Co-extruded backsheets for PV modules: Past approaches and recent developments

Dr. Gernot Oreski

Polymer Competence Center Leoben GmbH
Roseggerstraße 12
8700 Leoben, Austria
Tel: +43 3842 42962
Mobile: +43 664 8867 9331
gernot.oreski@pccl.at

Introduction

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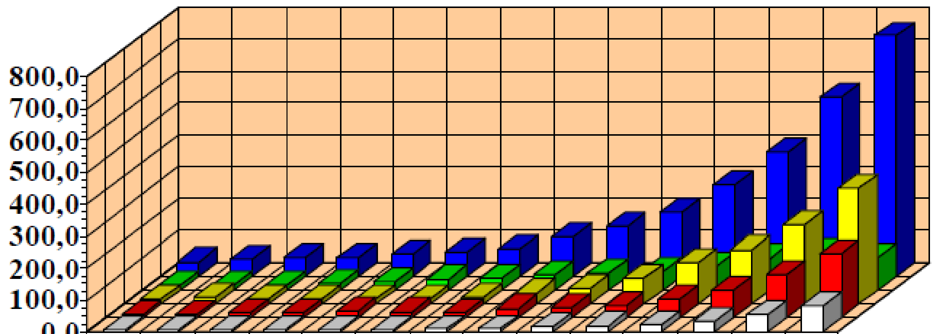
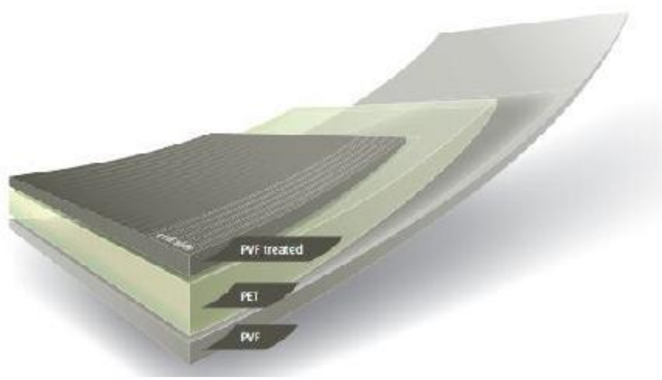
PV Market in 2003



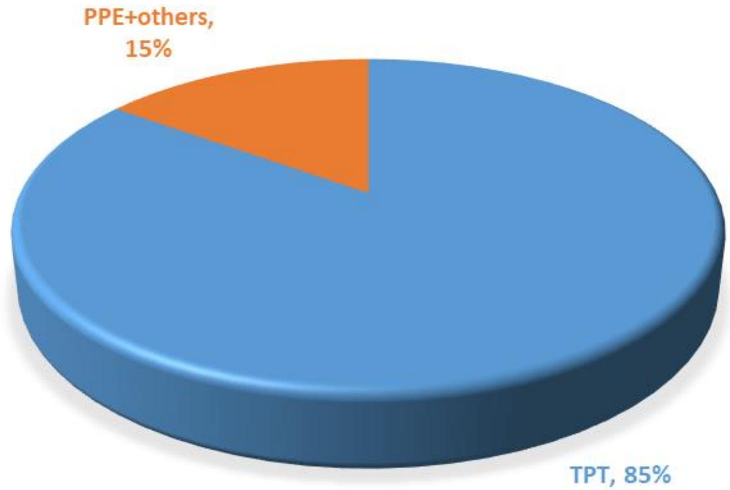
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Rest of World	4,7	5,0	4,6	4,4	5,6	6,4	9,8	9,4	18,7	20,5	23,4	32,6	55,5	83,8
Europe	10,2	13,4	16,4	16,6	21,7	20,1	18,8	30,4	33,5	40,0	60,7	86,4	135,1	202,4
Japan	16,8	19,9	18,8	16,7	16,5	16,4	21,2	35,0	49,0	80,0	128,6	171,2	251,1	363,9
United States	14,8	17,1	18,1	22,4	25,6	34,8	38,9	51,0	53,7	60,8	75,0	100,0	120,6	103,0
Total	46,5	55,4	57,9	60,1	69,4	77,6	88,6	125,8	154,9	201,3	287,7	390,2	561,8	753,1

Arnulf Jäger-Waldau, PV Status Report 2004, DOI: 10.13140/RG.2.1.1032.9840

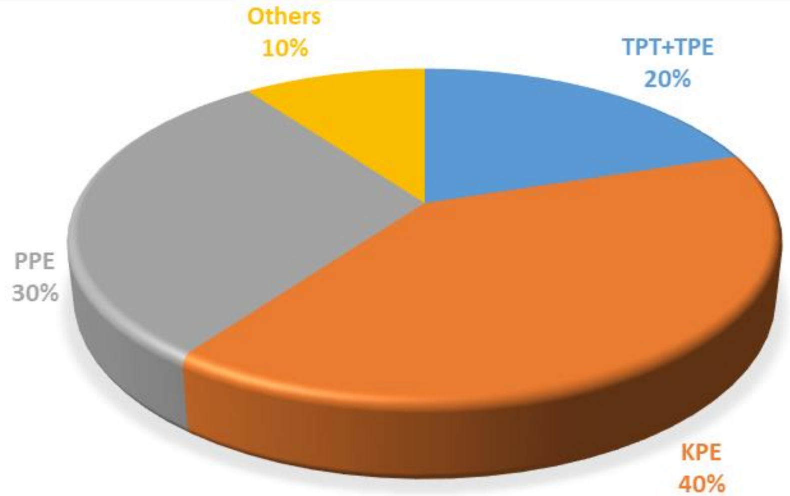


- Annual production: 750MWp
- Total installed capacity: ~2.6GWp
- EVA was the dominating encapsulant for glass-backsheet modules, PVB for glass-glass modules
- TPT was the dominating backsheet
- Few backsheet alternatives available, mostly PPE based
- Only few lamination/coating companies provided backsheets as secondary business
- Some companies worked on the introduction of PVDF into the market

Backsheet market



2006 [1]

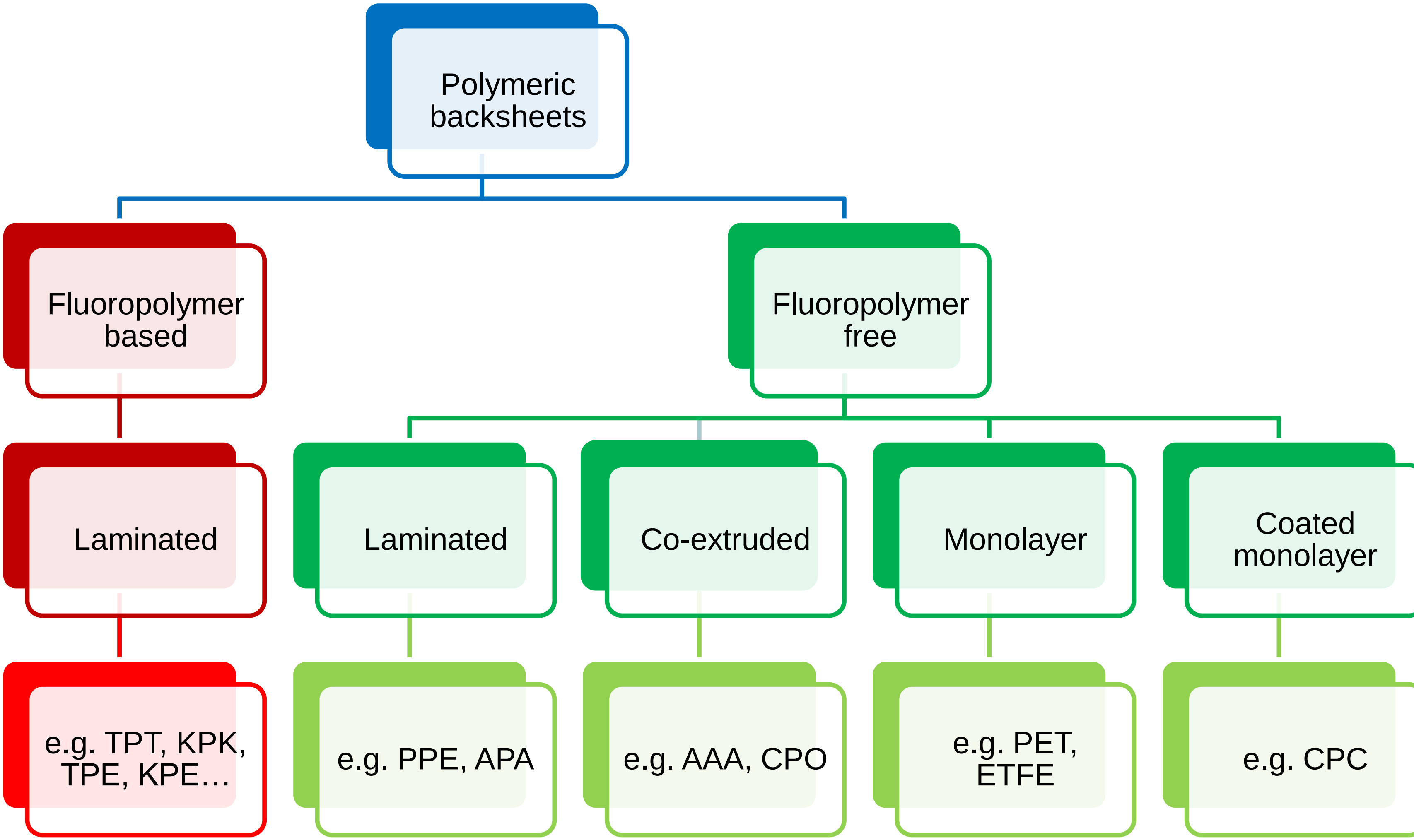


2016 [1]

- Fluoropolymer-based backsheets are still having the highest share on the market, even though exact numbers vary depending on source between 70 and 89% [1-3]
- According to survey conducted by Taiyang News in 2017, backsheets using PVDF had a share of 50%, PVF 25-30%, fluoropolymer free (PET&others) 15% and coated backsheets 5-10% [2]

[1] L. Maras: “Environmental challenges disposing of backsheet at PV module EOL” in EU-PVSEC, Munich, 2016.
[2] https://www.pv-magazine.com/2018/12/28/new-technologies-move-to-the-back/
[3] S.K. Chunduri, M. Schmela: “Market Survey: Backsheets for Solar Modules 2018”, TaiyangNews

Backsheet technology



Backsheet market offers a broad variety of layer and material configurations

Backsheet technology

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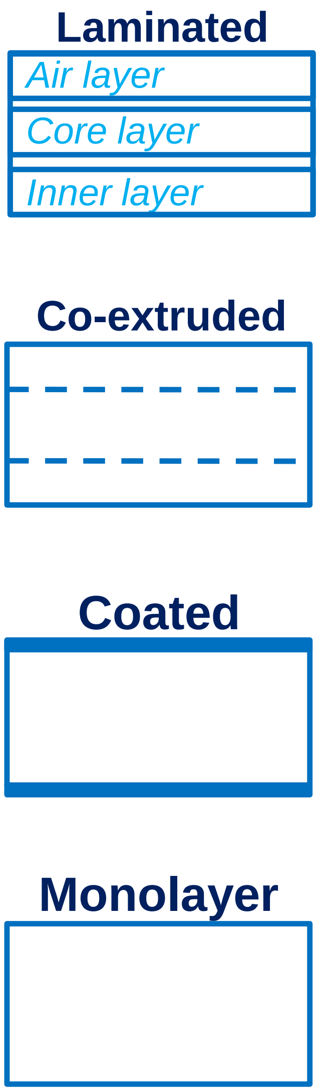
Type	Materials	Manufacturers
Laminated *Air layer* *Core layer* *Inner layer*	PVF, PVDF, PET PET PVF, PVDF, PET, PE, coating	*Jolywood, Cybrid, Hangzhou First, Krempel, Coveme*
Co-extruded	PP, PA PP, PA PP, PA, PE	*Bischof + Klein, DSM, Renolit, Tomark Worthen, Borealis*
Coated	PET + protective coating	*Aluminium Feron, Jolywood, Fuji Film*
Monolayer	PET	*Agfa*

Backsheet technology

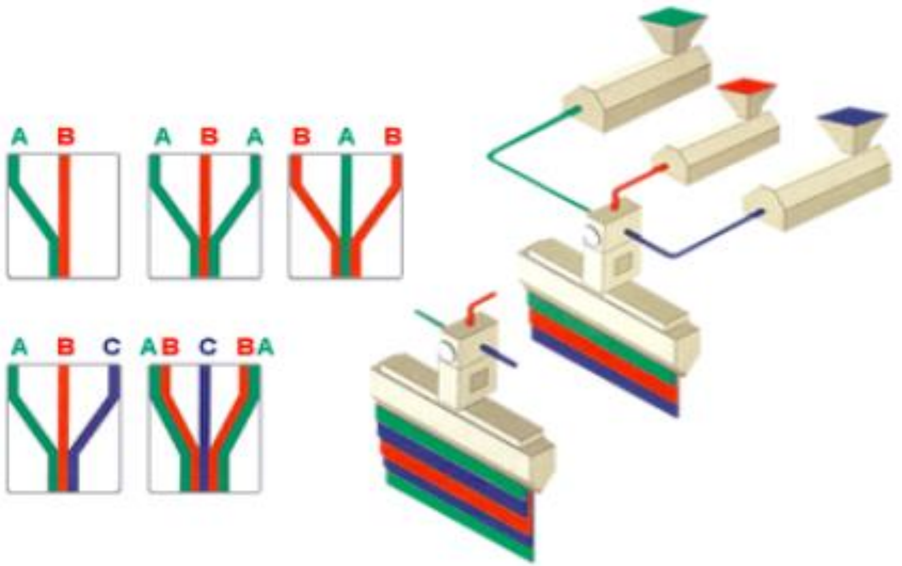


Driving factors for new developments

- **Cost reduction**
  - Thickness optimization in agreement with IEC backsheet and safety standards
  - Replacement of expensive fluoropolymers with more economic technical polymers (PET, PA, PP, PE derivates)
  - Reduction of processing steps via co-extrusion, mono-layer films or coating
- **New features – functional films**
  - Selective permeability – high AATR, low WVTR
  - Enhanced optical properties – increased reflectivity to gain higher power output via backscattering of light
  - Increased thermal conductivity

Backsheet technology

- **Advantages of co-extruded backsheets**
  - *Full back integration → easy material modifications are possible*
    - *Additive formulation*
    - *Fillers*
    - *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.

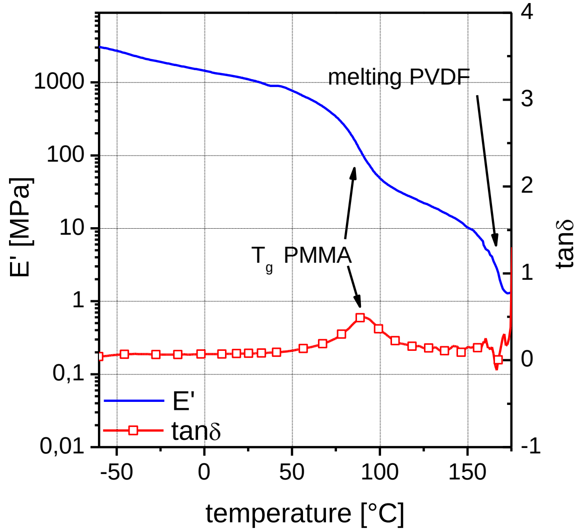
Polymers used (PA, PP, PE) are usually cheaper than fluoropolymers and easier to produce than PET films

Co-extruded backsheets

< 2009 | 2009 | 2010 | 2011 | 2012 | 2012

- **Assessment of suitability of a PMMA-PVDF co-extruded film for PV backsheets**
- **Strong rolling in after exposure at 85°C**
  - *Strong internal stresses due to orientation of the chain molecules during film extrusion and*
  - *Additional stresses due to the two layer build up*
- **Exposure at 85°C within glass transition region of PMMA**

  → *Softening and relaxation of internal stresses*



PERFORMANCE

„Performance" - A science base on PV performance for increased market transparency and customer confidence

(*EU-FP6, 2006-2009)*

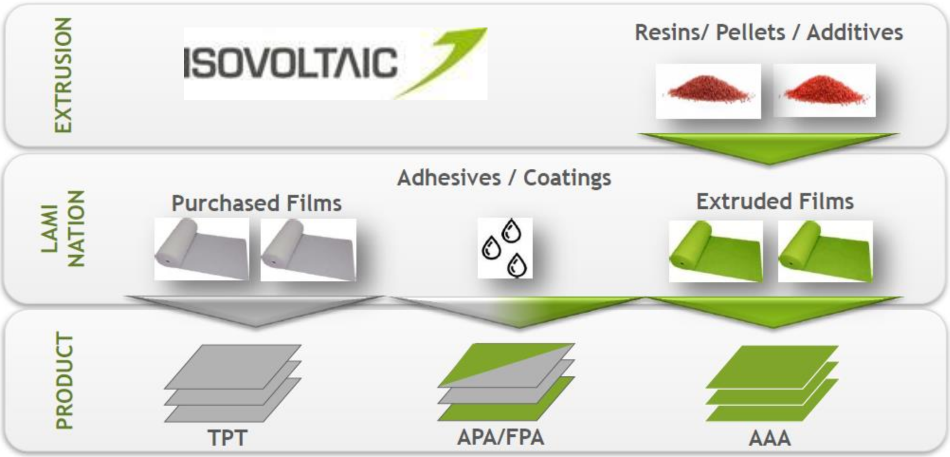
Co-extruded backsheets

< 2009 | 2009 | 2010 | 2011 | 2012 | 2013

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

Major motivation: Improved raw material supply

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

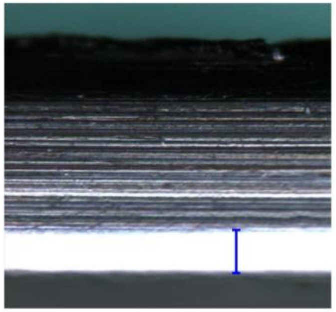


© C. Schinagl, Flexible Encapsulation with backsheets and frontsheets for PV applications, PVSEC 2012

3M

PE cross-linked

Polyolefin Backsheet, 3M^{TM} SF 800



Stollwerck et al. PVSEC 2013

Also other companies start to work on co-extruded backsheets

– *US Patent application 2010 - **Renolit**: Photovoltaic modules with polypropylene based backsheet*

Estimation: Around 10 GW of PV was sold with AAA backsheets

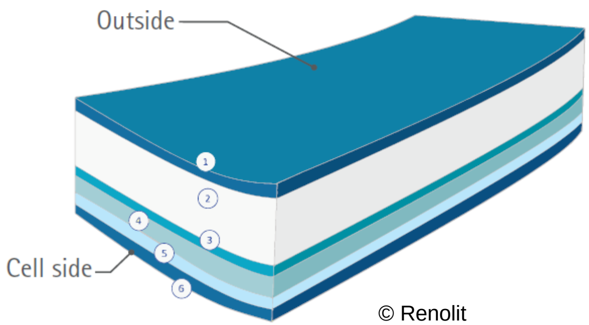
Co-extruded backsheets

2014 | 2015 | 2016 | 2017 | 2018 | 2019

DSM Endurance

© DSM

Renolit Reflexolar



© Renolit

① White formulated Polypropylene (outside)
② White GF-fPP
③ PP tie layer
④ White PA layer
⑤ White PE tie layer
⑥ Transparent PE layer (encapsulant side)

PA-Polyolefin

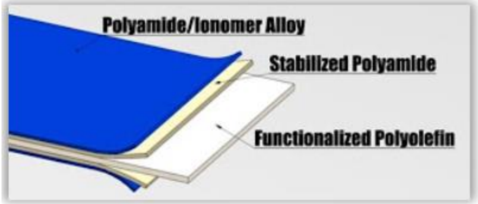
Bischof & Klein Backflex

© Bischof & Klein

Isovoltaic & Borealis CPO 3G

PP

Tomark Worthen Photomark Reflections



© Thomark Worthen

PA-Polyolefin

What about long term reliability of co-extruded backsheets?

Long term behavior of AAA backsheet

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Observed issues with AAA backsheets after some years in the field

- *Chalking & microcracks*
- *Longitudinal cracks along the busbars*
- *Squared crackes in the cell interspaces*

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ELSEVIER

Error analysis of aged modules with cracked polyamide backsheets

Gabriele C. Eder [a,*], Yuliya Voronko [a], Gernot Oreski [b], Wolfgang Mühleisen [c], Marlene Knausz [b], Antonia Omazic [b], Alois Rainer [a], Christina Hirschl [c], Horst Sonnleitner [d]

[a] OFI, Austrian Research Institute for Chemistry and Technology, Franz-Grill-Str. 5, 1030, Vienna, Austria
[b] PCCL, Polymer Competence Center Leoben, Leoben, Austria
[c] CTR, Carinthian Tech Research AG, Villach/St.Magdalen, Austria
[d] ENcome Energy Performance GmbH, Klagenfurt, Austria

Other recent publications dealing with PA backsheet cracking

- S. Lyu, et al., Progress in Photovoltaics, submitted
- P. Lechner et al., PVSEC 2019
- G. Eder et.al, PVSEC 2019
- M. Owen Bellini et al., IEEE PVSEC 2019
- S. Lyu et al., IEEE PVSEC 2019
- M. Kempe et al., IEEE PVSEC 2019
- J. Tracy et al., IEEE PVSEC 2019

Long term behavior of AAA backsheet

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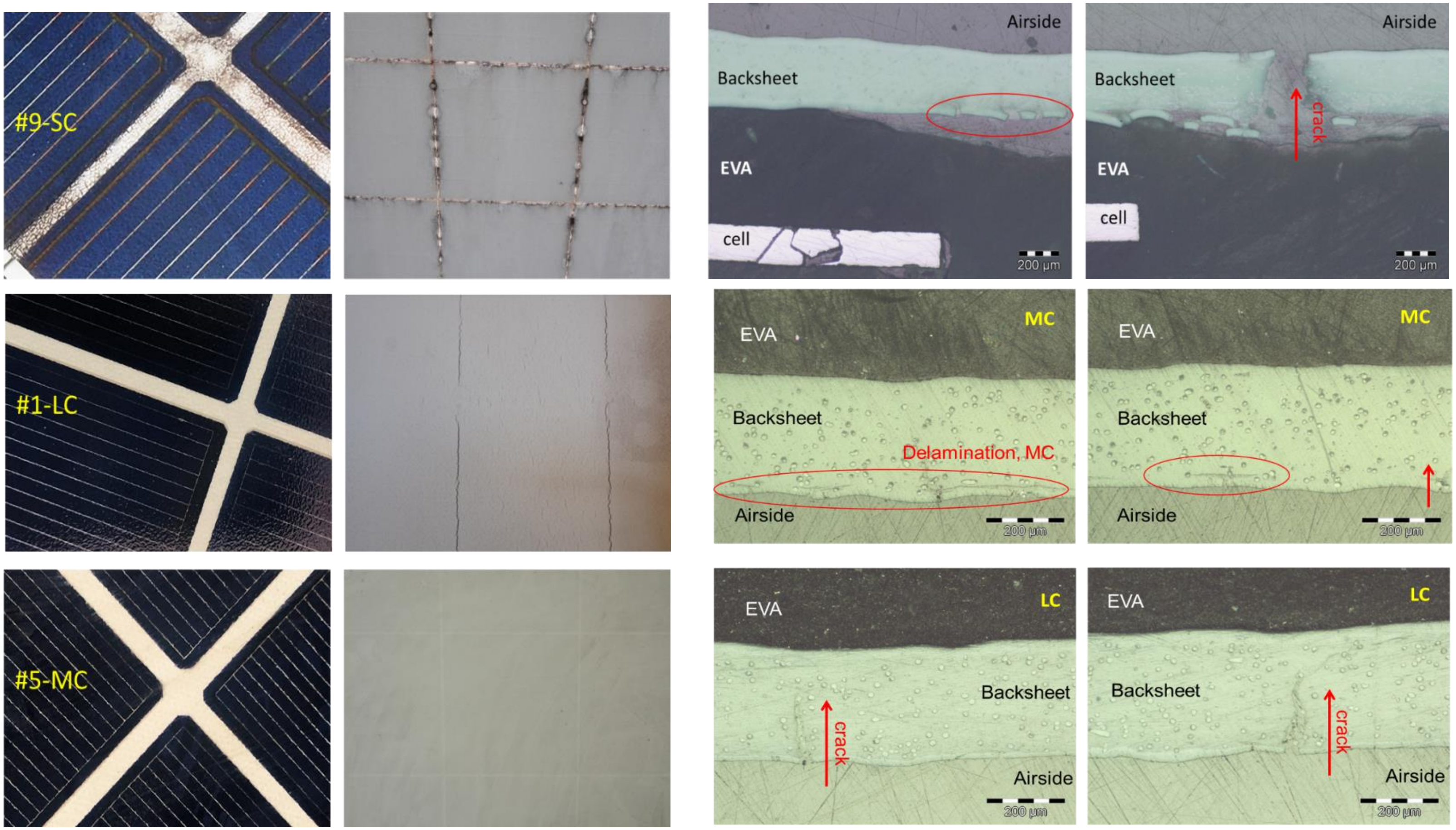
Cracking of co-extruded PA based backsheets

Squared
Longitudinal
Micro



- **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

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Long term behavior of AAA backsheet

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Cracking of co-extruded PA based backsheets

	Location	Operational Time	EVA	Failure mode of backsheet	Chalking	TD/GC		
						Acetic acid	Ethyl-hexanol	P-Additive
# 1	S-Italien	7 years	transparent	CH, MC, LC	x	-	x	-
# 2	Reference	1 years	transparent	-	-	-	x	-
# 5	Slowenia	7 years	transparent	MC, LC	-	-	x	-
# 6	Slowenia	7 years	transparent	MC, LC	-	-	x	-
# 7	Italy	5 years	yellowish	SC	-	x	x	x
# 8	Italy	5 years	transparent	Delamination /border area	-	-	x	-
# 9	S-Italy	5 years	yellowish	SC	-	x	x	x
# 10	S-Italy	5 years	transparent	MC	-	-	x	-

- **Cracking of PA backsheets after 5-8 years in operation**
- **P-Additive: Phosphoric acid, tris(2-ethylhexyl) ester**

G. Eder, Y. Voronko, G. Oreski, W. Mühleisen (2019) „Possible repair strategies for PV modules with cracked backsheets, SOPHIA PV Module Reliability Workshop 2019, Graz (Austria)

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Long term behavior of AAA backsheet

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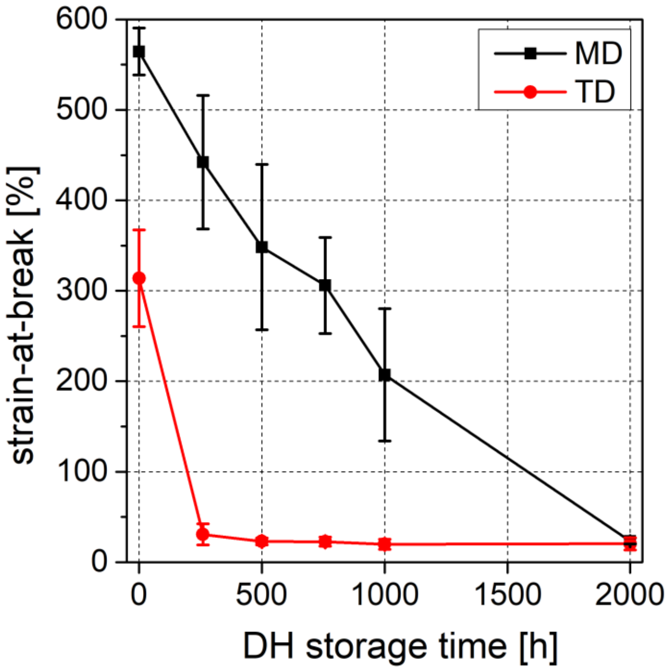
Crack initiation – Microcracks / Longitudinal cracks



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

Main drivers for crack formation and propagation

– *Daily and seasonal temperature changes cause random formation of micro-cracks at local stress concentrations*

→ *Thermo-mechanical stresses due to different thermal expansion coefficients of PV materials*

– *Height of ribbons impose additional tensile stress* → ***Formation of longitudinal cracks***

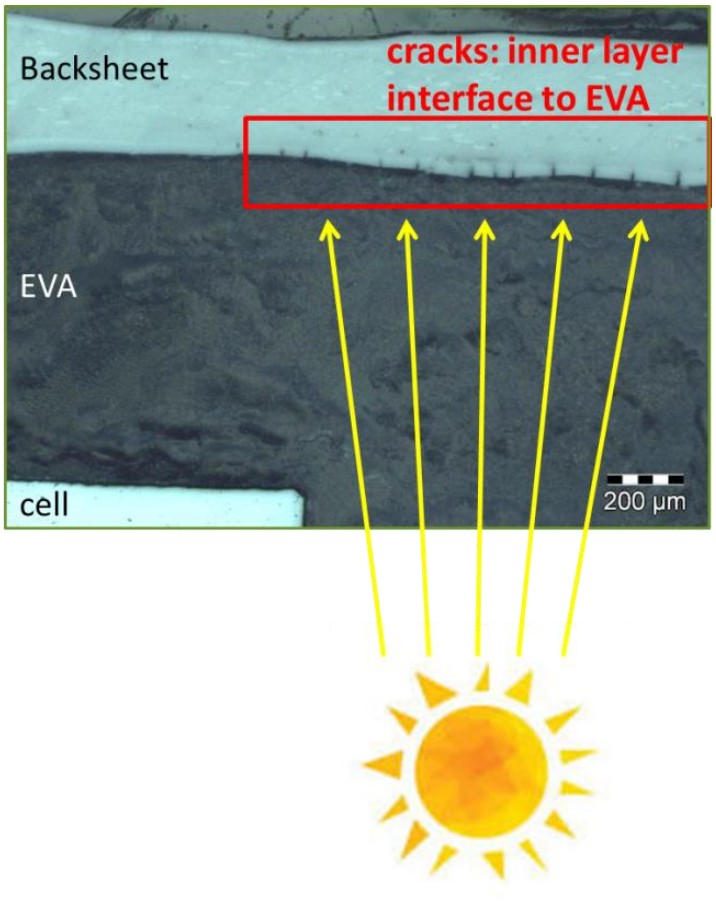
– *Chalking and photo-oxidative degradation of the outermost (only a few µm) PA-layer is caused by outdoor weathering and not related to crack formation*

– *Negligible acetic acid formation in EVA*

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

Long term behavior of AAA backsheet

Crack initiation – Squared cracks



Main driving factors for crack initiation

- *UV radiation in the cell interspaces*
- *Strong dependence on type of EVA*
  - → *In modules with squared cracks a phosphor additive was found, which was not present for cracks above busbars*
  - → *Weak chemical resistance of PA12 towards acetic acid and weak to moderate towards phosphoric acid compounds [Ehrenstein 2013]*

Additional observations

- *High content of acetic acid in EVA above the cracks*
- *Strong oxidation of inner and core layer*

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

Long term behavior of PP backsheets

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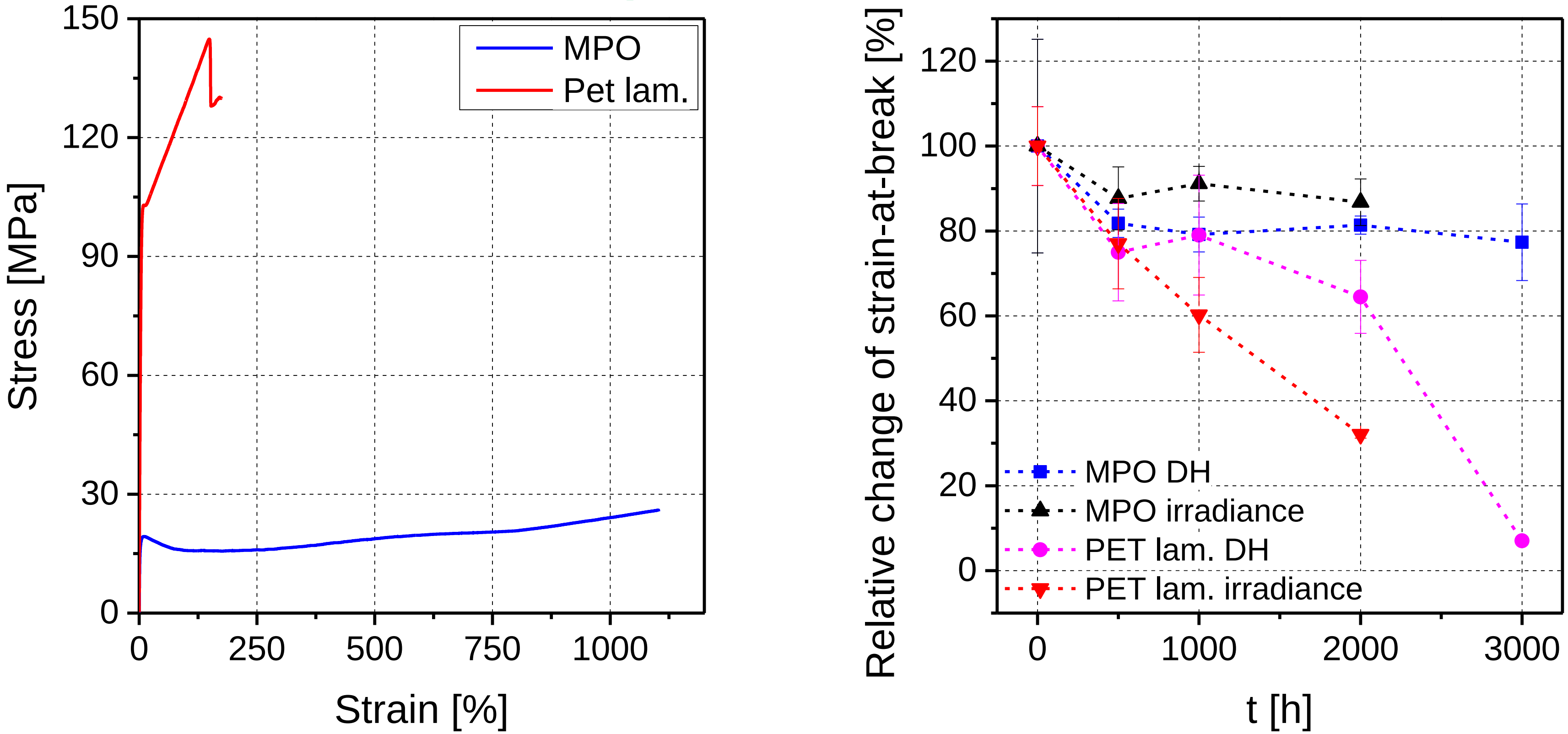
Tensile test results: Comparison between MPO and PET laminate



- *MPO has lower stiffness and higher flexibility than PET laminate*
- *Only slight decrease of strain-at-break values after 3000h DH and 2000h irradiance for MPO → **No embrittlement***
- *Strong embrittlement of PET laminate after accelerated aging tests → **faster degradation after UV exposure***

Oreski, G.; Omazic, A.; Eder, G.; Hirschl, C.; Neumaier, L.; Edler, M.; Ebner, R. (2018): 35th EU PVSEC, Brussels, 27.09.2018

Long term behavior of PP backsheets

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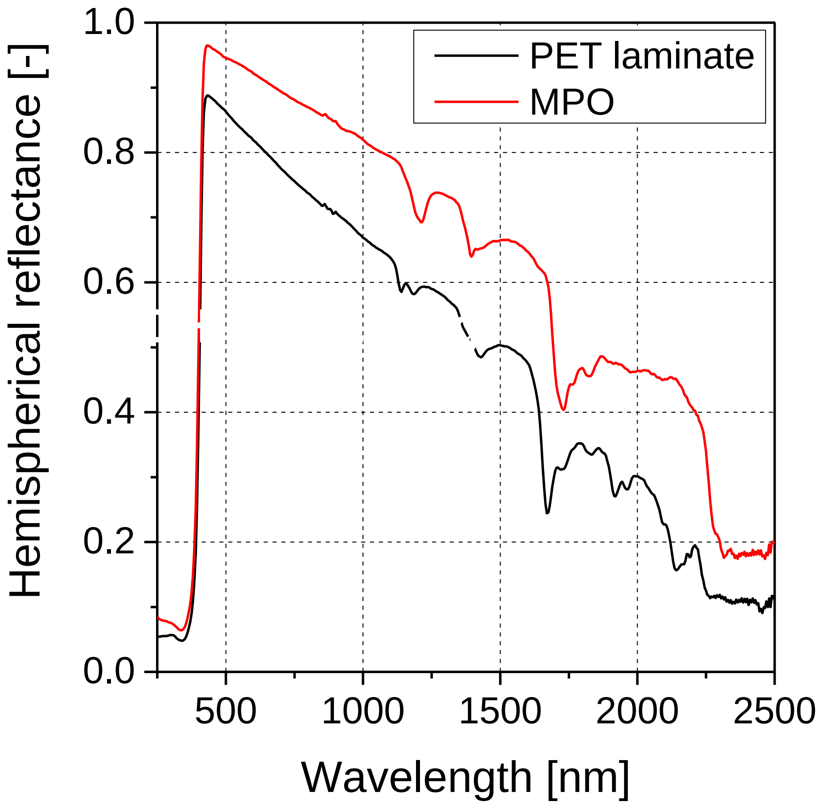
Comparison between MPO and PET laminate



- ***Significantly higher reflectance of MPO backsheet***

→ *Increased back scattering*

→ *Increased power output for 6 cell modules using MPO backsheet*

→ *Could be highly relevant for new bifacial PERC or PERT cells used in monofacial PV module*

Design matching with encapsulant needed in order to avoid discoloration at the backsheet encapsulant interface

Increase in P_{MPP}

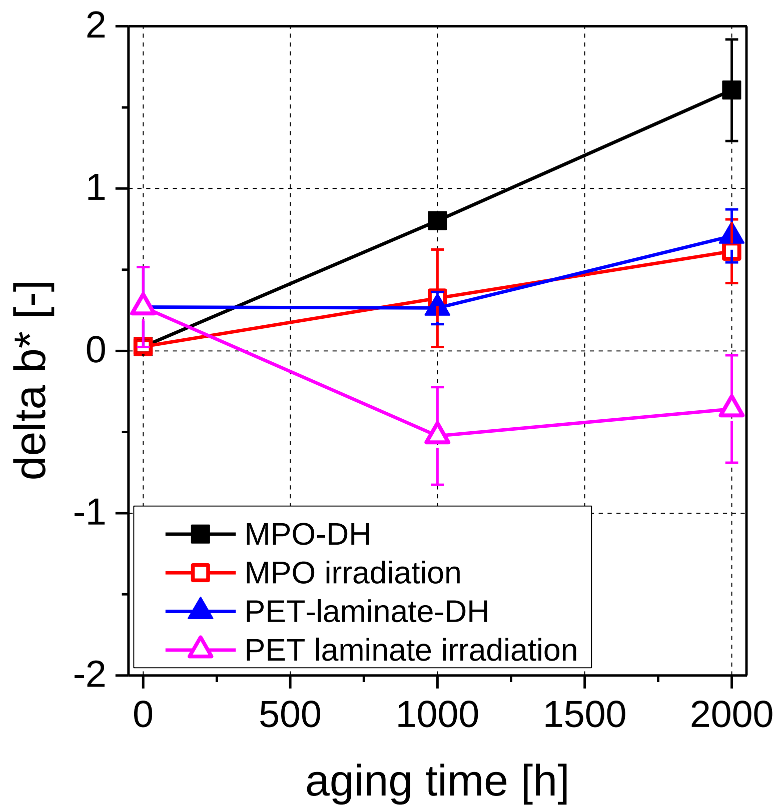
+ 2.5% with EVA

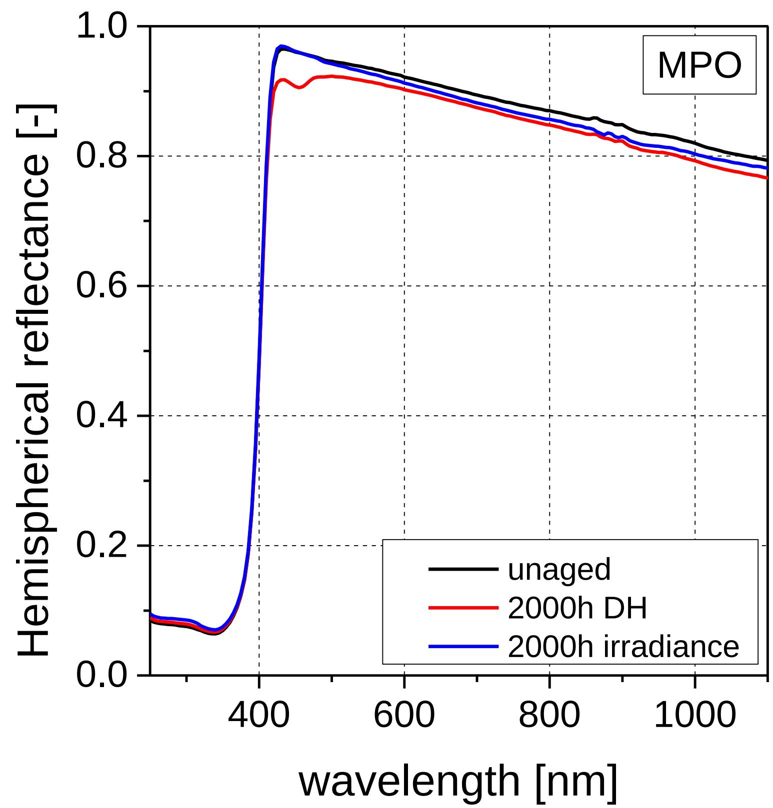
+ 2.5% with TPO

+ 1.5% with POE

Oreski, G.; Omazic, A.; Eder, G.; Hirschl, C.; Neumaier, L.; Edler, M.; Ebner, R. (2018): 35th EU PVSEC, Brussels, 27.09.2018

Long term behavior of PP backsheets





- ***Yellowing after damp heat tests – stronger effect for MPO***
- ***Nearly no yellowing after irradiation***
- ***Cave: No yellowing due to material interactions as only backsheet was investigated!***

Oreski, G.; Omazic, A.; Eder, G.; Hirschl, C.; Neumaier, L.; Edler, M.; Ebner, R. (2018): 35th EU PVSEC, Brussels, 27.09.2018

Long term behavior of PP backsheets

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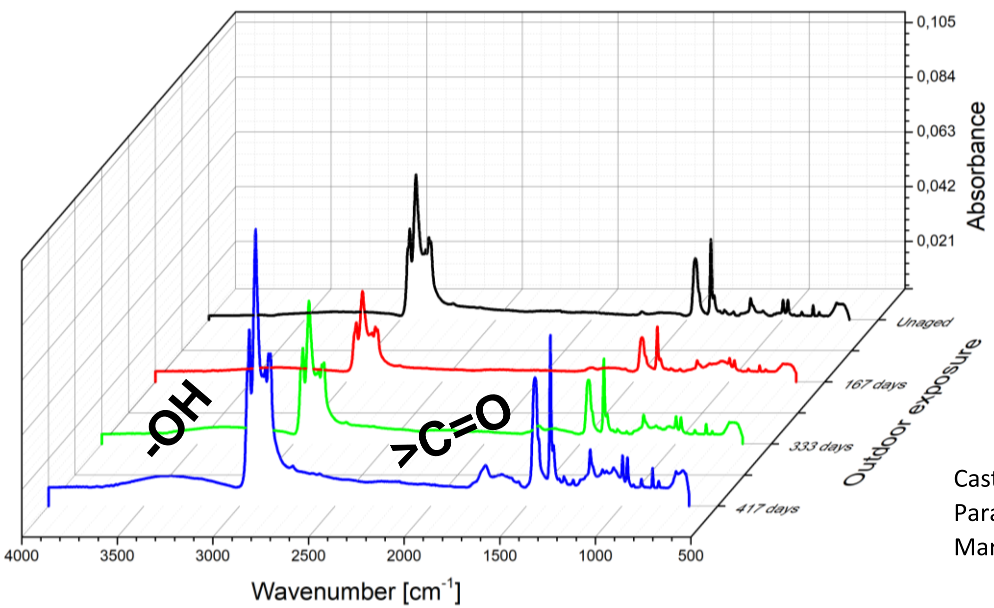
Natural weathering in three different locations

University of Leoben, Leoben, Austria

University of Ljubljana, Slovenia

Fraunhofer ISE, Freiburg, Germany



- **FTIR analysis on the surface of PP backsheets shows signs of photo-oxidation after 14 months of natural weathering**
- **No changes in thermal or mechanical properties**

Castillon, L.; Oreski, G.; Ascenio-Vasquez, J; Topic, M.; Panos, A.; Weiß, K.A. (2019): Parallel Natural Weathering of Backsheets across Europe, In: 36th EU PVSEC, Marseille, 09.09.2019.

Long term behavior of PP backsheets

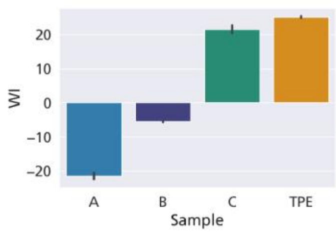
FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

Qualification of Polyolefin Backsheet for PV Modules

Paul Gebhardt[1], Philip Hülsmann[2], Daniel Philipp[1]
[1]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany, paul.gebhardt@ise.fraunhofer.de
[2]Bischof + Klein SE & Co. KG, Rahestrasse 47, 49525 Lengerich, Germany

Laminates – DH Test

- Laminates: Glass/EVA/Cell/EVA/Backsheet, 20 x 20 cm, manufactured at Fraunhofer ISE
- Damp-Heat (DH) aging: 85 °C, 85 % r.h. for 1000 h
- Strong differences in EVA yellowing



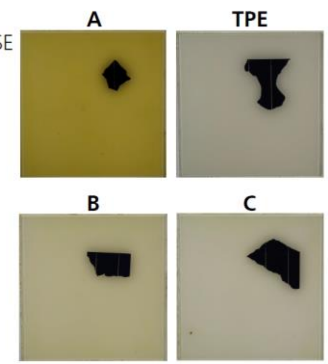
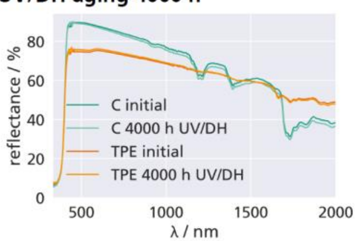
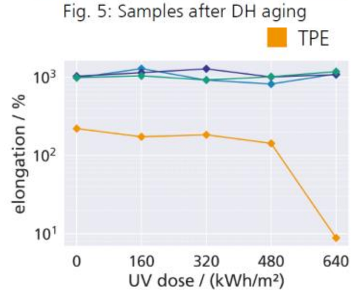


Fig. 5: Samples after DH aging

UV/DH aging 4000 h





- ***Strong yellowing after DH, dependent of PP stabilizers***
- ***No embrittlement of PP backsheets after DH, UV and combined DH/UV***

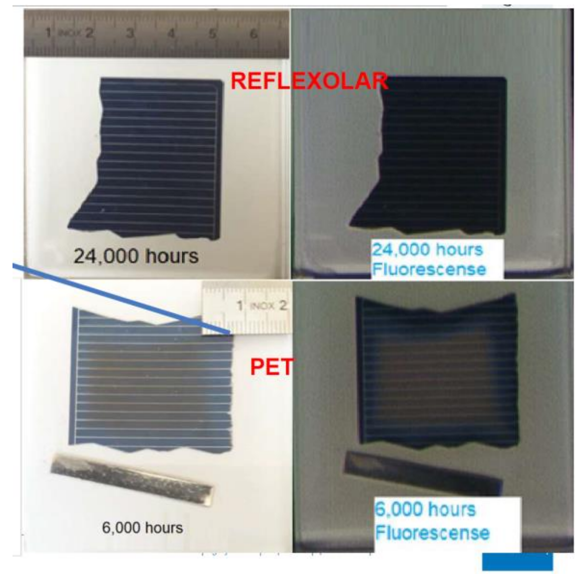
P. Gebhardt et al., EU PVSEC 2019, Marseille

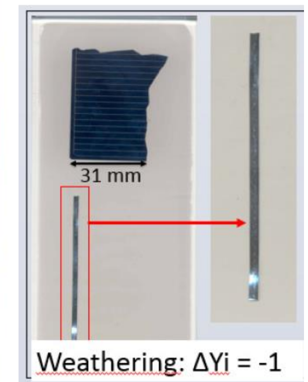
BISCHOF + KLEIN

RENOLIT
Rely on it.

Impact of Highly Breathable Polyolefin Backsheet on EVA Degradation

François Rummens[1] , Paul Gebhardt[2], Daniel Philipp[2]
[1]Renolit Belgium NV, Industriepark De Bruwaan 43, 9700 Oudenaarde, Belgium, Phone +32 475 35 13 95
[2]Fraunhofer Institute for Solar Energy Systems ISE, Heidenhofstrasse 2, 79110 Freiburg, Germany, paul.gebhardt@ise.fraunhofer.de
RENOLIT N.V. and FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE





- **No embrittlement of PP backsheet after 24.000h of UV exposure**
- **Breathable backsheet: No discoloration nor fluorescence of encapsulant; No corrosion**

- F. Rummens et al., EU PVSEC 2019, Marseille
- F. Rummens, EU-PVSEC 2015, Hamburg

Long term behavior of co-extruded backsheets

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So why have the failure mechanisms of AAA not been observed before market introduction? Can this happen to other PP based backsheets as well?

- **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*
- **Situation in 2010**
  - *Only single stress testing (DH, UV, TC), no combined/sequential stress tests*
    - → *Loss in strain-at-break was observed after DH and UV exposure, but no cracking due to missing thermo-mechanical loads*
    - → *Thermal load too low to induce the physical aging effect of the PA*
  - *Strain at break reduction was observed very early, but consequences of this behavior were totally underestimated*

Long term behavior of co-extruded backsheets

So why have the failure mechanisms of AAA not been observed before market introduction? Can this happen to other PP based backsheets as well?

- **Current situation**
  - *Reproduction of backsheet cracks at NREL by an indoor accelerated aging test utilizing simultaneous combined stresses (UV, humidity, temperature and thermo-mechanical load*
  - *Material interactions and incompatibilities are in the focus of material and module developers*

Owen-Bellini et al., EU-PVSEC 2018

- **Polypropylen has excellent stability towards acetic acid or phosphoric acid compounds**
  - *No environmental stress cracking expected*

Acknowledgement

Thank you for your attention!

Thanks to my colleagues M. Knausz, B. Ottersböck, A. Omazic, A. Rauschenbach (PCCL), G. Eder, Y. Voronko (OFI), C. Hirschl, L. Neumaier (SAL).

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