# SOLAR-Train: Climate, Materials and Performance

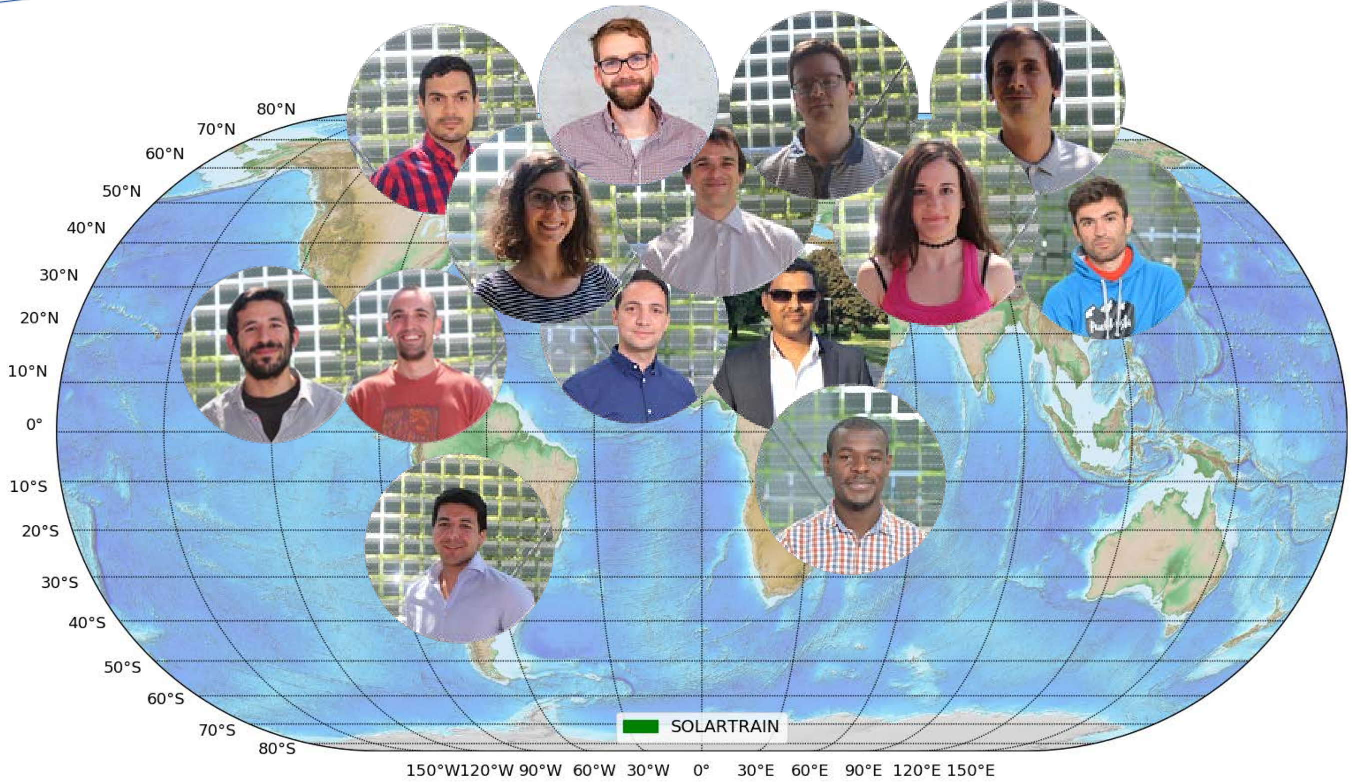
**PV Reliability SOPHIA Workshop 2020**

**Webinar**

29.05.2020

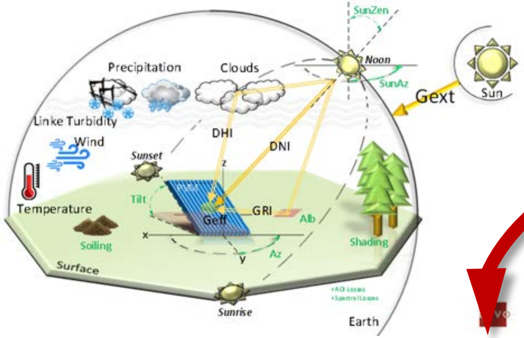
This project has received funding from the European Union's Horizon 2020 programme under GA. No. 721452.

# Outline



80°N
70°N
60°N
50°N
40°N
30°N
20°N
10°N
0°
10°S
20°S
30°S
40°S
50°S
60°S
70°S
80°S
SOLARTRAIN
150°W 120°W 90°W 60°W 30°W 0° 30°E 60°E 90°E 120°E 150°E

# Outline




Outdoor & Indoor Climate

Encapsulants & Backsheets

Test Sites & Large Systems

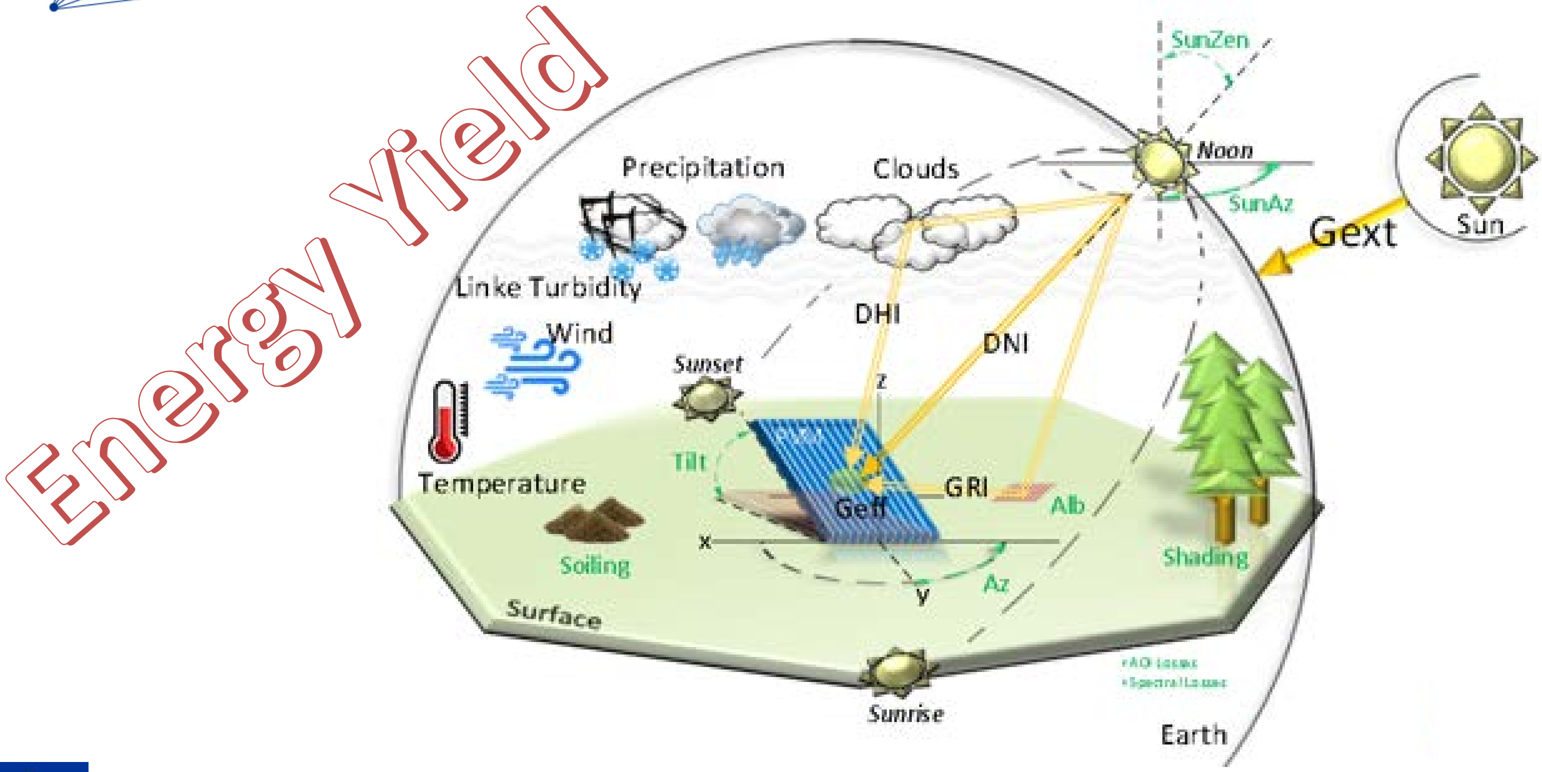
# Outline

- "Understanding climate related operation conditions of PV systems"
  - J. A-V: *Main climate degradation factors*
  - N.K.: *Equilibrium moisture content in PV polymers*
  - S.M.: *Moisture diffusion in different encapsulants and backsheets*
- "Advanced characterization of PV materials: natural and artificial ageing"
  - C.B.: *DH/UV of different encapsulants*
  - L.C.: *Accelerating testing of backsheets*
  - Dj.M.: *Effect of different backsheet on encapsulant degradation*
- "Understanding PV module performance evolution, Service Lifetime Prediction & O&M activities "
  - I.K.: *PV degradation modelling*
  - S.L.: *Nonlinear Multi-step Performance Loss Rate*
  - N.H.: *Electrical parameter evolution*
  - G.O.: *Modelling applied to O&M activities*

# Climate related conditions

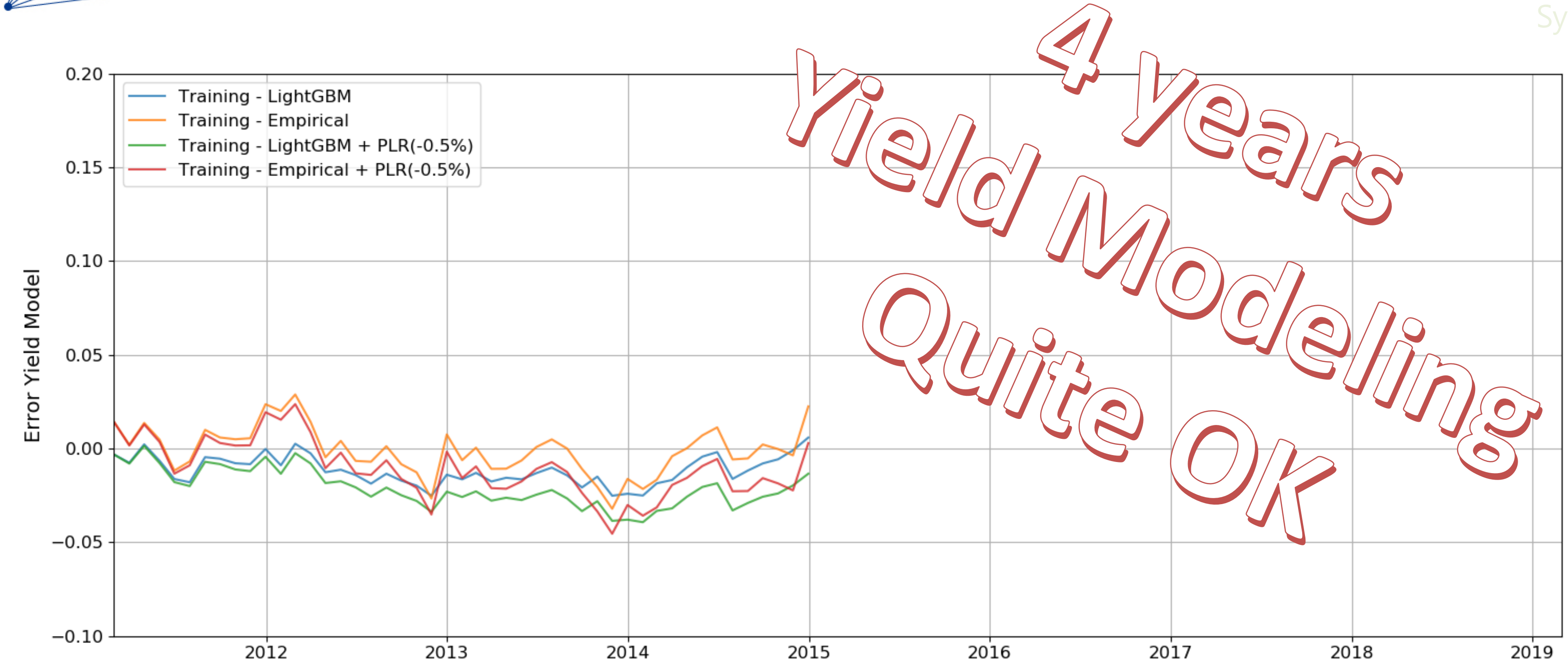

- "Understanding climate related operation conditions of PV systems”
  - J. A-V: *Main climate degradation factors*
  - N.K.: *Equilibrium moisture content in PV polymers*
  - S.M.: *Moisture diffusion in different encapsulants and backsheets*
- "Advanced characterization of PV materials: natural and artificial ageing”
  - C.B.: *DH/UV of different encapsulants*
  - L.C.: *Accelerating testing of backsheets*
  - Dj.M.: *Effect of different backsheet on encapsulant degradation*
- "Understanding PV module performance evolution, Service Lifetime Prediction & O&M activities ”
  - I.K.: *PV degradation modelling*
  - S.L.: *Nonlinear Multi-step Performance Loss Rate*
  - N.H.: *Electrical parameter evolution*
  - G.O.: *Modelling applied to O&M activities*

# Climate degradation factors




[1] Ascencio et al, *Solar Energy*, 2019
[2] Ascencio et al, *Energies*, 2019

# Climate degradation factors




[2] Ascencio et al, *Energies*, 2019
[3] Ascencio et al, *Energies*, 2020

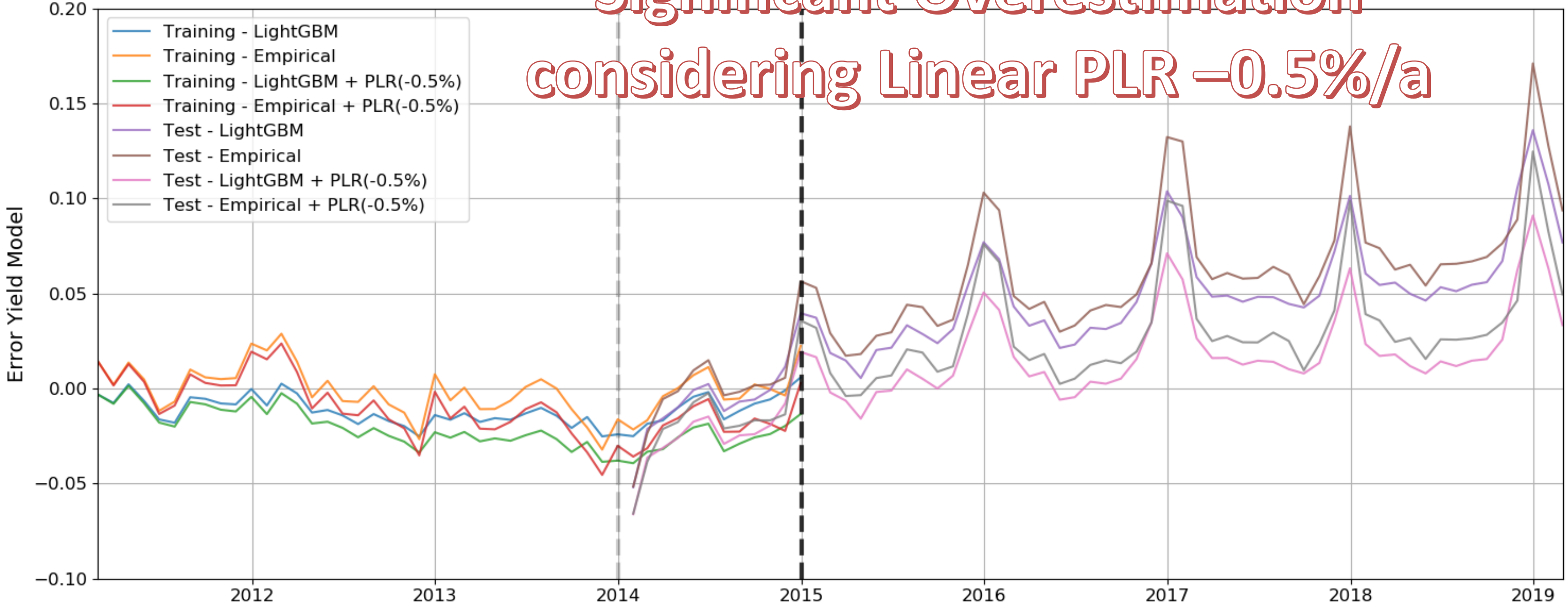


J. Ascencio-Vásquez
University *of Ljubljana*
Faculty *of Electrical Engineering*

# Climate degradation factors

Climate
Materials
Modules
Systems

**Significant Overestimation considering Linear PLR –0.5%/a**



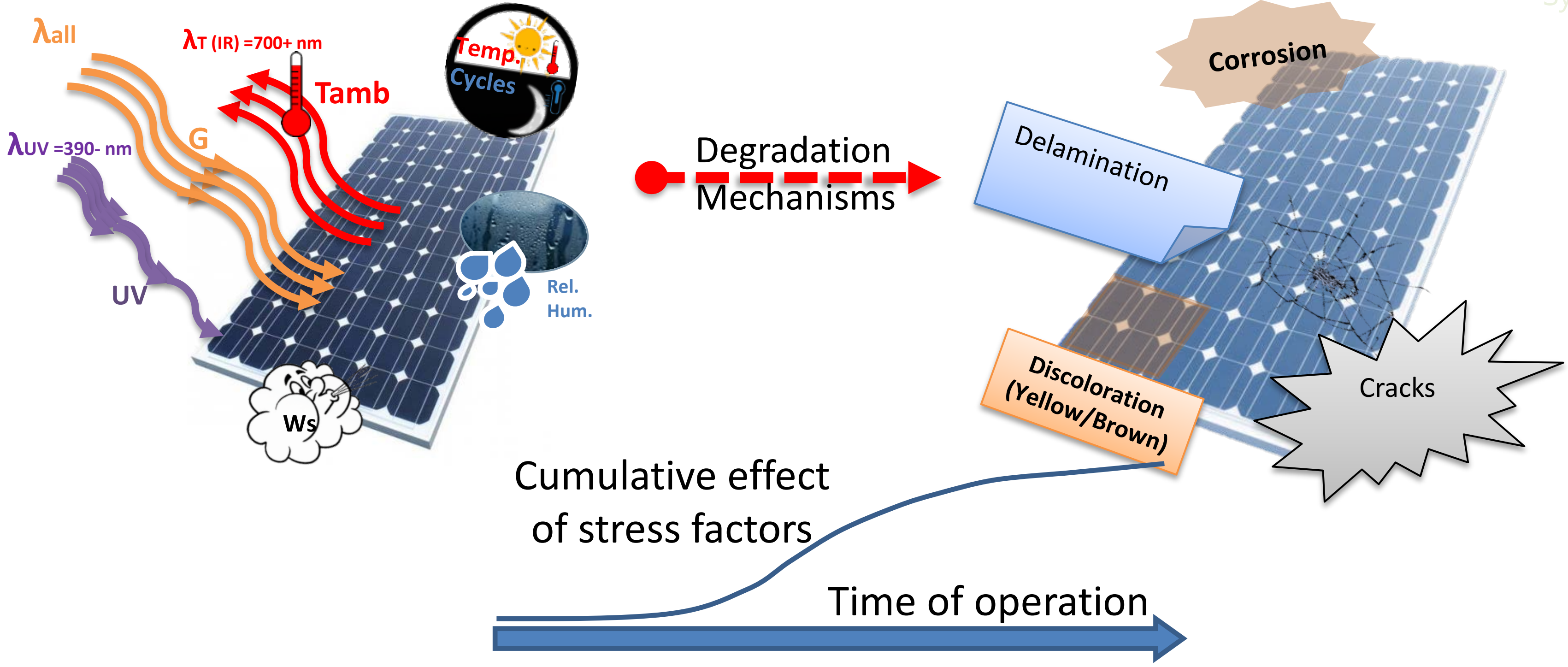

[2] Ascencio et al, *Energies*, 2019
[3] Ascencio et al, *Energies*, 2020



J. Ascencio-Vásquez

LPVO
University *of Ljubljana*
Faculty *of Electrical Engineering*

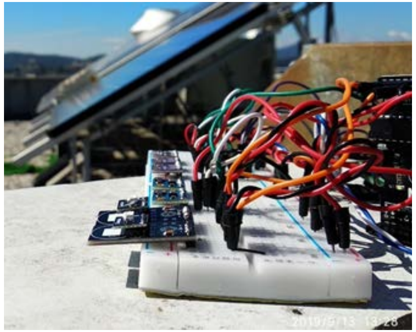
# Climate degradation factors

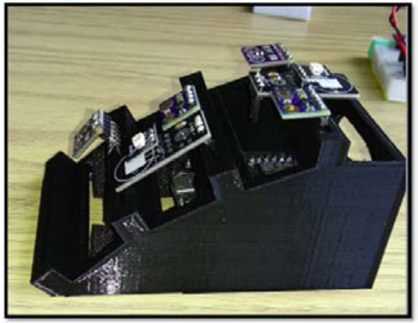


# UV dose in different climates

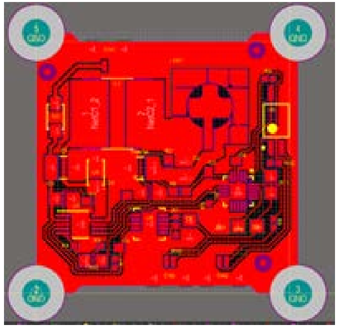
| | KGPV zones [2] | Surface's Tilt angle | Altitude (m) | Global Irradiation (kWh/m²/a) | UV irradiation (kWh/m²/a) | UV/G (%) | UV/G Winter-Summer |
|---|---|---|---|---|---|---|---|
| **FRBG** | DM (Temperate) | 45° | 265 | 1372.93 | 60.01 | 4.37% | 2.6 – 5.1 % |
| **UFS** | DM (Alpine) | 45° | 2650 | 1702.13 | 81.68 | 4.81% | 2.9 – 5.8 % |
| **GC** | CH (Steppe) | 22.5° | 5 | 2273.68 | 100.47 | 4.42% | 3.7 – 5.1 % |
| **NEG** | BK (Desert) | 31° | 300 | 2401.04 | 95.08 | 3.96% | 3.4 – 4.4 % |

## Outdoor Measurements





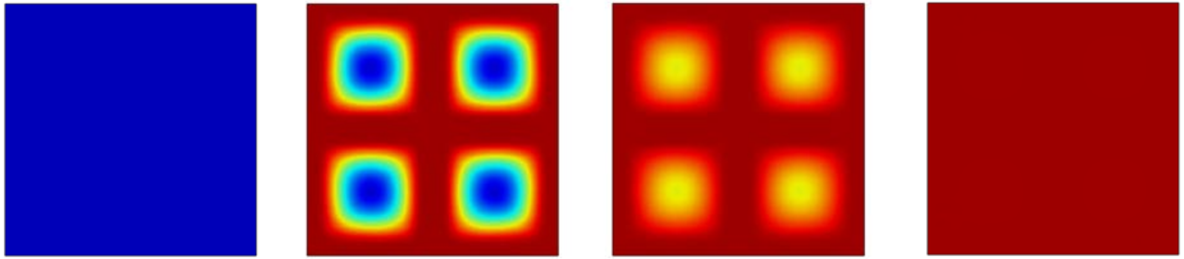
## Indoor Light Source

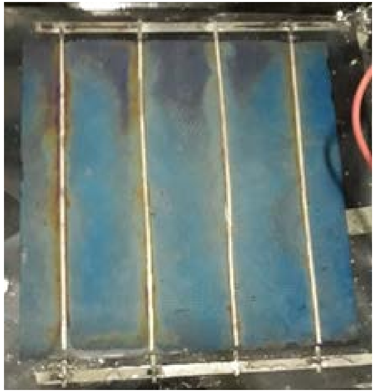


[2] Ascencio et al, *Energies*, 2019

# Equilibrium moisture content in PV polymers

## Is Henry law valid for real polymers?





$RH_{environment}$ → $C_{module}$

???

# Equilibrium moisture content in PV polymers

Climate
Materials
Modules
Systems

## Is Henry law valid for real polymers?

- **Henry law:**

$$c_{polymer} = K_H \cdot RH_{environment}$$

- Valid for ideal, hydrophobic and non-porous materials
- Assumes only polymer-polymer interactions

- **ENSIC model of Perrin and Favre:**

$$c_{polymer} = \frac{e^{(k_s - k_p)RH_{env.}} - 1}{(k_s - k_p)/k_p}$$

- Valid for less hydrophobic, macroporous/non-porous materials
- Assumes penetrant-penetrant and polymer-penetrant interactions
- Describes adequately the absorption isotherm of Polyvinyl Butyral encapsulant [1].

[1] Meitzner, Schulze. *Sol Energy Mater Sol Cells*. 2016;144:23–8.

# Equilibrium moisture content in PV polymers

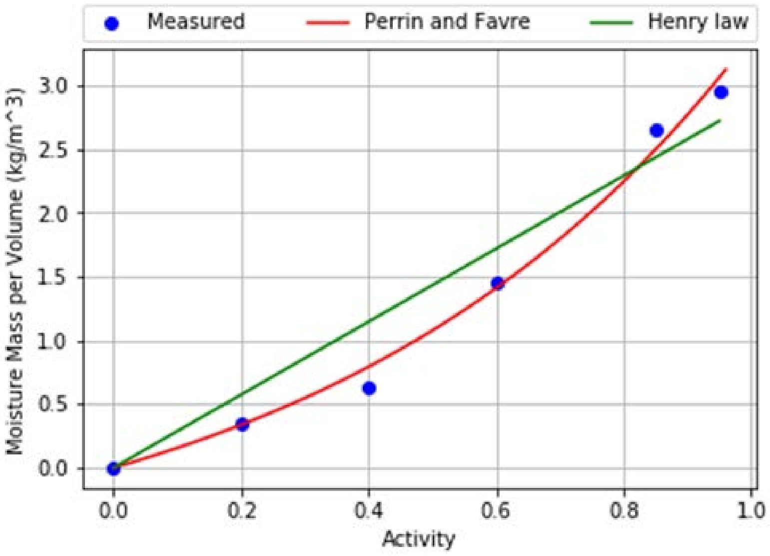
## Is Henry law valid for real polymers?

- **Procedure**

Karl-Fischer Titration applied on PET+Al / 2xEVA stacks loaded into environmental chamber at 85 °C and different RH levels.

- **Fitting: $R^2$ values**

| | Perrin and Favre | Henry’s law |
|---|---|---|
| $R^2$ Value | 0.992 | 0.937 |

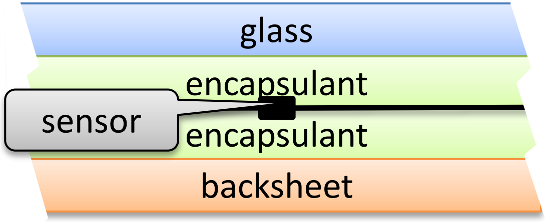





N. Kyranaki

# Moisture diffusion

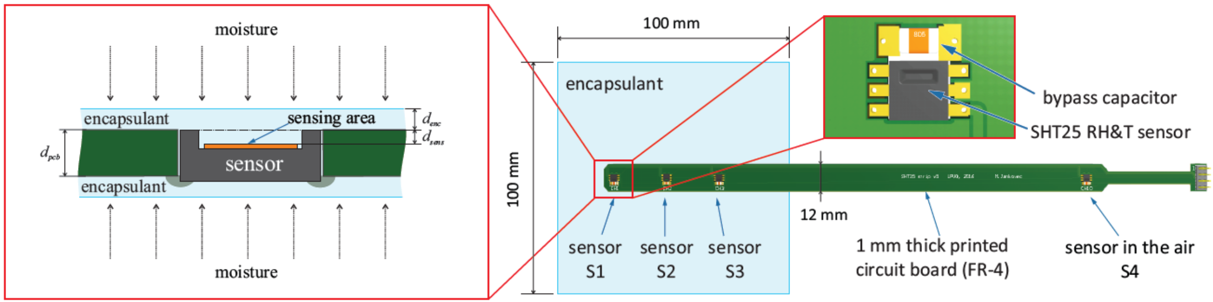
## Measurements




- Deviations from equilibrium state: diffusion

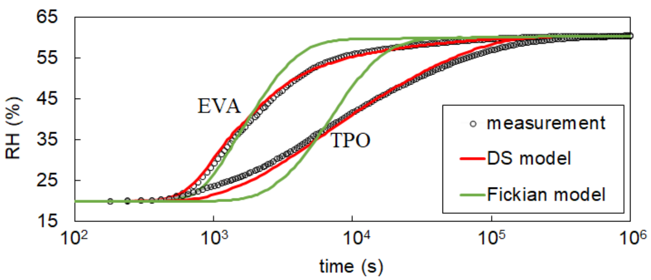
$$\frac{\partial C}{\partial t} = D \cdot \Delta C$$

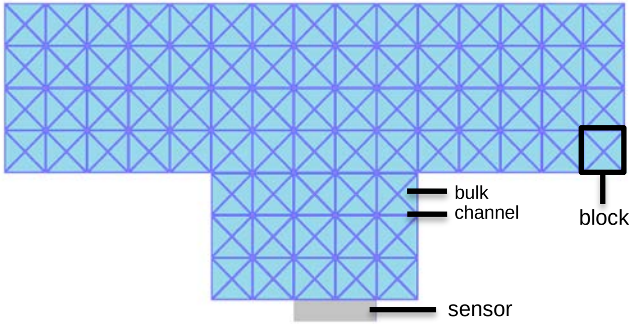
- Measurement with encapsulated miniature moisture sensors

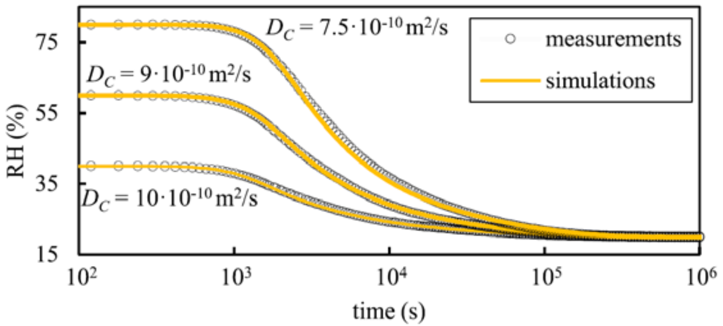



# Moisture diffusion

- FEM simulations – Fickian model
  - Reasonably accurate in some encapsulants and backsheets (e.g. EVA, PET)
  - Inaccurate in others (e.g. TPO)
- Inhomogeneous mesh: 2 transport mechanisms
- Hysteresis:
  - Ingress independent of C
  - Egress slower at high C





[3] Mitterhofer et al, *IEEE JPV*, 2020.
[4] Mitterhofer et al, *EUPVSEC*, 2019.

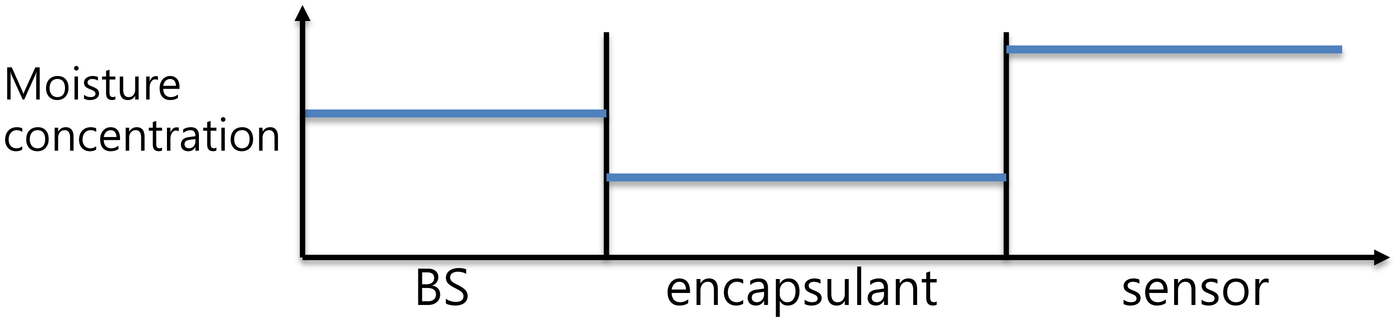
# Moisture diffusion

## Simulating flow across material interfaces

- Boundary conditions on material interfaces

$$\frac{c_{enc}}{c_{BS}} = \frac{s_{enc}}{s_{BS}}$$ (equilibrium state on boundary)

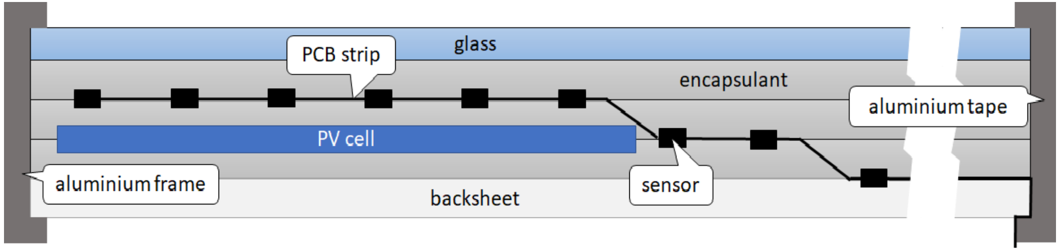
$$\vec{J}_{enc} = \vec{J}_{BS}$$ (flow into equals flow out of the boundary)

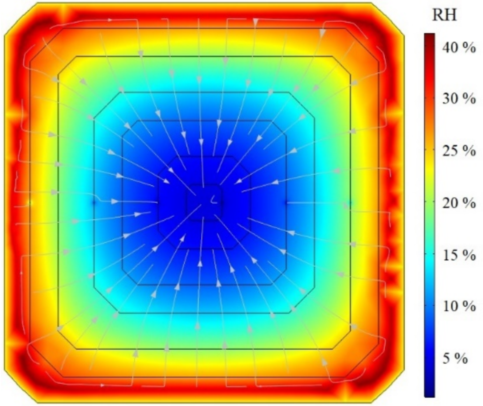


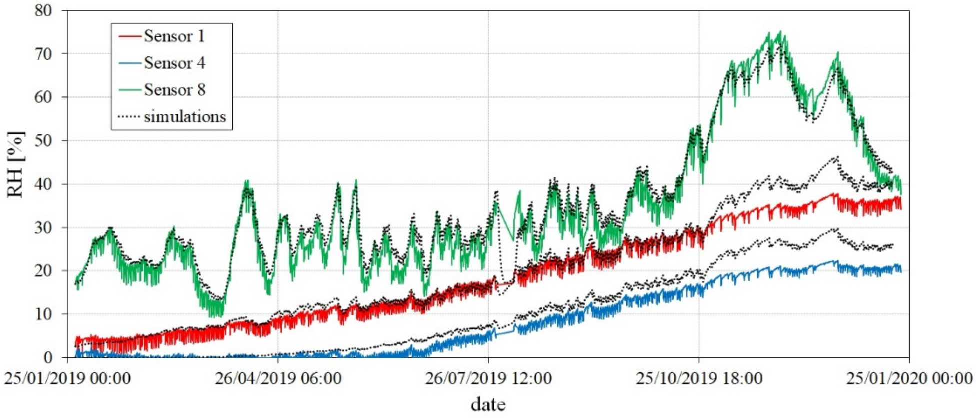
# Moisture diffusion

## Outdoor measurements






Mitterhofer et al, accepted for visual presentation at *EUPVSEC* 2020

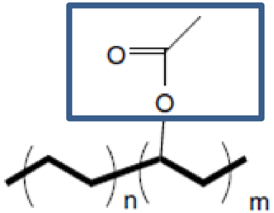
# Characterization



- "Understanding climate related operation conditions of PV systems"
  - J. A-V: *Main climate degradation factors*
  - N.K.: *Equilibrium moisture content in PV polymers*
  - S.M.: *Moisture diffusion in different encapsulants and backsheets*
- "Advanced characterization of PV materials: natural and artificial ageing"
  - C.B.: *DH/UV of different encapsulants*
  - L.C.: *Accelerating testing of backsheets*
  - Dj.M.: *Effect of different backsheet on encapsulant degradation*
- "Understanding PV module performance evolution, Service Lifetime Prediction & O&M activities "
  - I.K.: *PV degradation modelling*
  - S.L.: *Nonlinear Multi-step Performance Loss Rate*
  - N.H.: *Electrical parameter evolution*
  - G.O.: *Modelling applied to O&M activities*

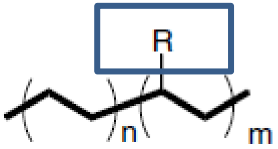
# Artificial ageing of encapsulants

## Exposure to DH and UV



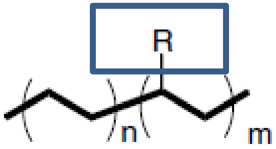

Ethylene Vinyl Acetate (EVA)

- **Chemically crosslinked**
- **Low melting temperature (~70 °C)**
- **Formation of acetic acid**




Polyolefin Elastomer (POE)

- **Chemically crosslinked**
- **Low melting temperature (65°C-70°C)**
- **No formation of acetic acid**



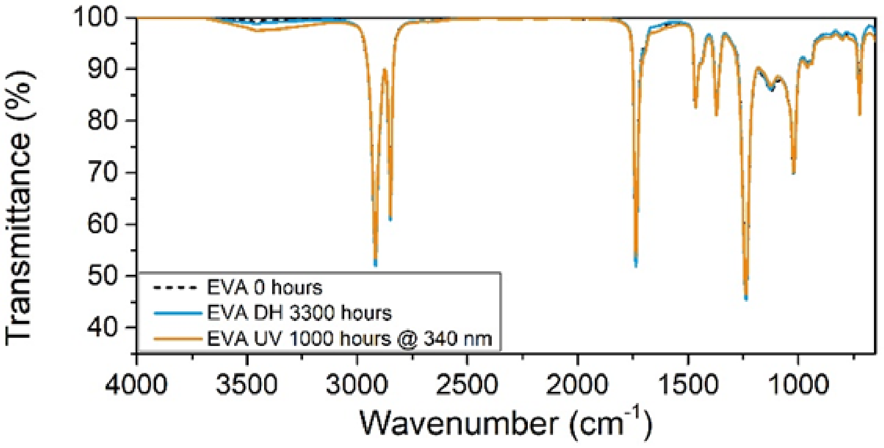

Thermoplastic Polyolefin (TPO)

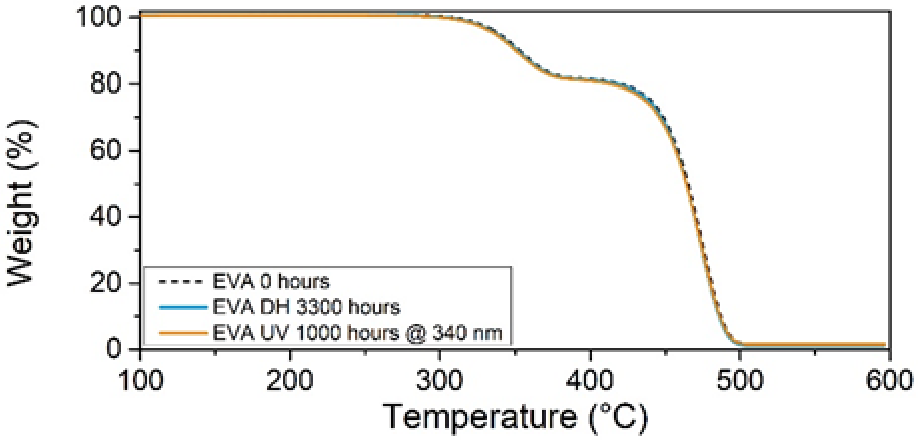
- **Physically crosslinked**
- **High melting temperature (~110°C)**
- **No formation of acetic acid**

# Artificial ageing of encapsulants

## Exposure to DH and UV: TPO

| | Additive | 0 hours | DH 3300 hours | UV 1000 hours |
|---|---|---|---|---|
| EVA | Antioxidant (BHT) | ✓ | ✓ | ✓ |
| | UV absorber (Octabenzone) | ✓ | ✓ | ✓ |
| | UV absorber (Benzotriazol) | | ✓ | |



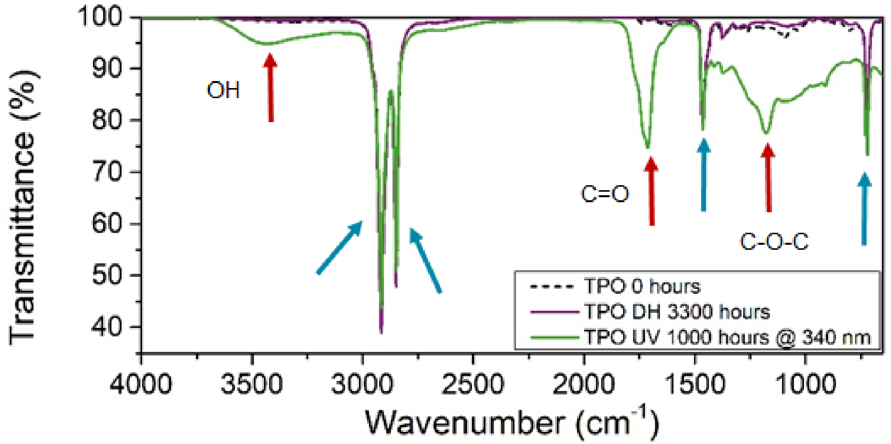



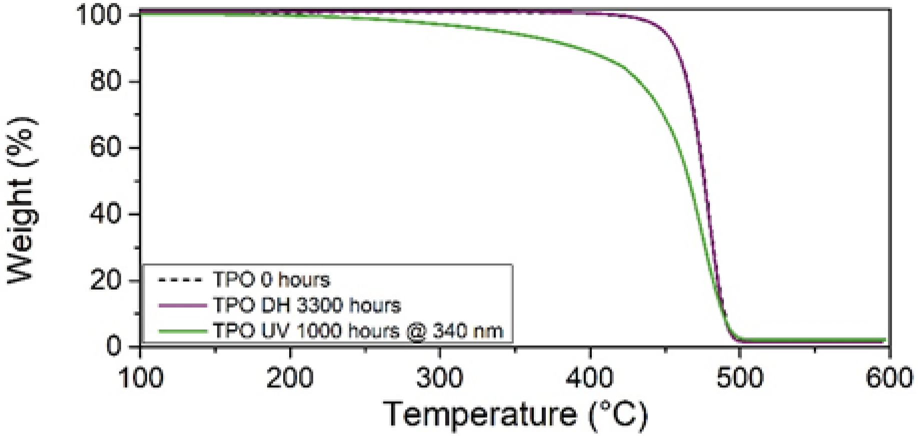

[1] Barretta et al, *EUPVSEC*, 2019.

# Artificial ageing of encapsulants

## Exposure to DH and UV: TPO

| | Additive | 0 hours | DH 3300 hours | UV 1000 hours |
|---|---|---|---|---|
| TPO | UV absorber (Benzotriazol) | | ✓ | |
| | Antioxidant (Irganox) | ✓ | (✓) | |

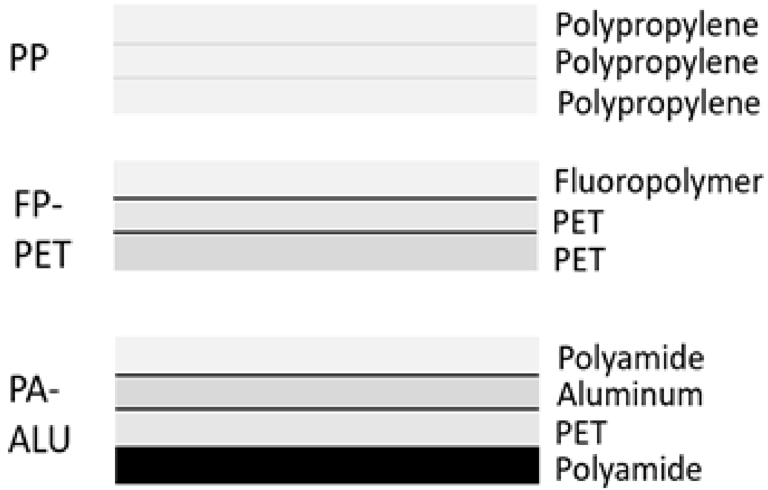



[1] Barretta et al, *EUPVSEC*, 2019.

# Accelerated testing of backsheets

## Exposure to DH and UV




PP

- **Coextruded**
- **Max reflectance of 90%**

FP-PET

- **Multilayer, PET core**
- **Max reflectance of 95%**

PA-ALU

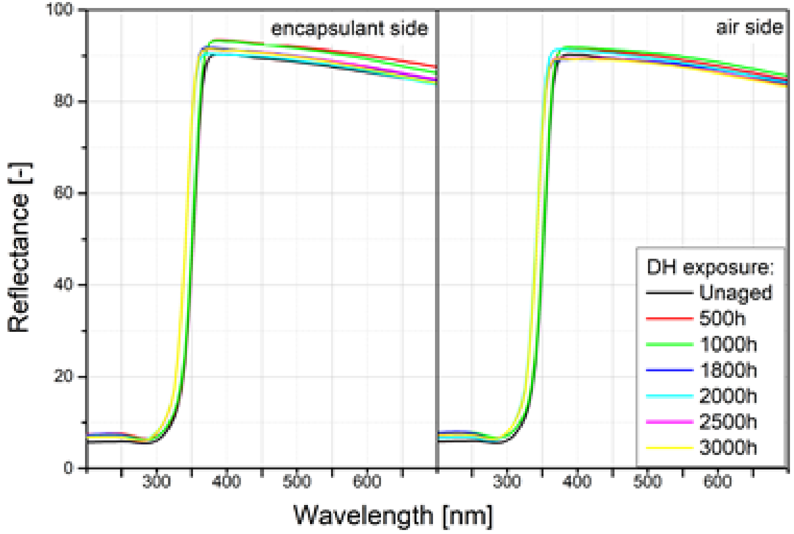
- **Multilayer, PET core**
- **Black frontside**

# Accelerated testing of backsheets

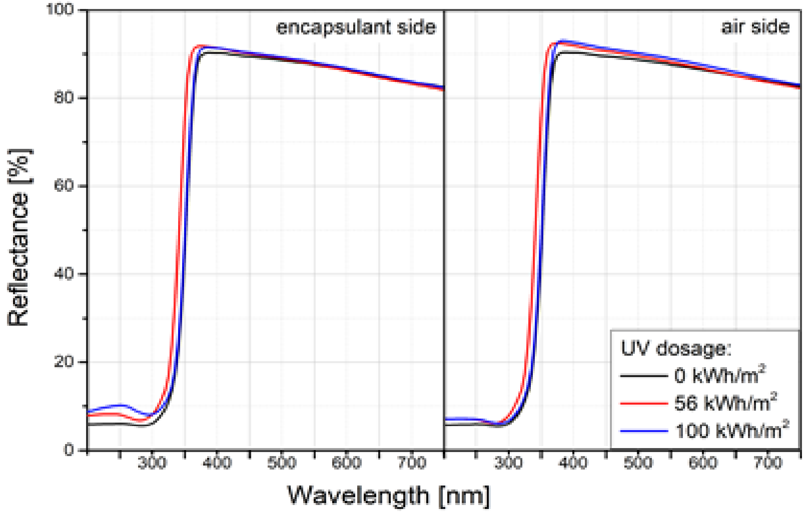
## Exposure to DH and UV: PP

Climate
*Materials*
Modules
Systems

### Damp Heat




### UV





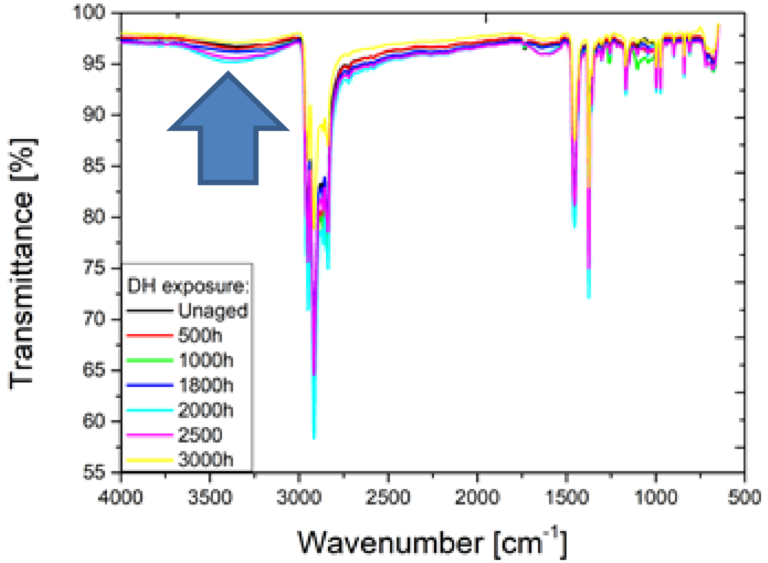

L. Castillon

Polymer Competence Center Leoben

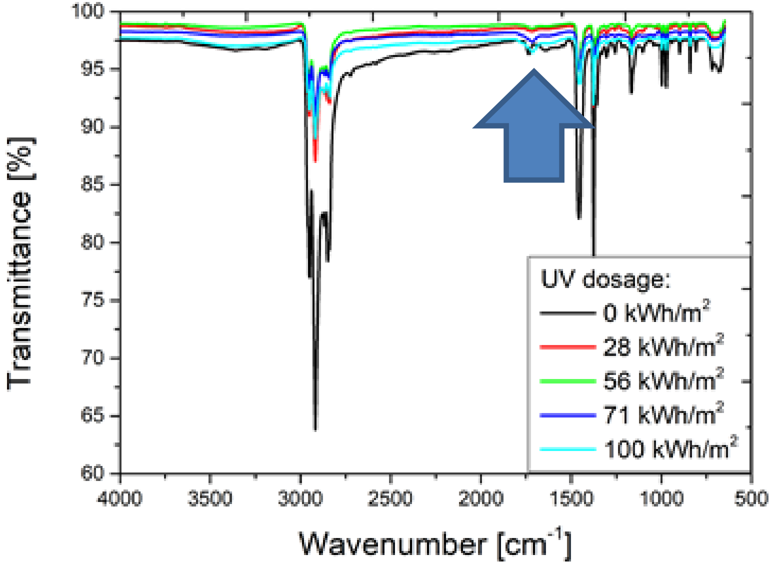
# Accelerated testing of backsheets

## Exposure to DH and UV: PP

**Damp Heat**



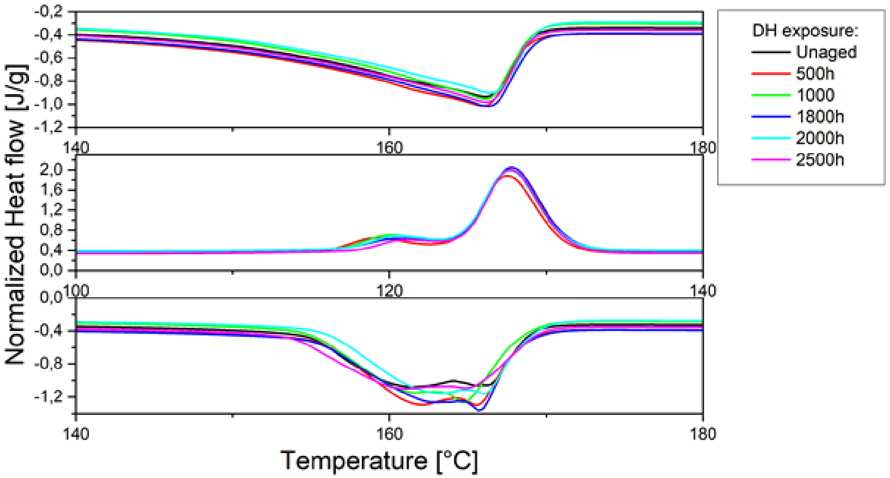

**UV**



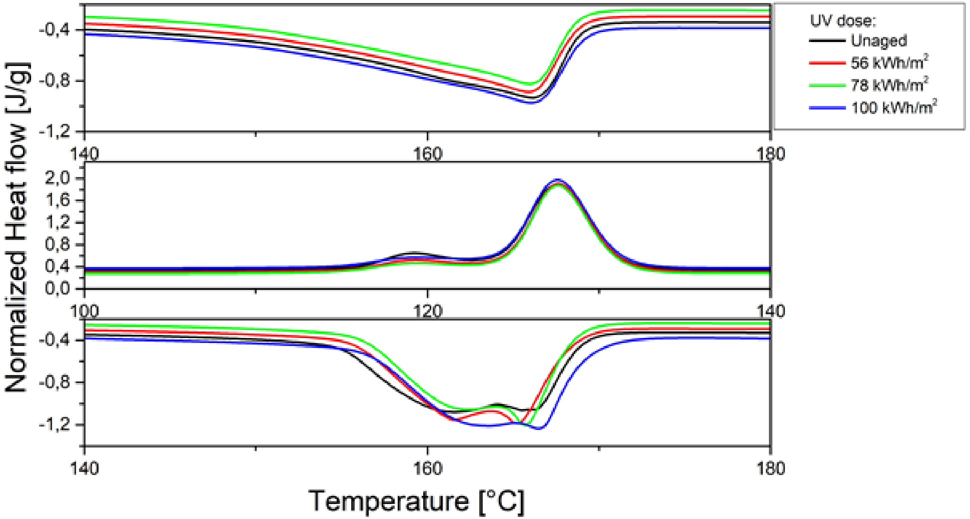
# Accelerated testing of backsheets

## Exposure to DH and UV: PP

Damp Heat




UV




**No signs of polymer degradation**

solartrain

Climate
Materials
Modules
Systems

# Accelerated testing of backsheets

## Summary

- PP Backsheet
  - Most optical stable backsheet during accelerated weathering
  - Surface modification with apparition of the hydroxyl and carbonyl groups
  - No polymer degradation observed
  - No embrittlement of backsheets
- PET based backsheet
  - Changes in the optical properties signaling yellowing
  - Signs of hydrolysis of the PET (outer) layer, but not for the PA (outer) layers.
  - Changes in the crystalline region showing signs of lamella thickening and chain scission
  - Embrittlement of backsheets

solartrain

Climate
*Materials*
Modules
Systems

# Effect of backsheet type on encapsulant

## DSC analysis

The decrease of the melting enthalpy is a good indicator for material/polymers degradation [1]

Different backsheets

PET- based Backsheet_1

PET- based Backsheet_2

PA- based Backsheet

Same encapsulant

EVA

**Different material combinations lead to different EVA degradation rate**

[1] Patel, et al., *IEEE JPV*, 2019.

# Effect of backsheet type on encapsulant

## FTIR spectroscopy

PA- based Backsheet

PET- based Backsheet_2

- **Both PET-based backsheets:**
  - More degradation products are detected: di and tri-alkyl substances
- **Pa-based backsheet:**
  - Thermal-oxidation after DH
  - Photo-oxidation after UV-DH

- **Glass/EVA interface [2]:**
  - The glass seems to act as a catalyst for EVA chemical changes of DH

**Different material combinations lead to different EVA degradation Mechanisms**

[2] Spinella, Bosco. *IEEE JPV*, vol. 9, no. 3, pp. 790–795, 2019.

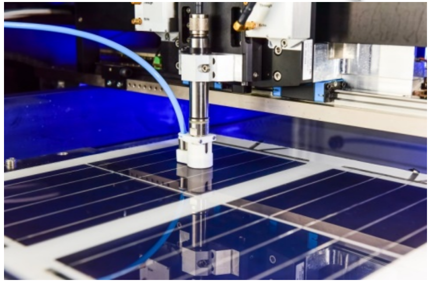
Mansour et al, to be submitted to Journal

# Effect of backsheet type on encapsulant

## Scanning Acoustic Microscopy imaging

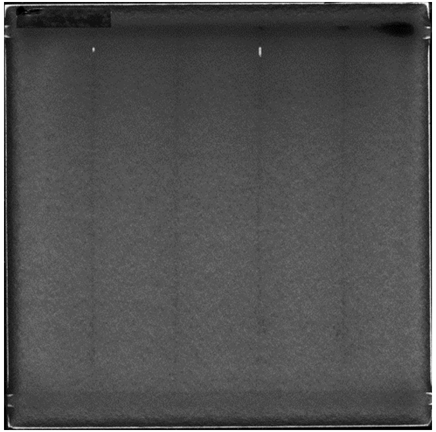
PA- based Backsheet

Mansour et al, accepted for visual presentation at *EUPVSEC* 2020

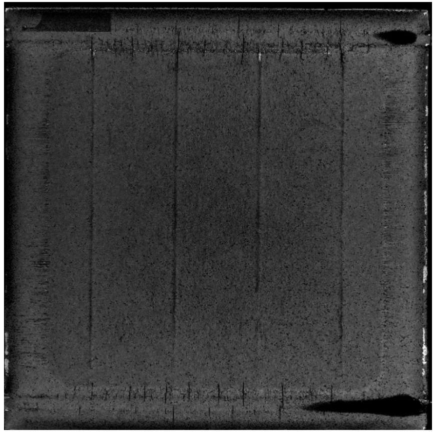


- **Multiple characterizations:**
  - Degradation under combined UV-DH is higher than both individual stresses
  - Moisture plays a synergistic role with UV in the formation of surface BS cracking [3]
- **SAM imaging:**
  - Non-destructive method for BS interlayer cracking quantification

**Before aging**



**UV-DH 240 kWh/m$^2$**

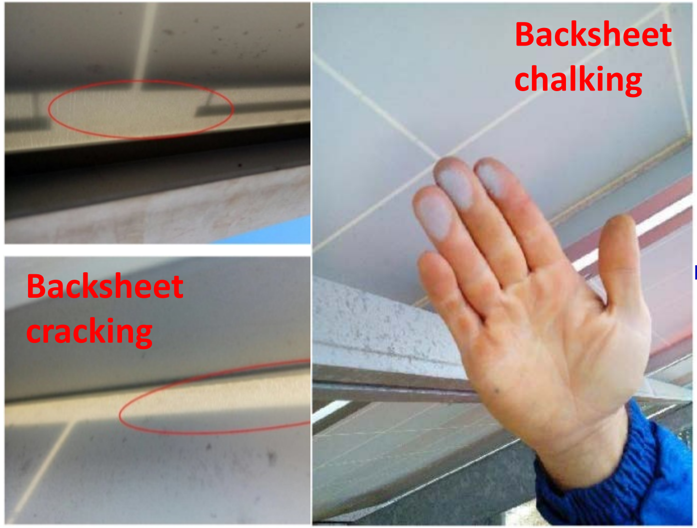


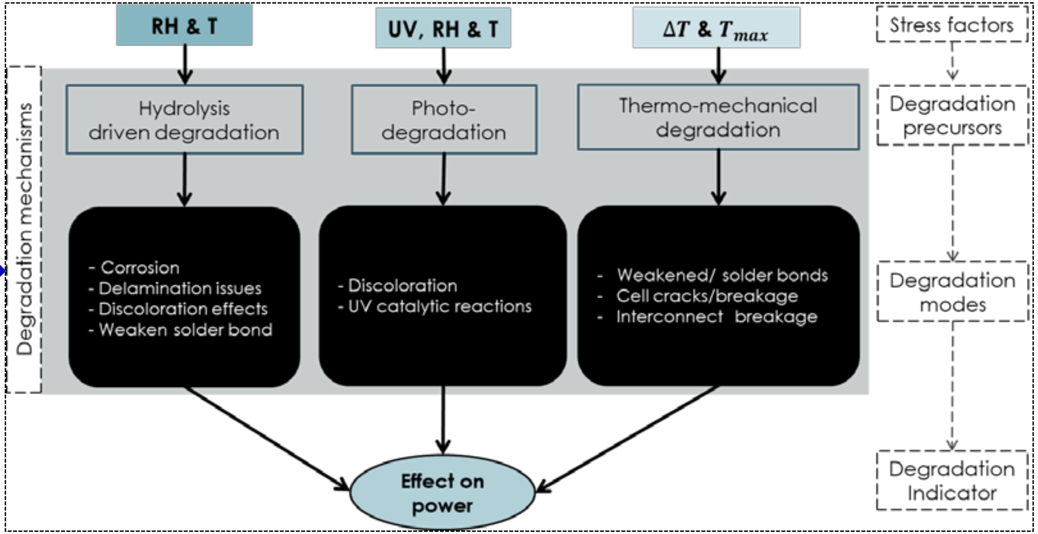
**Laboratory-produced backsheet cracking to simulate fielded-degraded backsheets**

[3] Lin, et al. *Progress in Photovoltaics: Research and Applications*, vol. 89, 2-3, p. 139, 2018.

# Fielded-degraded backsheet

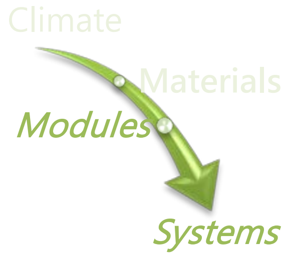
## PV material degradation to PV module modeling




Quantitative, experimental understanding of the polymeric degradation mechanisms can then be used to better model PV module lifetimes

# PV System Performance: O&M




- "Understanding climate related operation conditions of PV systems"
  - J. A-V: *Main climate degradation factors*
  - N.K.: *Equilibrium moisture content in PV polymers*
  - S.M.: *Moisture diffusion in different encapsulants and backsheets*
- "Advanced characterization of PV materials: natural and artificial ageing"
  - C.B.: *DH/UV of different encapsulants*
  - L.C.: *Accelerating testing of backsheets*
  - Dj.M.: *Effect of different backsheet on encapsulant degradation*
- **"Understanding PV module performance evolution, Service Lifetime Prediction & O&M activities "**
  - I.K.: *PV degradation modelling*
  - S.L.: *Nonlinear Multi-step Performance Loss Rate*
  - N.H.: *Electrical parameter evolution*
  - G.O.: *Modelling applied to O&M activities*

Climate
Materials
*Modules*
*Systems*

# PV module performance

## Method: Climate based degradation model: Quantification of climatic stresses

**RH and T** → **Hydrolysis**

$$k_h = A_H \times rh_{eff}^{n} \times \exp\left(-\frac{E_H}{k_B.T_m}\right)$$

**UV, RH and T** → **Photo-degradation**

$$k_P = A_P \times (UV_{dose})^{X}(1 + rh_{eff}^{n}) \times \exp\left(-\frac{E_P}{k_B.T_m}\right)$$

**$\Delta T$ and $T_{max}$** → **Thermo-mechanical degradation**

$$k_{Tm} = A_{Tm} \times (\Delta T)^{\theta} \times C_N \times \exp\left(-\frac{E_{Tm}}{k_B.T_{max}}\right)$$

$$k_T = (1 + k_h) \times (1 + k_p) \times (1 + k_{Tm}) - 1$$

# PV module performance

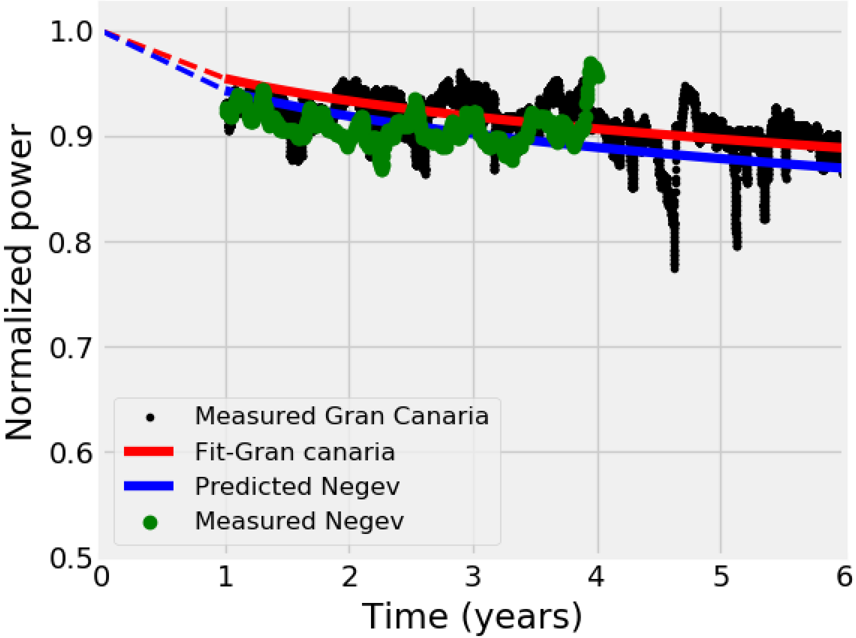
## Experimental part, model calibration & validation

Climate
Materials
*Modules*
*Systems*

### Outdoor exposure: 3 benchmarking climates




### Calibration and validation






I. Kaaya

# PV module performance

## Degradation rates & lifetime evaluation



Failure time (FT) → -20% of the initial power

$$\frac{P_{MPP}(t)}{P_{MPP}(0)} = 1 - \exp\left(-\left[\frac{\varepsilon}{k_T \times t}\right]^{\mu}\right)$$

⇩

$$FT = \frac{\varepsilon}{k_T \times [|log(0.2)|]^{\mu^{-1}}}$$

Values for the 3 locations

| Location | $k_T$ [%/year] | FT [years] |
|---|---|---|
| Gran Canaria | 0.50 | 30.2 |
| Negev | 0.74 | 20.5 |
| Zugsptize | 0.30 | 50.7 |

[1] Kaaya et al. *IEEE JPV,* 2019.

solartrain

# PV module performance

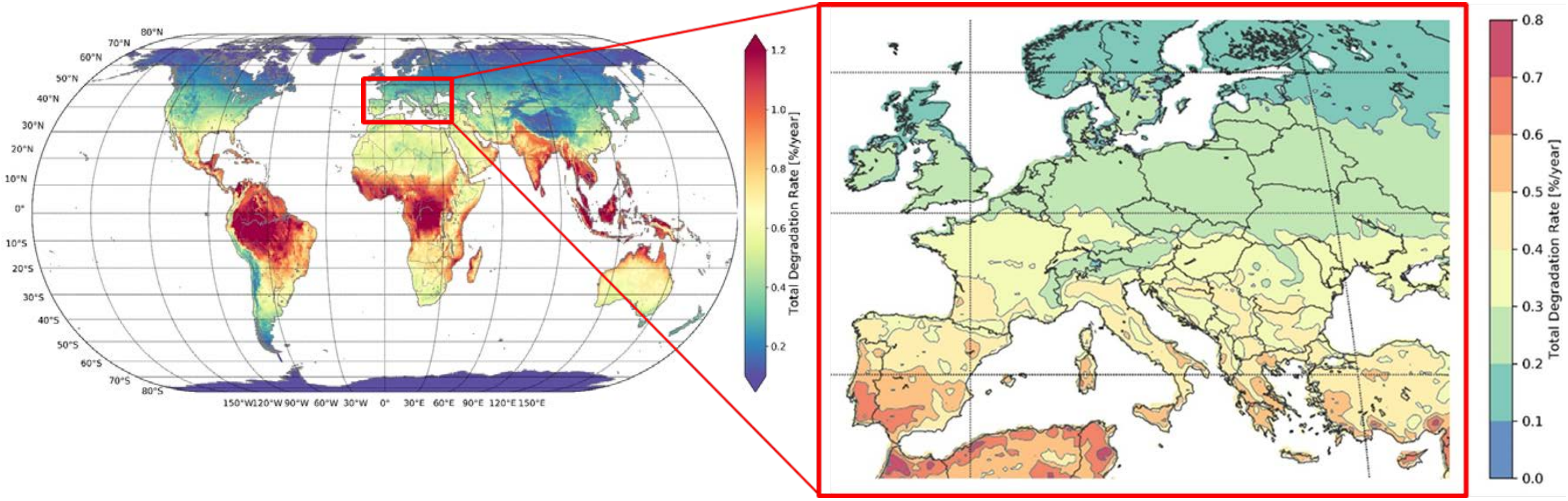
## Degradation rates evaluation:

## A global degradation risk map

Climate
Materials
*Modules*
*Systems*

Global degradation map

Zoom for Europe




[2] Ascencio-Vasquez, Kaaya et al. *Energies,* 2019.



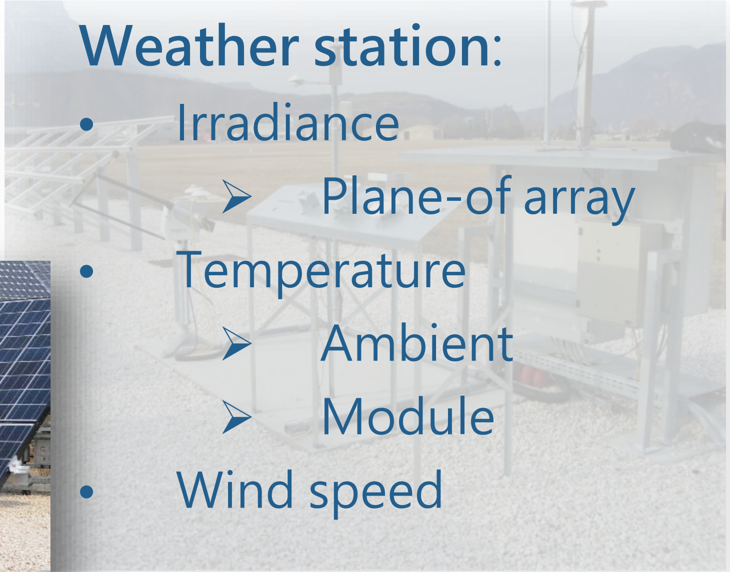


Fraunhofer ISE

# Example PV plant – Bolzano (IT)

**Poly-crystalline silicon system:**

- Nominal power 4.2kWp
- In operation since 2010
- Parameter: DC power



## Weather station:

- Irradiance
  - Plane-of array
- Temperature
  - Ambient
  - Module
- Wind speed



S. Lindig

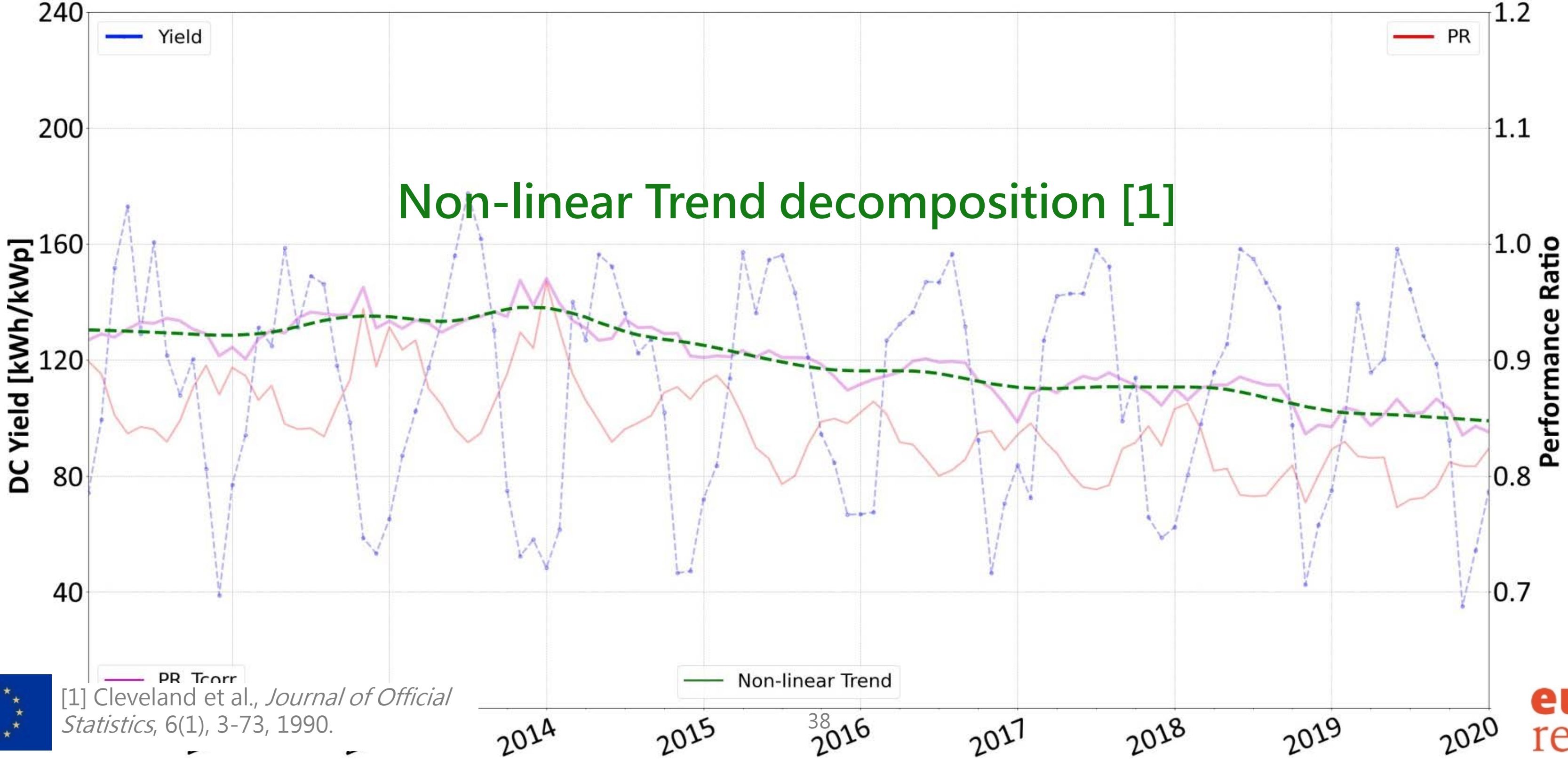
# Novel MS-PLR methodology

## Performance Loss Rates:

- Purpose of Performance Loss Rates is to describe the performance evolution of PV systems
- Important for
  - Performance evaluation
  - Heath-status
  - Possible warranty claims
  - Everyday O&M activities

# Novel MS-PLR methodology

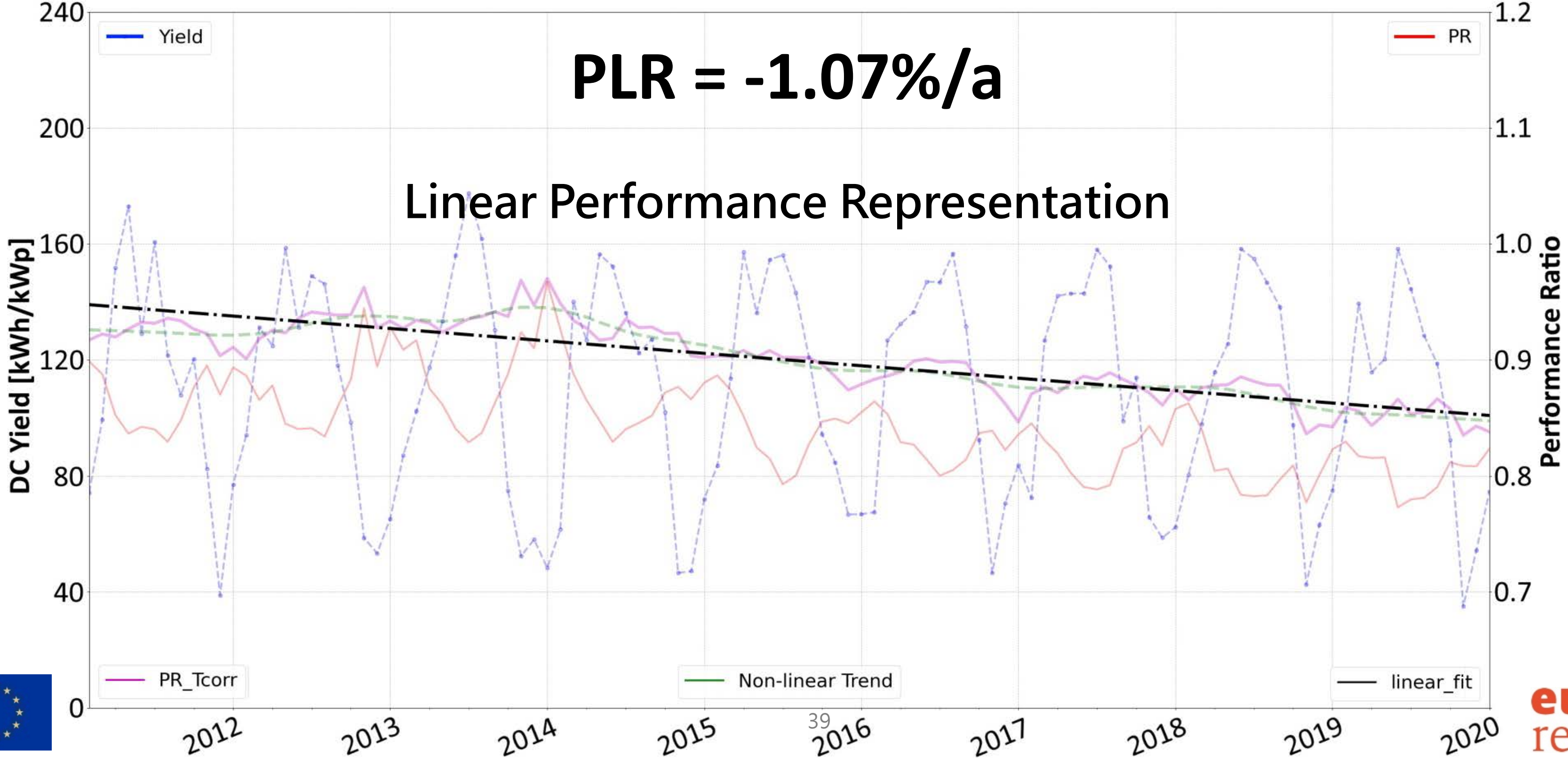
## Steps - Linear Performance Loss




[1] Cleveland et al., *Journal of Official Statistics*, 6(1), 3-73, 1990.

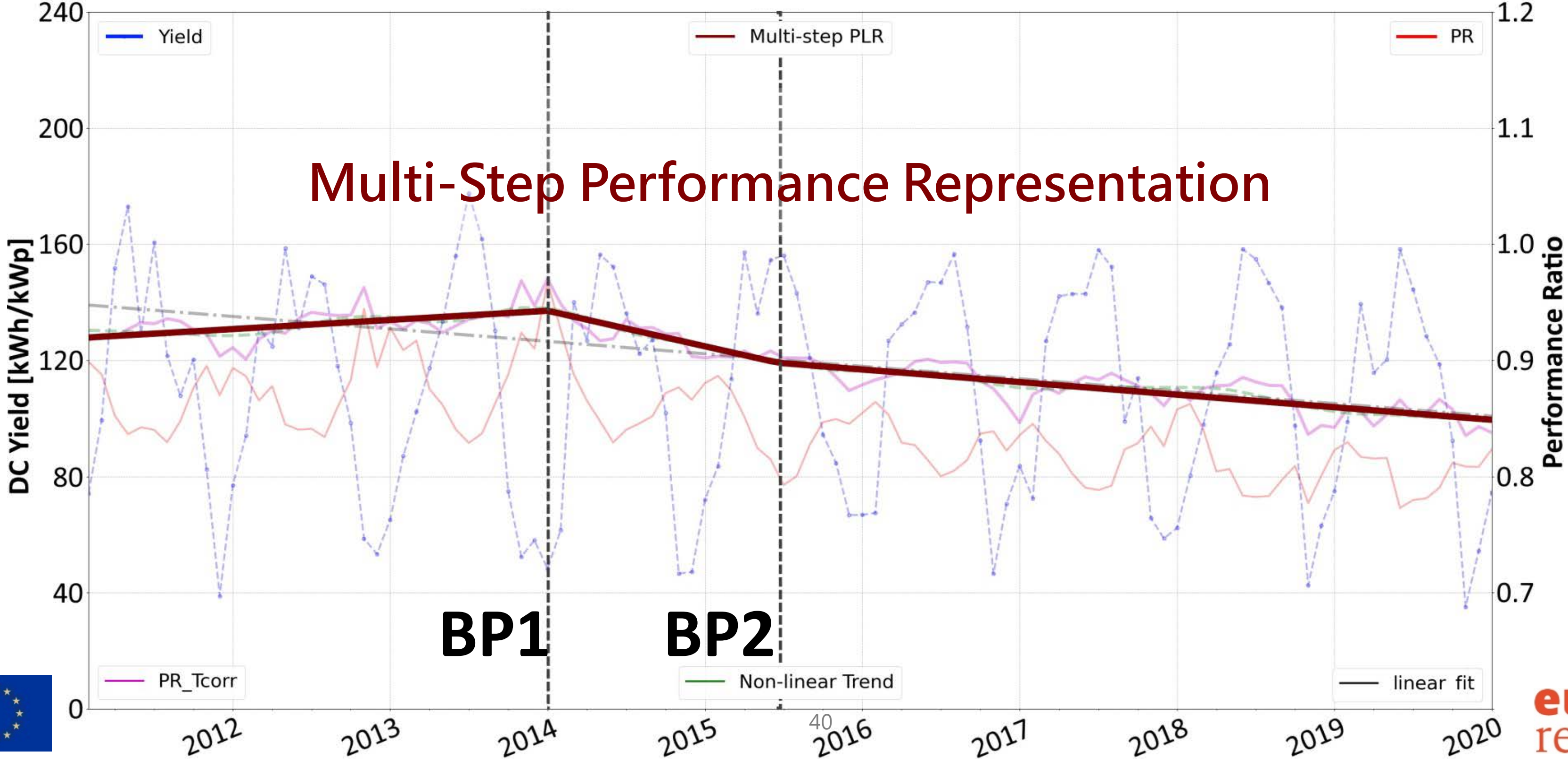
# Novel MS-PLR methodology

## Steps - Linear Performance Loss



# Novel MS-PLR methodology

## Transition to Multi-step Performance Loss




Climate
Materials
*Modules*
*Systems*

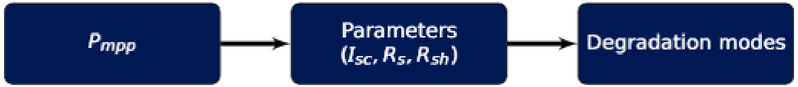
# Electrical Parameter Evolution

## Signatures of Degradation Mechanisms

Degradation of PV performance is usually determined with the decrease of power where the same magnitude of losses can have **various causes.**

Using the **physical performance model parameters** of PV could help identifying various degradation pathways and assess the time dependent health of the modules.

**METHOD**



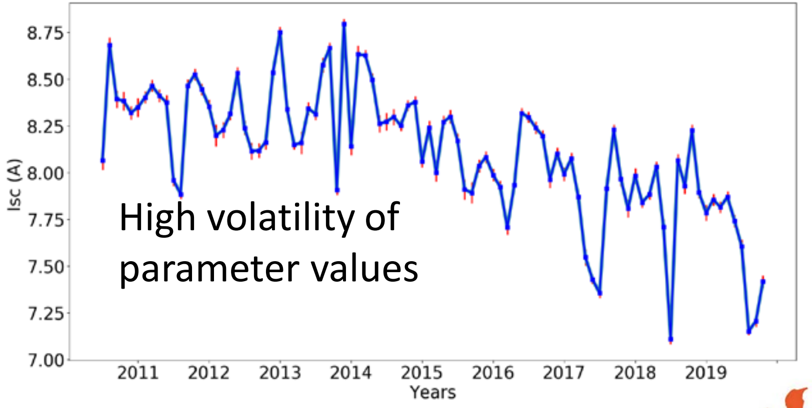

Searching for a set of parameter values θ such that the computer model *f(x, θ)* fits as closely as possible the field data *R*.

For the calibration, the Approximate Bayesian Computation (ABC) is used:

- Robust to measurements noise

**5 days of highest PV production selected in every month**

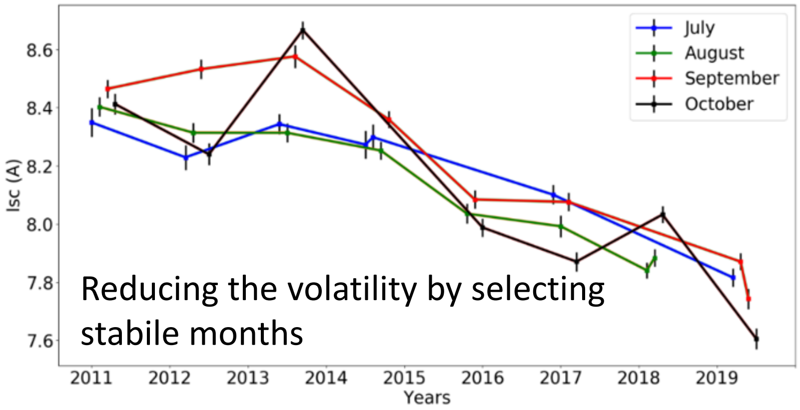
Calibrating the short circuit current

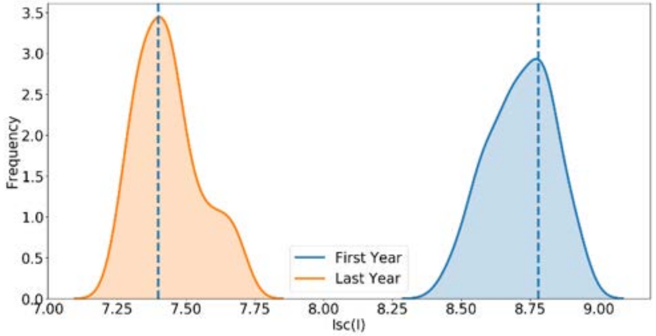


# Electrical Parameter Evolution

## Results based on 8 years of data

The degradation in power (Pmpp) is related to the degradation in short circuit current (Isc). Average decrease of Isc over 8 years period is 13%.




No detectable change in series resistance (Rs) and shunt resistance (Rsh) over the period of 8 years.

**Possible causes:**

- Discoloration of encapsulant
- Degradation of anti-reflective coating
- Glass corrosion
- Cracks?

solartrain

Climate
Materials
Modules
Systems

# Modelling applied to O&M activities

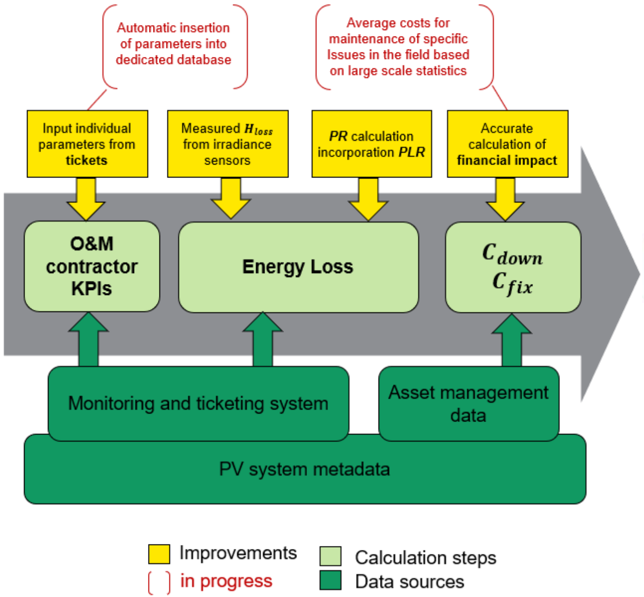
## Putting the pieces together

**First steps taken:**

Optimization of the CPN methodology (methodology for the assessment of the economic impact of failures occurring during operation)

Status: approach based on measured monitoring data and *a posteriori* scenarios

(*no lifetime predictions done… yet*)




SOLAR BANKABILITY

$$\mathrm{CPN} = C_{down} + C_{fix} \quad [€/kW_p/year]$$


[1] Moser et al, *Progress in Photovoltaics*, 2017.
[2] Oviedo Hernández et al, *EU PVSEC*, 2019.

solartrain

# Modelling applied to O&M activities

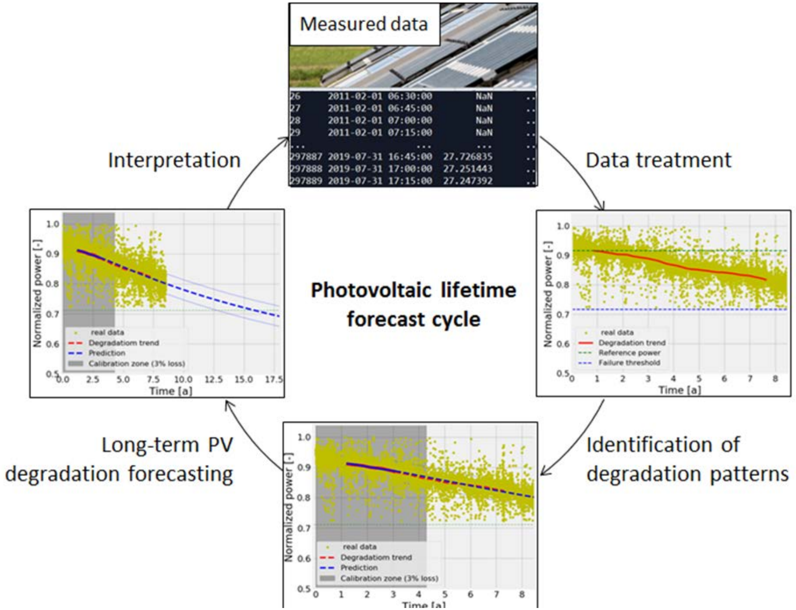
## Putting the pieces together

Climate
Materials
Modules
Systems

**The link: Data driven model for long-term forecast (RUL)**

New modelling approach proposed

- Reliable for PV system level applications
- Improves long-term degradation forecast from a short degradation history
- Applicable for any module technology
- Separates reversible degradation trends from non-reversible




[3] Kaaya et al, *Progress in Photovoltaics*, 2020.

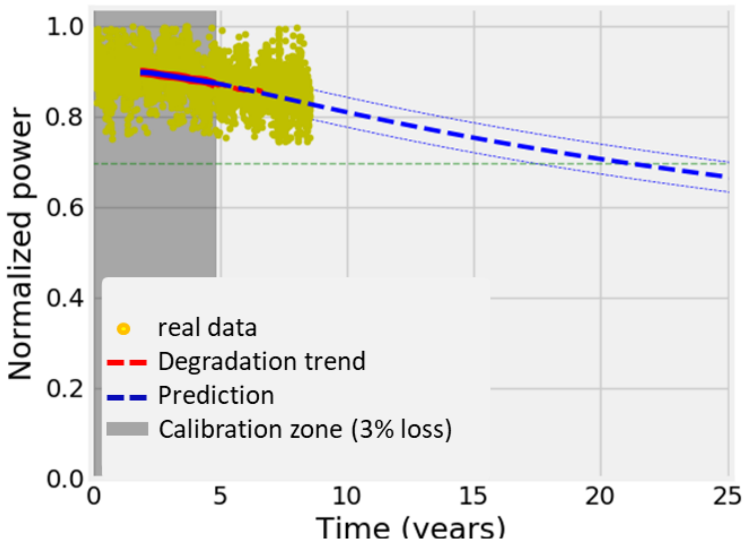


G. Oviedo Hernández

BayWa r.e.

# Modelling applied to O&M activities

## Putting the pieces together




[3] Kaaya et al, *Progress in Photovoltaics*, 2020.



G. Oviedo Hernández

# Modelling applied to O&M activities

## Putting the pieces together



**Key challenges for the adoption of lifetime predictions in the O&M sector** (*work in progress and future steps):*

- Move away from linear (constant) degradation rates from datasheets

  Partially achieved with the implementation of PLR -> Next step: application of more adaptive approaches (e.g. multi-step PLR)

- Data-driven approaches preferred to physical models

  Correlation of the degradation patterns with degradation modes -> data labelling with the support of field diagnostic techniques (IR, EL, IV-curves, etc.)
  Lower prediction uncertainty by using field knowledge -> constant re-calibration of the models

- Failure Time and Remaining Using Lifetime (RUL) of PV systems

  How would accurate RUL and FT predictions change the O&M paradigm? How to adapt O&M strategies accordingly taking also into account the financial models?

- The secondary market and hand-over procedures

  Forecasting long-term behavior (20-30 years) based on few data points (2-5 years)

# Conclusions

## Key findings

**"Understanding climate related operation conditions of PV systems"**

- UV irradiance, moisture and thermal stress are the main PV degradation factors.
- Indoor and outdoor weather exposure helped us to identify and model PV degradation mechanisms.
- Henry type sorption and Fickian diffusion: simple, but can be inaccurate in some polymers
- Other models, e.g. Perrin and Favre sorption: more complex, but fit better

# Conclusions

## Key findings

**"Advanced characterization of PV materials: natural and artificial ageing"**

- Understanding polymer degradation is a challenging task because many factors are involved (environmental stresses, microclimate conditions, etc.).
- Laminated but not encapsulated TPO showed most severe degradation compared to EVA.
- Appropriate selection of characterization methods helps in understanding degradation mechanisms.
- Current PV backsheets have a great resistance to degradation under accelerated ageing conditions
- Different material combinations (backsheet/encapsulant) lead to different degradation mechanisms.

# Conclusions

## Key findings

**"Understanding PV module performance evolution, Service Lifetime Prediction & O&M activities"**

- Development of analytical models for climatic stresses sensitivity analysis of photovoltaic modules worldwide and a data-driven methodology for PV lifetime forecast using very limited degradation history
- Cross-comparison of commonly used linear Performance Loss Models in the field
- Development of multi-step performance loss algorithm for advanced performance monitoring"
- Electrical parameter evolution as signatures of degradation mechanism
- Optimization of the CPN methodology for O&M economic analysis

# Thank you for your attention!

Visit us:

www.solar-train.eu

@MSCA_SolarTrain

This project has received funding from the European Union's Horizon 2020 programme under GA. No. 721452.

# Publications

## Journals


- Lindig, S.; Kaaya, I.; Weis, K.-A.; Moser, D.; Topič, M., *Review of Statistical and Analytical Degradation Models for Photovoltaic Modules and Systems as Well as Related Improvements*. IEEE Journal of Photovoltaics 2018, 1–14.
- Kaaya, I.; Koehl, M.; Mehilli, A.P.; de Cardona Mariano, S.; Weiss, K.A., *Modeling Outdoor Service Lifetime Prediction of PV Modules: Effects of Combined Climatic Stressors on PV Module Power Degradation*. IEEE J. Photovoltaics 2019, 9, 1105–1112
- Ascencio-Vásquez, J.; Brecl, K.; Topič, M., *Methodology of Köppen-Geiger-Photovoltaic climate classification and implications to worldwide mapping of PV system performance*. Solar Energy 2019, 191, 672–685.
- Ascencio-Vásquez, J.; Kaaya, I.; Brecl, K.; Weiss, K.A.; Topič, M., *Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules*. Energies 2019, 12, 4749.
- Mitterhofer, S.; Glažar, B.; Jankovec, M.; Topič, M., *The development of thermal coefficients of photovoltaic devices*, Informacije MIDEM 2019, 49.4, 219–227.
- Ascencio-Vásquez, J.; Bevc, J. Reba, K.; Jankovec, M.; Topič, M., *Advanced PV Performance Modelling Based on Different Levels of Irradiance Data*. Energies 2020, 13, 2166.
- Mitterhofer, S.; Barretta, C.; Castillon-Gandara, L.F.; Oreski, G.; Topič, M.; Jankovec, M.; *A dual-transport model of moisture diffusion in PV encapsulants for finite-element simulations.* IEEE Journal of Photovoltaics 2020, 10.1, 94–102.

# Publications

## Conferences

- Ascencio-Vásquez, J., Topič, M., "An Overall Data Analysis Methodology for PV Energy Systems" *53rd MIDEM*, Ljubljana, 2017.
- Mitterhofer, S., Jankovec, M., Topič, M., "A setup for in-situ measurements of potential and UV induced degradation of PV modules inside a climatic chamber," *53rd MIDEM*, Ljubljana, 2017.
- Kyranaki, N., Zhu, J., Gottschalg, R., Betts, T. R.,"The Impact of Acetic Acid Corrosion on the Front-side Contacts and the Finger Electrodes of c-Si PV Cells," pp. 1–4, *14th Photovoltaic Science, Applications and Technology Conference (PVSAT-14)*, 2018.
- Kyranaki, N., Zhu, J., Gottschalg, R., Betts, T. R., "Investigating the Degradation of Front and Rear Sides of c-Si cells Exposed to Acetic Acid," pp. 1372–1375, *35th EU PVSEC conference*, Brussels, 2018.
- Barretta, C., Oreski, G., Resch-Fauster, K., Pinter, G., "Development of non-destructive methods for acetic acid detection in photovoltaic modules," *35th EU PVSEC conference*, Brussels, 2018.
- Mansour, D. E., Swientek, F., Kaaya, I., Philipp, D., Pitta Bauermann, L., "Nanoindentation analysis of PV module polymeric components after accelerated aging," *35th EU PVSEC conference*, Brussels, 2018.
- Castillon, L. Oreski, G. "Analysis and developement of transport phenomena models for PV modules", *35th EU PVSEC conference*, Brussels, 2018.
- Lindig, S.; Ingenhoven, P., Belluardo, G., Moser, D., Topič, M., "Evaluation of Technology-Dependent MPP Current and Voltage Degradation in a Temperate Climate," *35th EU PVSEC conference*, Brussels, 2018.
- Ascencio-Vásquez, J., Brecl, K., Topič, M., "Köppen-Geiger-Photovoltaic climate classification", *IEEE 7th World Conference on Photovoltaic Energy Conversion*, Hawaii, 2018.
- Mitterhofer, S., Jankovec, M., Topič, M., "Using UV LEDs for PV module aging and degradation study," *35th EU PVSEC conference*, Brussels, 2018.

solartrain

# Publications

## Conferences

- Ascencio-Vásquez, J., Brecl, K., Smole, F., Topič, M., "Application of the full thermal model for PV devices", 555th *MIDEM,* Bled, 2019.
- Mitterhofer, S., Barretta, C., Castillon-Gandara, L.F., Oreski, G., Topič, M., Jankovec, M., "Analysis of ethylene vinyl acetate degradation under UV-A LED light", *55th MIDEM*, Bled, 2019.
- Kyranaki, N., Jankovec, M., Topic, M., Gottschalg, R., Betts, T. R., "Investigation of Moisture Ingress and Egress in Polymer – Glass Laminates for PV Encapsulation," pp. 1–4, *15th Photovoltaic Science, Applications and Technology Conference (PVSAT-15)*, 2019.
- Lindig, S., Moser, D., Curran, A. J., French, R. H., "Performance Loss Rates of PV systems of Task 13 database," *IEEE PVSC Conference*, Chicago, 2019.
- Lindig, S., "Do we really know how to calculate Performance Loss Rates?," *Intersolar*, Munich, 2019.
- Barretta C., Oreski G., Resch-Fauster K., "Additive analysis in encapsulant materials and correlation to encapsulant degradation modes," *36th EU PVSEC conference*, Marseille, 2019.
- Oviedo Hernandez, G., Lindig, S., Moser, D., Chiantore, P.V., "Optimization of the Cost Priority Number (CPN) Methodology to the Needs of a Large O&M Operator," pp. 1613 – 1617, *36th EU PVSEC conference*, Marseille, 2019.
- Kyranaki, N., Whalley, D., Hutt, D., Gottschalg, R., Betts, T. R., "Direct measurement of moisture ingress in PV laminates," pp. 1045–1049, *36th EU PVSEC conference*, Marseille, 2019.
- Castillon, L., Ascencio-Vásquez, J., Mehilli, A.P., Oreski, G., Topič, M., Weiß. K-A., "Parallel natural weathering of laminated backsheets across Europe", *36th EU PVSEC conference*, Marseille, 2019.
- Mitterhofer, S., Barretta, C., Castillon-Gandara, L.F., Oreski, G., Topič, M., Jankovec, M., "Dual sorption modelling of water ingress in PV encapsulants using a heterogeneous mesh in finite element simulations", *36th EU PVSEC conference*, Marseille, 2019.
- Lindig, S., "Theory & Practice of Performance Loss Rate Calculations," *13th PV Performance Modeling and Monitoring Workshop*, Shanghai, 2019.



SOPHIA European Research Infrastructure