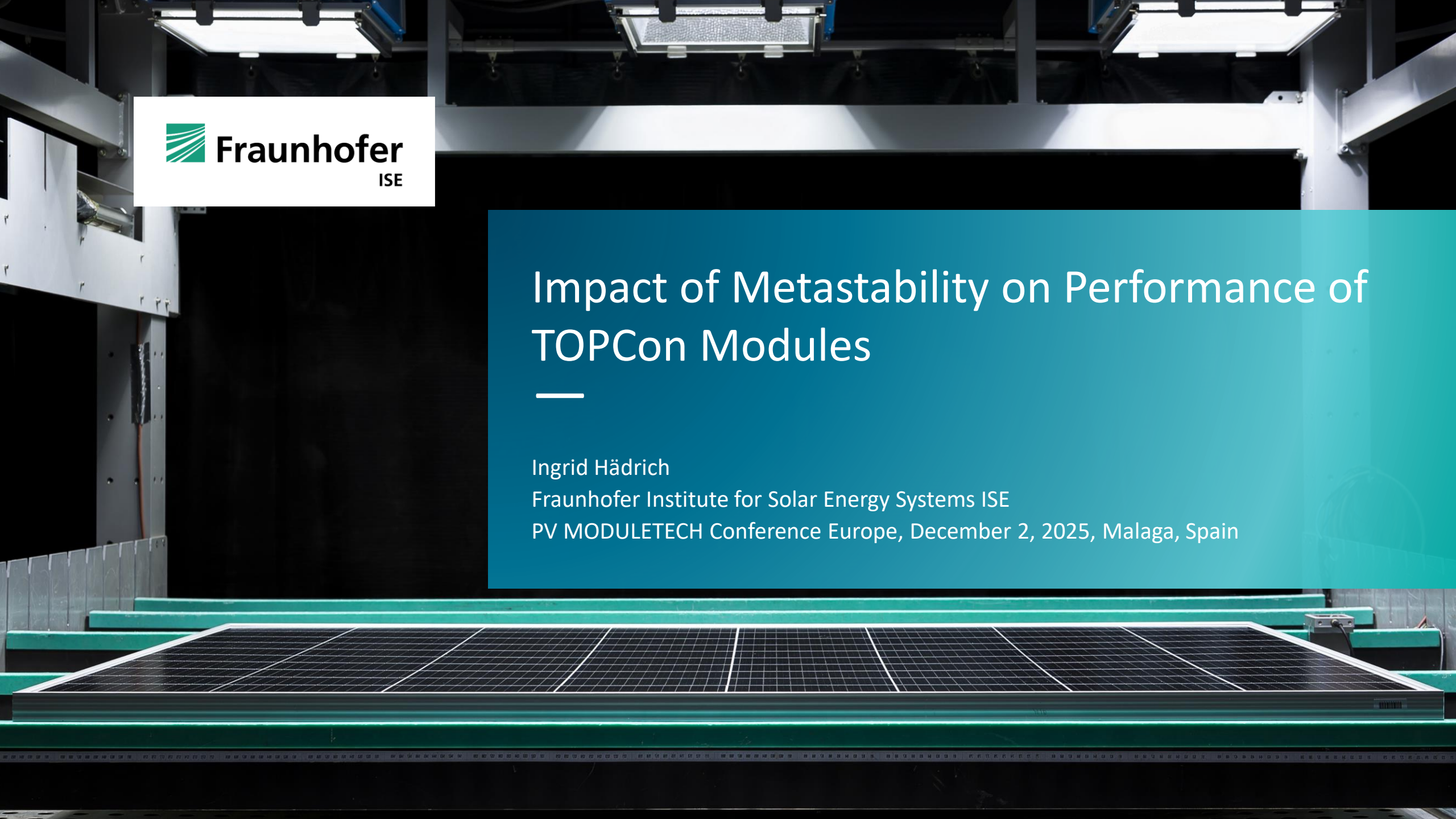


Impact of Metastability on Performance of TOPCon Modules

Ingrid Hädrich
Fraunhofer Institute for Solar Energy Systems ISE
PV MODULETECH Conference Europe, December 2, 2025, Malaga, Spain

Unique Independent Test-Infrastructure

CalLab and TestLab PV Modules

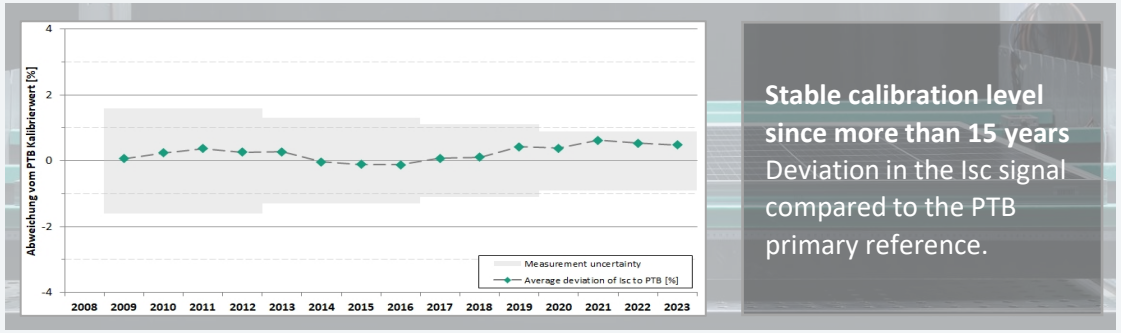
CalLab PV Modules

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

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.

TestLab PV Modules

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

IEC IECEE Certificate of Acceptance

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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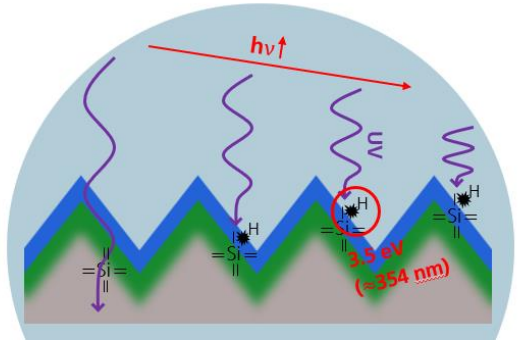
Agenda

1. UVID vs Metastability

2. Methods to Stabilize TOPCon Modules

3. Indoor vs. Outdoor Degradation Comparison

4. Metastability on Out of the Box Modules



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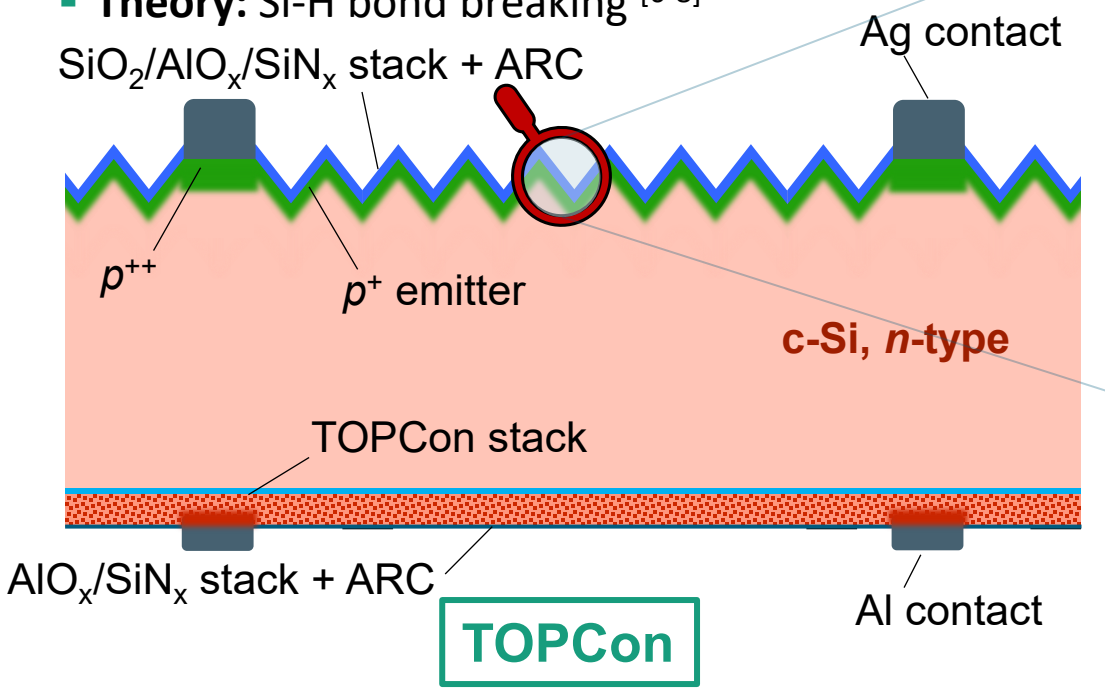
UVID vs Metastability

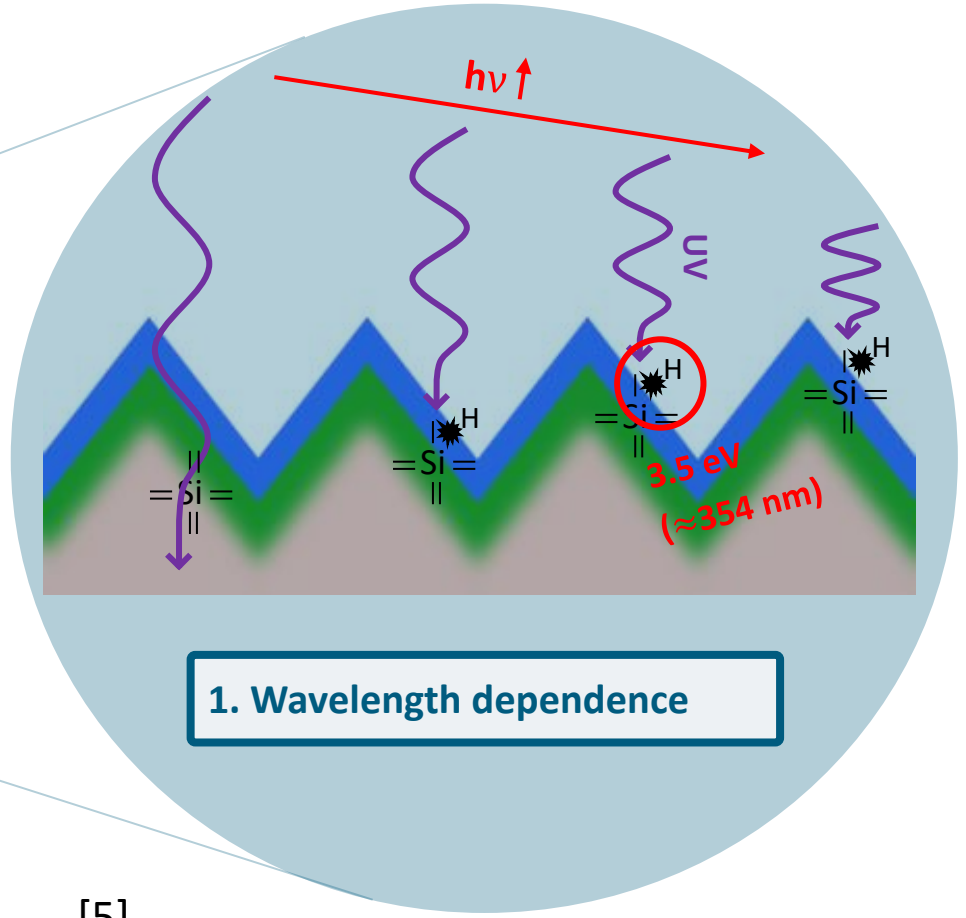
Modern silicon solar cells suffer from UV degradation

[3,4]

- **Theory:** Si-H bond breaking [6-8]



UVID



[5]

[3] Thome, F.T. et al., SolarRRL, 2024.
[4] Sinha, A. et al., Progress in PV, 2023.
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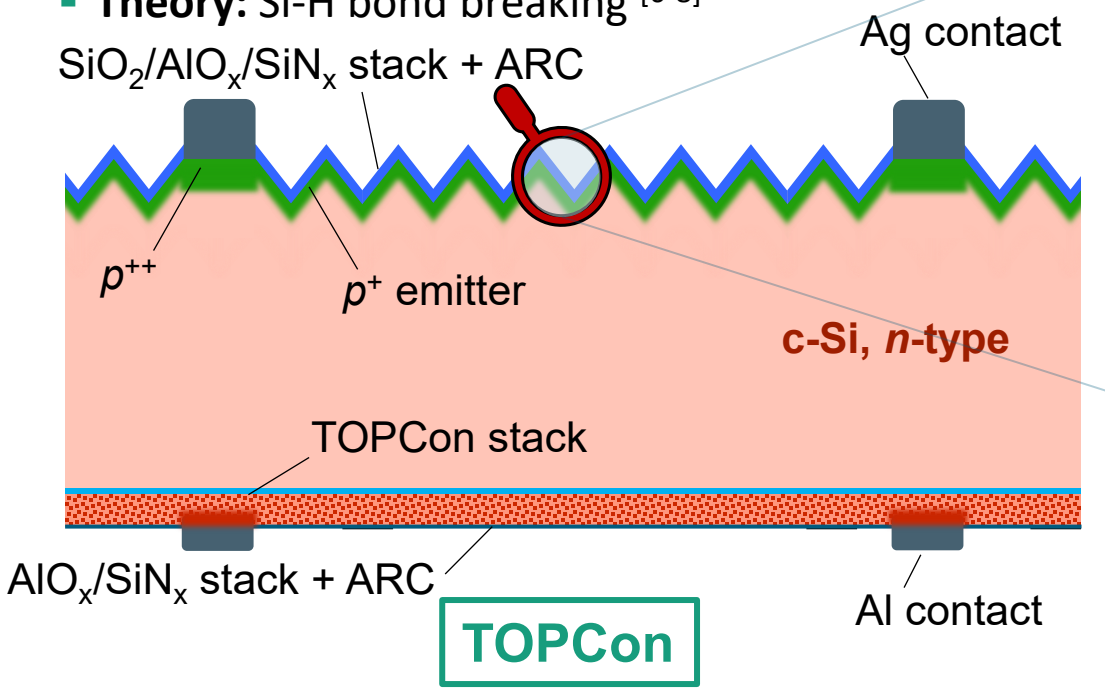

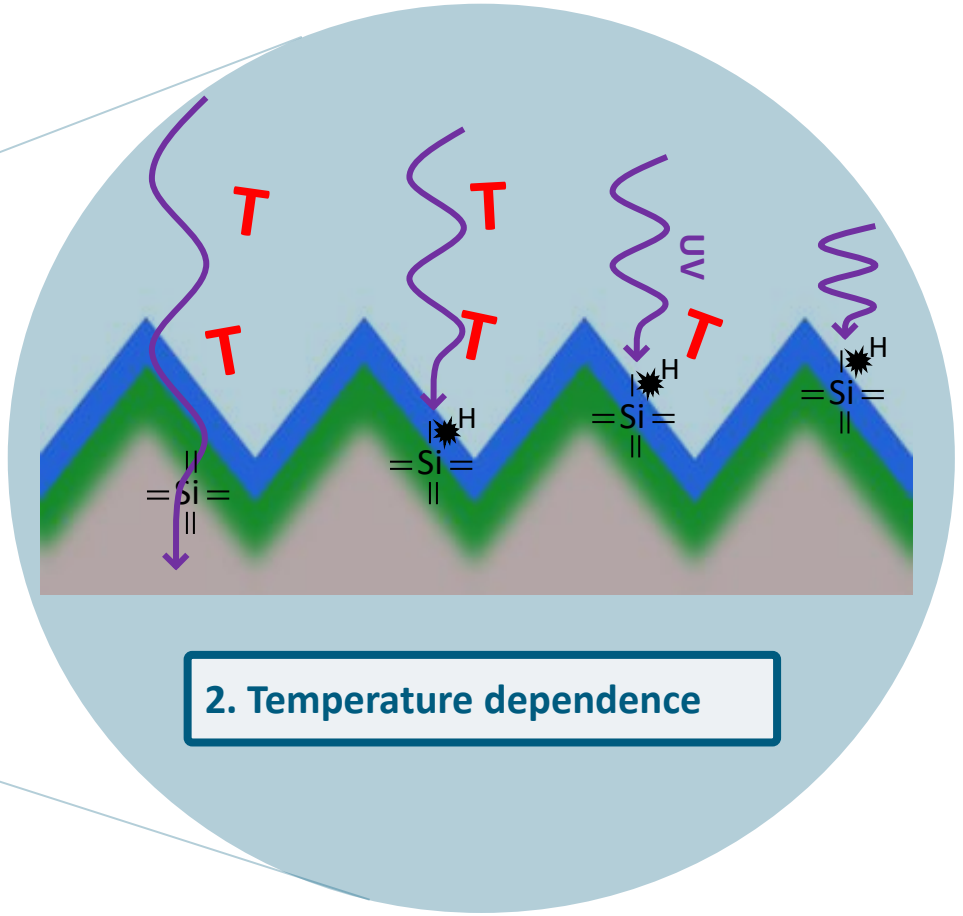

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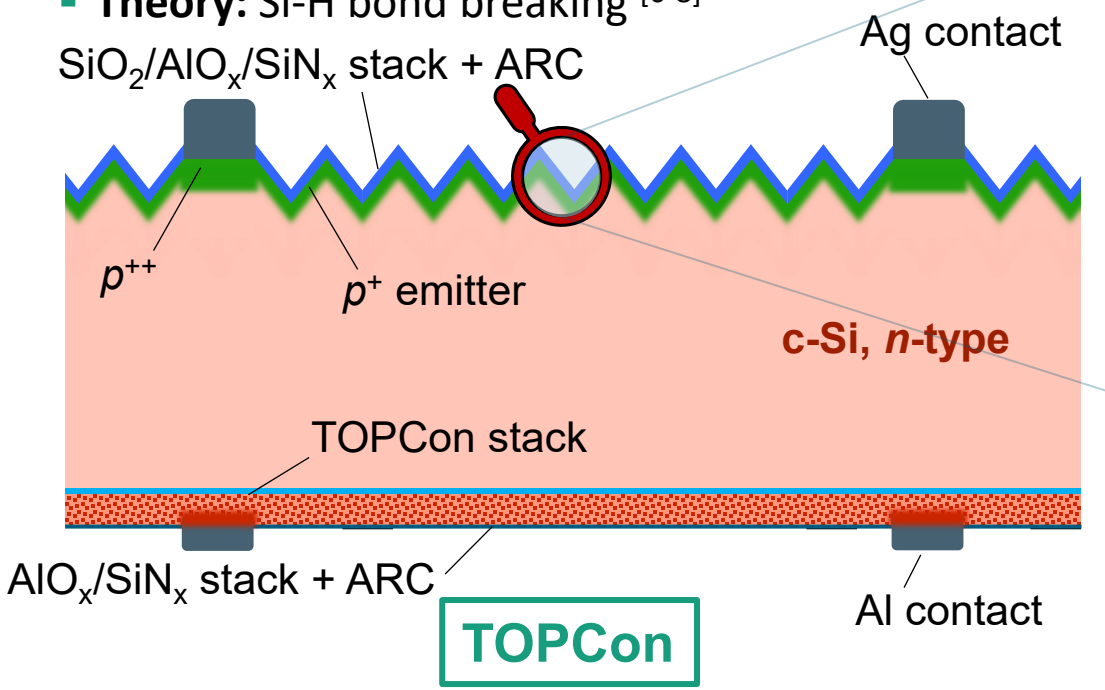

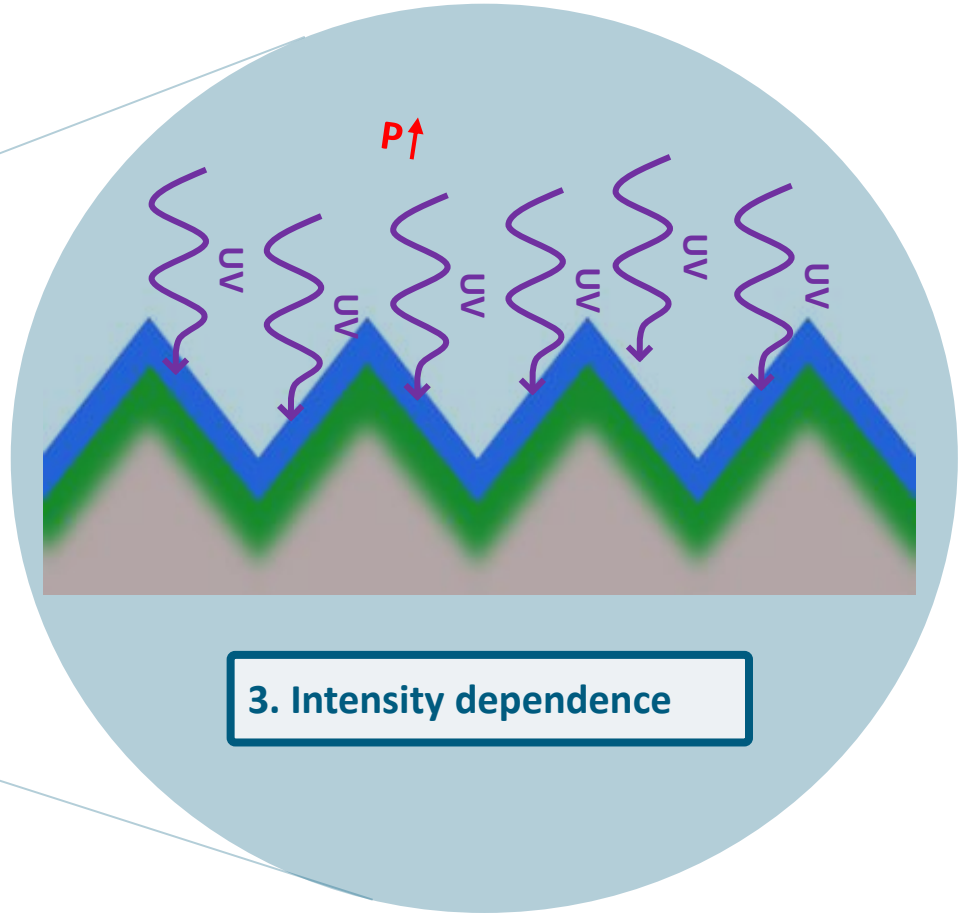

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UVID vs Metastability

UVID

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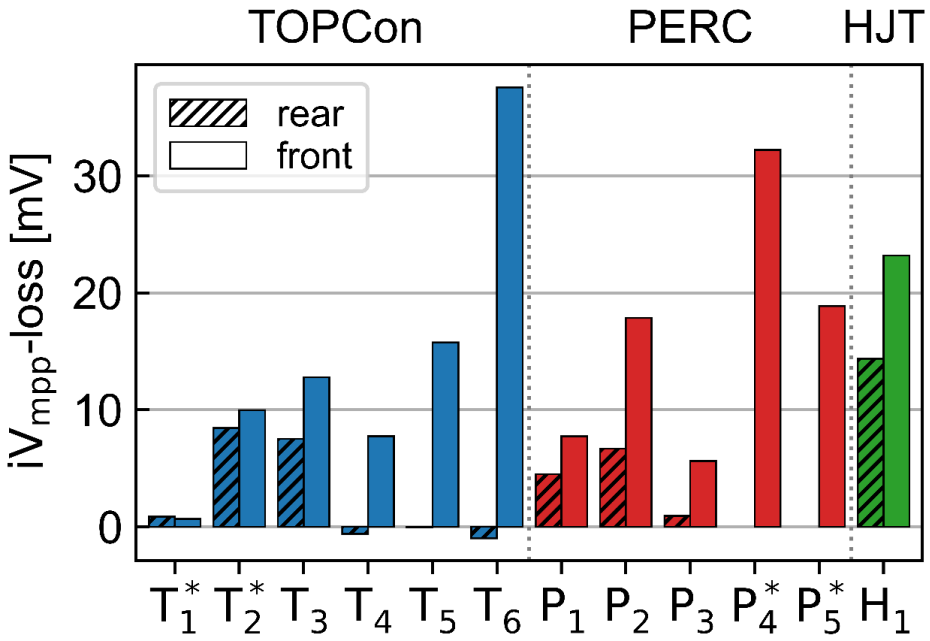

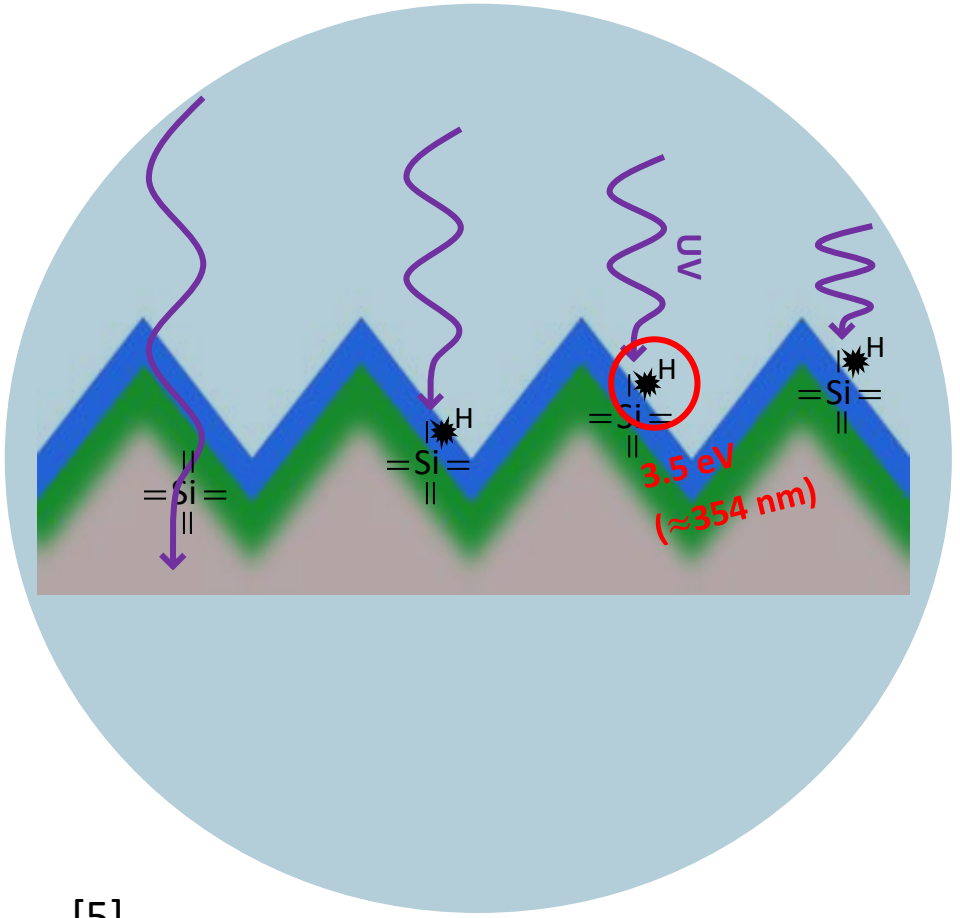

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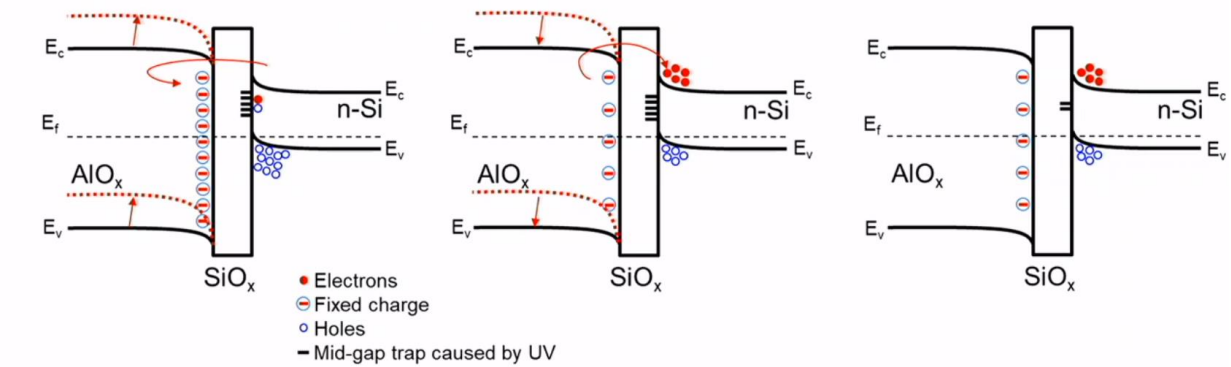
Dark Storage and „Recovery“

- Dark storage reduces charges at SiOx/AlOx stack
→ reduces field passivation

- Illumination restores charges at the interface
→ passivation restored



- **UV:** Si–H bond breakage ↑D_{it}, but charge trapping boosts Q_f
- **Dark storage:** D_{it} stable; Q_f released → higher recombination
- **Recovery:** Anneal diffuses H, ↓D_{it}, restores passivation.

[1] Bram Hoex UNSW, EUPVSEC Bilbao, 2025.

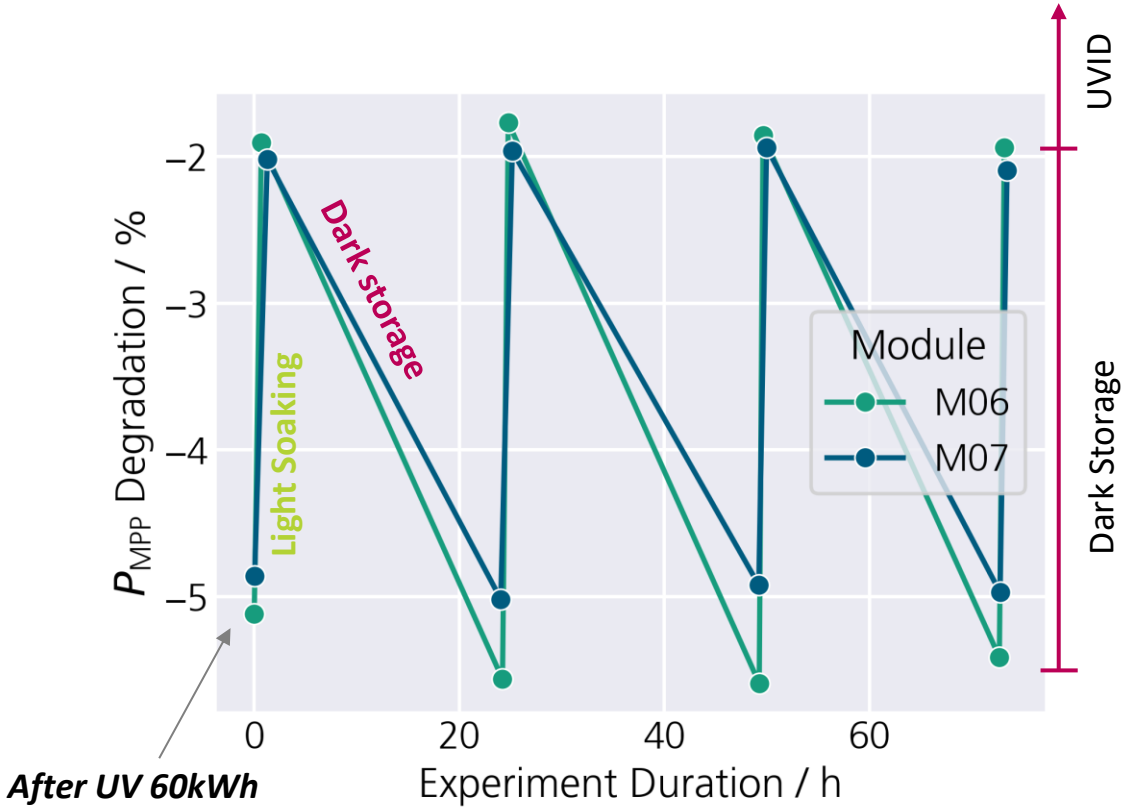
Dark Storage and „Recovery“

- Dark storage reduces charges at SiOx/AlOx stack
→ reduces field passivation

- Illumination restores charges at the interface
→ passivation restored

- Dark Storage and Recovery is repeatable!
- Highly important for Quality Assurance process!
- ***Large impact on Testlab procedures***

→ How to run recovery as reliable, as repeatable and as cost efficient as possible?



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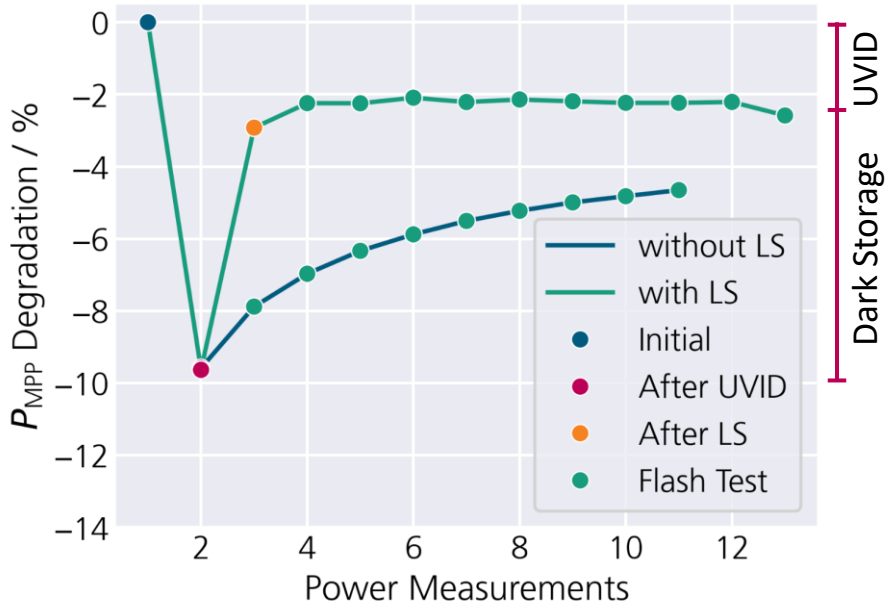
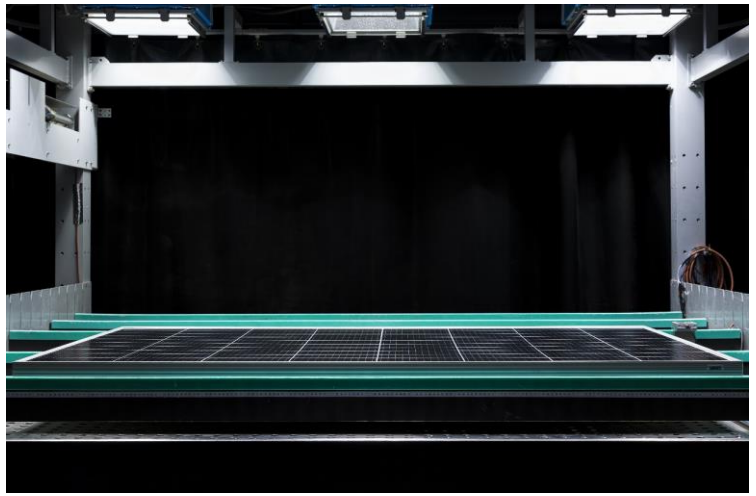
UVID vs Metastability

Dark Storage and „Recovery“



Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization



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

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Dark Storage and „Recovery“

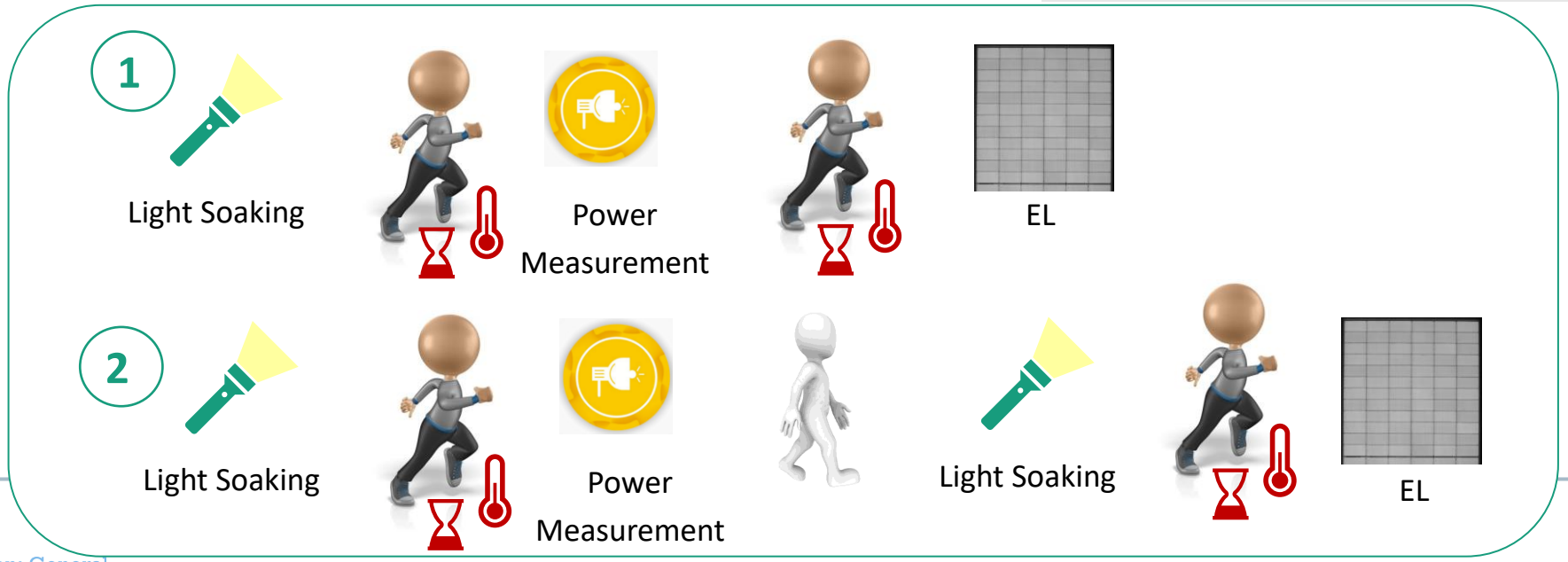
Current procedure

- Stabilization generally necessary after UV test and for fielded modules
  - Lightsoaking 5 min, 1000 W, 25 °C
  - UV portion mainly responsible [1]

BUT: Additional effort → higher cost!

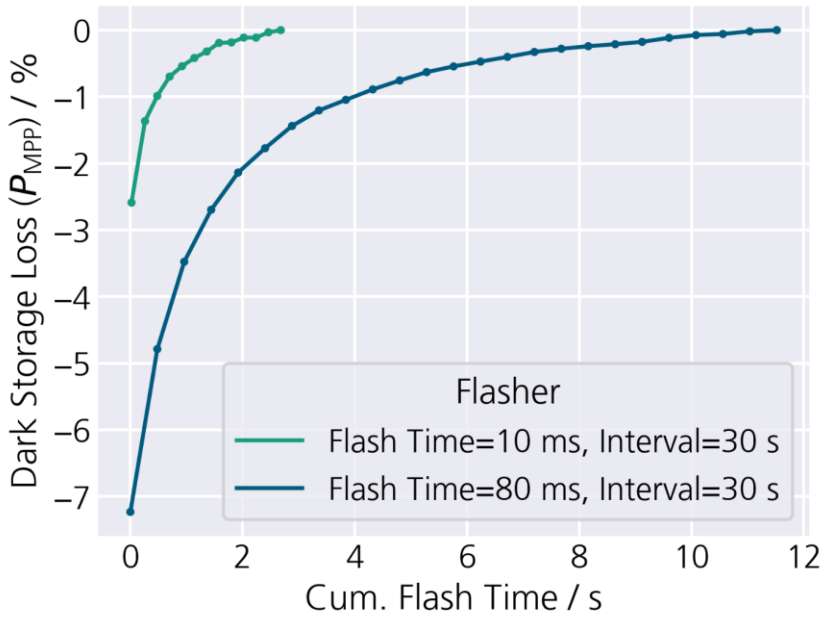
Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization



OR: Build a combinded Testsation with Lightsoaking and EL and STC

Dark Storage and „Recovery“

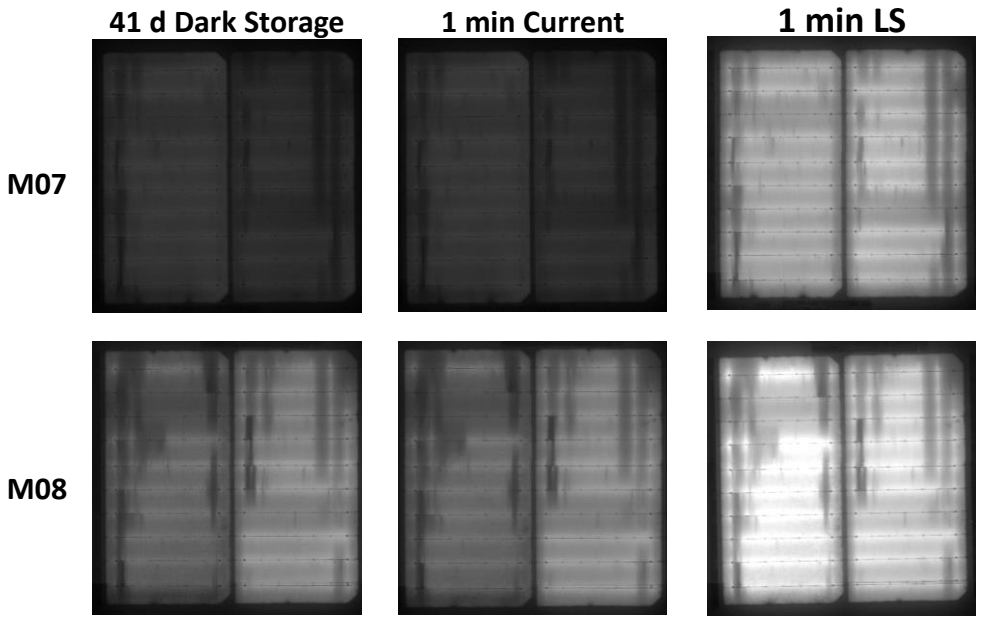


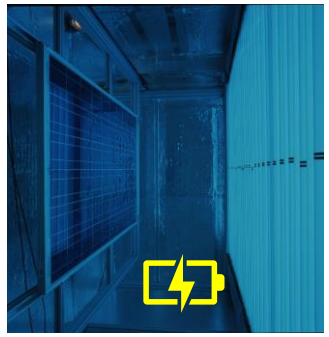
Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization
Multiflash $_n$	Stabilization

- *Complete stabilization upon repeated flashing is possible*
  - *But requires long time in flasher*
- *Required light dose depends on individual flash duration*

Dark Storage and „Recovery“



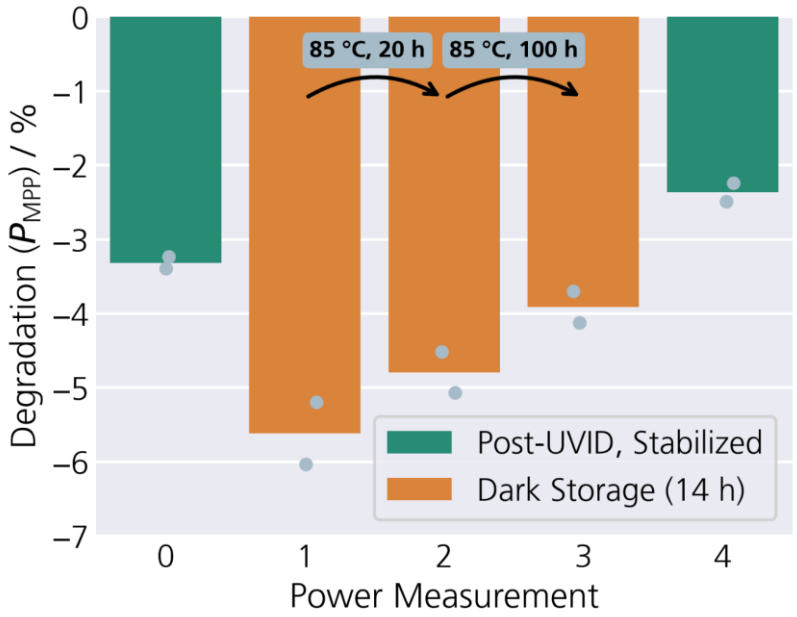


- EL measurements at different stages of test sequence
- No significant power increase by EL measurement or current

Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization
Multiflash $_n$	Stabilization
Current feed	✗ Negligible effect

Dark Storage and „Recovery“



Post-UVID experiment on one full-scale module in light soaking and subsequent dark storage over night is diminished by high temperature

Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization
Multiflash $_n$	Stabilization
Current feed	✗ Negligible effect
High T	Reduction of DS degradation

Dark Storage and „Recovery“

- **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

Methods of Stabilisation

Approach	Result
Light Soaking	✓ Fast stabilization
Multiflash $_n$	Stabilization
Current feed	✗ Negligible effect
High T	Reduction of DS degradation

Indoor vs. Outdoor Degradation Comparison

- Comparison of degradation in three outdoor sites
- Dark storage effect outdoors

Parameter	Details
Module Types	3 different commercial utility-scale modules
Technology	2 × TOPCon, 1 × PERC (Type D)
Outdoor Sites	3 locations (commercial power plants)
Exposure Period	12–28 months

Outdoor Aging

VS

Indoor Aging

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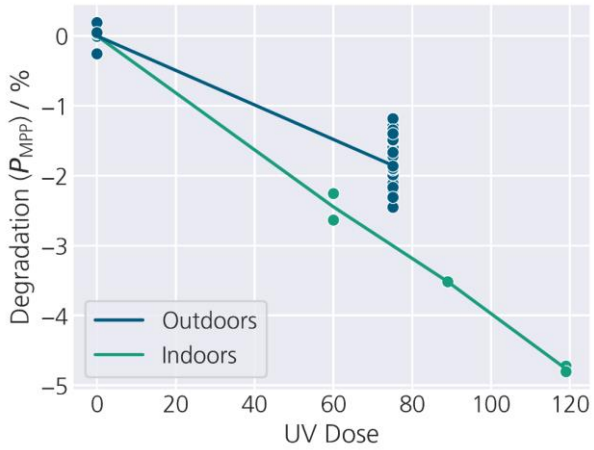
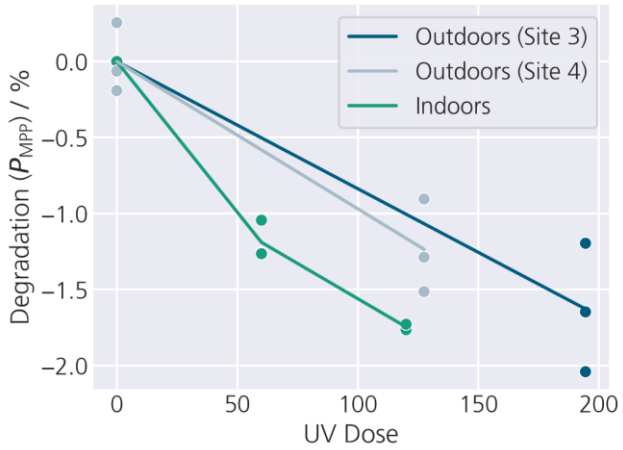
Indoor vs. Outdoor Degradation Comparison

Validation Results Across Three Sites

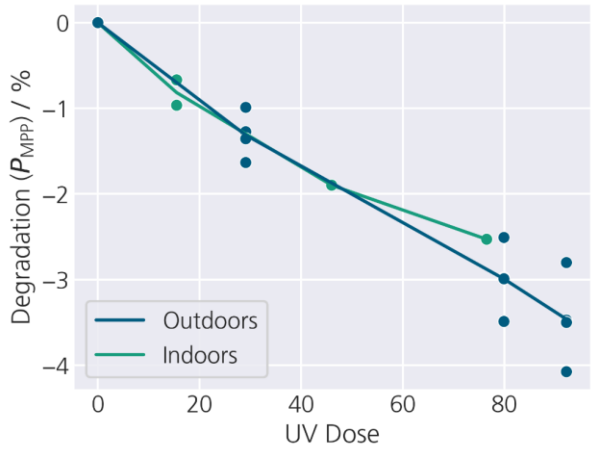
Module Type B (TOPCon)



Module Type C (TOPCon)



Module Type D (PERC)



Summary of Indoor-Outdoor Comparison

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

Possible Reasons for Overestimation

- Estimation of UV dose: 5 % of total in-plane irradiance
  - No available data on differences in UV spectrum and no consideration of spectral sensitivity
- No consideration of temperature effect on UVID

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Indoor vs. Outdoor Degradation Comparison

Dark Storage effect in the field

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

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

Modules was flipped upside down in the field!

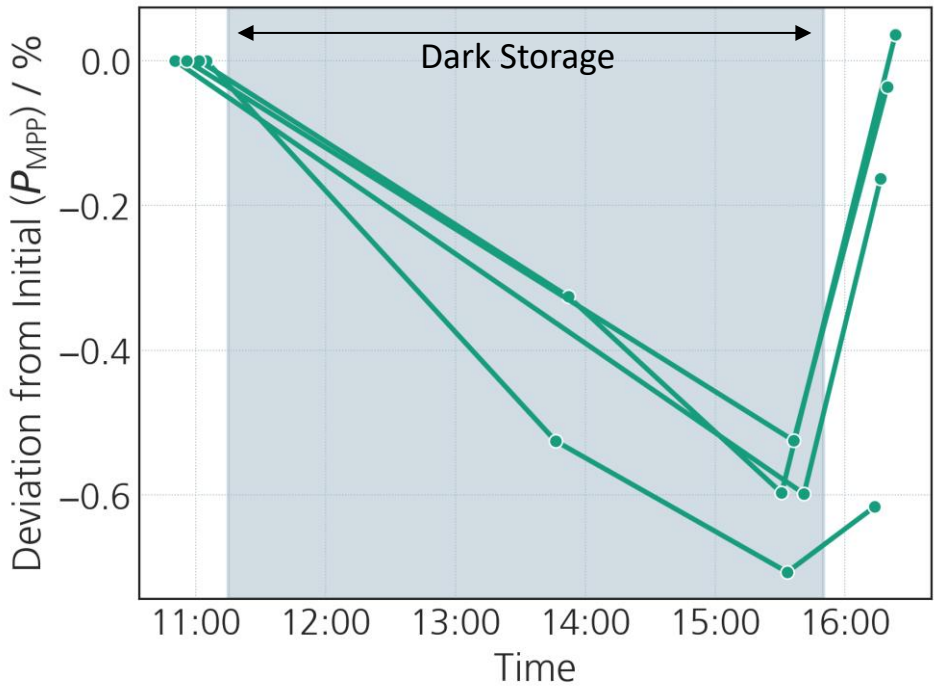

Figure: PV modules were temporarily removed from their installation and stored in the dark from 11:30 – 4:00 PM.

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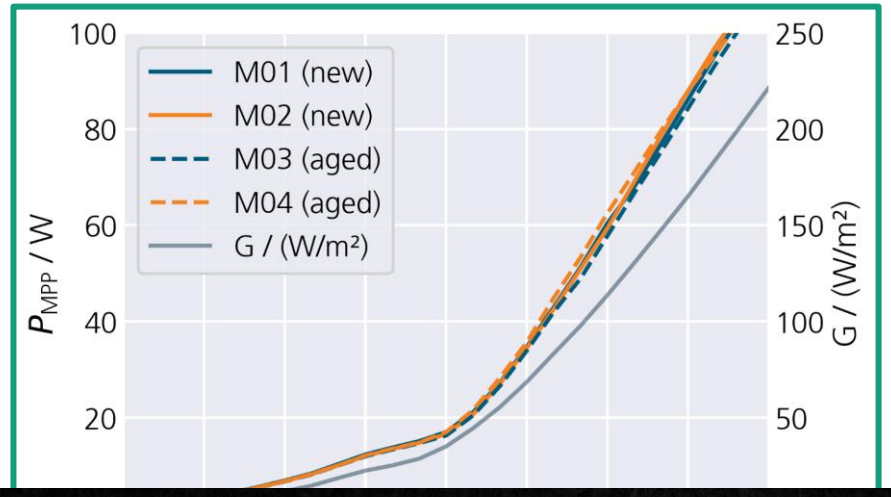
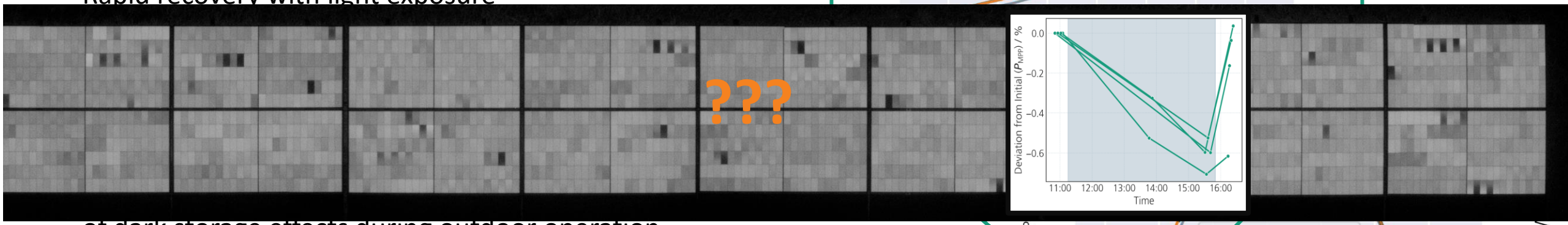
Dark Storage Effects

Laboratory vs. Field Behavior

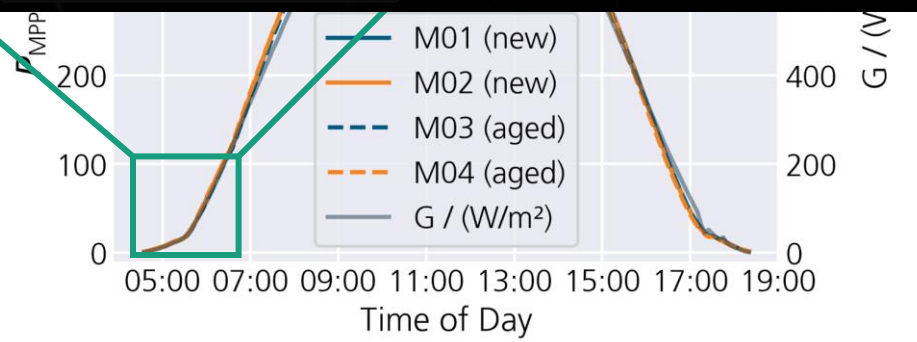
In the Laboratory:

- Significant power loss during dark storage (after UVID) over duration of hours/days
- Rapid recovery with light exposure





of dark storage effects during outdoor operation



Conclusion

- Dark storage effects are a laboratory artifact that don't impact real-world yield

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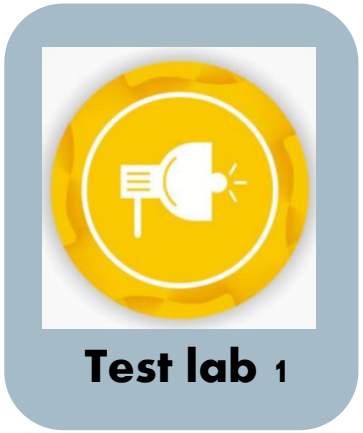
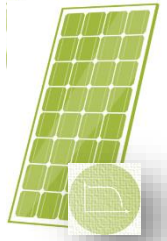
Stabilization of „Out of the Box Modules“

Binning process for module manufacturers

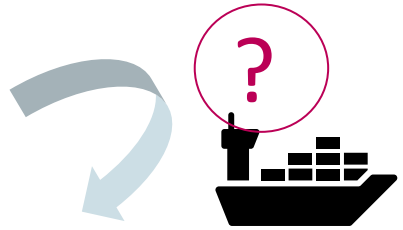
Installer



‘gold module‘



600 W

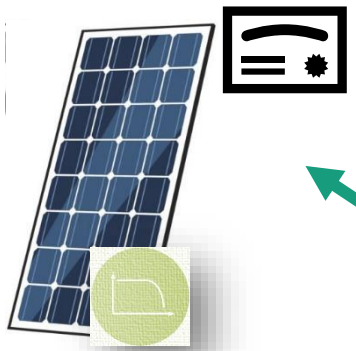


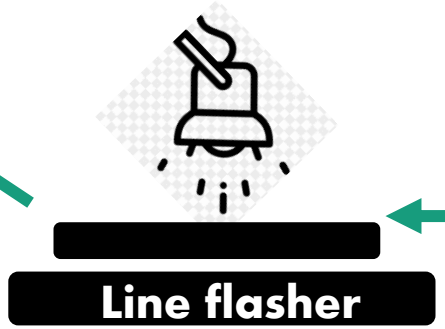
Value of the reference module determines the output!

Manufacturer

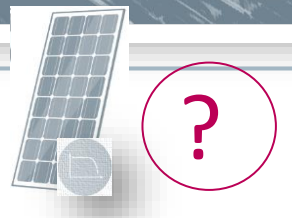
Label power class: 580Wp, 590Wp, 600Wp,...

?





‘silver module‘



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TOPCon Metastability

Test Sequence – **Storage and Light Soaking**

Performance test P_{STC}

Storage

Performance test P_{STC}

2 kWh/m² irradiation

Performance test P_{STC}

1

Storage

Performance test P_{STC}

2 kWh/m² irradiation

Performance test P_{STC}

2

...

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TOPCon Metastability – Storage Effects

4 Cycles

2 different module types (stabilized)

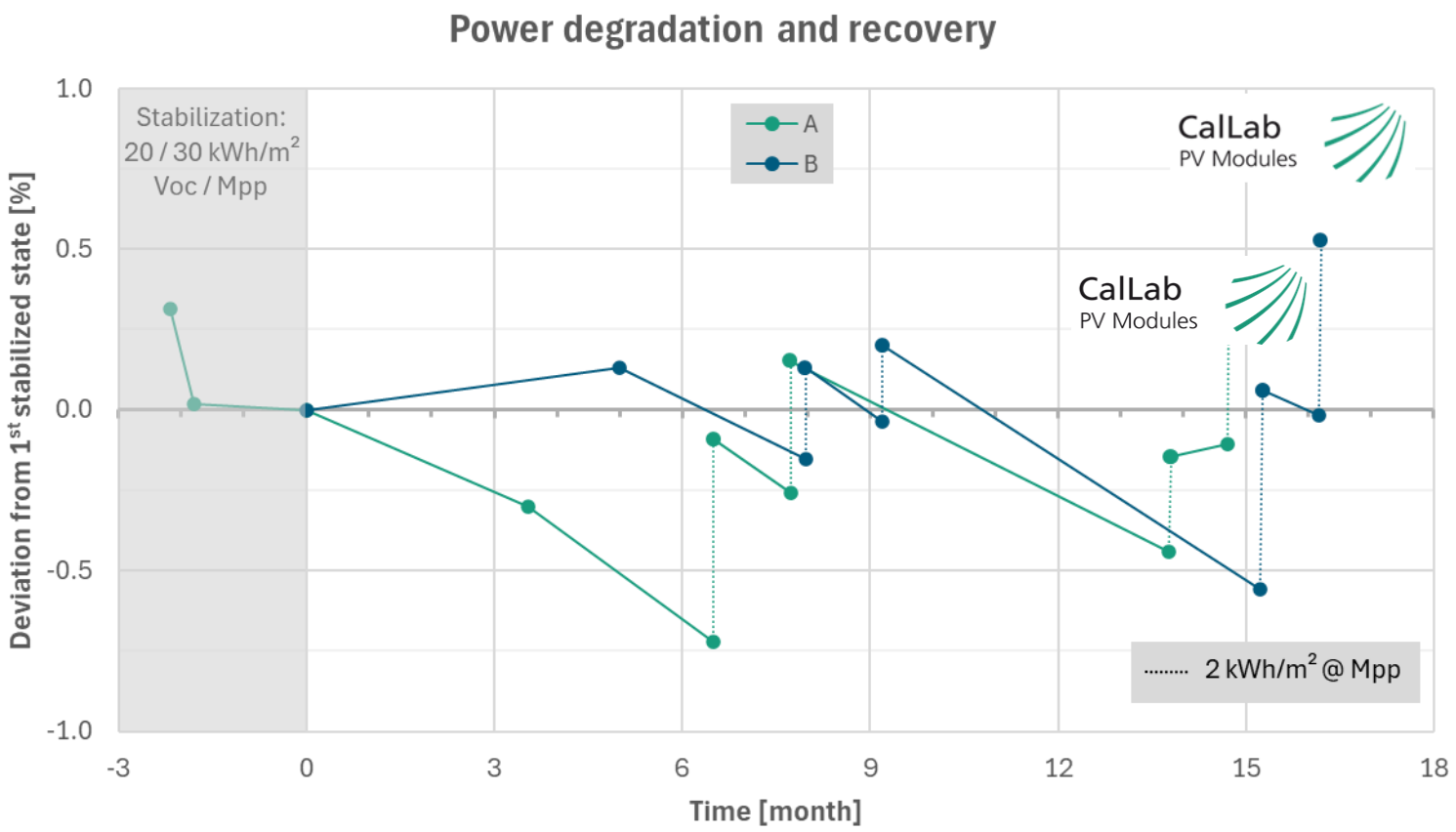
- Storage at ordinary lab conditions
- Degradation observed for both types

Degradation rate

- -0.1% / month

Recovery

- No general statement
- Range of gains: 0.2% – 0.6%
- No reproducible result for P_{MPP}



TOPCon storage effects

Degradation and recovery observed ⟷ stable according to IEC 61215-2 MQT 19.1 (<1%)
Critical for reference (golden) modules / comparisons

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STC Results

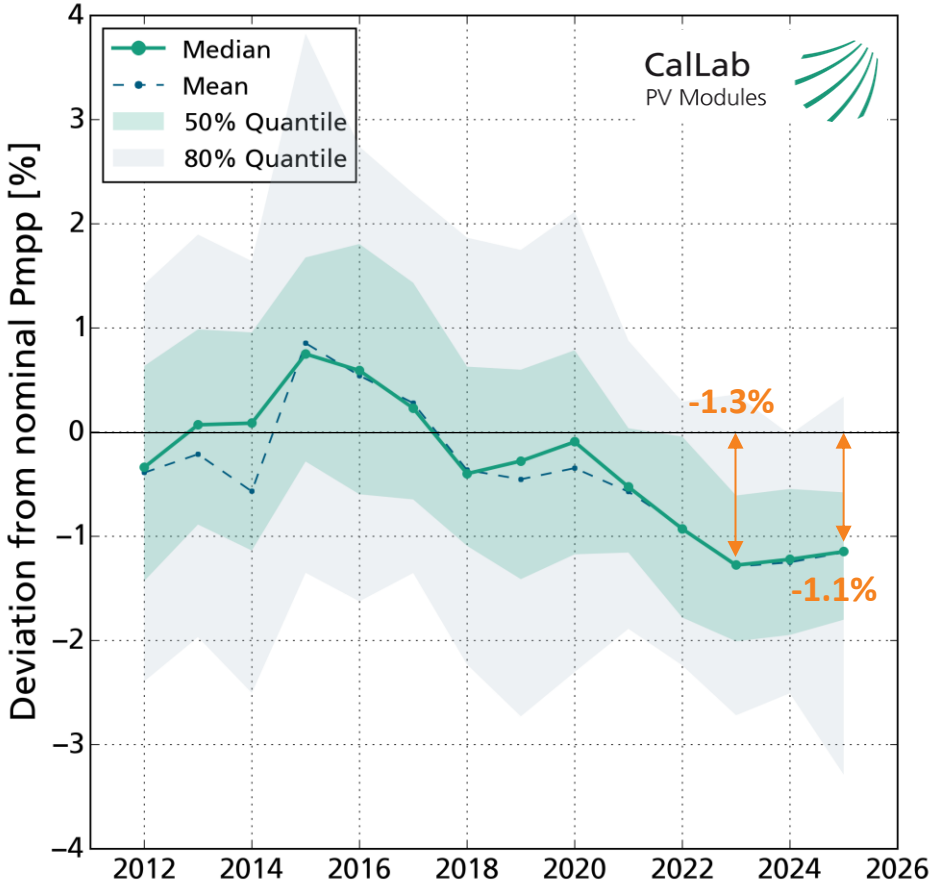
Performance Deviation from Nameplate since 2012

Significant negative deviation in the last years

- Average deviation in 2025: **-1.1%**

Stabilized after 2023 (first publication)

- Change from 2023 to 2025: **+0.2%**



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Contact

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Federal Ministry for Economic Affairs and Climate Action

GagaRIn (03EE1133A)
MoQa (020E-100550326)
Quelle (03EE1172E)

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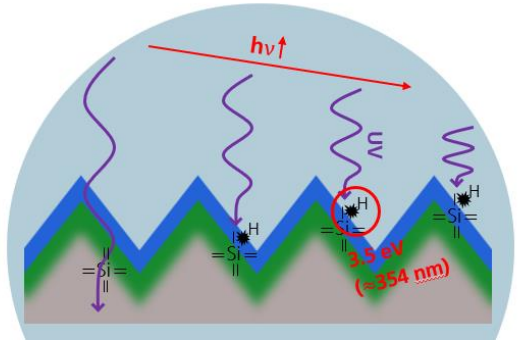

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