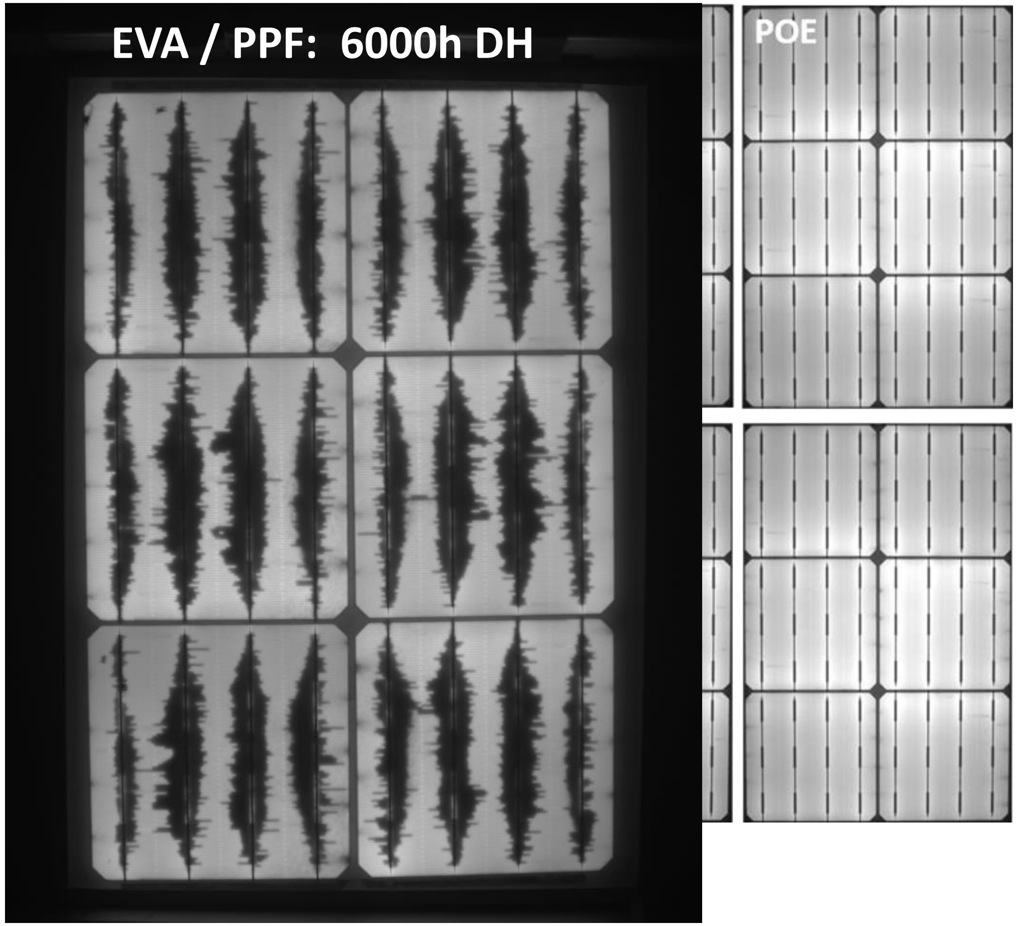
DH-Storage
up to 6000h



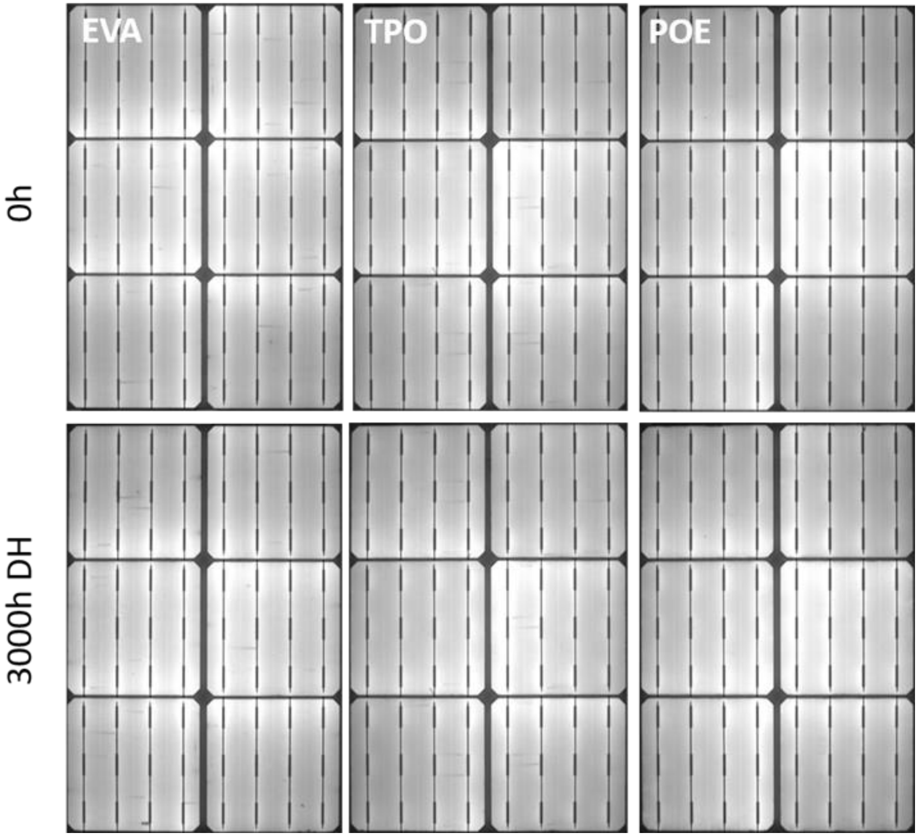
…still work in progress…

Analysis of EL-images by Backsheet and Encapsulant (0 and 3000h DH)

PPF-Backsheets



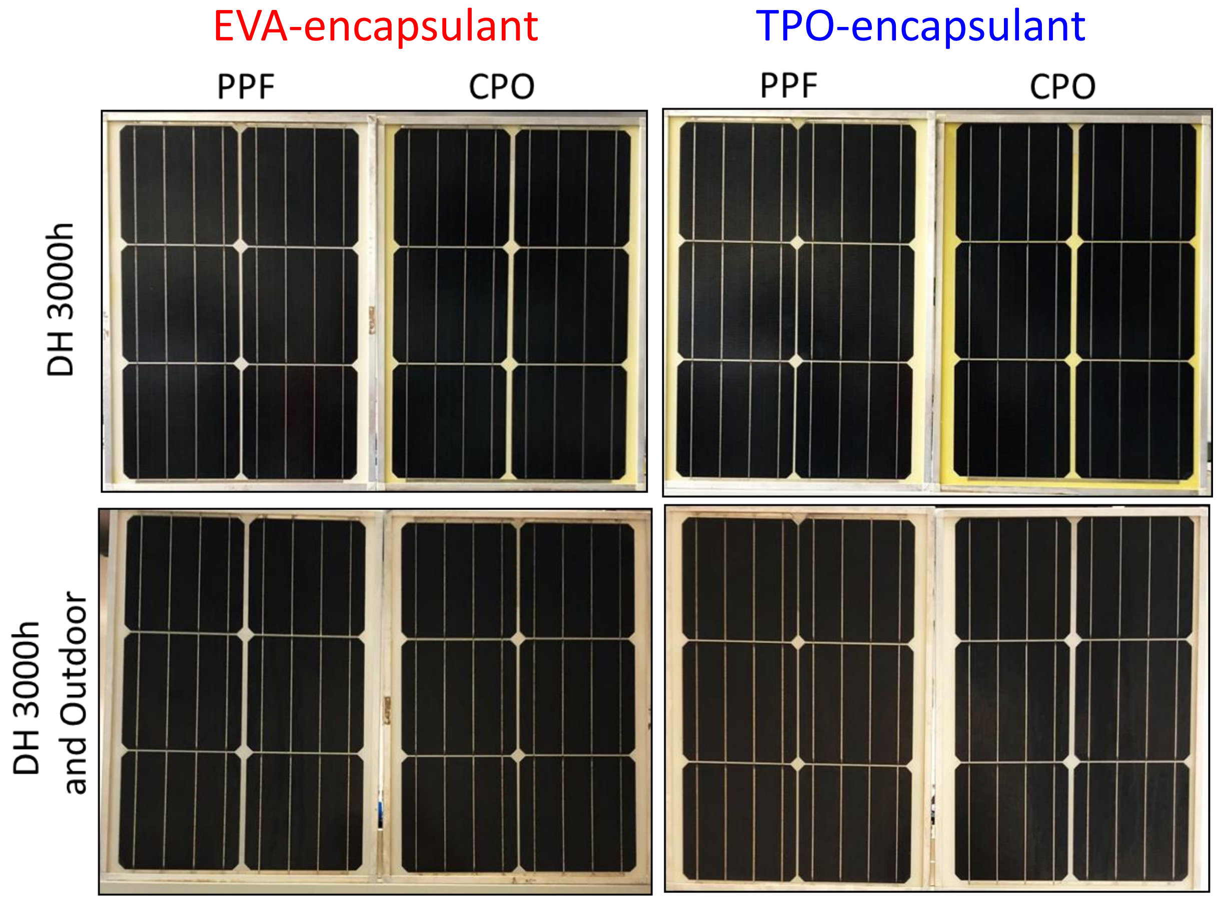
CPO-Backsheets



high AATR

Performance of PV modules using co-extruded backsheets based on polypropylene, Solar Energy Materials and Solar Cells,223,2021,110976; G. Oreski, G.C. Eder;
https://doi.org/10.1016/j.solmat.2021.110976

Yellowing / Material Incompatibility by Backsheet and Encapsulant (3000h DH + Outdoor)



→ the electrical module performance was not affected by discolouration or bleaching

After DH storage:

significant discolouration effect:

STRONG: combination TPO / CPO

MODERATE: combination EVA / CPO

LIGHT: combination TPO / PPF

NO discolouration: EVA / PPF

The IR-spectra of the encapsulants did NOT show any additional bands characteristic for conjugated double bonds

After DH and Outdoor:

all discoloration effects disappeared completely (photo bleaching effect)

Analysis of drivers for PV-material yellowing upon artificial ageing; EU-PVSEC 2020; ISBN 3-936338-60-4 ; Y. Voronko, G.C. Eder; et al.

Analysis of UV Fluorescence-images by Backsheet and Encapsulant (3000h DH + Outdoor)

<u>After DH storage:</u>

TPO: UVF was especially strong above BS; homogenous above cells

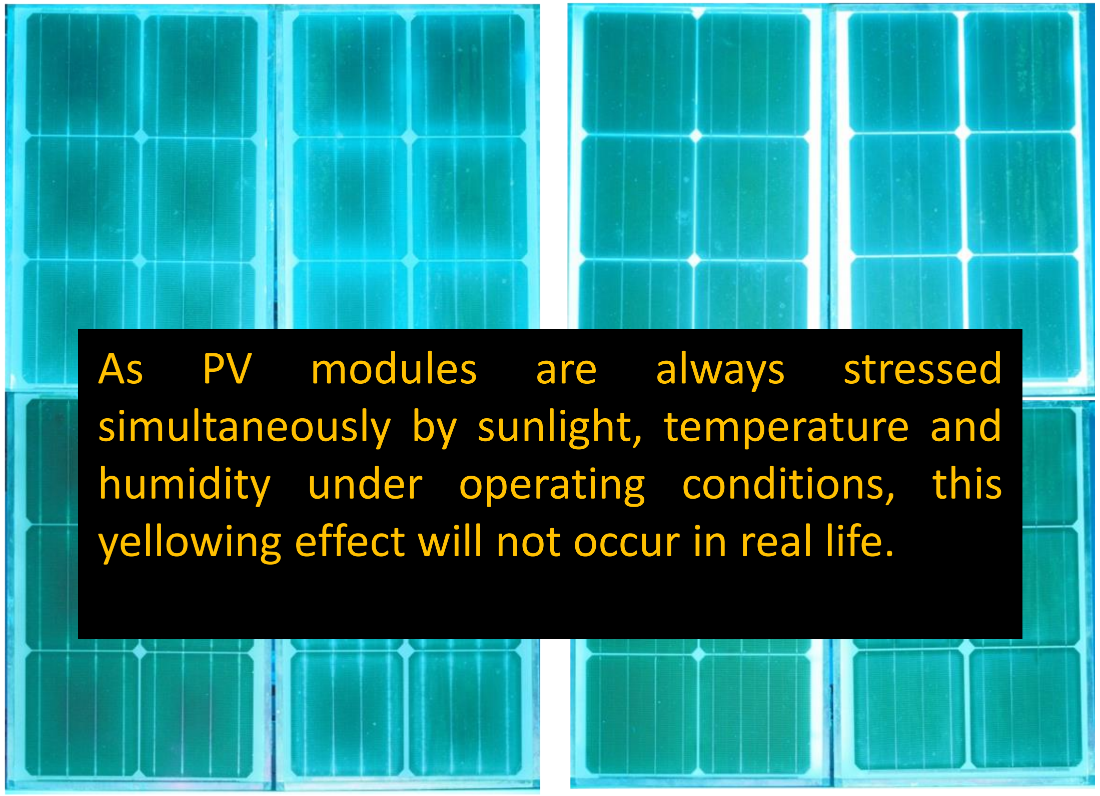
EVA: inhomogeneous distribution of UVF (low intensity above cell center)

<u>After DH and Outdoor:</u>

UVF decreased in intensity when irradiated with sunlight (photo bleaching effect)

→ yellowing results from an undesired interaction of oxidized additives of the encapsulants with additives of the CPO-backsheet

→ chromophoric compounds (with conjugated double bonds) were formed upon T and H impact (DH testing) and decomposed upon irradiation (photo bleaching)



As PV modules are always stressed simultaneously by sunlight, temperature and humidity under operating conditions, this yellowing effect will not occur in real life.

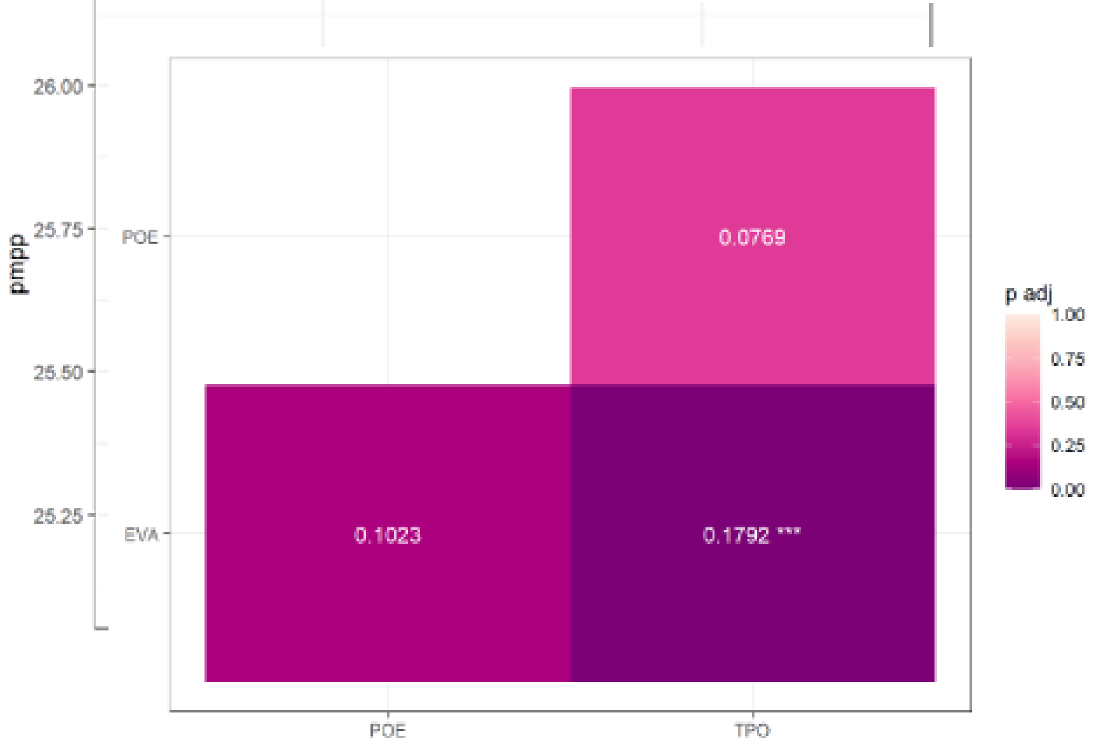
Analysis of drivers for PV-material yellowing upon artificial ageing; EU-PVSEC 2020; ISBN 3-936338-60-4 ; Y. Voronko, G.C. Eder; et al.

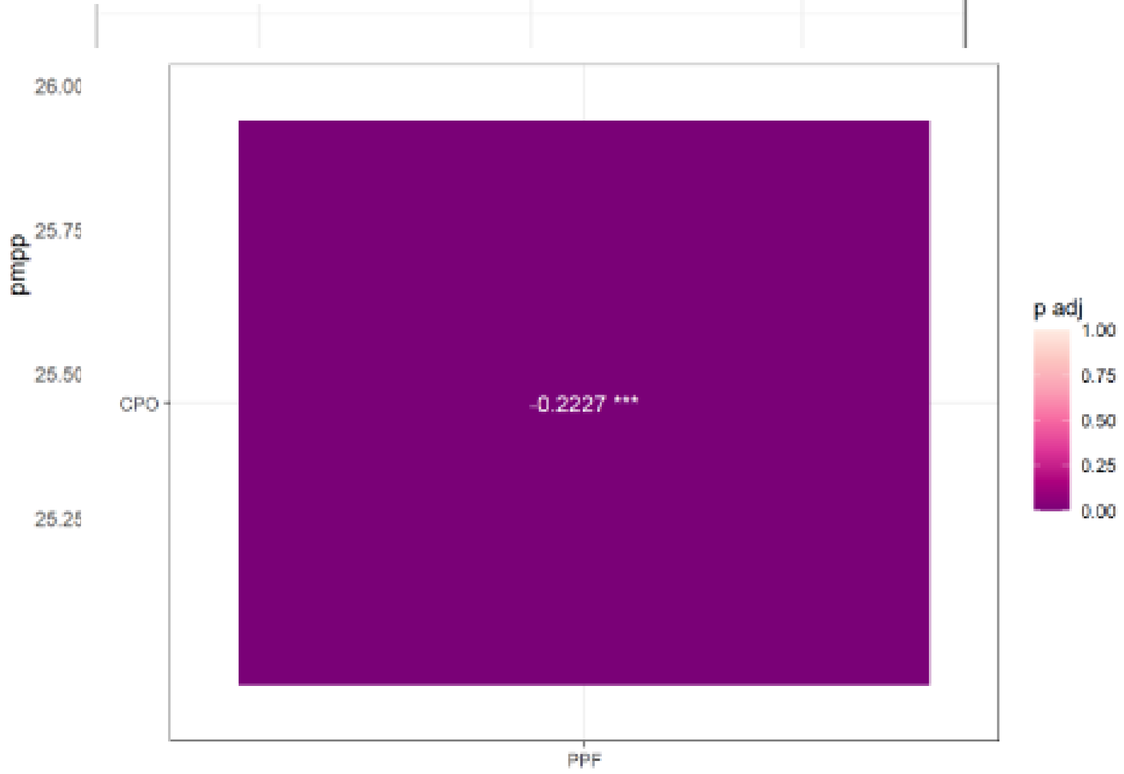
Results – Performance (Degradation) Modelling

Model 1: Mean power for different Material-combinations

Statistical modelling: analysis of variance

Matrices contain information about the significant differences between the materials





Model 2: Effects of material on degradation

Statistical modelling: mixed effects models

Goal:

Quantify and compare material-specific degradation rates over time

- Classic linear modelling is not sufficient (dependent measurements for each module)!
  - *Mixed effects models* are a class of statistical models for dependent data
  - *fixed effects* describe the overall (material-specific) degradation rates
  - *random effects* describe the variation between modules

Model setup for the effect of encapsulant material

Power of module *i* with backsheet material *j* at measurement time *t*

Initial power increase up to 500h

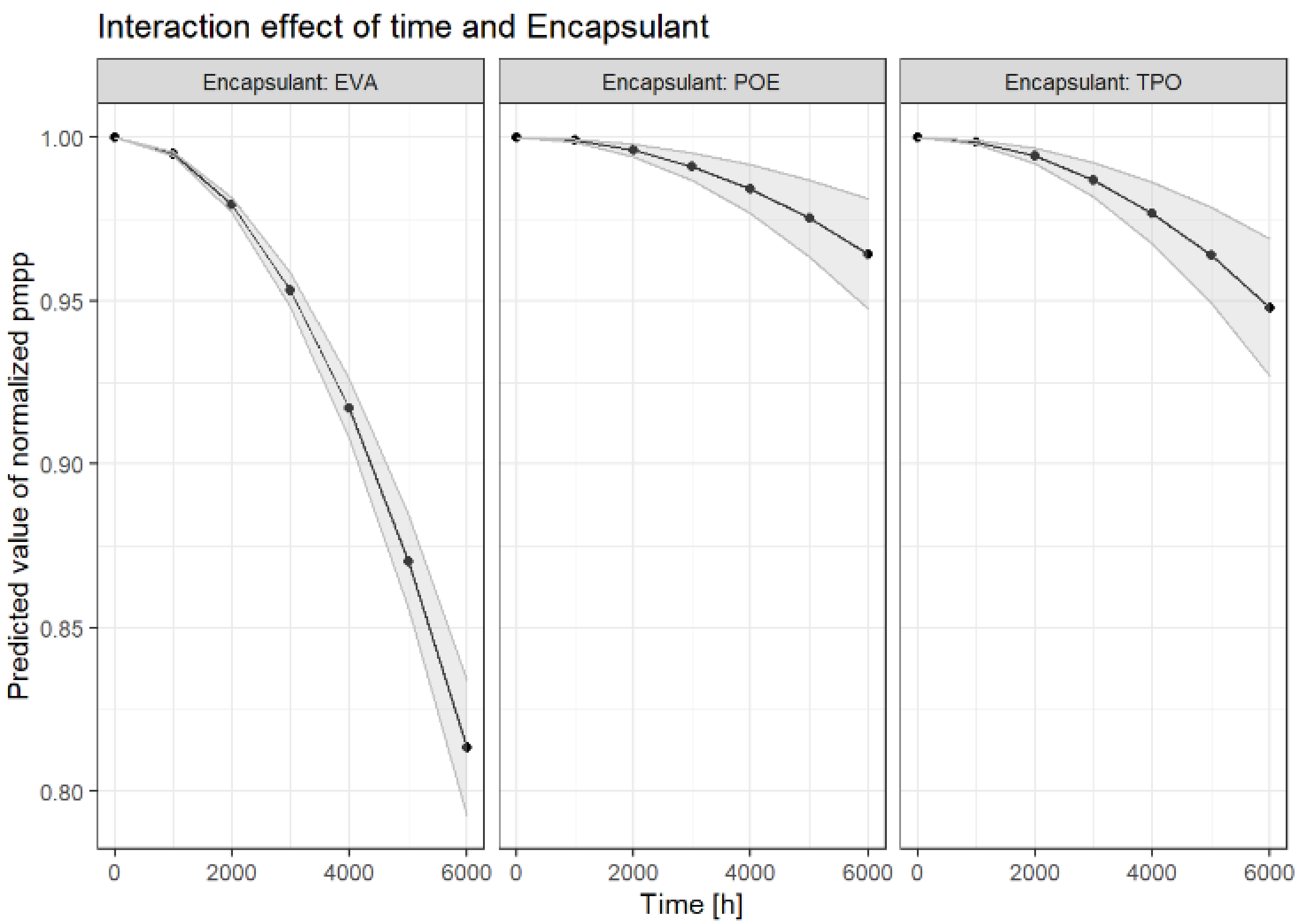
Encapsulant-specific degradation rates (*fixed effects*)

$$\mathrm{pmpp}_{i,j,t} = 1 + \beta_1 \cdot \mathrm{Ramp}(t) + \beta_2 \cdot t^2 \cdot \mathbf{1}\{\text{Encapsulant EVA}\}$$
$$+ \beta_3 \cdot t^2 \cdot \mathbf{1}\{\text{Encapsulant POE}\} + \beta_4 \cdot t^2 \cdot \mathbf{1}\{\text{Encapsulant TPO}\}$$
$$+ a_i \cdot \mathrm{Ramp}(t) + b_j \cdot t^2 + \varepsilon_{i,j,t}$$

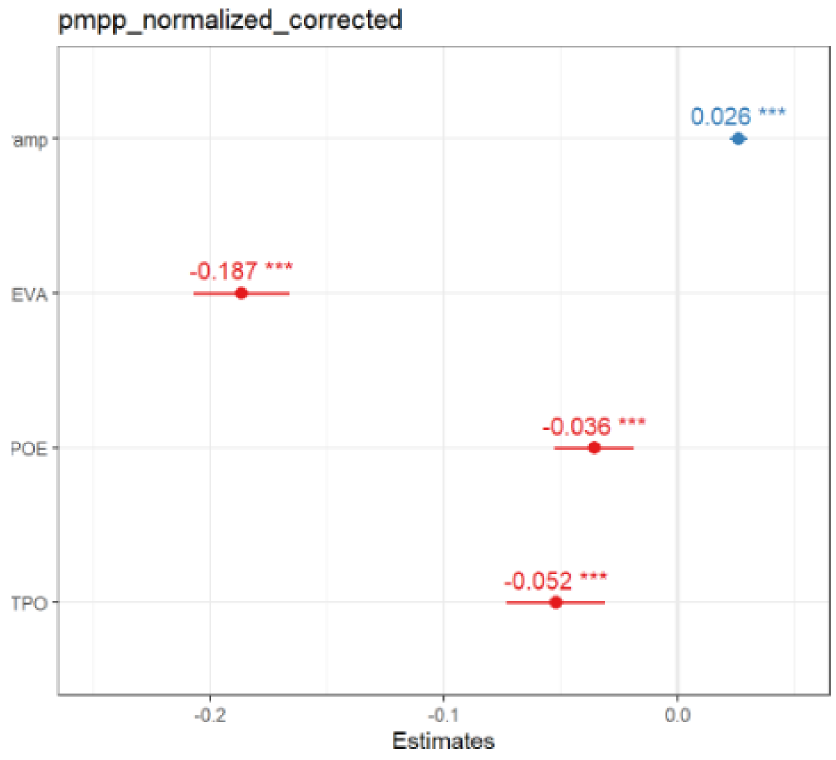
Module-specific power increase (*random effect*)

Backsheet-specific degradation rate (*random effect*)

Effect Type of Encapsulant



Coefficients $\beta 1 - \beta 4$



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Model setup for the effect of backsheet material

Power of module *i* with encapsulant material *j* at measurement time *t*

Initial power increase up to 500h

Backsheet-specific degradation rates (*fixed effects*)

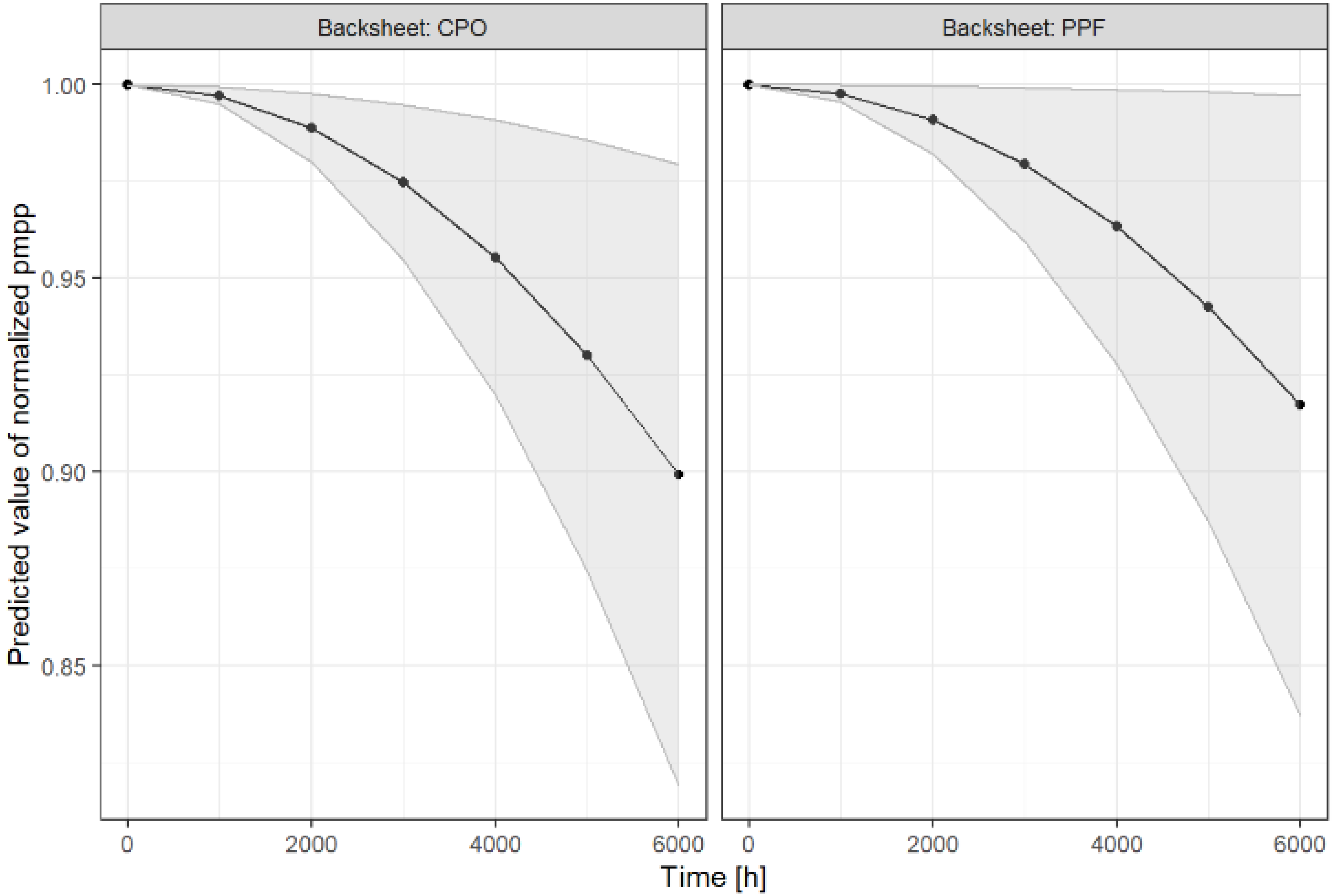
$$\begin{aligned}\mathrm{pmpp}_{i,j,t} &= 1 + \beta_1 \cdot \mathrm{Ramp}(t) \\ &+ \beta_2 \cdot t^2 \cdot \mathbf{1}\{\mathrm{Backsheet\ PPF}\} + \beta_3 \cdot t^2 \cdot \mathbf{1}\{\mathrm{Backsheet\ CPO}\} \\ &+ a_i \cdot \mathrm{Ramp}(t) + b_j \cdot t^2 + \varepsilon_{i,j,t}\end{aligned}$$

Module-specific power increase (*random effect*)

Encapsulant-specific degradation rate (*random effect*)

Effect Type of Backsheet

Interaction effect of time and Backsheet



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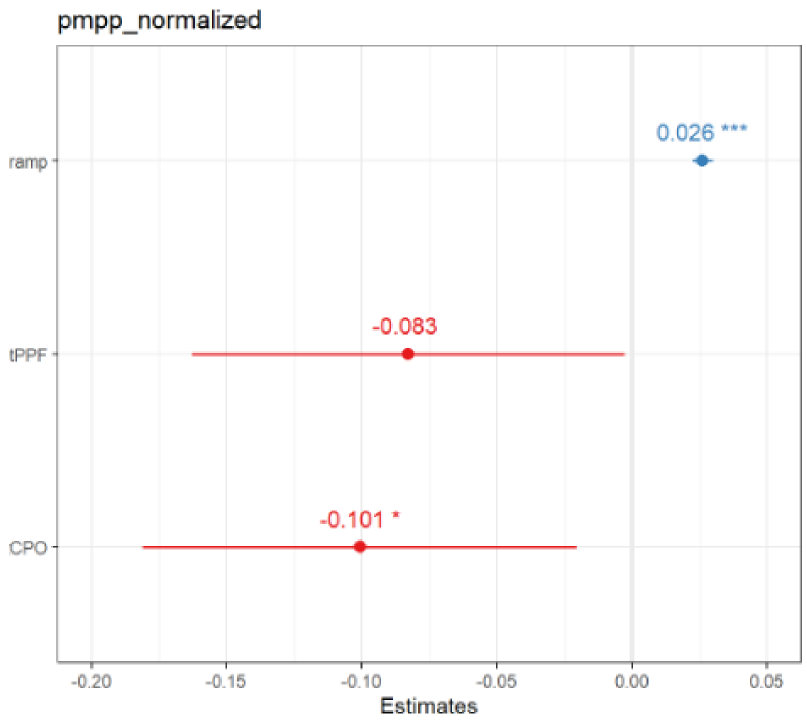
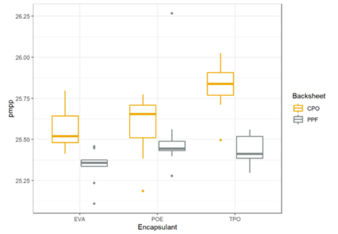
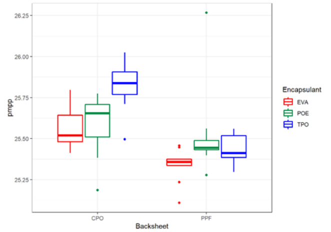
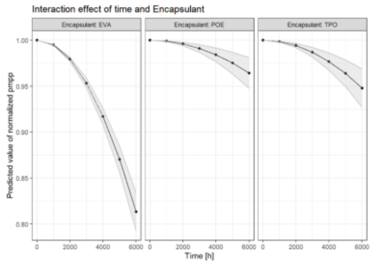


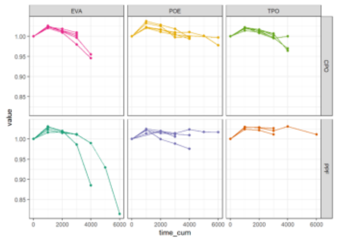
Conclusions & Summary

- Polyolefin backsheet CPO shows higher P_{mpp} compared to PET-based backsheet (higher reflectance) – irrespective of the encapsulant used
- Polyolefin encapsulants show higher P_{mpp} compared to EVA (higher transmittance)
- Polyolefin encapsulants show high chemical stability (superior over EVA) -> much lower degradation rates in reliability test
- Polyolefin backsheet CPO shows comparable rate of degradation as PET-based backsheet









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Advanced data treatment
and modelling

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Klimaschutz, Umwelt,
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Innovation und Technologie