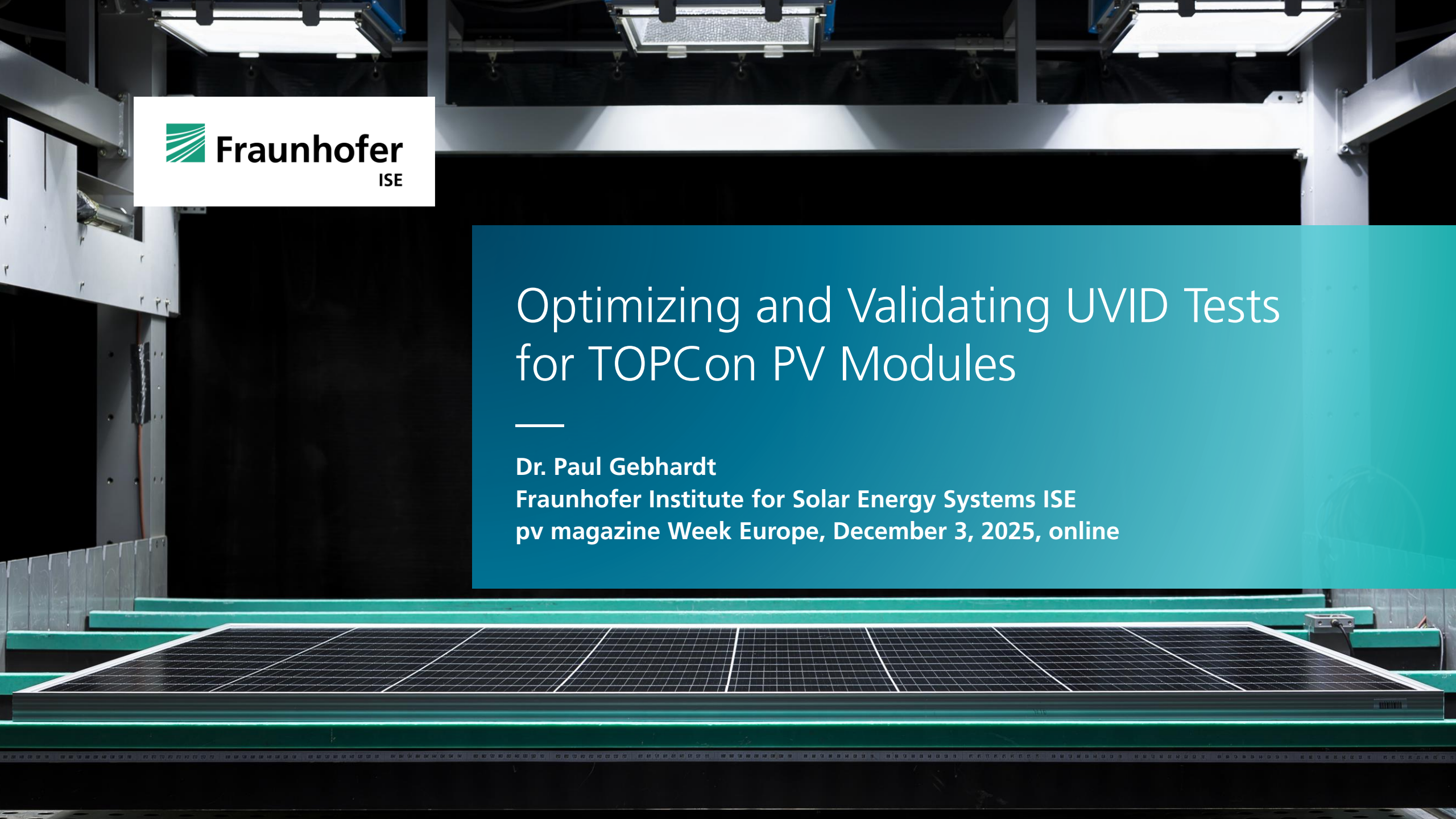

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Optimizing and Validating UVID Tests for TOPCon PV Modules

Dr. Paul Gebhardt
Fraunhofer Institute for Solar Energy Systems ISE
pv magazine Week Europe, December 3, 2025, online

Unique Independent Test-Infrastructure

CalLab and TestLab PV Modules

CalLab PV Modules

ilac-MRA DAkkS Deutsche Akkreditierungsstelle D-K-11140-02-00

TestLab PV Modules

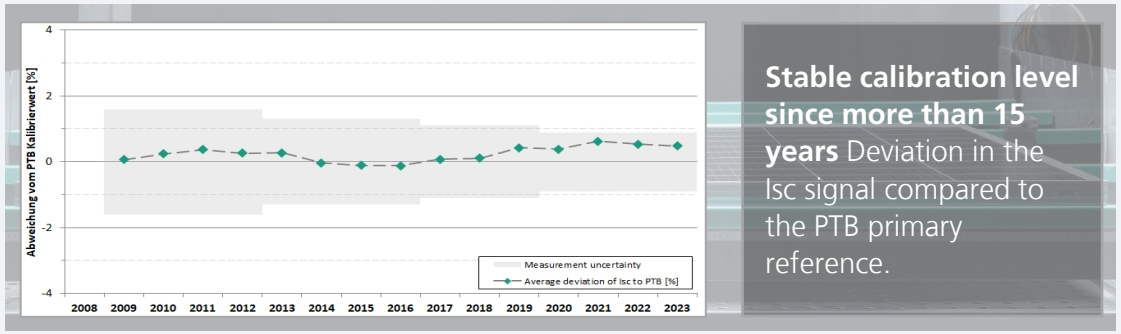
ilac-MRA DAkkS Deutsche Akkreditierungsstelle D-PL-11140-03-02

IEC IECEE Certificate of Acceptance

Accredited Calibration Laboratory

(DIN EN ISO/IEC17025)

- One of only 5 Calibration Lab's for Modules
- Precise Module characterization since 1993
- Worldwide acknowledged Reference Laboratory
- Leading Measurement Uncertainty



Stable calibration level since more than 15 years Deviation in the Isc signal compared to the PTB primary reference.

Accredited Test Laboratory

(DIN EN ISO/IEC17025)

- Accredited for all relevant Performance, Reliability and Safety Tests
- Authorized Certification Body Test Laboratory

CBTL Status: CB Testing Laboratory (CBTL) | IECEE

Scope of accredited Work: TestLab PV Modules - Fraunhofer ISE

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Outline

Optimizing and Validating UVID Tests for TOPCon PV Modules

- UV-induced Degradation (UVID)
- Dark storage effect
  - Stabilization
- Outdoor UVID
  - Comparison with lab tests
  - Effects of light spectrum

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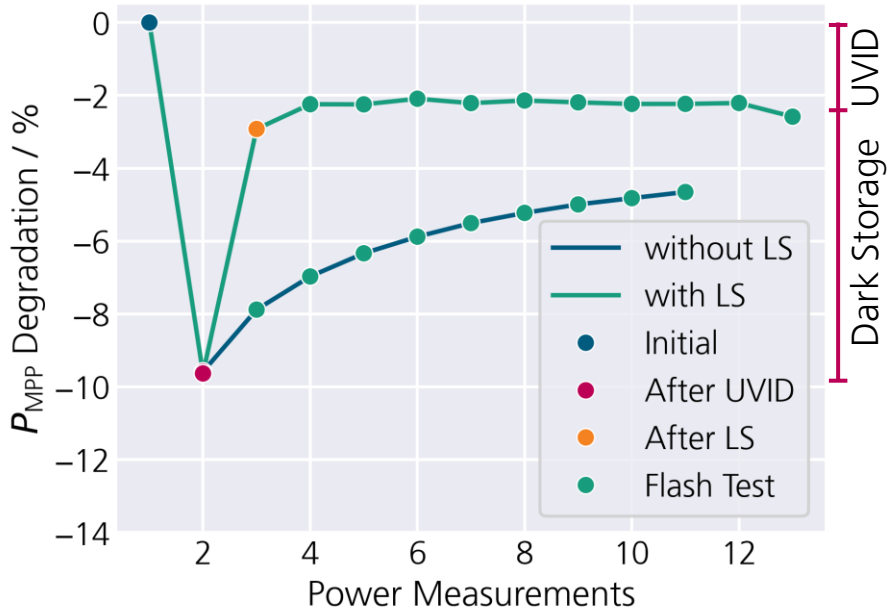
Post-UVID Metastable Behavior

Degradation in Dark Storage, Stabilization in Light Soaking [1]

Wording: "Stabilization" = measurement is not affected by metastability



- Degradation in "Dark Storage" not only when completely dark
- Lightsoaking @1000 W/m² very effective
  - UV portion mainly responsible [2]

[1] P. Gebhardt et al., "Stabilization procedures for TOPCon PV modules after UV-induced degradation," SolMat 2026

[2] T. Karin (PVEL Kiwa) et al., "UVID initiates metastability in the dark" PVRW: Photovoltaic Reliability Workshop, 2025.

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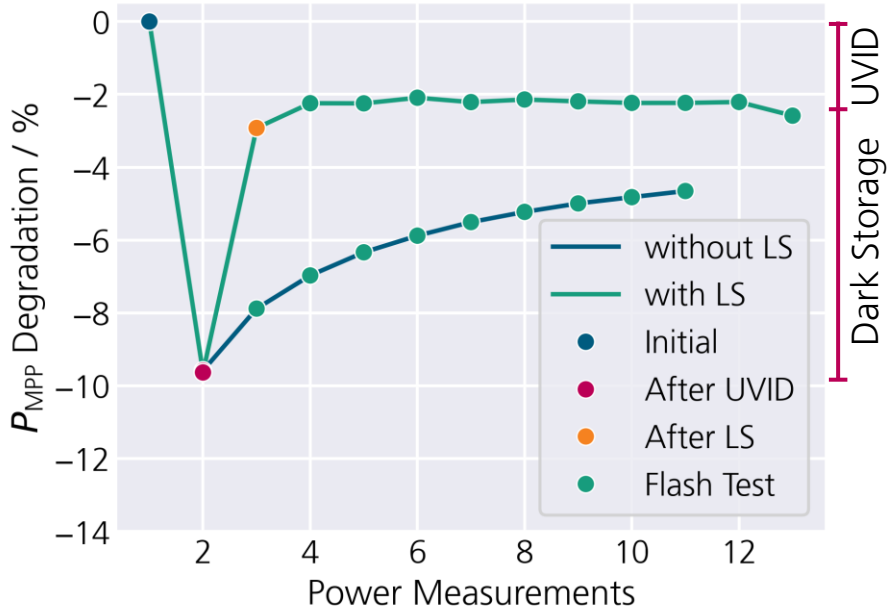

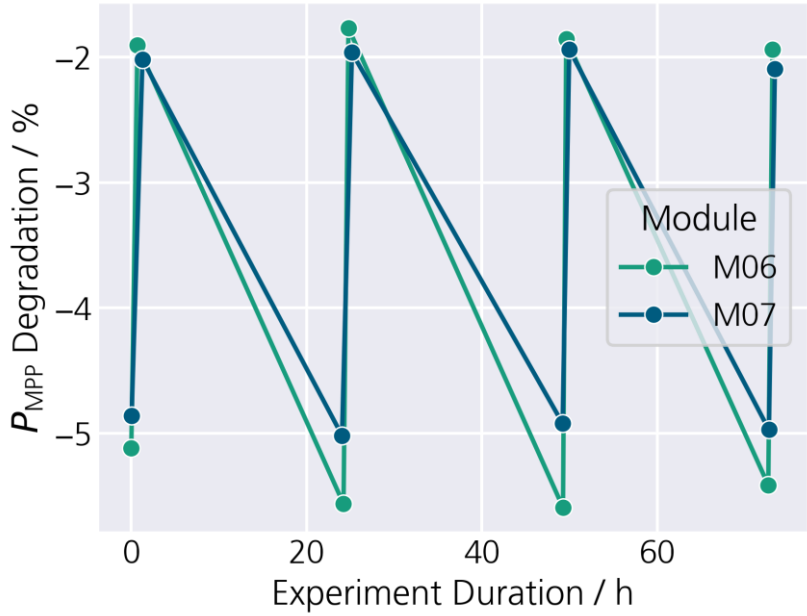

- Degradation in "Dark Storage" not only when completely dark
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  - UV portion mainly responsible [2]

Reversible behavior after UVID

- Degradation by dark storage
- Stabilization by light soaking

[1] P. Gebhardt et al., "Stabilization procedures for TOPCon PV modules after UV-induced degradation," SolMat 2026

[2] T. Karin (PVEL Kiwa) et al., "UVID initiates metastability in the dark" PVRW: Photovoltaic Reliability Workshop, 2025.

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Post-UVID Metastable Behavior

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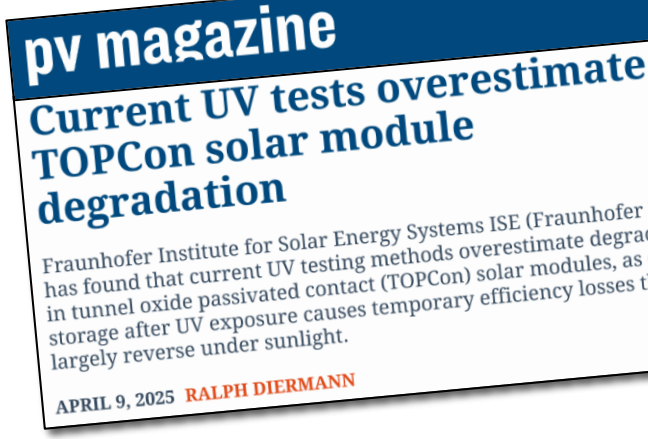
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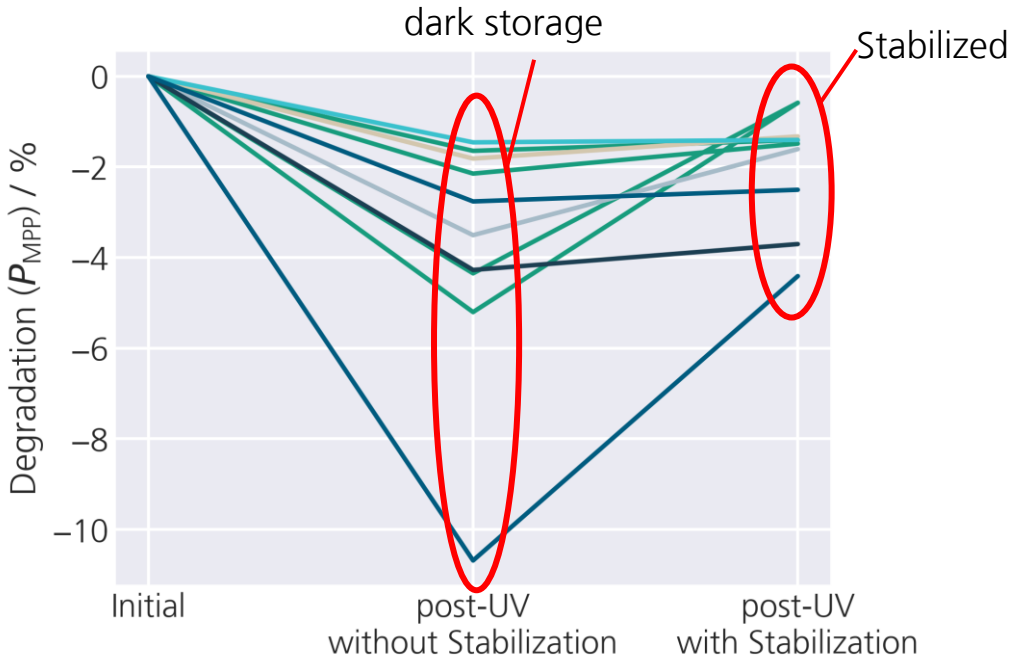
Current UV tests overestimate TOPCon solar module degradation

Fraunhofer Institute for Solar Energy Systems ISE (Fraunhofer has found that current UV testing methods overestimate degra in tunnel oxide passivated contact (TOPCon) solar modules, as storage after UV exposure causes temporary efficiency losses t largely reverse under sunlight.

APRIL 9, 2025 RALPH DIERMANN

Comparison of UVID test methods

- Test according to standard (i.e. without stabilization) leads to exaggerated degradation
- After stabilization: still significant UVID observed for some module types



Degradation (P_{MPP}) after UV test. Color code: Module types

[1] P. Gebhardt et al., "Stabilization procedures for TOPCon PV modules after UV-induced degradation," SolMat 2026.

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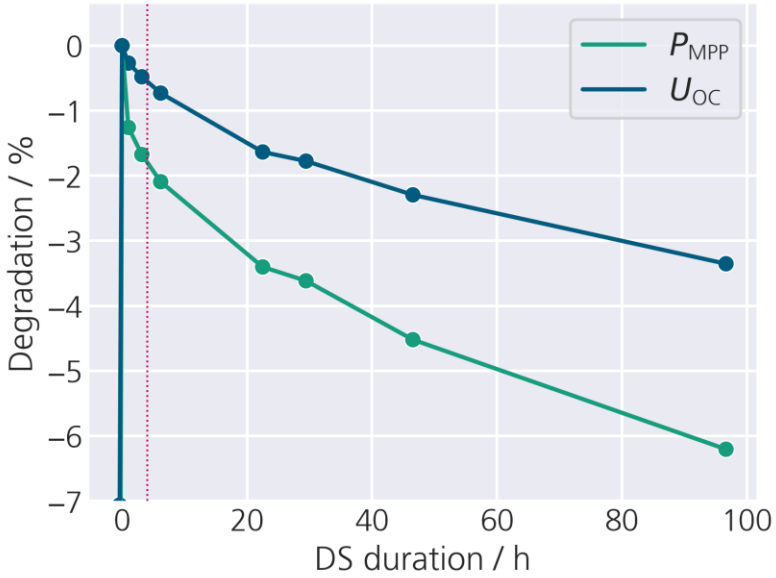
Post-UVID Metastable Behavior

Degradation in Dark Storage, Stabilization in Light Soaking [1]

Stabilization Procedure

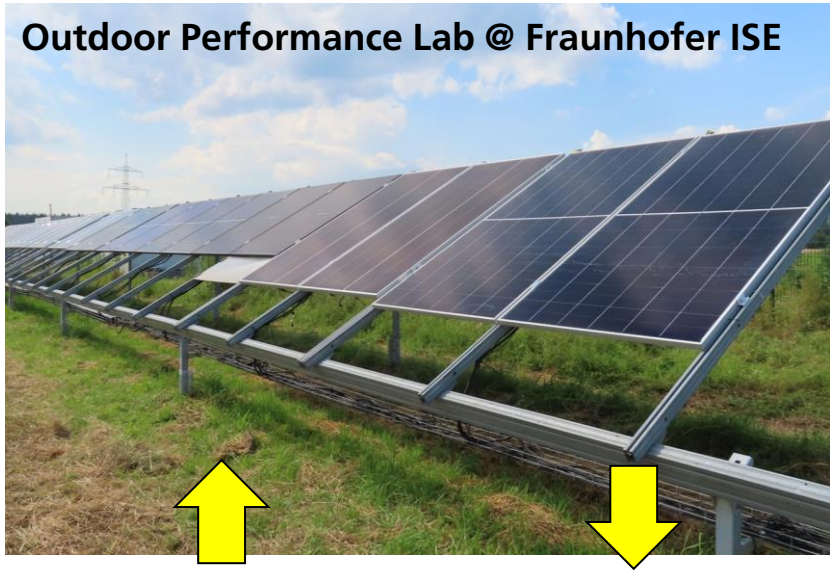
- IEC TS 63624-1 „Test methods for UV-induced degradation - Part 1: Crystalline Silicon“ under development
  - In discussion: max. 4 h between lightsoaking and power measurement
- Light soaking at 25 °C allows direct measurement



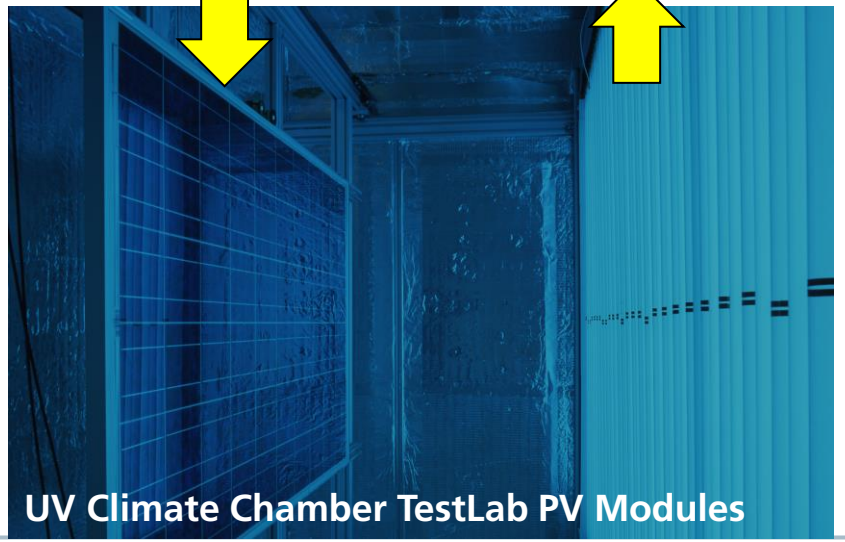
Example of degradation upon dark storage after UVID

[1] P. Gebhardt et al., "Stabilization procedures for TOPCon PV modules after UV-induced degradation," SolMat 2026.

Field-Relevance of UVID Tests



Comparison and **Combination**



Comparison

- Validiation of accelerated aging tests in the lab
  - Extent of degradation
  - Dark storage effect
- Observation of degradation progression

Combination

Step 1: Accelerated aging (1-2 years equivalent UV dose)

Step 2: Observation of effects under realistic outdoor exposure:

- Yield
- Influence of temperature
- Influence of irradiance intensity

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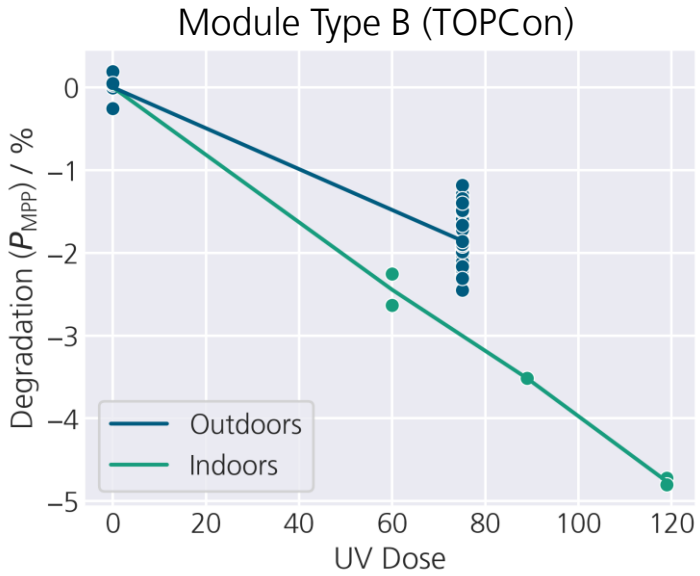
Indoor vs. Outdoor Degradation Comparison

Validation Results Across Four Sites [1]



Outdoor Aging (Type B)

- Power measurements on-site after 14 months
- Outdoor A+A+A+ flasher (3rd party)
- Mean of spare modules as reference

UV Aging in the Lab (Type B)

- According to IEC 61215-2, MQT10
- Light stabilization after UV aging

Key Observations

- Modules with lab-induced UVID also degrade in the field
- TOPCon: *Consistent* trend of slight overestimation of UVID by lab tests

[1] P. Gebhardt et al., EPJ PV, 2026., *under revision*

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Indoor vs. Outdoor Degradation Comparison

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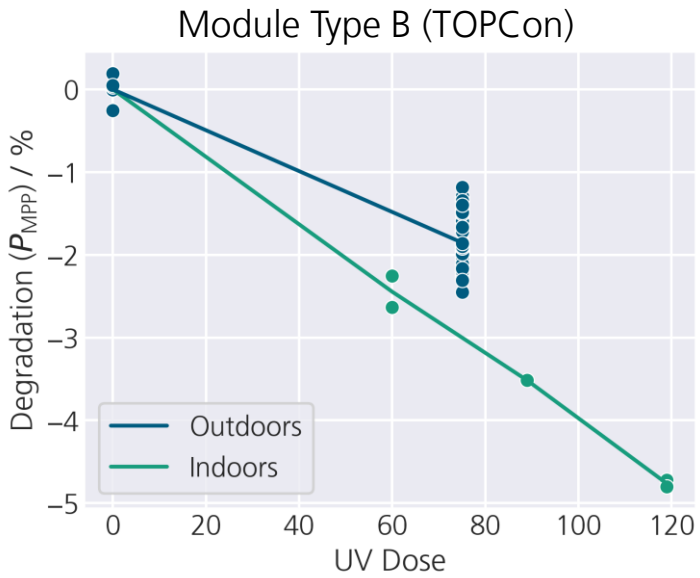

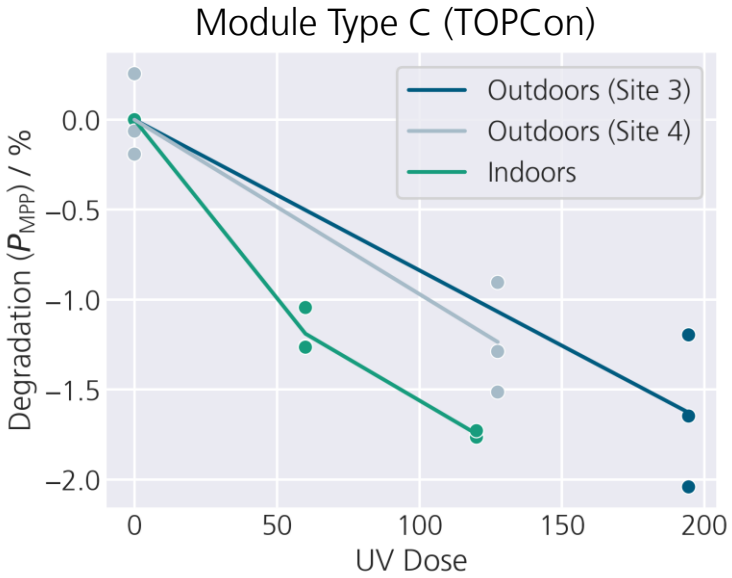

Outdoor Aging (Type C)

- Power measurements in lab after ~2 years
- Mean of spare modules as reference

UV Aging in the Lab (Type C)

- According to IEC 61215-2, MQT10
- Light stabilization after UV aging

Key Observations

- Modules with lab-induced UVID also degrade in the field
- TOPCon: *Consistent* trend of slight overestimation of UVID by lab tests

[1] P. Gebhardt et al., EPJ PV, 2026., *under revision*

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Indoor vs. Outdoor Degradation Comparison

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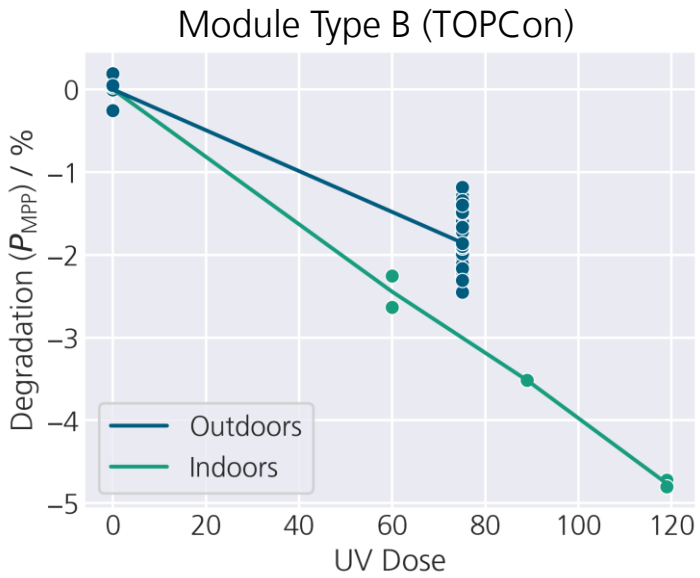

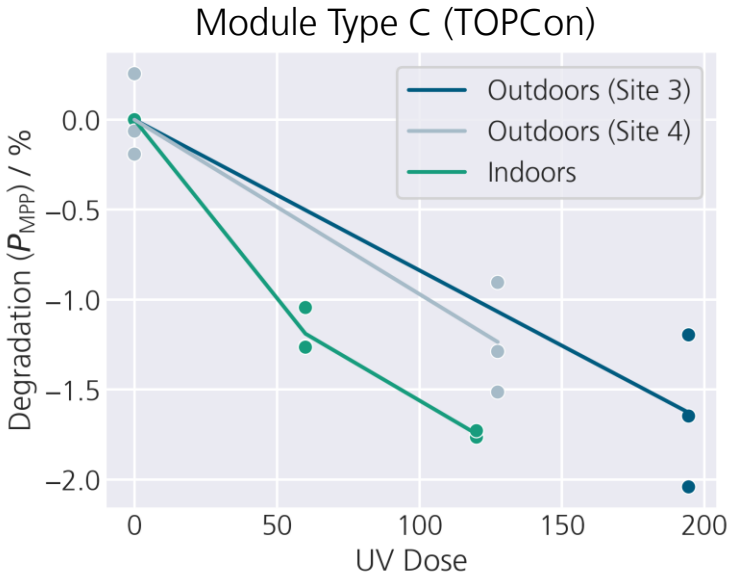

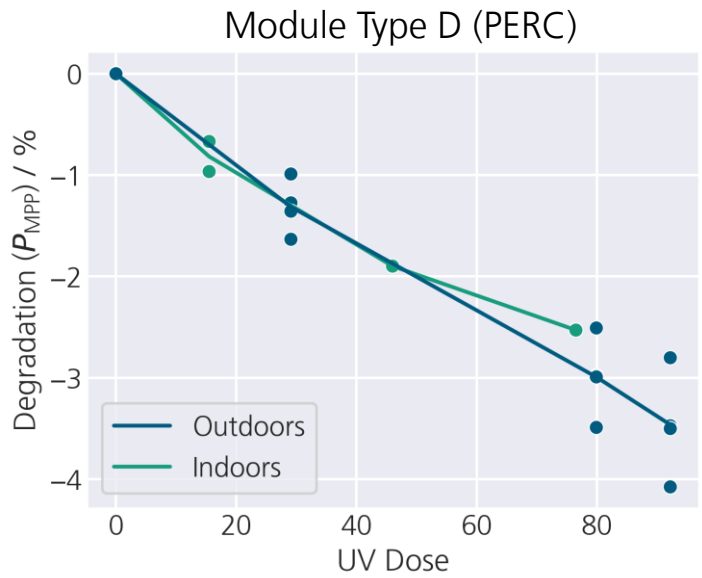

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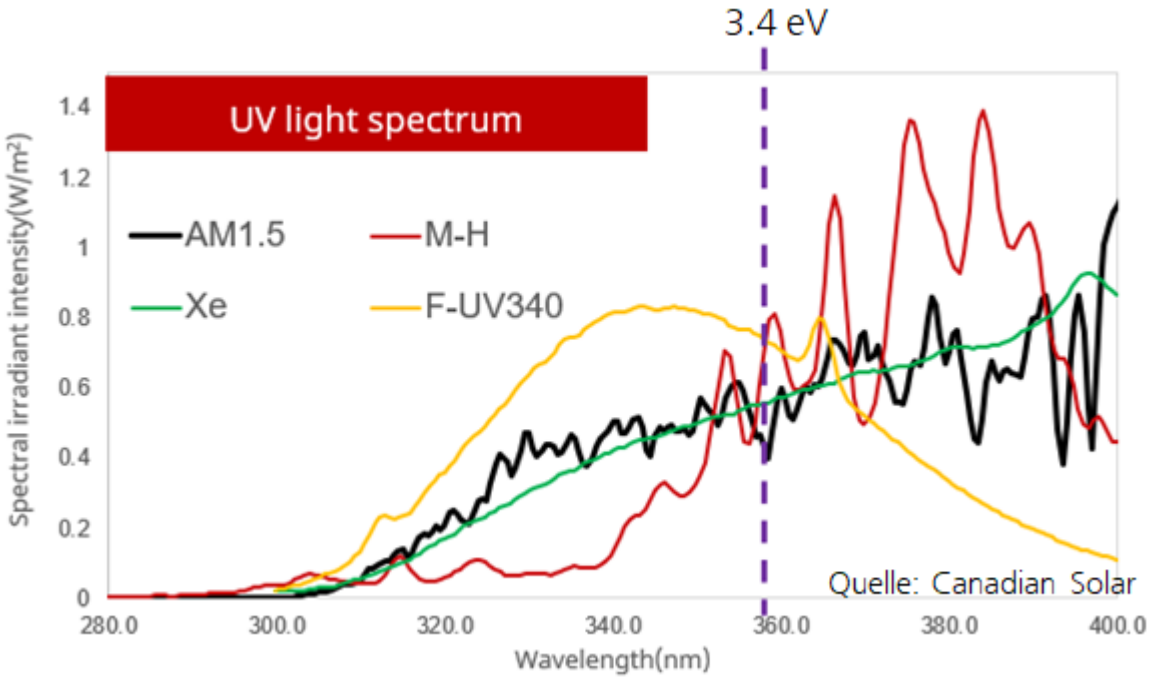
Effect of light sources in UVID testing

Possible Reasons for Overestimation

- Estimation of UV dose: 5 % of total in-plane irradiance
  - No available data on outdoor UV spectrum
  - No consideration of spectral sensitivity of UVID

Mechanism of UVID

- Initiated by cleavage of Si-H bonds (3.4 eV) [1]
- UVB light causes stronger UV degradation than UVA [2]
- Considering only light below 3.4 eV in calculation of UV dose results in better correlation between indoor and outdoor



Normalized spectra of different artificial light sources compared with AM1.5 sun spectrum

[1] R. Witteck et al., Phys. Status Solidi RRL, 2017.

[2] M. U. Khan, B. Hoex et al., SolMat, 2026.

Dark Storage Effects

Laboratory vs. Field Behavior [1]

In the Laboratory:

- Significant power loss during dark storage (after UVID) over duration of hours/days
- Rapid recovery with light exposure (often < 1 minute at 1000 W/m²)

In the Field (Site 2, Type B):

- Dismounted modules stored in the dark for 4.5 h
- ~0.6 % power loss (P_{MPP})
- Quick recovery upon illumination

- No Effect on yield expected

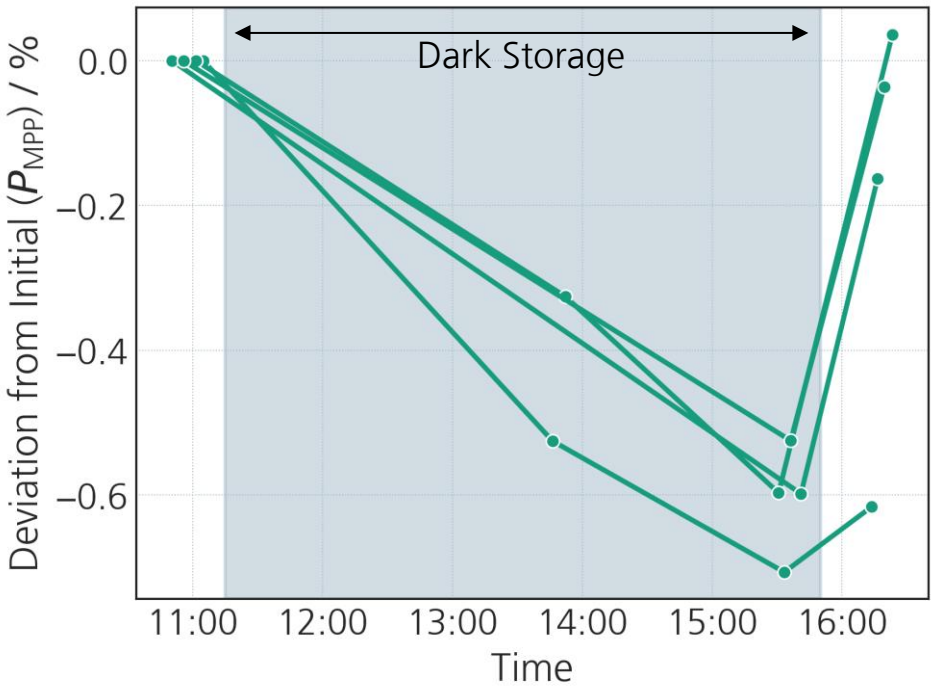


Figure: PV modules were temporarily removed from their installation and stored in the dark from 11:30 – 4:00 PM.

[1] P. Gebhardt et al., EPJ PV, 2026., *under revision*

Conclusion

- Post-UV stabilization is essential for accurate laboratory assessments
- No signs of dark storage effects impacting outdoor yield
- Modules that showed UVID in the lab also degraded in the field
- Indoor tests *consistently* overestimated field degradation for TOPCon modules
  → Light source spectrum needs to be considered

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TestLab PV Modules

CalLab PV Modules

Contact

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Photo: TestLab PV Modules at Fraunhofer ISE