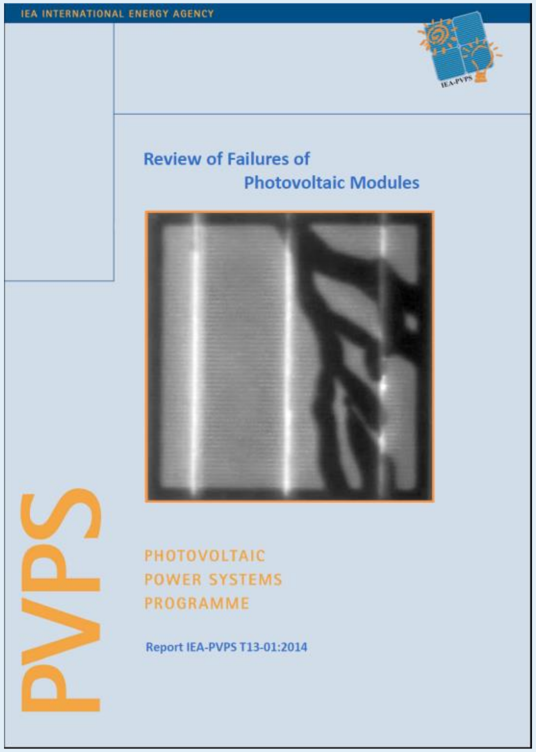
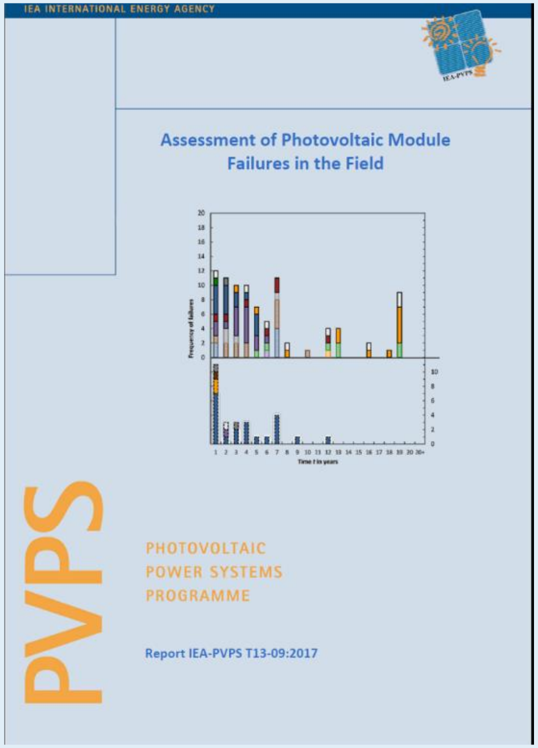
Degradation of materials in PV modules

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

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/

Definition of aging [3]

"Ageing is the negative and positive, irreversible chemical and physical change in the property profile of a material over time.

- **Service life**

  Period of use under operating conditions
- **Life time**

  Time, where component is fully functional
  - *Support of all operational loads*
  - *Life time > Service life*
- **Damage**

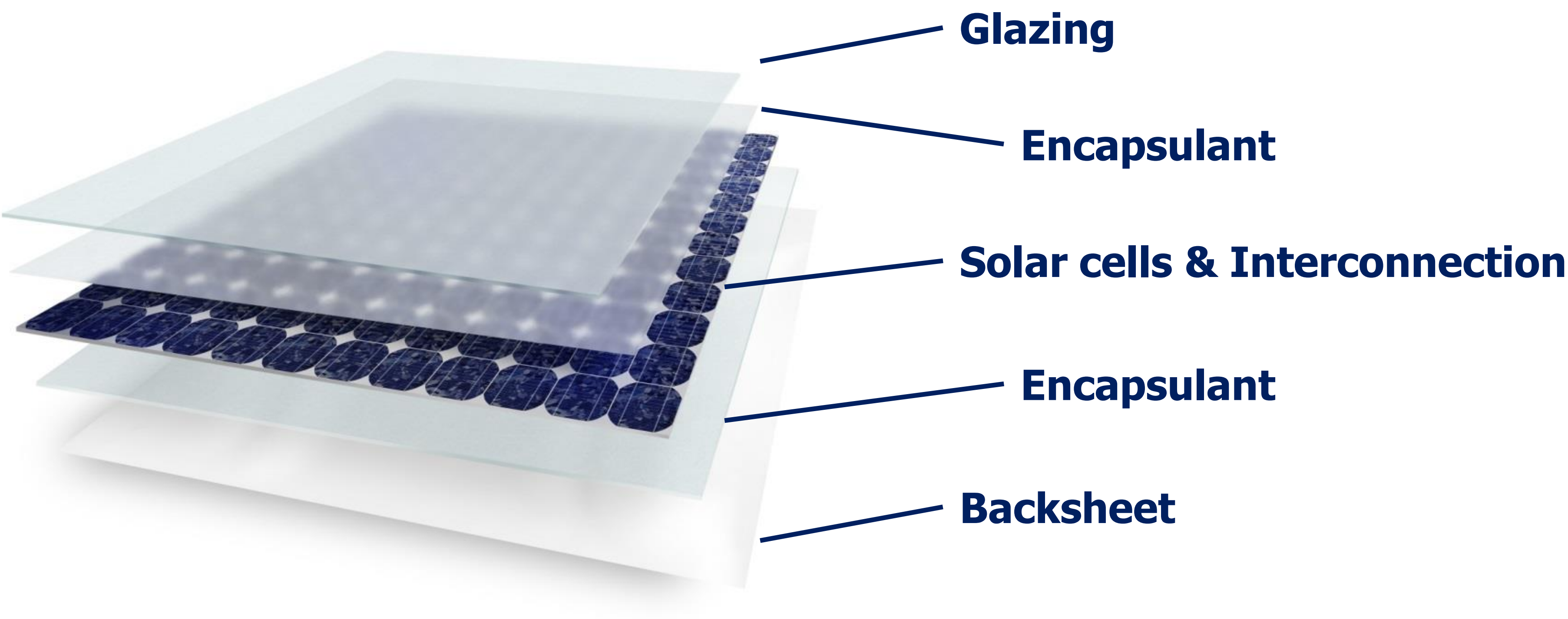
  Negative impact on capacity to withstand stresses up to an acceptable limit
- **Reliability**

  Capacity to withstand stresses during service life and retaining the full functionality

[3] DIN 50035, „Begriffe auf dem Gebiet der Alterung von Materialien - Polymere Werkstoffe“

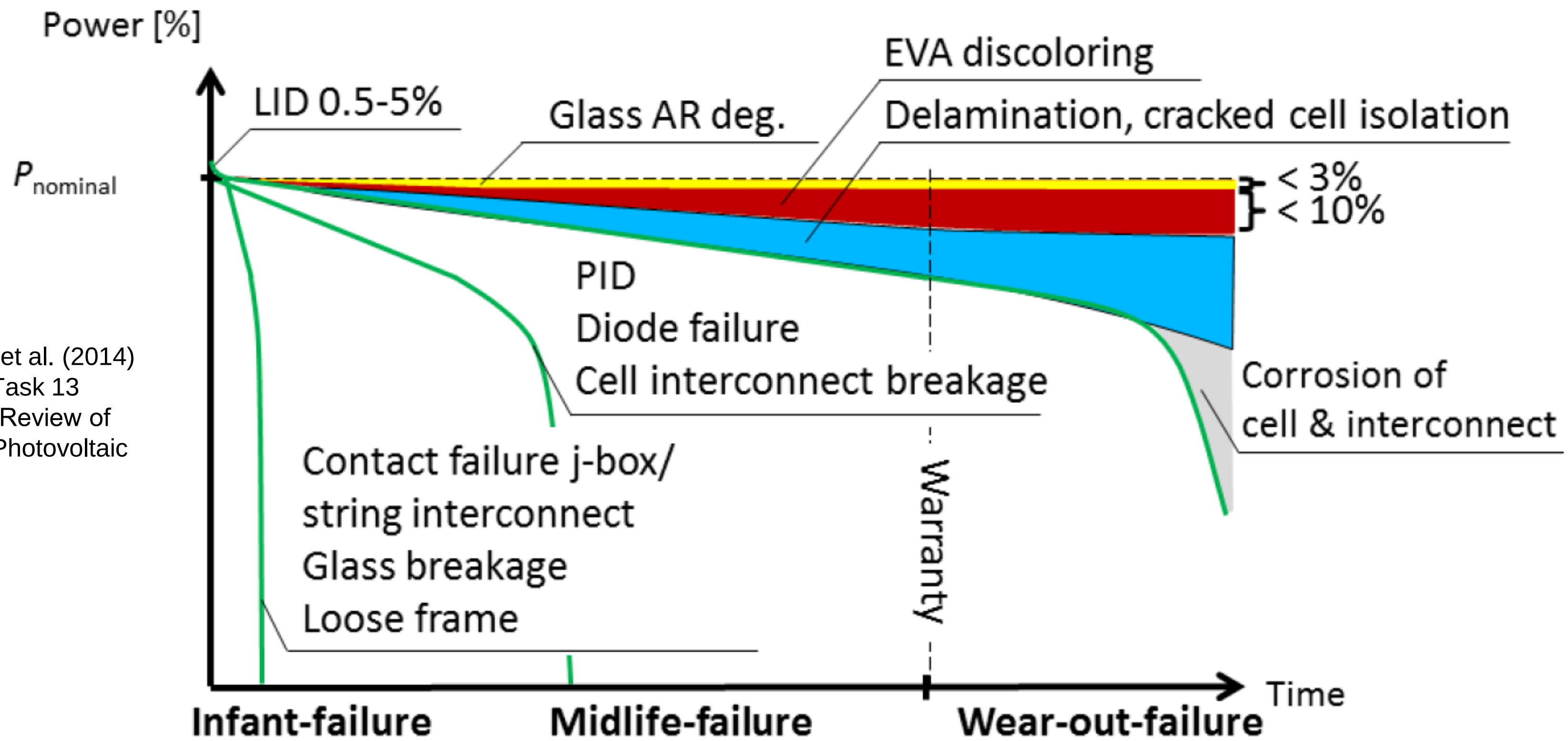
PCCL
Polymer Competence Center Leoben

Photovoltaic modules



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

Failure scenarios of c-Si PV modules [1]

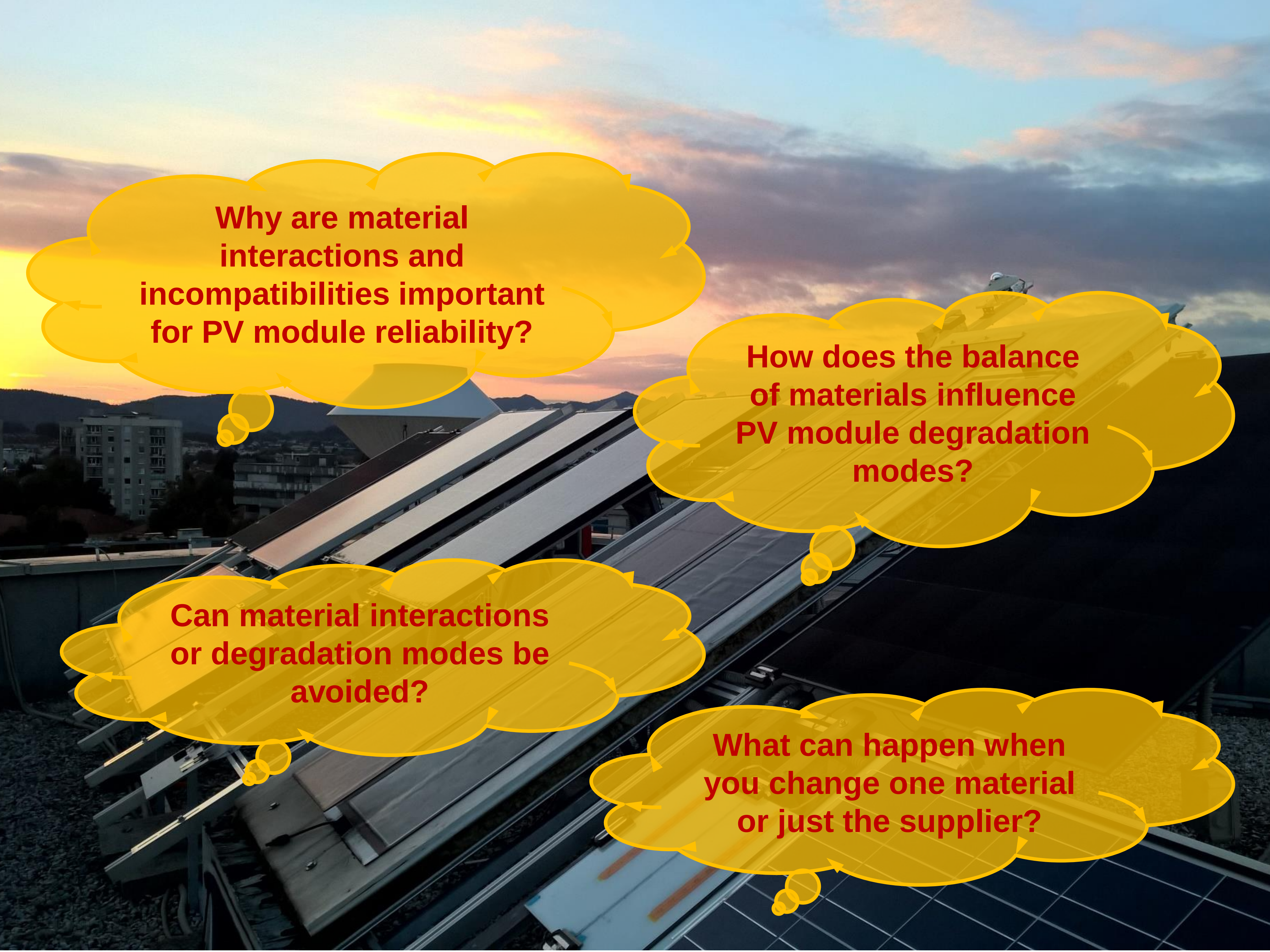


[1] Köntges et al. (2014) IEA-PVPS Task 13 Report on "Review of Failures of Photovoltaic Modules"

Module lamination | Component selection | Material degradation

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

Can be delayed to some extent


Why are material interactions and incompatibilities important for PV module reliability?
How does the balance of materials influence PV module degradation modes?
Can material interactions or degradation modes be avoided?
What can happen when you change one material or just the supplier?

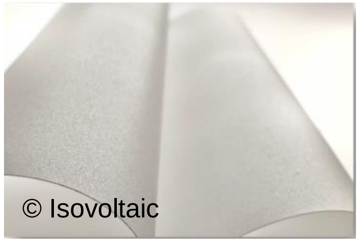
Factors affecting PV module reliability

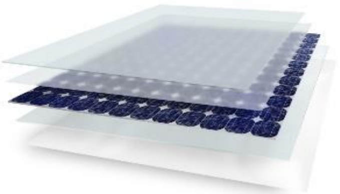
Components
- *R&D*
- *Process parameters*
- *Process stability*
- *Quality inspection*

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

Installation
- *Transport*
- *Handling*
- *Mounting*

Operation
- *Climate*
- *Micro-climate*
- *O&M*





Quality and Reliability issues related to module design and production phase

(1) Known material incompatibilities

(2) Insufficient reliability testing

(3) No outgoing / incoming quality inspection of components

(4) Insufficient processing

a. Low module lamination temperature

b. Reduced lamination time

Effects of known material incompabitibilities

Backsheet – encapsulant adhesion

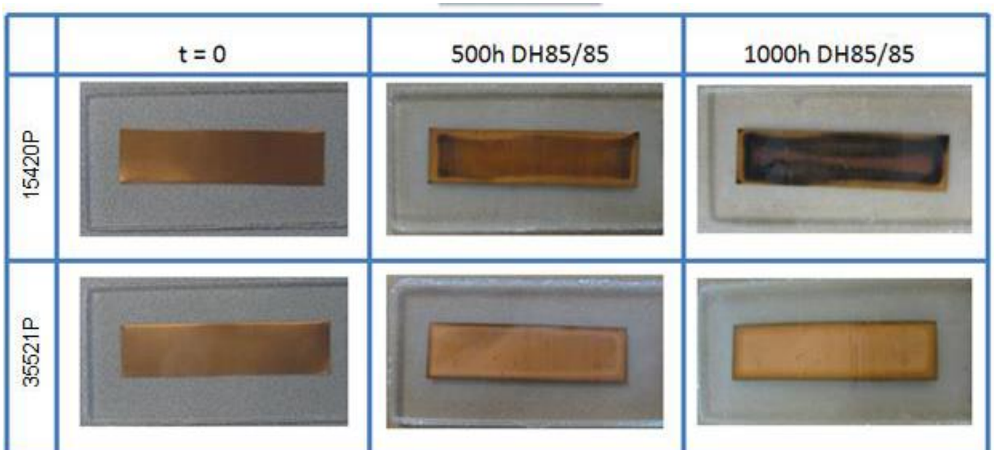
- *Surface treatment of backsheets usually optimized for adhesion to EVA*
- *New co-extruded backsheets based on PP may have adhesion issues with polyolefin encapsulants based on solely PE*

*“**Polyethylene** (**PE**) and isotactic **polypropylene** (iPP) constitute nearly two-thirds of the world's plastic. Despite their similar hydrocarbon makeup, the polymers are immiscible with **one** another. Thus, common grades of **PE** and iPP **do** not adhere or blend…[4] .*

Corrosion of copper ribbons in EVA encapsulants [5][6]

EVA

POE



Glas / POE / copper film / POE

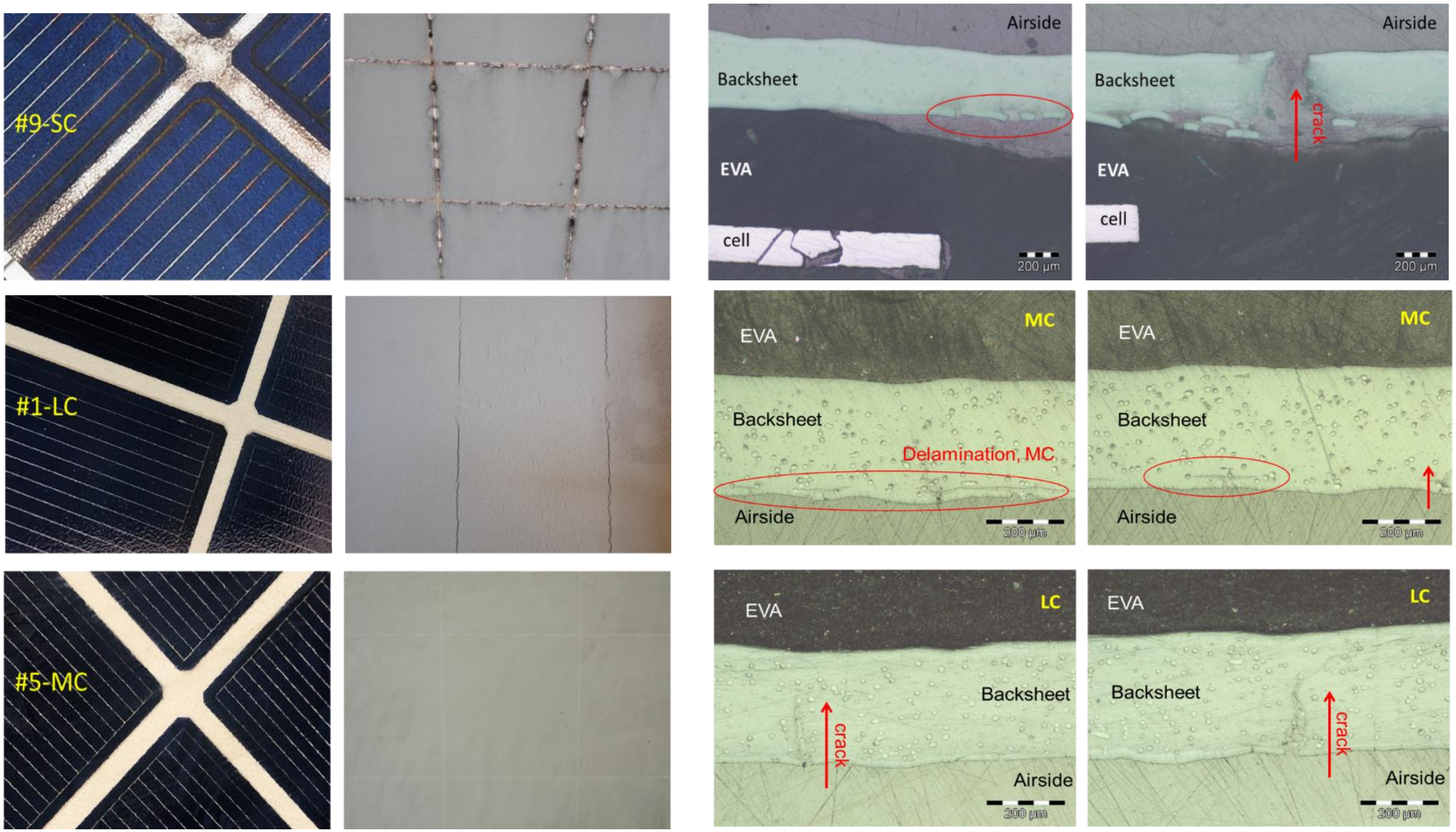
$$2\,Cu^0 + 4\,AcH + O_2 \rightarrow 2\,Cu(Ac)_2 + 2\,H_2O$$

Unsuitable component / material selection

Insufficient reliability testing

Cracking of co-extruded PA based backsheets [7]

Squared
Longitudinal
Micro

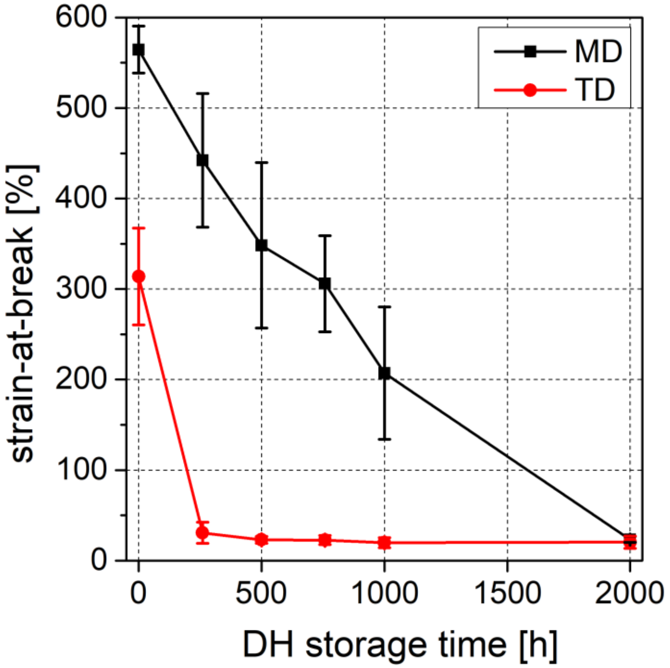


- **Cracking of PA backsheets after 5-8 years in operation**
- **No cracking during accelerating indoor testing**

[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

Insufficient reliability testing

Cracking of co-extruded PA based backsheets [7]



- *Maximum simulated tensile strain of 18% between the area of the cells and backsheet [76]*
- *Random formation of micro-cracks at local stress concentrations*
- *Height of ribbons impose additional tensile stress → **Formation of longitudinal cracks***
- *Only recently these cracks have been reproduced by an combined stress test (UV, RH, T and DML) at NREL*

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

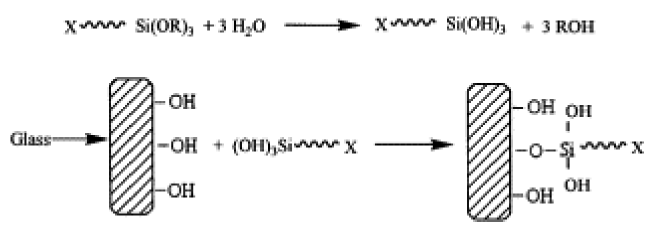
→ **Physical aging effect was observable after single stress testing (DH, UV), but crack formation needs combined or sequential testing including thermo-mechanical loads**

Insufficient reliability testing

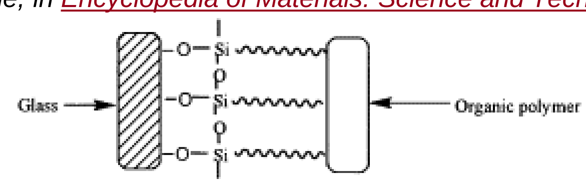
Processing related effects

Glass – encapsulant adhesion

- **Adhesion promoters based on unsaturated alkane silanes are used to establish adhesion of encapsulant to glass and solar cell**
  - *Covalent bonding of silan with hydroxyl group at glass surface*
  - *Unsaturated alkane tail is covalently bonded to the encapsulants using peroxides*



C. Kumudinie, in Encyclopedia of Materials: Science and Technology, 2001



→ *Insufficient lamination may cause lack of adhesion*

Encapsulant – backsheet adhesion

- **Backsheets are often modified to increase adhesion to encapsulant**
  - *Primers & Surface treatment*
- **Example for reliability issues:**
  - *No adhesion of EVA – TPT laminates*
  - *Inner Tedlar layer was primed with an special adhesive*

Flexible Product Adhesives for Use with DuPont™ *Tedlar*® Polyvinyl Fluoride Film

Stock temperatures of 149°C (300°F) or higher are necessary to heat activate the adhesive and adequately bond the film.

  - *Cause: New EVA type was used with lamination temperature given at 145°C*

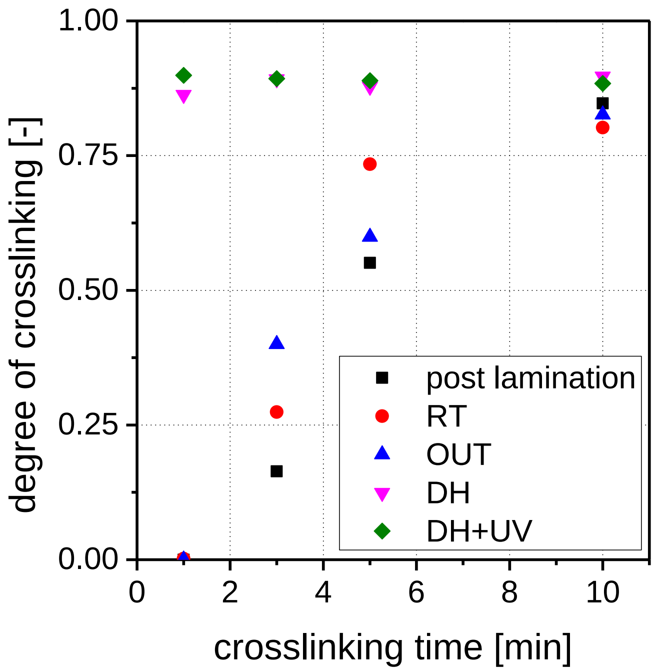
Insufficient lamination temperature

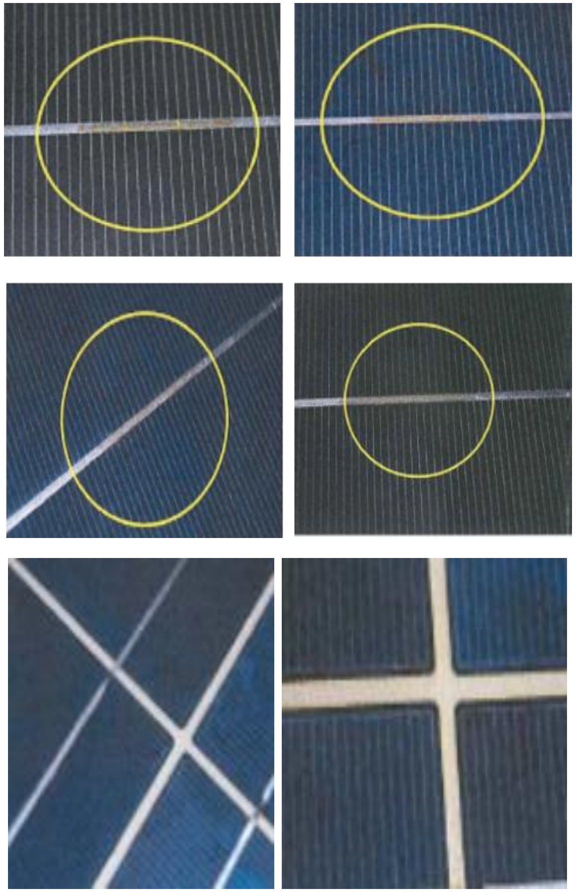
Processing related effects

Poor crosslinking of EVA [8]

→ *EVA encapsulants not fully cured in the lamination process undergo post-lamination crosslinking*

→ *Abundance of active peroxide causes discoloration at soldering ribbons after accelerated aging*

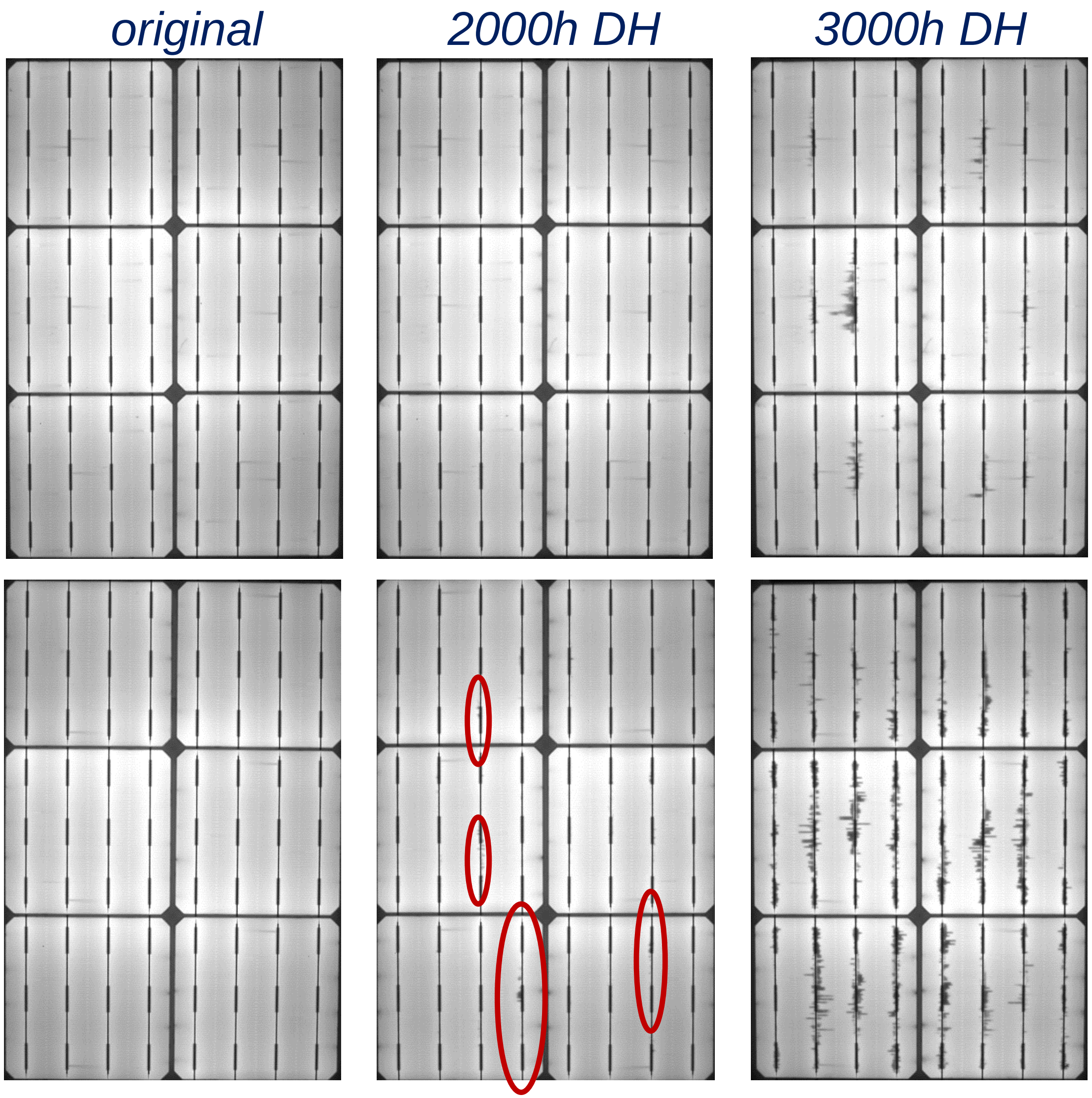




Insufficient lamination parameters

[8] Oreski, G., Rauschenbach, A., Hirschl, C., Kraft, M., Eder, G.C., Pinter, G. (2017) Journal of Applied Polymer Science, 134 (23), art. no. 44912

Processing related effects



Poor crosslinking of EVA

Grid finger corrosion of EVA after damp heat test [9]

Fully crosslinked EVA

- *Grid finger corrosion after 3000h*

Poorly crosslinked EVA (< 40%)

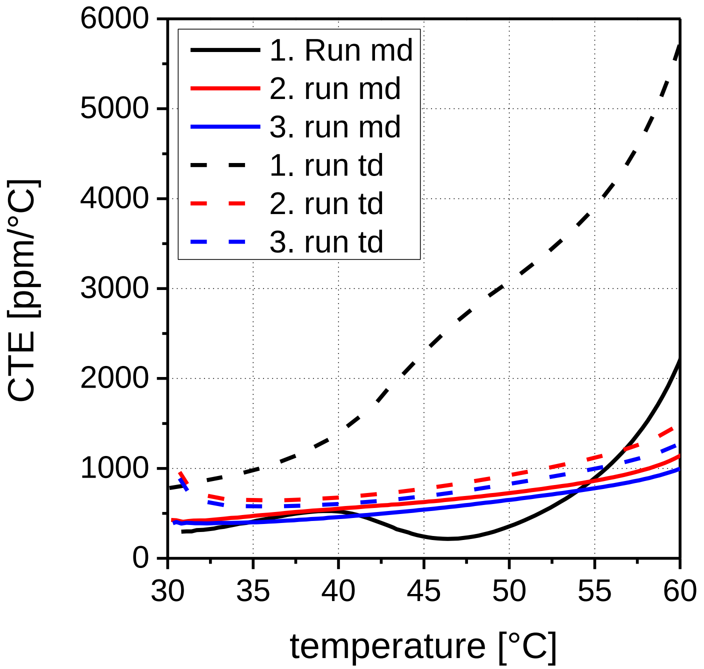
- *Faster progress of corrosion*

Insufficient lamination parameters

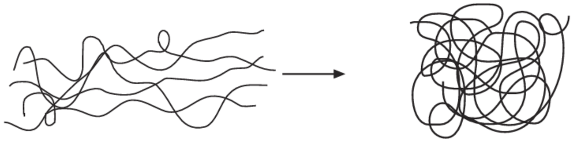
[9] Oreski, G.; Omazic, A.; Eder, G.; Hirschl, C.; Neumaier, L.; Edler, M.; Ebner, R. (2018)
In: 35th EU PVSEC, Brussels, 27.09.2018

Processing related effects

Improper extrusion of encapsulant film [10]



Strong anisotropy and enhanced thermal expansion of EVA film

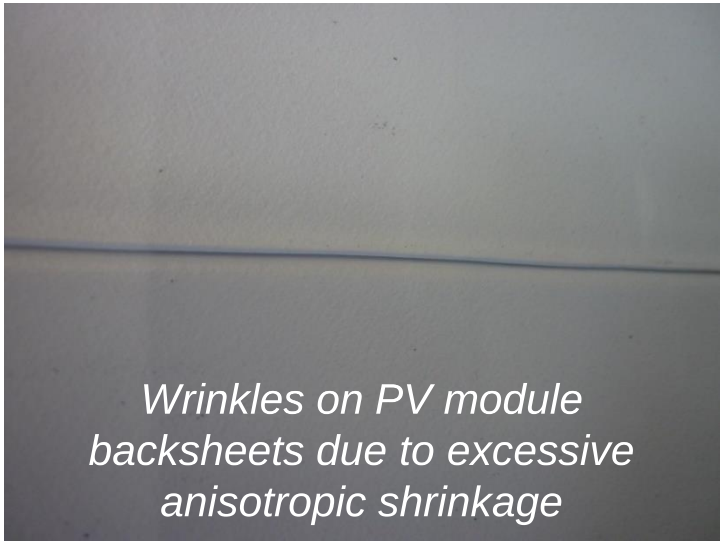


Relaxation of molecular orientations [11]

During lamination:

- *Sheet of 150 x 100 cm expands to 183 x 132 cm already at 60℃*
- *Subsequent shrinking during cooling of laminated modules*

→ *Cell displacement*
→ *Backsheet deformation*



Wrinkles on PV module backsheets due to excessive anisotropic shrinkage

[10] Oreski, G. (2014): Advanced methods for discovering PV module process optimization potentials" (2014) In: Photovoltaics International 23, pp. 71-78

No quality inspection

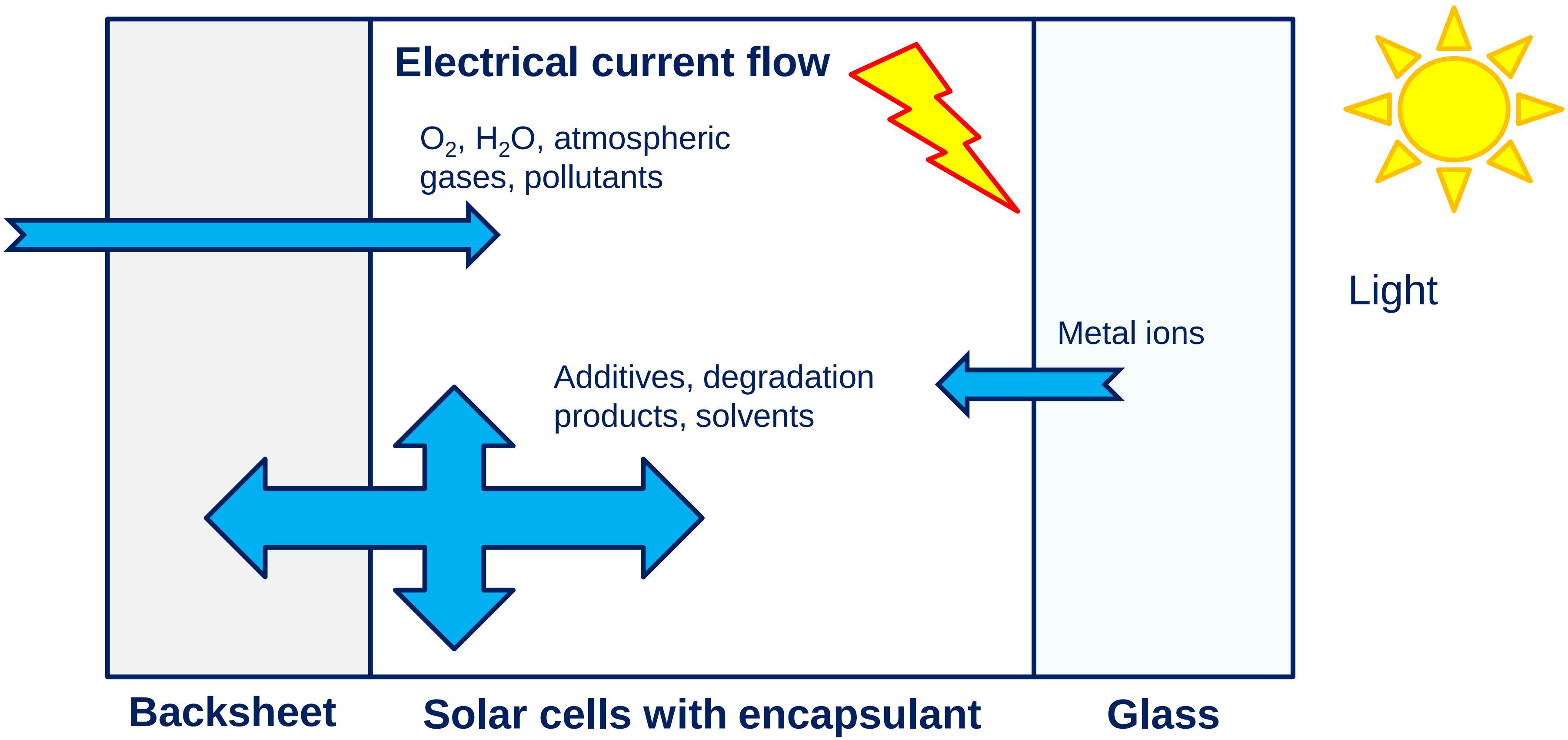
Quality and Reliability issues during operation

(1) Material degradation

(2) Material interactions and module degradation modes

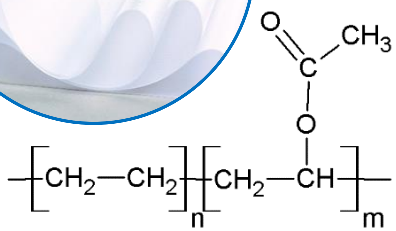
PCCL Polymer Competence Center Leoben

PV module degradation – material interactions

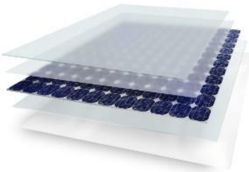


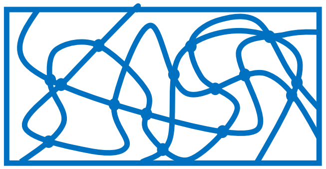
→ **Interactions may lead to unintended degradation effects:**
Yellowing, corrosion, potential induced degradation, snail trails

PV module degradation modes



Module lamination

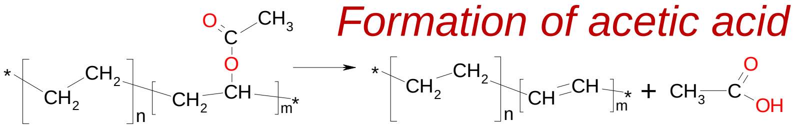




Peroxide induced chemical crosslinking

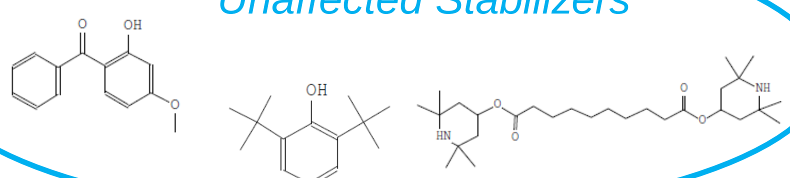
Degree of crosslinking after module lamination: 70-90% [12]

Formation of acetic acid [13]

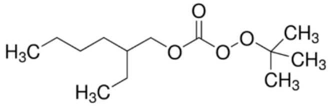


UV, T, RH

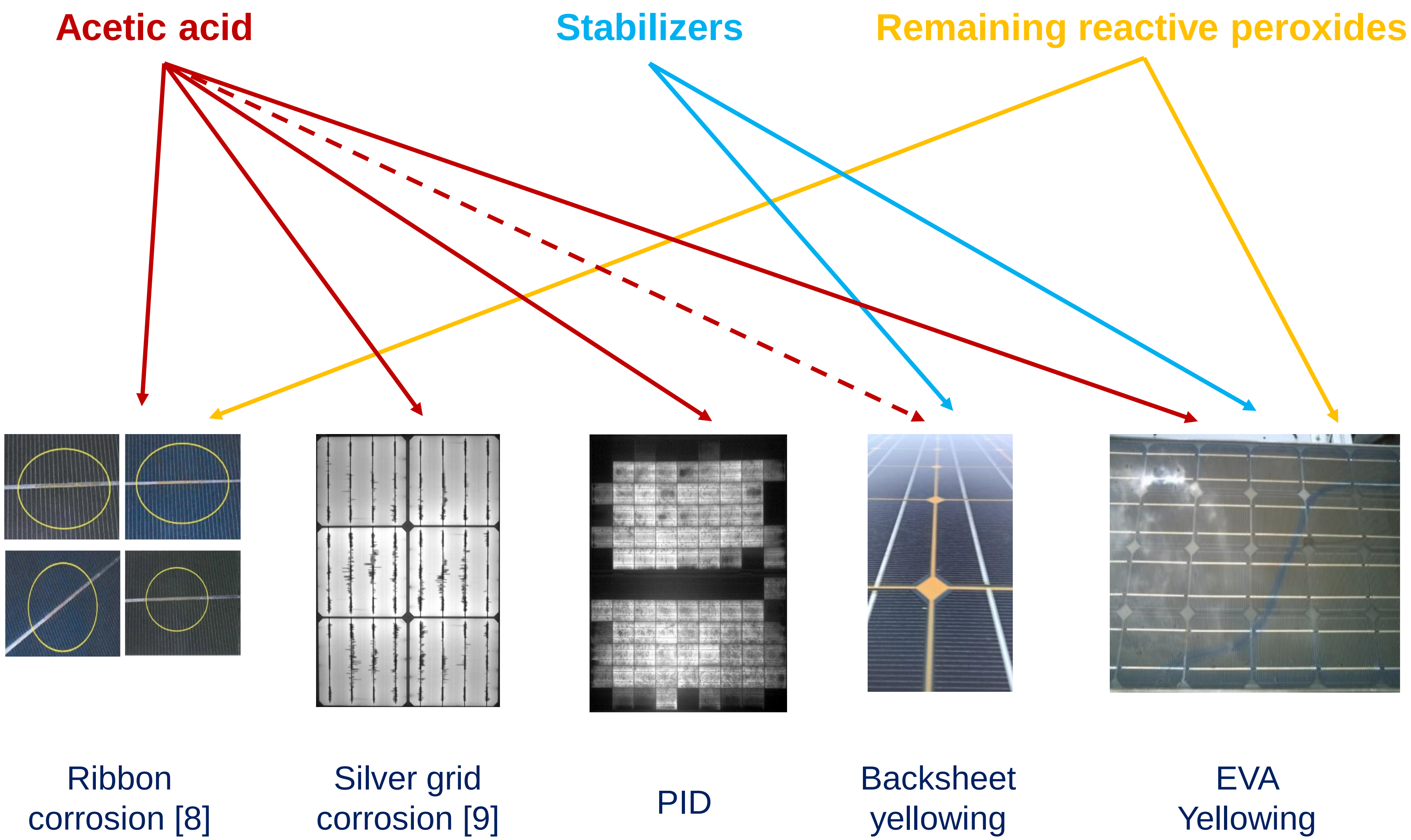
Unaffected Stabilizers



Remaining reactive peroxides [14]



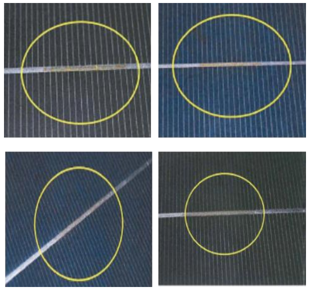
PV module degradation modes



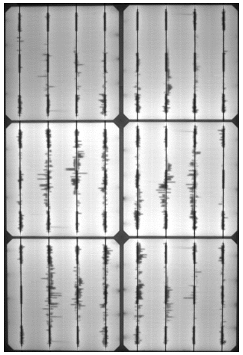
PV module degradation modes

Acetic acid **Stabilizers** **Remaining reactive peroxides**

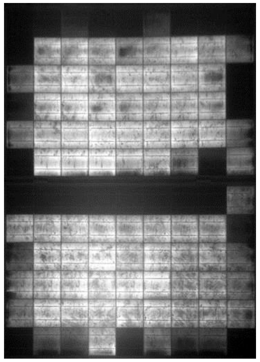
- → **Influenced or driven by permeation processes of O_2, H_2O and corrosive degradation products**
- → **Polymeric materials (E+BS) play major role in PV module degradation**



Ribbon corrosion [8]



Silver grid corrosion [9]



PID

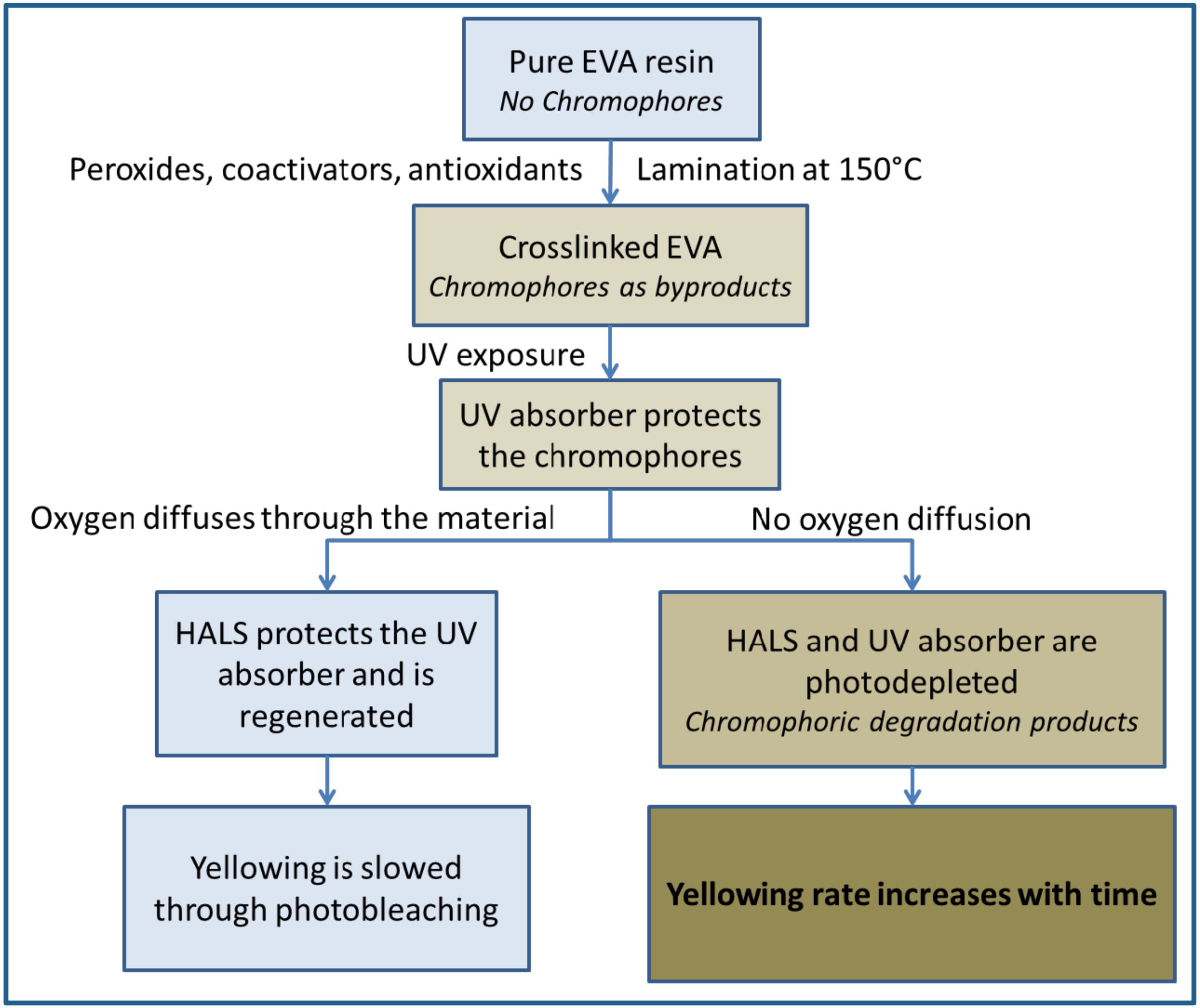
Backsheet yellowing

EVA Yellowing

PV module degradation modes
Yellowing

Browning of EVA

Optimized choice of stabilizers is crucial to the long-term stability of EVA [2]



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

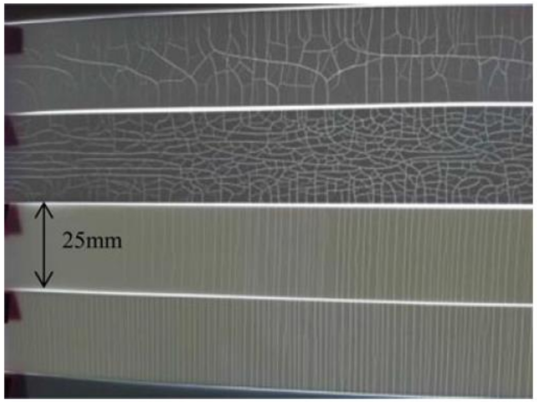
PV module degradation modes
Backsheet degradation

PCCL Polymer Competence Center Leoben

Chemical aging processes

- *Thermo-oxidation*
- *Photo-oxidation*
- *Hydrolysis*

"Changes in chemical structure and molar mass distribution"

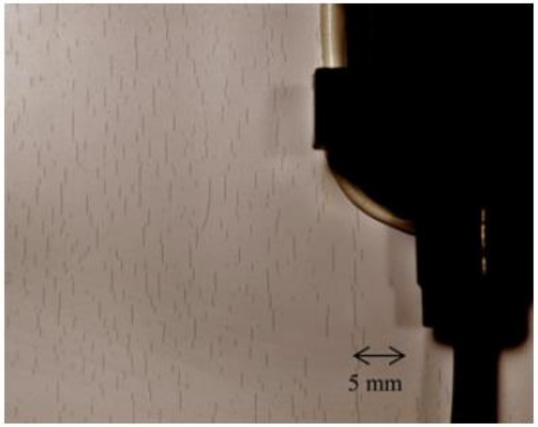


Cracking of PET based backsheets [15]

Physical aging processes

- *Post and re-crystallization*
- *Relaxation of orientations*
- *Migration of plasticizers*
- *Swelling*

"Changes in polymer morphology"



Cracking of a PVDF layer of backsheet [15]

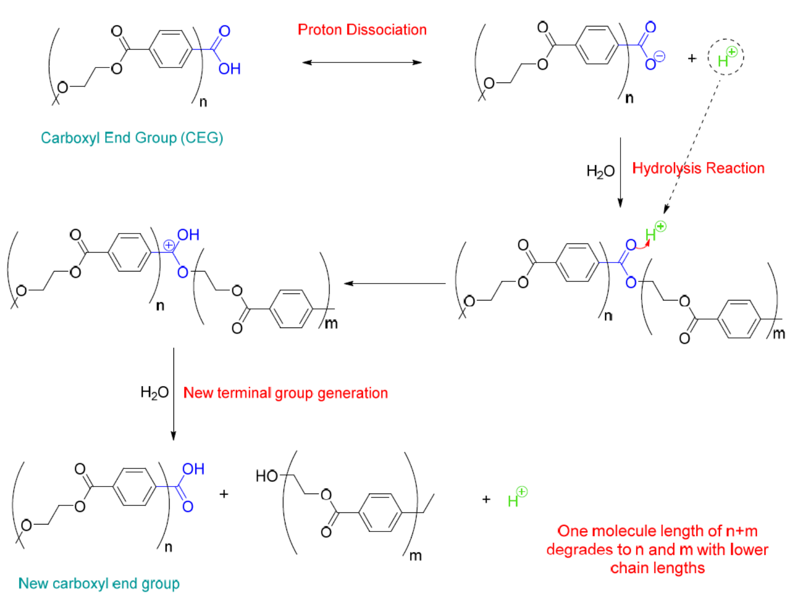
➢ **Crack formation due to embrittlement**

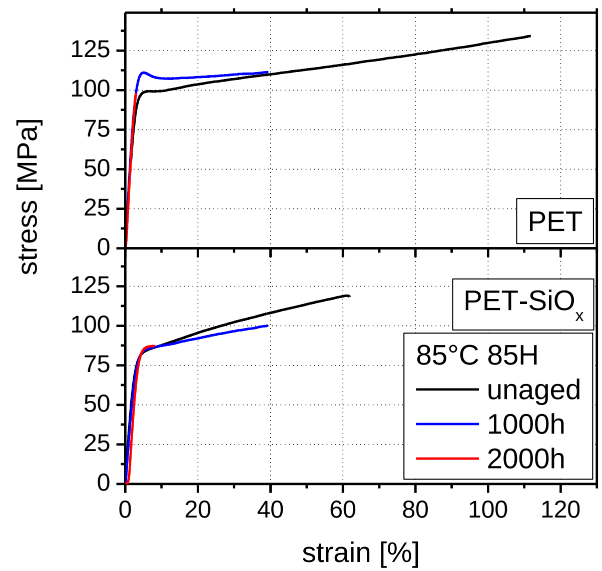
→ **Significant reduction of maximum strain values**

[15] W. Gambogi, Y. Heta, K. Hashimoto, J. Kopchick, T. Felder, S. MacMaster, A. Bradley, B. Hamzavytehrany, L. Garreau-Iles, T. Aoki, K. Stika, T. J. Trout, and T. Sample „A Comparison of Key PV Backsheet and Module Performance from Fielded Module Exposures and Accelerated Tests ", IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 4, NO. 3, 2014

PV module degradation modes
Mechanisms of backsheet cracking

Chemical aging processes: Hydrolysis and photo-oxidation of PET based backsheets [16-17]





- ➢ Reduction of molar mass
  - → **Strong embrittlement**

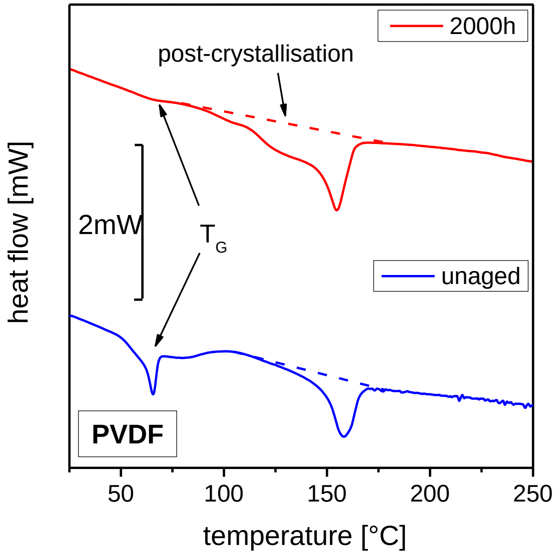
[16] K. Looney, B. Brennan, „Modelling the correlation between DHT and true field lifetimes for PET based backsheet“, 5.D0.10.5, EU PVSEC 2014, Amsterdam.

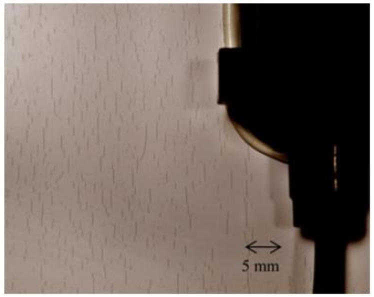
[17] G. Oreski, G. Wallner, „Aging mechanisms of polymeric films for PV encapsulation”, Solar Energy 79 (2005) 612–617

PV module degradation modes
Mechanisms of backsheet cracking

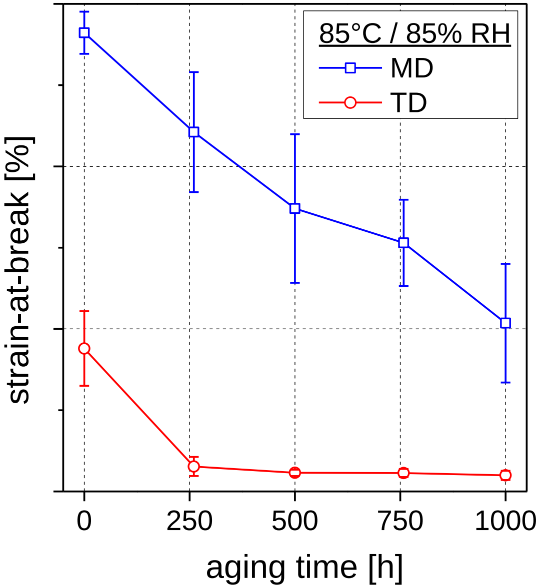
Post-crystallization of PVDF

– *Accelerated aging at 85°C (damp heat conditions) is above glass transition of PVDF*
– *Enhanced chain mobility lead to strong increase in degree of crystallinity from 13 to 30% [17]*
– *Post-crystallization of α-PVDF in β-PVDF matrix*
  → **Significant reduction of maximum strain values – strong embrittlement**
  → **Formation of cracks due to expansion during thermal cycling [17]**





Cracking of a PVDF layer of backsheet [15]



Mechanisms of crack formation in PV module backsheets

Chemical aging processes:
Photo/thermo-oxidation and hydrolysis

- **Cause**
  - *External stress factors*
- **Main driving factors**
  - *UV radiation*
  - *Oxygen and humidity*
  - *Temperature*
- **Long term effect with defined inhibition period depending on stabilization system of the polymers**

vs.

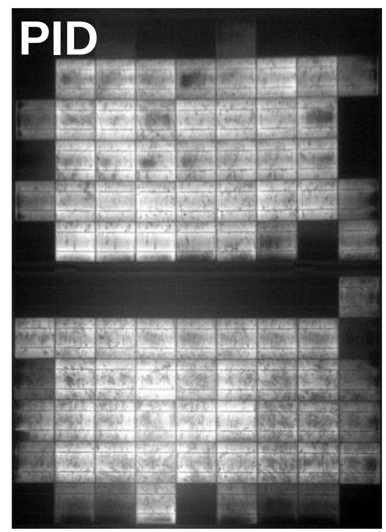
Physical aging processes:
Post-crystallization and relaxation of orientations

- **Cause**
  - *Thermo-dynamical imbalance due to polymer processing*
- **Main driving factor**
  - *Temperature*
- **Short term effect after exposure to temperatures above thermo-dynamic transitions (e.g. glass transition)**

Photovoltaic module degradation modes

Complex interactions between external stresses and different material degradation modes, resulting in power loss

- *Visible material degradation does not necessarily lead to a power loss*
- *Visually inconspicuous modules may have severe power loss*

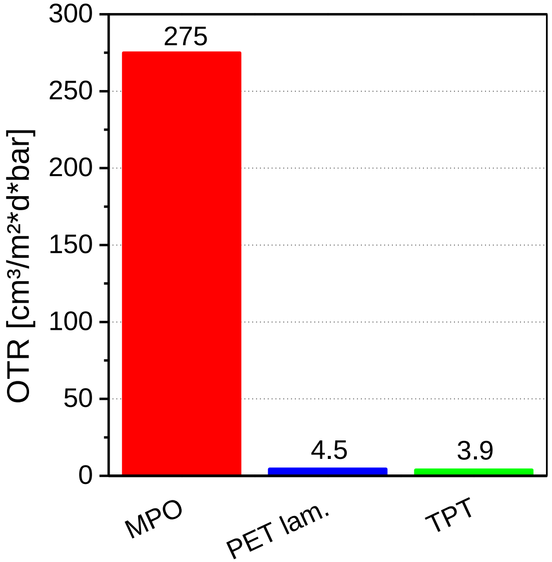


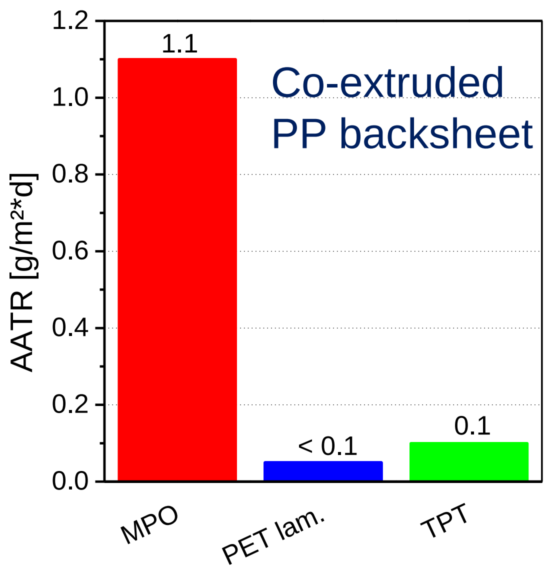
Cell breakage due to hail [18]

How to avoid certain degradation modes?

- *Choice of right components and materials*
- *Knowledge about long term behavior*

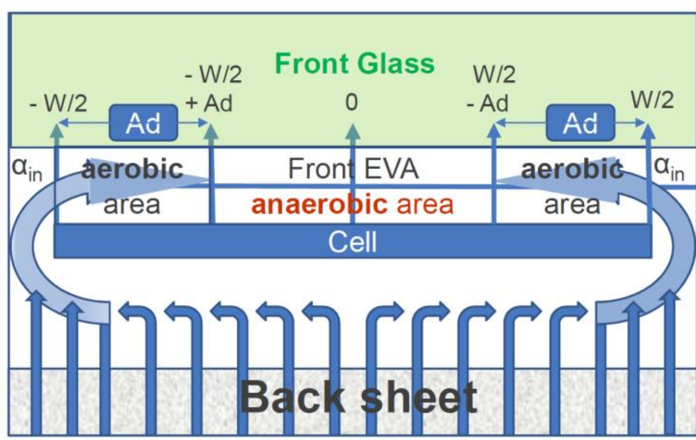
PV module degradation modes



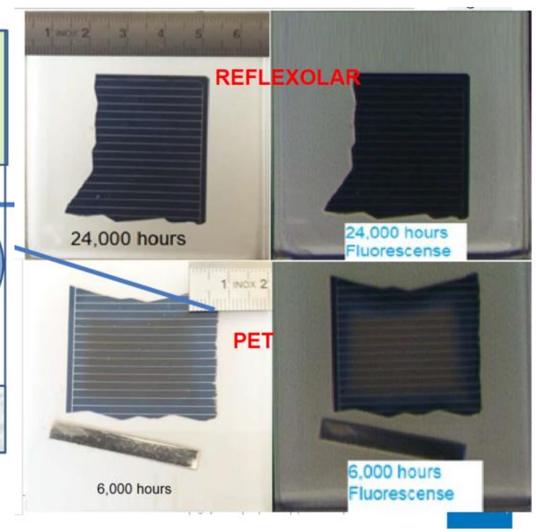


Yellowing prevention: Backsheets with selective permeability [18-19]

- *Backsheets with low water vapour but high oxygen and acetic acid permeability [18]*
- *Acetic acid can permeate out of the modules, oxygen can go into the module*
- *Effects like PID, oxidation of EVA are slowed down; photobleaching of yellowing [19]*



ϕ_{bs} is the flow entering the gap, for $\alpha_{in} = 0$
ϕ_{bs} S is the backsheet OTR



PID prevention: New encapsulation films [5] [21-22]

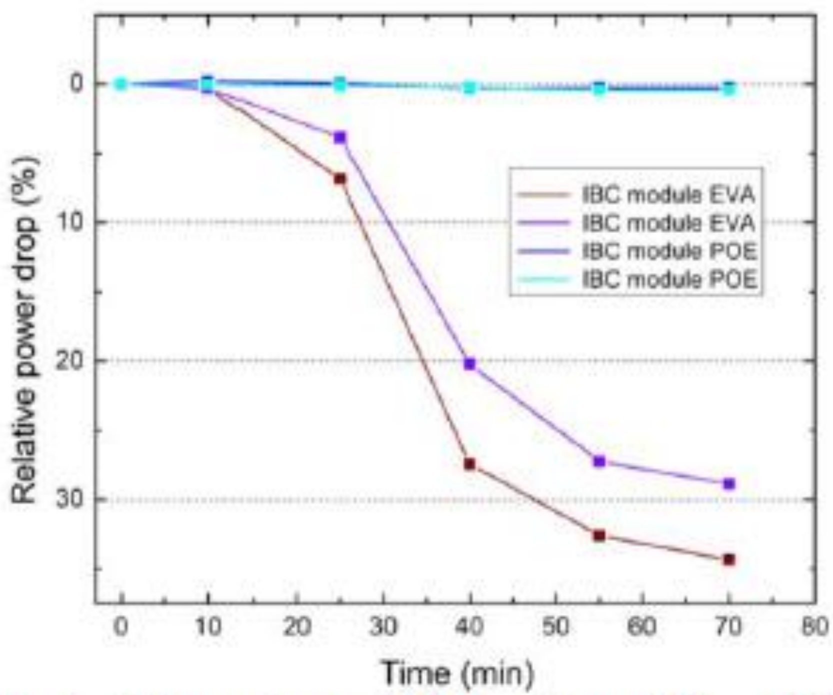


Figure 3: PID testing on Zebra mini-modules exhibiting POE and EVA as encapsulation material

Table II: Encapsulants used in this study.

Code	Encapsulant Grade Name	VR[1] ohm-cm (23°C)	MVTR[2] g/m^2/day (25°C)
EVA-1	STR 15295P	5×10^{13}	23
EVA-2	STR 15420P	2×10^{14}	23
EVA-3	STR 15455P	5×10^{14}	23
EVA-4	STR 15580P	3×10^{15}	18
EVA-5	China source	1×10^{14}	25
EVA-6	Japan source	1×10^{15}	17
POE-1	STR X-28-138	1×10^{17}	1.5
POE-2	STR X-44 series	1×10^{16}	1.7
POE-3	STR X-31 series	1×10^{16}	5.2
POE-4	China source	8×10^{13}	2.3

(1) VR = volume resistivity, tested per method described in section 2.2
(2) MVTR = moisture vapor transmission rate, tested per ASTM F1249.

Factor 10-1000 ↑

Factor 10 ↓

No PID

[

PV module degradation modes

PID Prevention using Ionomers [23]

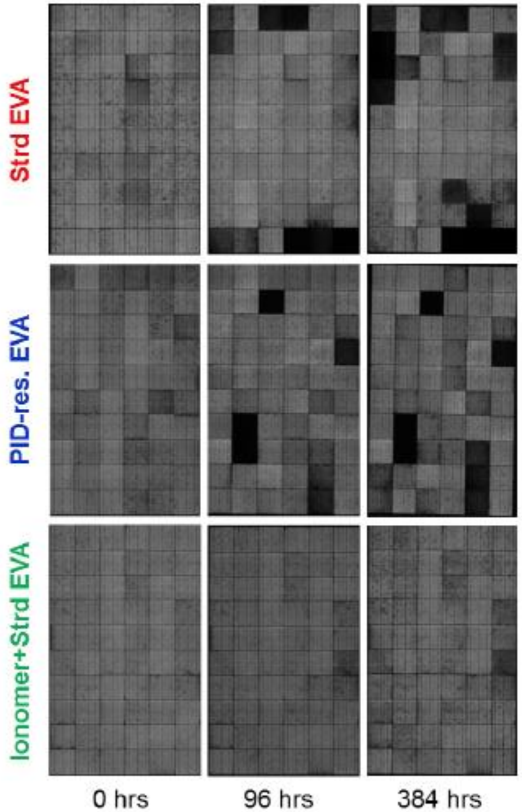


Figure 3: Electroluminescence images of full-size modules made with (i) Standard EVA (red circles), (ii) EVA designated as 'PID-free' (blue triangles), and (iii) an Ionomer film on top of a Standard EVA layer (green diamonds), after PID exposure at 85 °C / 85 % / -1000 V of varying duration.

Introduction of a thin Ionomer layer of 100 µm thickness between a standard EVA and the front glass [1]

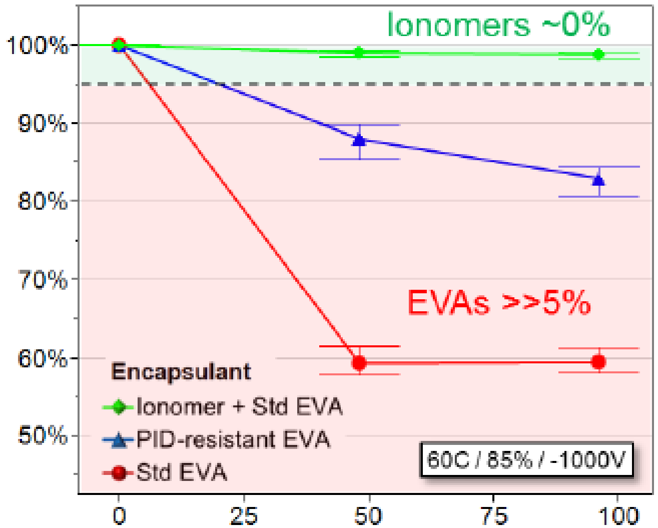


Figure 6: Comparison of relative output power for different encapsulants in 2nd set of nine full-size modules after PID exposure at 60 °C / 85 %RH / -1000 V of 96 hours. All modules were built at the Yingli production facility in Baoding, China.

"The ionomer provides a barrier to sodium ion migration into the EVA layer, and thereby effectively protects the solar cell and module from PID"

Summary
Role of material degradation in PV module reliability

- **Encapsulation materials play an important role in PV module reliability**
  - *Most prominent PV module failure mechanisms are linked to the used polymeric encapsulation materials*
- **Long term stability is determined by bill of materials and their material interactions - Design matching of components and materials may reduce degradation rates or avoid certain degradation modes**
- **Each material combination should be tested thoroughly before introduction into the market**
- **Single stress testing often does not reveal certain degradation modes observed in the field → combined stress testing necessary**

→ Better understanding of PV module and material degradation processes is a precondition for a successful development of new components and PV module designs

Development of new materials

Technical Challenges

- *Processability*
- *Thermo-mechanical stability – no creep*
- *Spectral selectivity for enhanced light yield*
- *Good adhesion between glass, encapsulants, solar cells and backsheet films*
- *High weathering stability for lifetimes > 25 years*
- *Prevention or reduction of chemical and physical degradation processes*
- *No harmful interactions with other PV module materials*
- *Reliable accelerated tests and characterization tools for fast and reliable assessment of new materials*

Cost driven development

- *So far, only direct material costs are counting*
- *Total cost of life is not considered*

→ ***Difficult market entry situation for new materials and new suppliers***

Conclusions

Four (not so) serious advices to produce (bio) degradable PV modules

(1) Everybody can design PV modules, no need for comprehensive R&D. Buy the cheapest materials & components you find. Material incopatibilities are overrated!

(2) Who needs quality management systems? Avoid incoming inspections of components and materials. Datasheets are a sufficient source of information. But you don´t need to read them in detail.

(3) Save time and money. Reduce lamination temperature and shorten lamination times.

(4) Do it without suitable accelerated aging tests. It takes way too long, and they are expensive too!

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 (CTR).

This research work was performed within the project "Infinity" (Energieforschungsprogramm 2015 - Leitprojekte, FFG No. 850414, Klima- und Energiefonds). The PCCL is funded by the Austrian Government and the State Governments of Styria, Lower Austria and Upper Austria.

References

[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”

[3] DIN 50035, „Begriffe auf dem Gebiet der Alterung von Materialien - Polymere Werkstoffe“

[4] James M. Eagan, Jun Xu, Rocco Di Girolamo, Christopher M. Thurber, Christopher W. Macosko, Anne M. LaPointe, Frank S. Bates, Geoffrey W. Coates, Combining polyethylene and polypropylene: Enhanced performance with PE/iPP multiblock polymers, *Science*24, 2017: 814-816

[5] I. Fidalgo, „New POE encapsulants for PV modules” Polymers in PV, Düsseldorf,2.-3.2.2016

[6] B.X.Huang et al.: “IR and Raman spectroelectrochemical studies on corrosion films on tin”, Electrochimica acta 46 (2000) 671-679

[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

[8] Oreski, G., Rauschenbach, A., Hirschl, C., Kraft, M., Eder, G.C., Pinter, G. (2017) Journal of Applied Polymer Science, 134 (23), art. no. 44912

[9] Oreski, G.; Omazic, A.; Eder, G.; Hirschl, C.; Neumaier, L.; Edler, M.; Ebner, R. (2018): Do PV Modules Optimized for Different Climatic Conditions Make Sense? Discussion by Using the Example of Backsheet and Encapsulant Films. In: 35th EU PVSEC, Brussels, 27.09.2018

[10] Oreski, G. (2014): Advanced methods for discovering PV module process optimization potentials” (2014) In: Photovoltaics International 23, pp. 71-78

[11] Ehrenstein, Gottfried W., Riedel, Gabriela, and Trawiel, Pia (2004) hermal Analysis of Plastics: Theory and Practice, Carl Hanser Verlag GmbH & Co. KG. https://doi.org/10.3139/9783446434141

[12] Hirschl, C., Biebl-Rydlo, M., Debiasio, M., Mühleisen, W., Neumaier, L., Scherf, W., Oreski, G., Eder, G., Chernev, B., Schwab, W., Kraft, M. ”Determining the degree of crosslinking of ethylene vinyl acetate photovoltaic module encapsulants - A comparative study” (2013) Solar Energy Materials and Solar Cells, 116, pp. 203-218.

[13] Czanderna A.W., Pern F.J., “Encapsulation of PV modules using ethylene vinyl acetate copolymer as a pottant: A critical review”, Sol. Energy Mater. Sol. Cells 43(2): 101-181 (1996)

References

[14] Oreski, G., Rauschenbach, A., Hirschl, C., Kraft, M., Eder, G.C., Pinter, G. Crosslinking and post-crosslinking of ethylene vinyl acetate in photovoltaic modules (2017) Journal of Applied Polymer Science, 134 (23), art. no. 44912

[15] W. Gambogi, Y. Heta, K. Hashimoto, J. Kopchick, T. Felder, S. MacMaster, A. Bradley, B. Hamzavytehrany, L. Garreau-Iles, T. Aoki, K. Stika, T. J. Trout, and T. Sample „A Comparison of Key PV Backsheet and Module Performance from Fielded Module Exposures and Accelerated Tests “, IEEE JOURNAL OF PHOTOVOLTAICS, VOL. 4, NO. 3, 2014

[16] K. Looney, B. Brennan, „Modelling the correlation between DHT and true field lifetimes for PET based backsheet“, 5.D0.10.5, EU PVSEC 2014, Amsterdam.

[17] G. Oreski, G. Wallner, „Aging mechanisms of polymeric films for PV encapsulation”, Solar Energy 79 (2005) 612–617

[18] W. Mühleisen, C. Hirschl, G.C. Eder, Y. Voronko, M. Spielberger, H. Sonnleitner, „Scientific Investigation of a PV Generator After Hail”, PVSEC 2017, 6BO.8.3, 10.4229/EUPVSEC20172017-6BO.8.3

[19] Oreski, G.; Mihaljevic, A.; Voronko, Y.; Eder, G. C. (2017): Acetic acid permeation through photovoltaic backsheets. Influence of the composition on the permeation rate. In: Polymer Testing 60, pp. 374–380. DOI: 10.1016/j.polymertesting.2017.04.025.

[20] F. Rummens, Increasing PV module service life by a factor 4, using RefleXolar PO backsheet: a tentative demonstration! PVPS Task 13 workshop Innovations in Photovoltaic Materials –EU PVSEC 2019 Marseille Parallel Event

[21] A. Schneider et al., “MATERIAL DEVELOPMENTS ALLOWING FOR NEW APPLICATIONS, INCREASED LONG TERM STABILITY AND MINIMIZED CELL TO MODULE POWER LOSSES, PVSEC 2015, 1BV.6.36

[22] Reid et al., “CONTRIBUTION OF PV ENCAPSULANT COMPOSITION TO REDUCTION OF POTENTIAL INDUCED DEGRADATION (PID) OF CRYSTALLINE SILICON PV CELLS, PVSEC 2013, 4AV5.49

[23] S.C Pop et al., „IONOMER-BASED PID-RESISTANT ENCAPSULANT FOR PV MODULES“, PVSEC 2015, Hamburg, 1BV.6.37