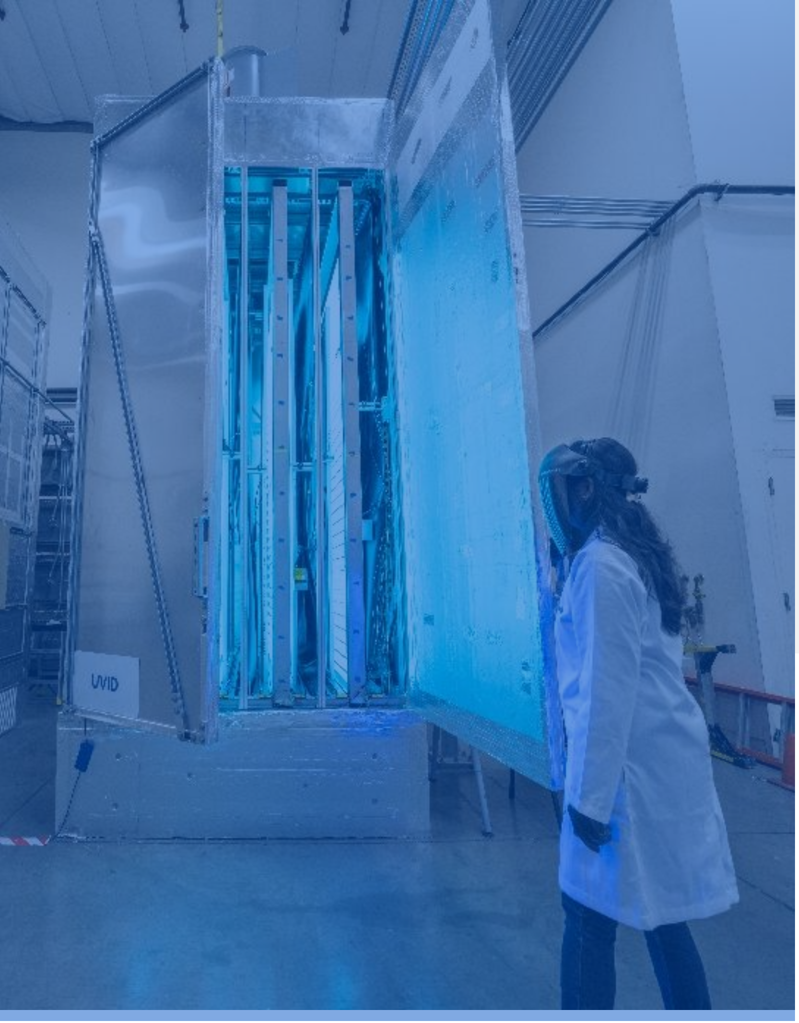


UV-Induced Degradation in TOPCon Modules:

Linking Accelerated Testing and Field Evidence

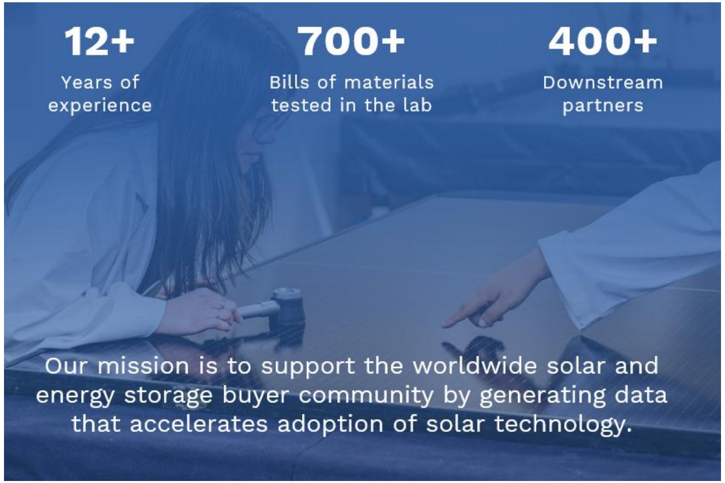
Archana Sinha, Jean-Nicolas Jaubert, Todd Karin (Kiwa PVEL)
Dana B. Kern (NLR)

creating trust, ***driving progress***

Kiwa PVEL

- Independent lab for PV Module **Performance and Reliability Testing.**
- Headquarter test lab at Napa, US and a sister company at Suzhou, China.
- Known for **PQP test sequences**, which gets updated every 2 years.

See more details at kiwa.com/pvel

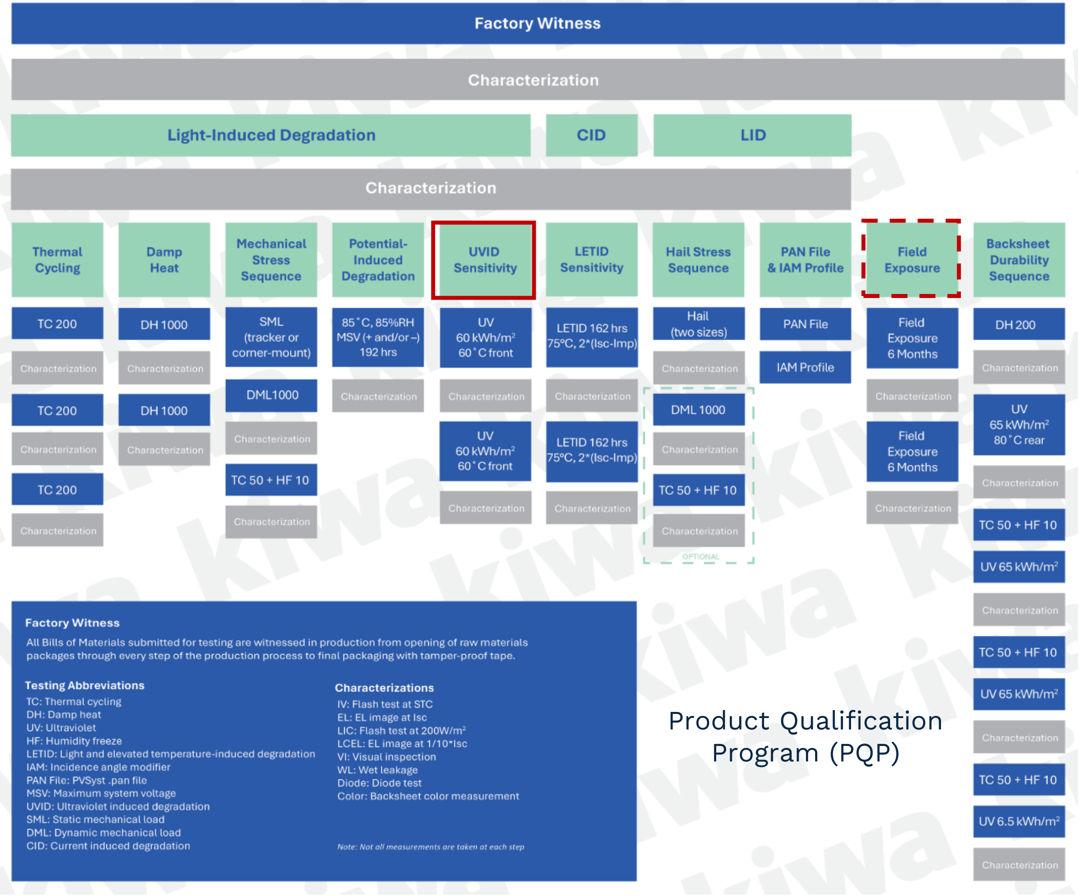


12+
Years of experience

700+
Bills of materials tested in the lab

400+
Downstream partners

Our mission is to support the worldwide solar and energy storage buyer community by generating data that accelerates adoption of solar technology.



Factory Witness

Characterization

Light-Induced Degradation | CID | LID

Characterization

Thermal Cycling
TC 200
Characterization
TC 200
Characterization
TC 200
Characterization

Damp Heat
DH 1000
Characterization
DH 1000
Characterization

Mechanical Stress Sequence
SML (tracker or corner-mount)
DML1000
Characterization
TC 50 + HF 10
Characterization

Potential-Induced Degradation
85 °C, 85%RH MSV (+ and/or –) 192 hrs
Characterization

UVID Sensitivity
UV 60 kWh/m^2 60 °C front
Characterization
UV 60 kWh/m^2 60 °C front
Characterization

LETID Sensitivity
LETID 162 hrs 75°C, 2*(Isc-Imp)
Characterization
LETID 162 hrs 75°C, 2*(Isc-Imp)
Characterization

Hail Stress Sequence
Hail (two sizes)
Characterization
DML 1000
Characterization
TC 50 + HF 10
Characterization
OPTIONAL

PAN File & IAM Profile
PAN File
IAM Profile

Field Exposure
Field Exposure 6 Months
Characterization
Field Exposure 6 Months
Characterization

Backsheet Durability Sequence
DH 200
Characterization
UV 65 kWh/m^2 80 °C rear
Characterization
TC 50 + HF 10
UV 65 kWh/m^2
Characterization
TC 50 + HF 10
UV 65 kWh/m^2
Characterization
TC 50 + HF 10
UV 6.5 kWh/m^2
Characterization

Factory Witness

All Bills of Materials submitted for testing are witnessed in production from opening of raw materials packages through every step of the production process to final packaging with tamper-proof tape.

Testing Abbreviations

TC: Thermal cycling
DH: Damp heat
UV: Ultraviolet
HF: Humidity freeze
LETID: Light and elevated temperature-induced degradation
IAM: Incidence angle modifier
PAN File: PVSyst .pan file
MSV: Maximum system voltage
UVID: Ultraviolet induced degradation
SML: Static mechanical load
DML: Dynamic mechanical load
CID: Current induced degradation

Characterizations

IV: Flash test at STC
EL: EL image at Isc
LIC: Flash test at 200W/m^2
LCEL: EL image at 1/10*Isc
VI: Visual inspection
WL: Wet leakage
Diode: Diode test
Color: Backsheet color measurement

Note: Not all measurements are taken at each step

Product Qualification Program (PQP)

Agenda

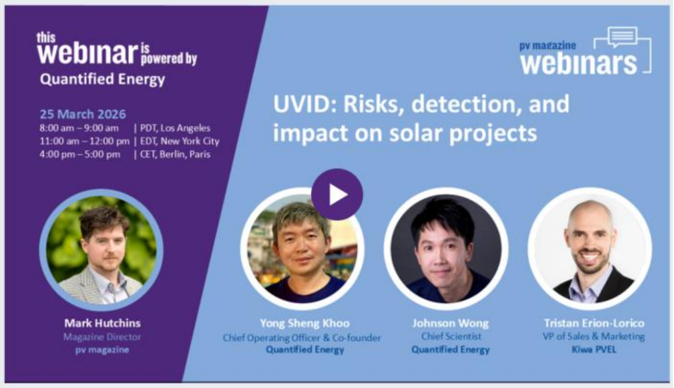
INDOOR UV TEST
(Accelerated Laboratory Exposure)

OUTDOOR FIELD TEST
(Real Environmental Exposure)

MITIGATION STRATEGIES

Why UVID?

- High-interest topic within the PV reliability community as newer cell architectures and module materials are deployed at scale
- Degradation occurs at cell level and adversely impacts the system performance and warranty in the field.



this **webinar** is powered by

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11:00 am – 12:00 pm | EDT, New York City

4:00 pm – 5:00 pm | CET, Berlin, Paris

pv magazine **webinars**

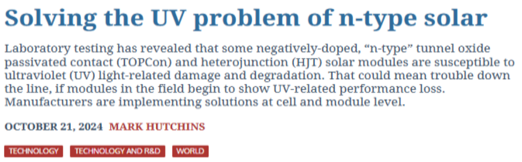
UVID: Risks, detection, and impact on solar projects

Mark Hutchins
Magazine Director
pv magazine

Yong Sheng Khoo
Chief Operating Officer & Co-founder
Quantified Energy

Johnson Wong
Chief Scientist
Quantified Energy

Tristan Erion-Lorico
VP of Sales & Marketing
Kiwa PVEL



Solving the UV problem of n-type solar

Laboratory testing has revealed that some negatively-doped, “n-type” tunnel oxide passivated contact (TOPCon) and heterojunction (HJT) solar modules are susceptible to ultraviolet (UV) light-related damage and degradation. That could mean trouble down the line, if modules in the field begin to show UV-related performance loss. Manufacturers are implementing solutions at cell and module level.

OCTOBER 21, 2024 **MARK HUTCHINS**

TECHNOLOGY | TECHNOLOGY AND R&D | WORLD

Solving the UV problem of n-type solar – pv magazine USA

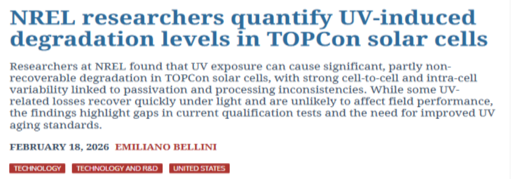
New research warns of unexpected UV-induced degradation in TOPCon solar cells from invisible light

Researchers from UNSW have found that invisible light accelerates UV-induced degradation in TOPCon solar cells, producing the same degradation effects as visible light but at a much faster rate. This can lead to significant open-circuit voltage losses and reduce cell efficiency.

AUGUST 11, 2025 **EMILIANO BELLINI**

MODULES & UPSTREAM MANUFACTURING | TECHNOLOGY AND R&D | AUSTRALIA

New research warns of unexpected UV-induced degradation in TOPCon solar cells from invisible light – pv magazine International



NREL researchers quantify UV-induced degradation levels in TOPCon solar cells

Researchers at NREL found that UV exposure can cause significant, partly non-recoverable degradation in TOPCon solar cells, with strong cell-to-cell and intra-cell variability linked to passivation and processing inconsistencies. While some UV-related losses recover quickly under light and are unlikely to affect field performance, the findings highlight gaps in current qualification tests and the need for improved UV aging standards.

FEBRUARY 18, 2026 **EMILIANO BELLINI**

TECHNOLOGY | TECHNOLOGY AND R&D | UNITED STATES

NREL researchers quantify UV-induced degradation levels in TOPCon solar cells – pv magazine USA

PROGRESS IN PHOTOVOLTAICS

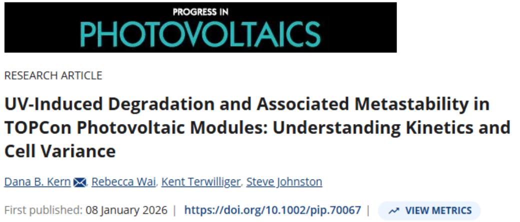
RESEARCH ARTICLE | Open Access

UV-induced degradation of high-efficiency silicon PV modules with different cell architectures

Correction(s) for this article

Archana Sinha, Jiadong Qian, Stephanie L. Moffitt, Katherine Hurst, Kent Terwilliger, David C. Miller, Laura T. Schelhas, Peter Hacke

First published: 07 July 2022 | https://doi.org/10.1002/pip.3606 | VIEW METRICS



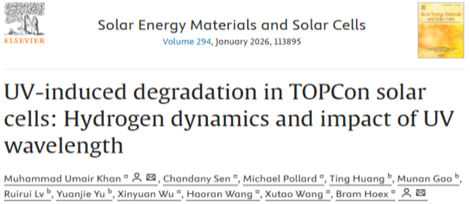
PROGRESS IN PHOTOVOLTAICS

RESEARCH ARTICLE

UV-Induced Degradation and Associated Metastability in TOPCon Photovoltaic Modules: Understanding Kinetics and Cell Variance

Dana B. Kern, Rebecca Wai, Kent Terwilliger, Steve Johnston

First published: 08 January 2026 | https://doi.org/10.1002/pip.70067 | VIEW METRICS



Solar Energy Materials and Solar Cells
Volume 294, January 2026, 113895

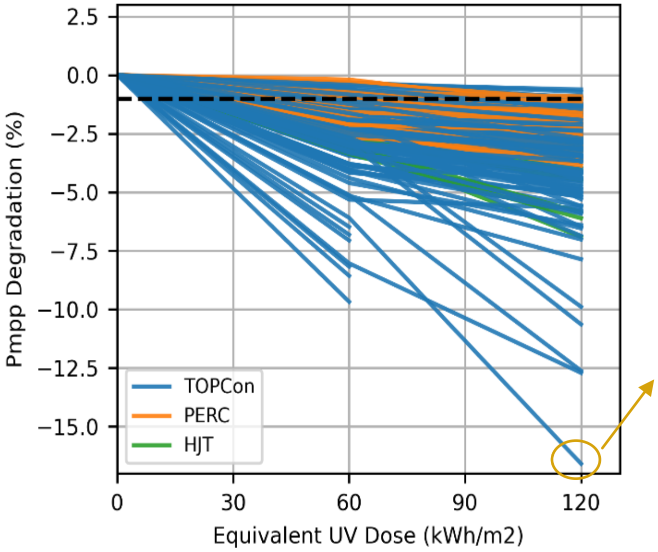
UV-induced degradation in TOPCon solar cells: Hydrogen dynamics and impact of UV wavelength

Muhammad Umair Khan [a], Chandany Sen [a], Michael Pollard [a], Ting Huang [b], Munan Gao [b], Ruirui Lv [b], Yuanjie Yu [b], Xinyuan Wu [a], Haoran Wang [a], Xutao Wang [a], Bram Hoex [a]

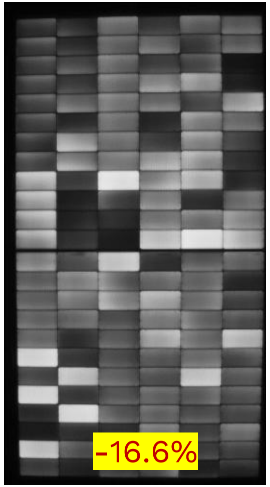
UVID Concern for N-Type Modules

- Rapid shift to n-type topologies.
- **TOPCon is the predominant technology**.
  - Offers higher module efficiency (>23%)
  - Greater power gain with transparent encapsulants.
  - Marketed with improved first year (1%) and annual degradation rates (<0.4%).
  - Resilience to LID and LETID. Combined loss <1%.
- Higher **vulnerability to UVID** due to increased cell sensitivity to UV radiation (280-360 nm).
  - TOPCon and HJT modules showed a broad range of UV susceptibility (0.4% to 16.6% deg)
  - Variability in bill of materials, cell architecture, and process non-uniformities.

Kiwa PVEL’s UVID testing

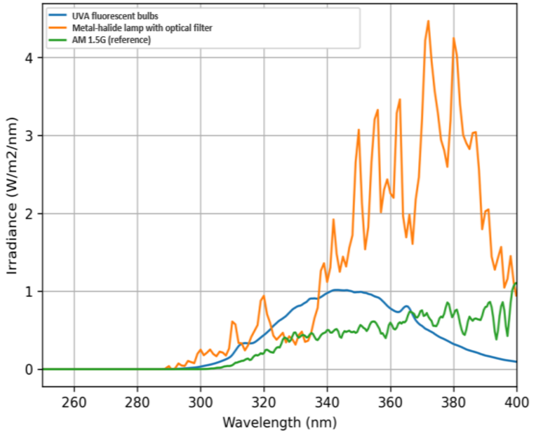


UVID 120 kWh/m²



Kiwa PVEL’s UVID Testing

- UV Testing with **front-side exposure**.
- UV exposure dose **120 kWh/m²** of UV (280-400 nm) when using **metal-halide lamps (PI China)** or 55 kWh/m² when using UV fluorescent lamps (Napa).
- Module temperature 60°C ± 5°C, under **short-circuit condition**.



UVID Sensitivity

UV 60 kWh/m²
60°C front

Characterization

UV 60 kWh/m²
60°C front

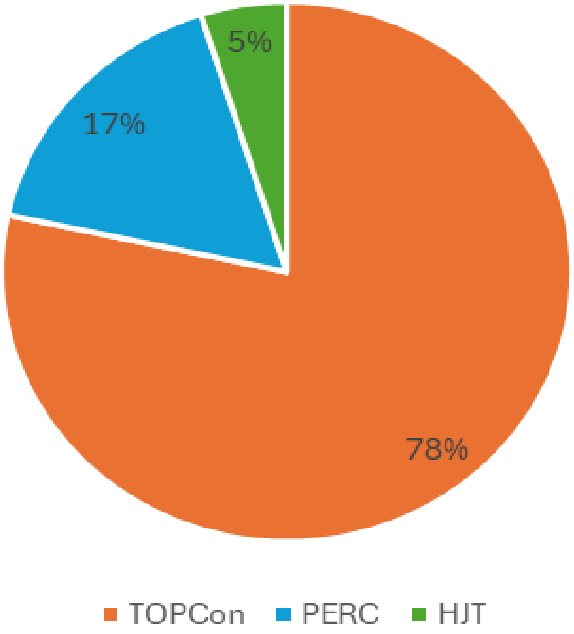
Characterization

UVF chamber at Napa, CA

Indoor UVID Testing

Test Population

- Largest “public” UVID dataset (2024-2026):
  - Total **370 modules**
  - All industrial modules, manufactured at different locations globally (China, India, US…).
  - TOPCon constitutes 78% of test population.
- General BOM trends:
  - Most of them are bifacial G/G modules
  - Encapsulants are a mix bag – EVA, POE, EPE, UV down conversion
- xBC and CdTe technology modules also tested but not included in this study.



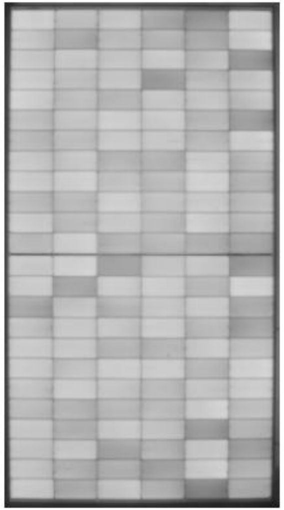
UVID Test Results

- Characteristic **“Checkerboard” pattern** in EL images.
  - More pronounced with prolonged UV exposure.
  - Degradation is not uniform across the cells.
  - Position-independent (unlike PID-s).

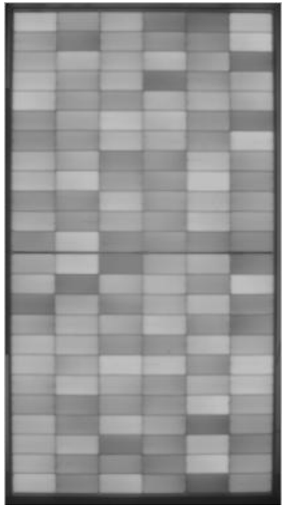
- **UV susceptibility can vary from cell to cell within the same module.**

- Testing based on one-cell sample is not sufficient.
  - Test multiple cells or modules from different batches.

Post-LID



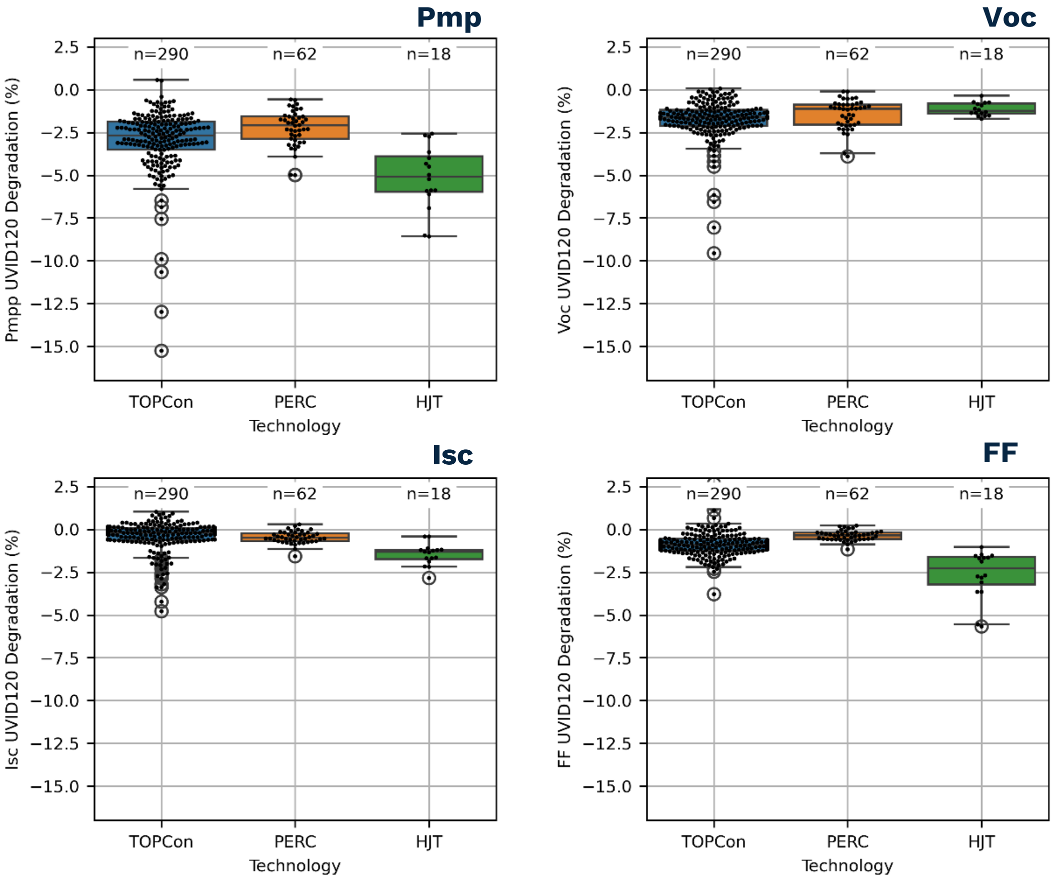
UVID60



UVID120

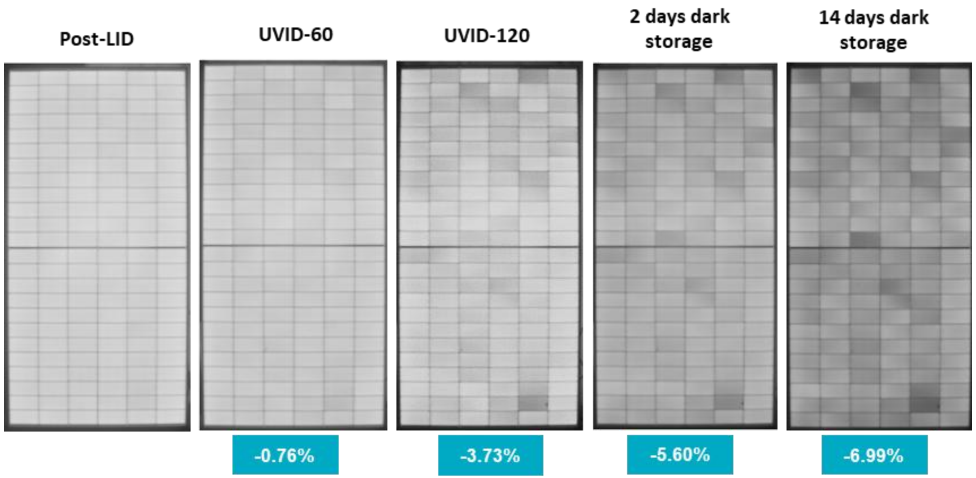
UVID Degradation Pathways

- UVID mechanisms vary by cell types.
  - **TOPCon:** 0.4-16.6% deg, median 3.0%
    - **Voc most affected →** cell ARC or passivation degradation
    - Greater Isc & FF losses in few BOMs → mismatch loss
  - **HJT:** 1.5-8.6% deg, median 5.2% (limited sample size)
    - **Isc and FF losses are significant →** front TCO/a-Si interface degradation
    - Voc is fairly stable
  - **PERC:** lower degradation, median 2.1%



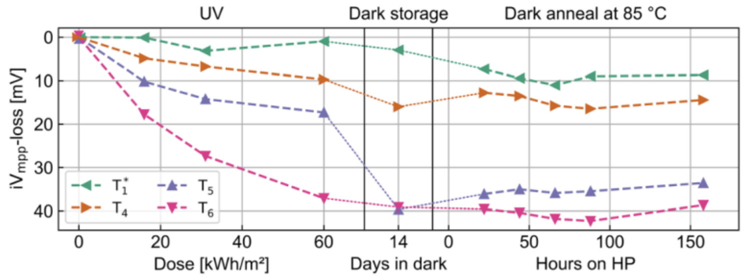
Dark Storage Degradation (Metastability)

- **Signs of metastability** observed in the modules following UV exposure when stored in the dark.
  - Significant power loss and pronounced checkerboard pattern.
  - **Higher degradation with longer dark storage period.**
  - Maximum degradation up to 1%/day.

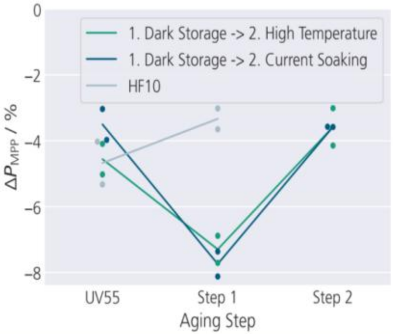


Other’s work

[1] Cell: 0.5%-3.0% degradation in dark



[2] TOPCon modules degraded under dark storage post UV test.



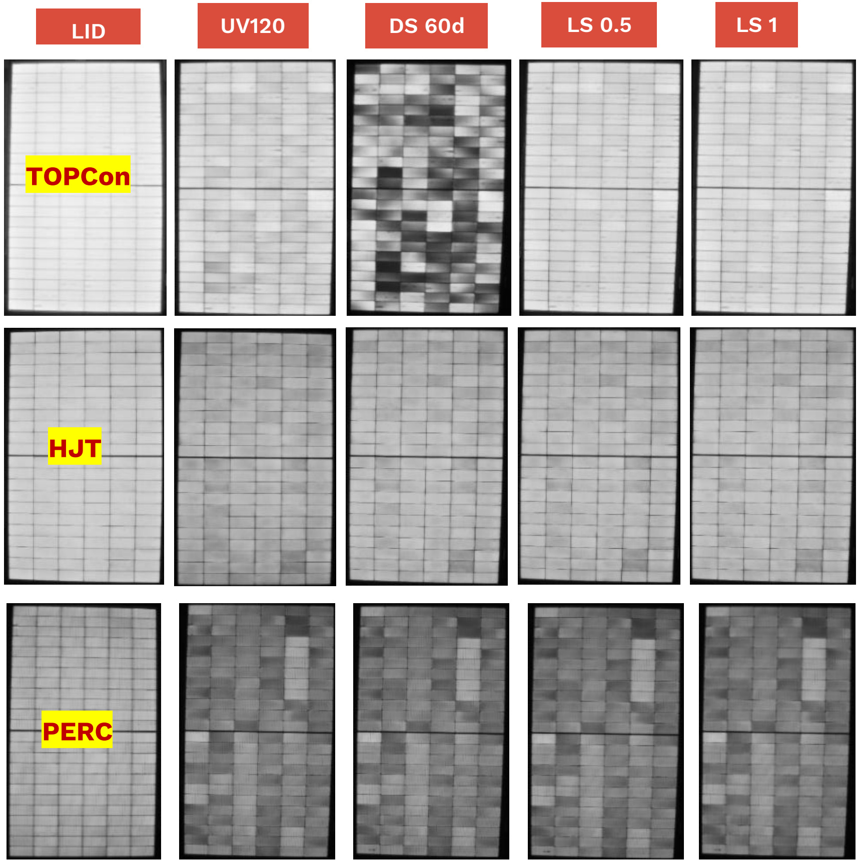
[1] Thome et. al. Solar RRL (2024), 8, 2400628
[2] Gebhardt, P., Kräling, (2024), Prog Photovolt Res Appl.

Dark Storage Degradation and Stabilization

- Dark storage degradation is partially or fully recoverable via full-spectrum light soak.
- **UV induced degradation isn't recovered.**

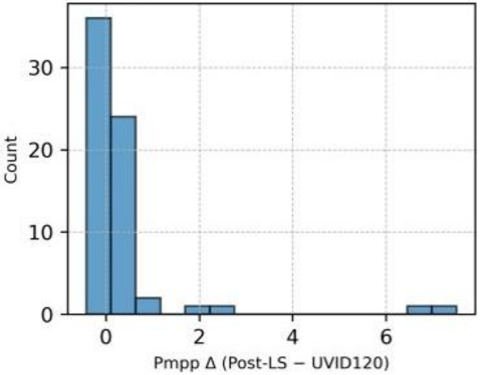
- In general,
  - TOPCon (extensive) - Fast and effective recovery.
  - HJT (moderate) - Slower recovery.
  - PERC (minimal) - No metastability.

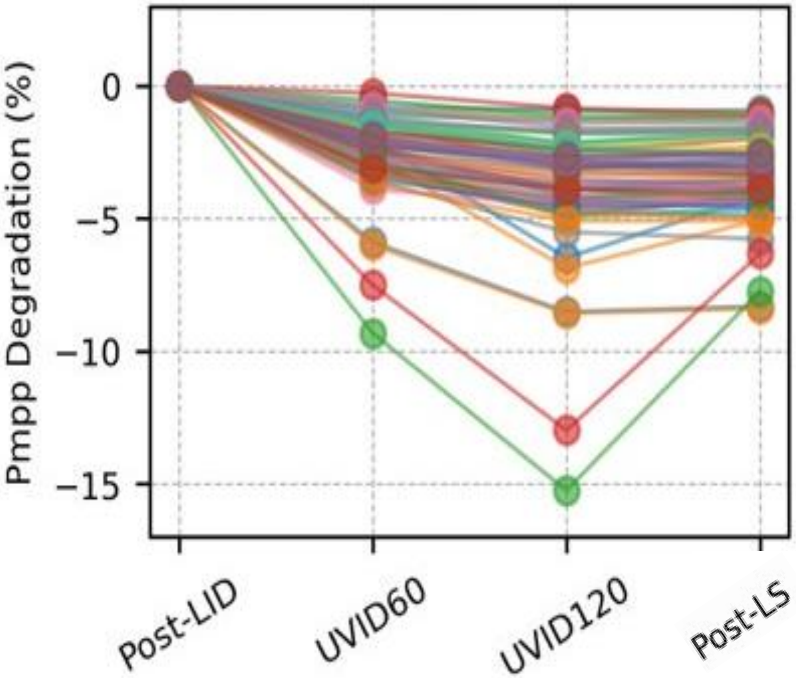
Pmax	Bad PERC	Good PERC	Bad TOPCon	Good TOPCon	HJT
LID	0.0%	0.0%	0.4%	-0.1%	0.1%
UVID120	-3.0%	-1.9%	-5.6%	-1.4%	-4.5%
Dark Storage	-3.8%	-2.3%	-12.3%	-2.6%	-6.3%
LS 0.5kWh/m²	-3.8%	-2.4%	-5.7%	-2.4%	-6.0%
LS 1kWh/m²	-3.7%	-2.3%	-5.6%	-2.3%	-5.5%



Light Soak Stabilization

- Kiwa PVEL implemented a LS stabilization step post-UVID120 (via 0.5-1 kWh/m^2 of full spectrum light soak).
- **For UVID-sensitive samples, light soak is crucial to get accurate results.**
- Many test samples are not affected by LS (change is <0.4%), but some are very affected.
- Characterization window to flash test UVID modules is controlled within 48 hours after test completion.





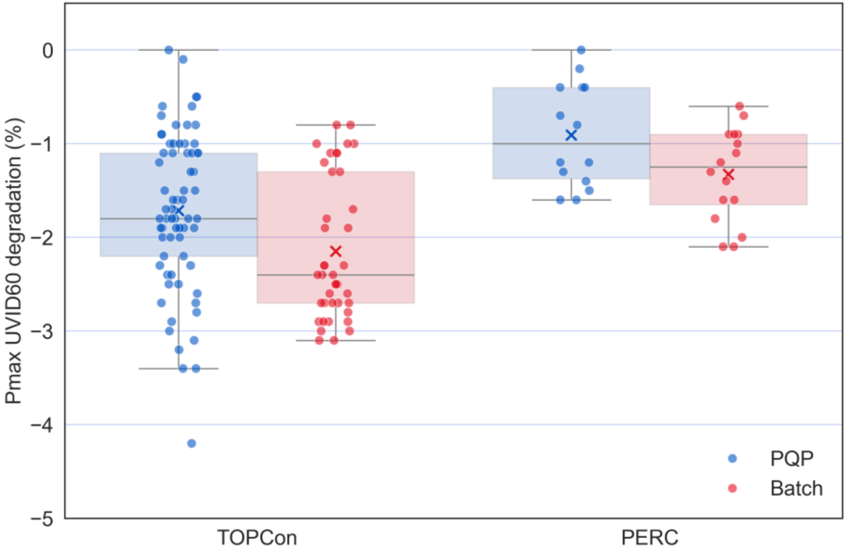
UVID Stability is Improving, But is Not Solved!

- Downstream customers batch vs manufacturer PQP testing results:
  - Projects tested during 2023 – 2026 period
  - TOPCon and PERC
  - Post-UVID60 Pmax losses

- UVID not yet solved in mass production:
  - **Higher Pmax losses for TOPCon** in batch testing.
    - Manufacturing inconsistency
    - Defect process shifts or material issues
  - **TOPCon (~2.4%) median degradations**.

- Batch testing is useful to detect UV susceptibility on random samples.

Napa test lab data only



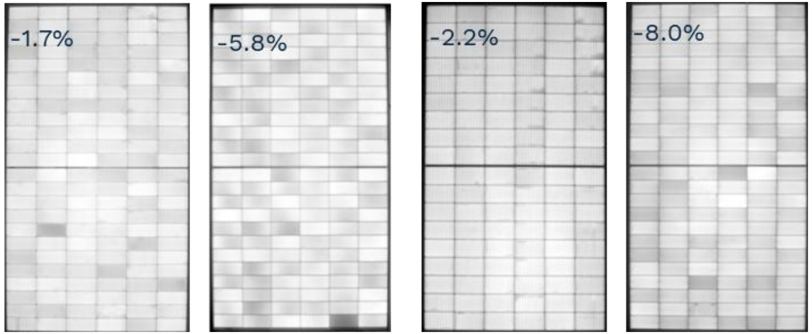
	PQP	Batch	PQP	Batch
Median	-1.8%	-2.4%	-1.0%	-1.3%
Average	-1.7%	-2.1%	-0.9%	-1.3%
Samples	69	40	14	16

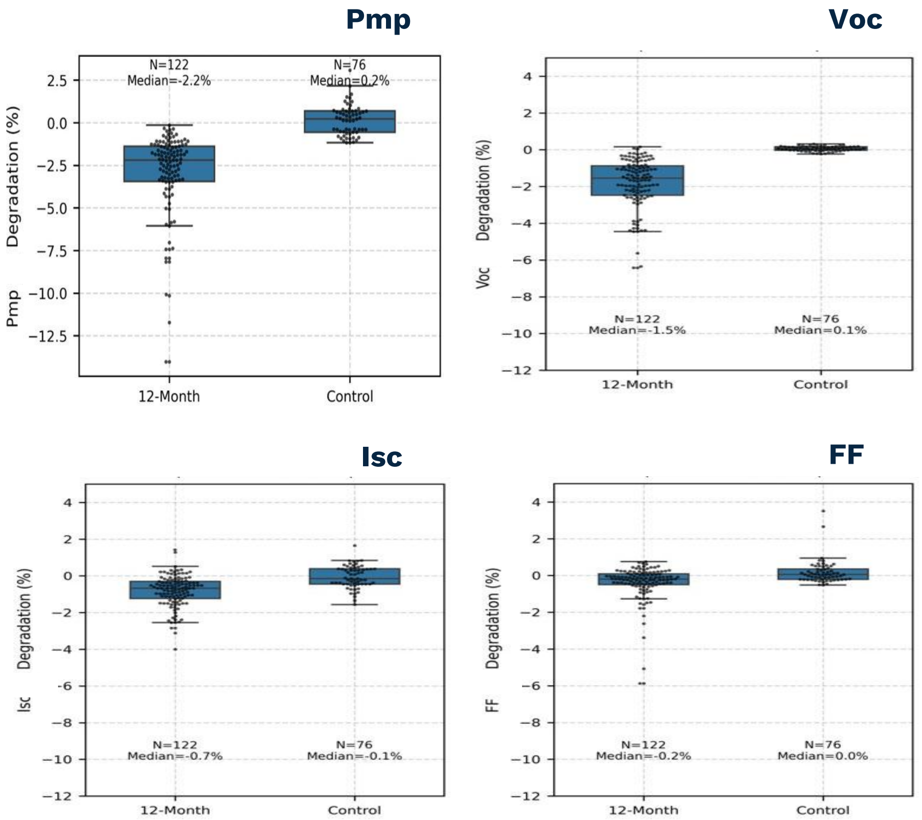
Outdoor Field Testing

Field Exposure Testing & UVID Signatures

- 1-year outdoor exposure in Davis, CA.
  - Modules installed in 2023-2025 period.
  - Control modules exhibited stable performance.

- Significant Pmp degradation in field-exposed (FE) modules - median of 2.2%
  - **Driven by Voc** and some Isc losses, while FF is stable.
  - Combined LID and LETID Pmp loss <1%.
  - **UVID checkerboard pattern is visible in EL images.**

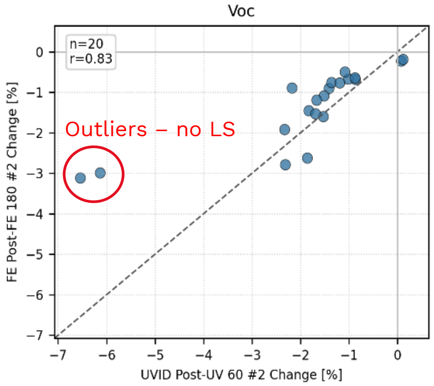


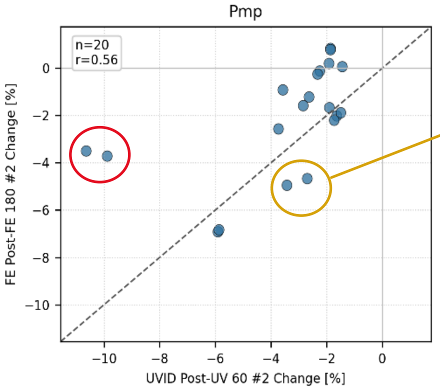


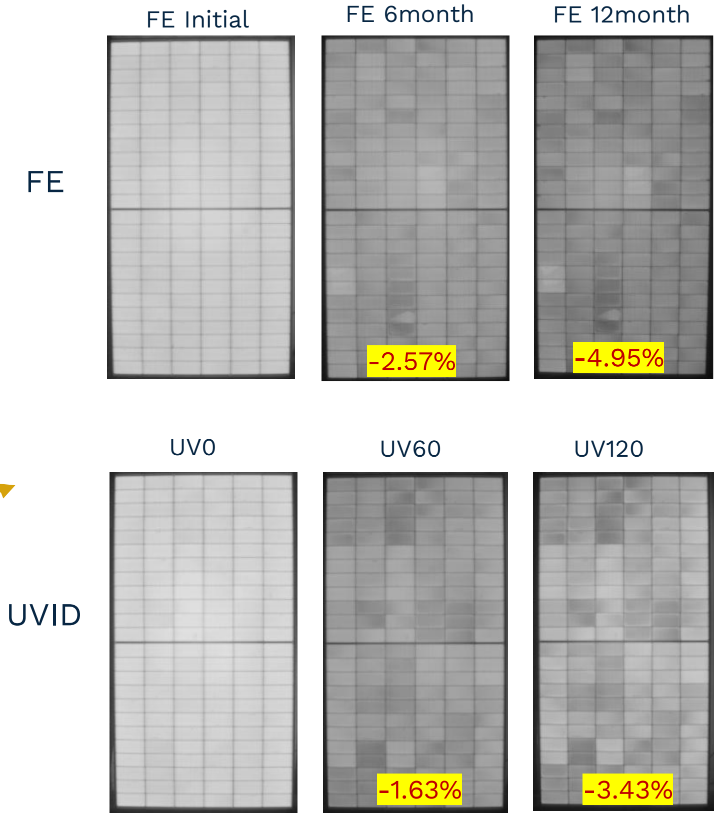
Most FE BOMs would not meet a <1% degradation warranty at the end of first year.

Correlation Between Outdoor Field and Indoor UVID Testing

- Common TOPCon BOMs between FE and UVID testing data.
- Voc exhibited a better correlation: **120 kWh/m² UVID test corresponds to ~1.4 years of outdoor exposure in Davis, CA**.
- Pmp showed a weaker correlation: Impact of additional degradation modes (e.g. encapsulant yellowing, soiling, delamination etc.).
- **Short-circuit condition in UVID test accelerates degradation**.

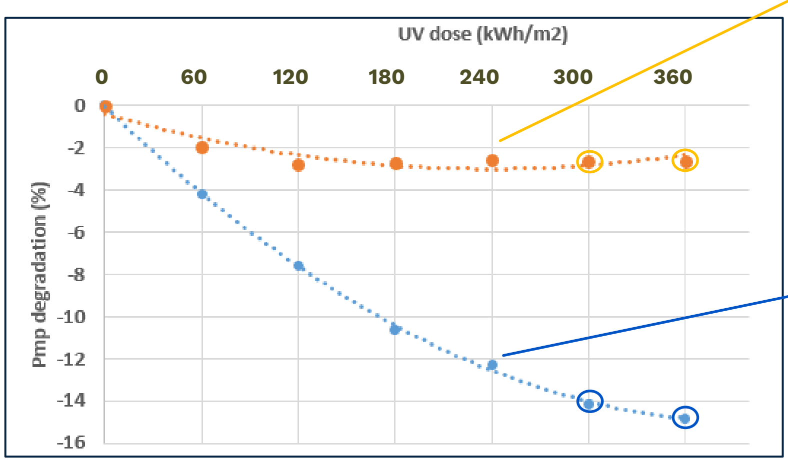


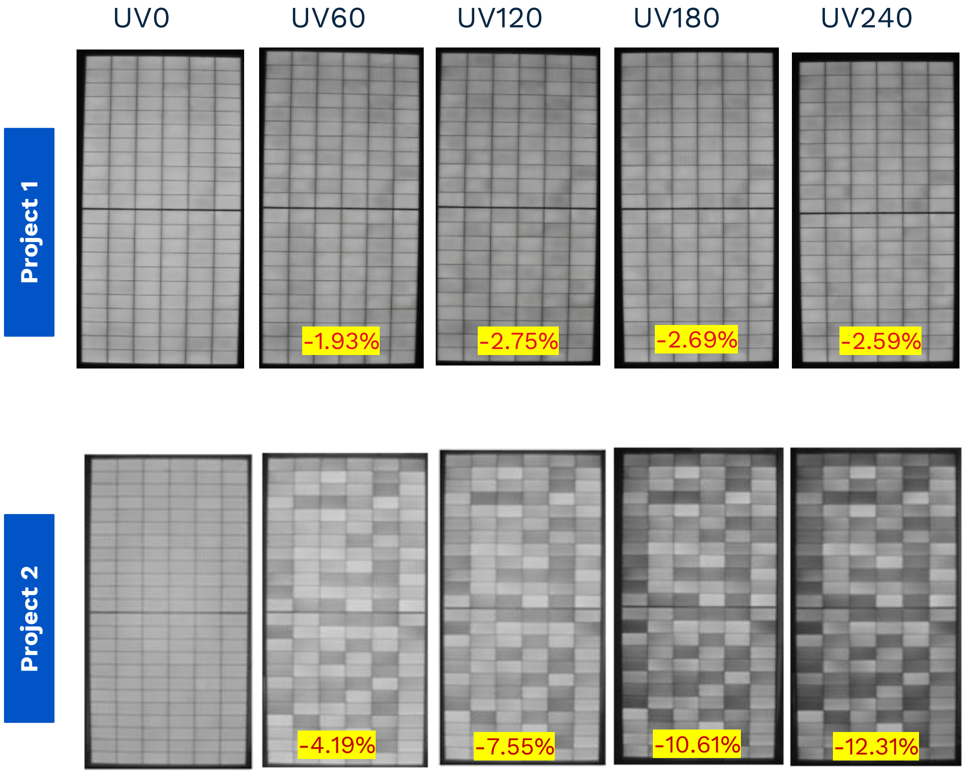




Long-term Reliability Testing

- UVID test run extended to 240 kWh/m².
- Project 1 (UV-stable modules) – Degradation reached saturation after UV120.
- Project 2 (UV-sensitive modules) - Degradation continued up to UV240, without stabilization.

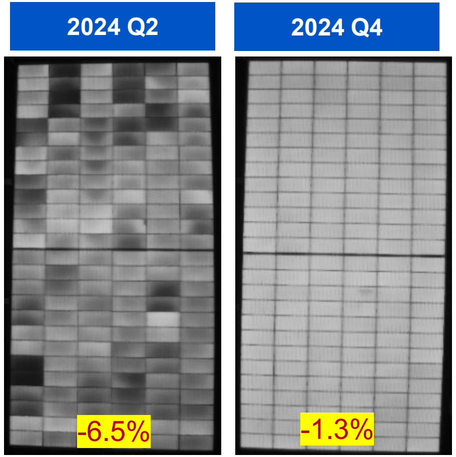


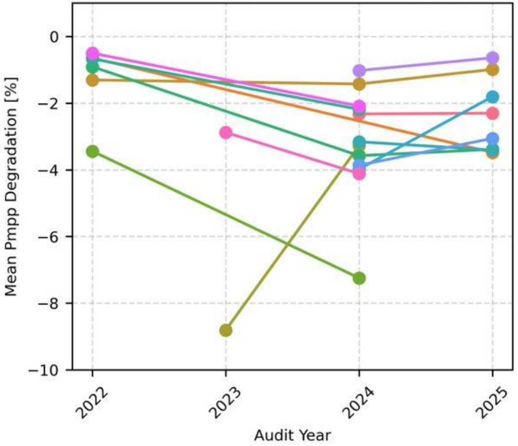


UVID Mitigation Strategies

UVID Mitigation at Cell Level

- Cell design improvements:
  - **Front cell ARC/passivation layer process controls** (thicker AlOx, ARC and passivation stack uniformity)
  - These fixes can come at the cost of cell efficiency and/or higher production costs.
- Example: A TOPCon BOM tested in 2024 Q2 with a retest in 2024 Q4.
  - Original: deg 6.5% (average), strong checkerboard pattern.
  - Retest: deg 1.3% (average), no EL anomalies.
- Many cell suppliers have improved their production quality processes.
  - **Better performance in 2025 compared to 2024.**

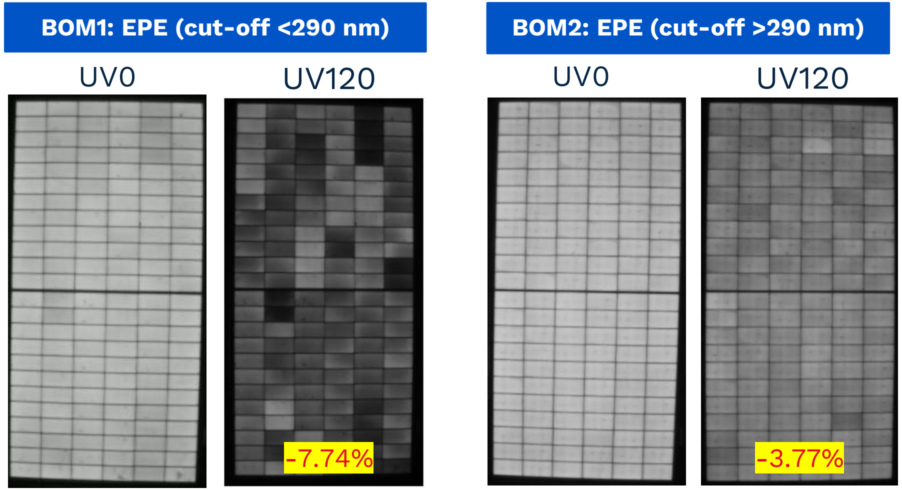




Note: Each line is an individual cell supplier.

UVID Mitigation at Module Level

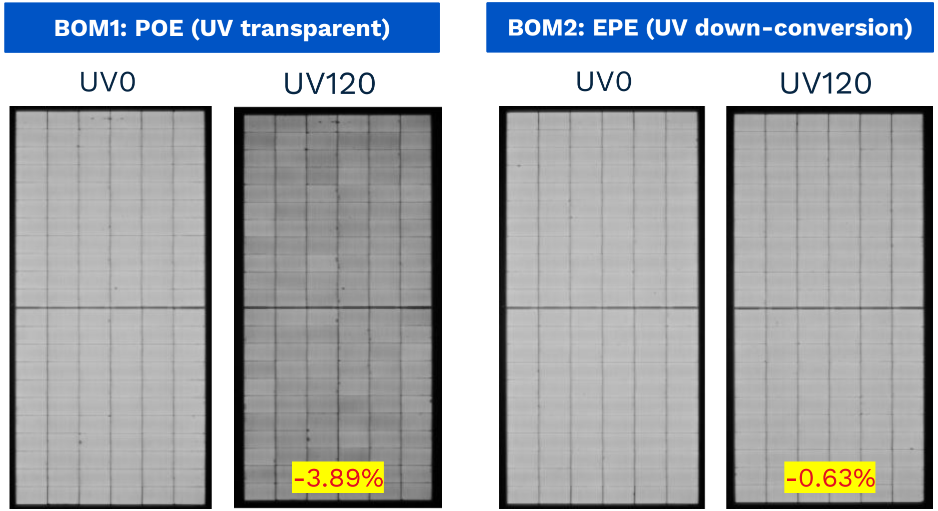
- Additives and UV cut-off wavelength can help mitigate UVID.
- Cut-off wavelength of front encapsulant varies in the range of 220-380 nm.
  - **Higher degradation below 300 nm cut-off.**
- Example: TOPCon BOMs, same cell supplier and same encapsulant type but different UV cut-off.
  - BOM1 – EPE (cut off <290 nm) | EPE
  - BOM2 – EPE (cut off >290 nm) | EVA
- UVID extent can be lowered when tailoring the encapsulant cut-off band.


BOM1: EPE (cut-off <290 nm)

BOM2: EPE (cut-off >290 nm)

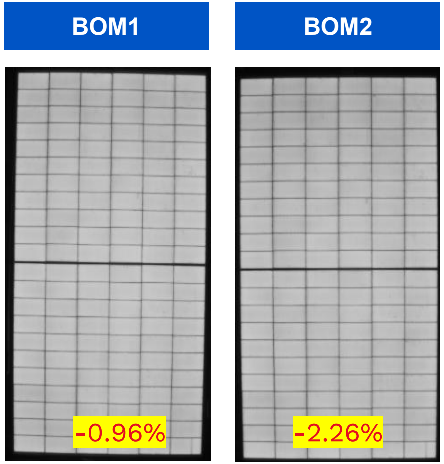
UVID Mitigation at Module Level

- **UV down-conversion encapsulants**.
  - Converts UV light to visible photons, allowing higher efficiency and less prone to UVID.
- Example: same cell supplier but two different encapsulation schemes.
  - BOM1 – POE (UV transparent) | POE
  - BOM2 – EPE (UV down conversion) | EVA
- Currently used in HJT module designs, not much in TOPCon.
- Other reliability issues may trigger, need to be tested further to validate stability.



Degradation Mechanism other than UVID

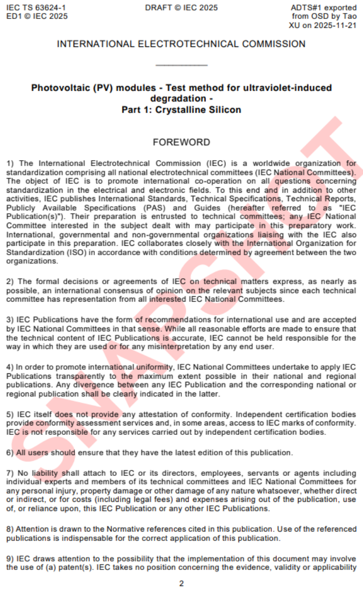
- **Not all UV degradation is cell-related.**
- Example: TOPCon BOMs, same encapsulant type and UV cut-off <290 nm
  - BOM1 – EPE (cut off 280 nm) | EVA
  - BOM2 – EPE (cut off 240 nm) | EVA
- BOM1 has no signs of degradation.
- BOM2 has negligible Voc loss and no checkerboard pattern in EL but significant Isc loss → **severe yellowing on the entire module**.
- Encapsulant additives/stabilizers play a role in degradation, that might be UV-unstable.



New Development in UVID Testing

- Streamlined UVID sequence in newer version of PQP
  - **Eliminate the interim UV60 characterization** in favor of a continuous 120 kWh/m² exposure
    - to avoid any influence of dark-storage degradation on the flash measurements.
  - Option to **extend up to 360 kWh/m²** for BOMs that show higher UVID susceptibility
    - to investigate the long-term reliability impacts.

- UVID test standard draft is in development
  - **IEC TS 63624-1** Ed 1 (2025): Photovoltaic (PV) Modules – Test method for ultraviolet-induced degradation Part 1: Crystalline Silicon



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

Photovoltaic (PV) modules - Test method for ultraviolet-induced degradation -
Part 1: Crystalline Silicon

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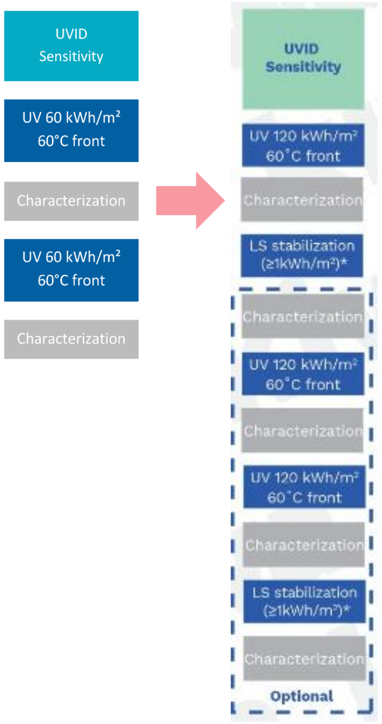


UVID Sensitivity
UV 60 kWh/m² 60°C front
Characterization
UV 60 kWh/m² 60°C front
Characterization

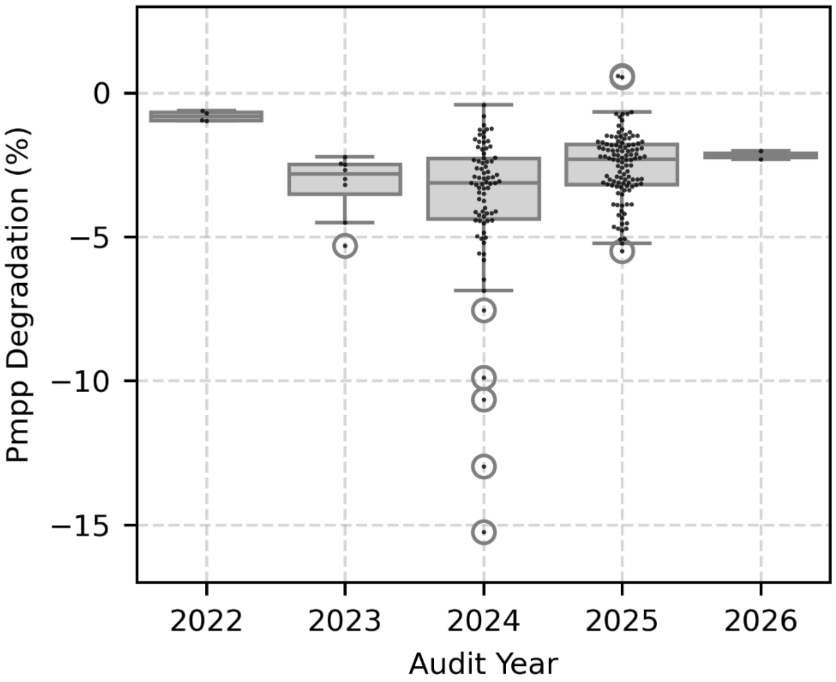
UVID Sensitivity
UV 120 kWh/m² 60˚C front
Characterization
LS stabilization (≥1kWh/m²)*
Characterization
UV 120 kWh/m² 60˚C front
Characterization
UV 120 kWh/m² 60˚C front
Characterization
LS stabilization (≥1kWh/m²)*
Characterization
Optional

Key Takeaways

- UVID is a reliability concern for n-type modules, identified both in the lab and field. Not all TOPCon and HJT BOMs exhibited higher susceptibility to UVID.
- UVID sensitivity depends not only on the cell architecture but also on the BOM.
- A short light soak under full spectrum can stabilize modules from metastability behavior in the dark post-UV exposure.
- Front cell ARC/passivation layer process controls and better encapsulant additives selection can help in mitigating UVID.
- Recent UVID testing on TOPCon modules showed a significant improvement in UV susceptibility.

UVID Stability is Improving, But is Not Solved Yet.

Kiwa PVEL’s UVID test results (TOPCon only)



Note: Some big outliers are partially a result of dark metastability.

Thank you!

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Check out our Poster

The 2026 PV Module *Reliability Scorecard*

Executive Summary

kiwa

Poster presentation: June 10 (Wed), 3:30 pm

[K1] What Solar Module Test Failures Reveal in 2026: Key Takeaways from Kiwa PVEL’s PV Module Reliability Scorecard

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