UV-Induced Degradation in N-Type Modules:
Exploring Metastability and Recovery Pathways

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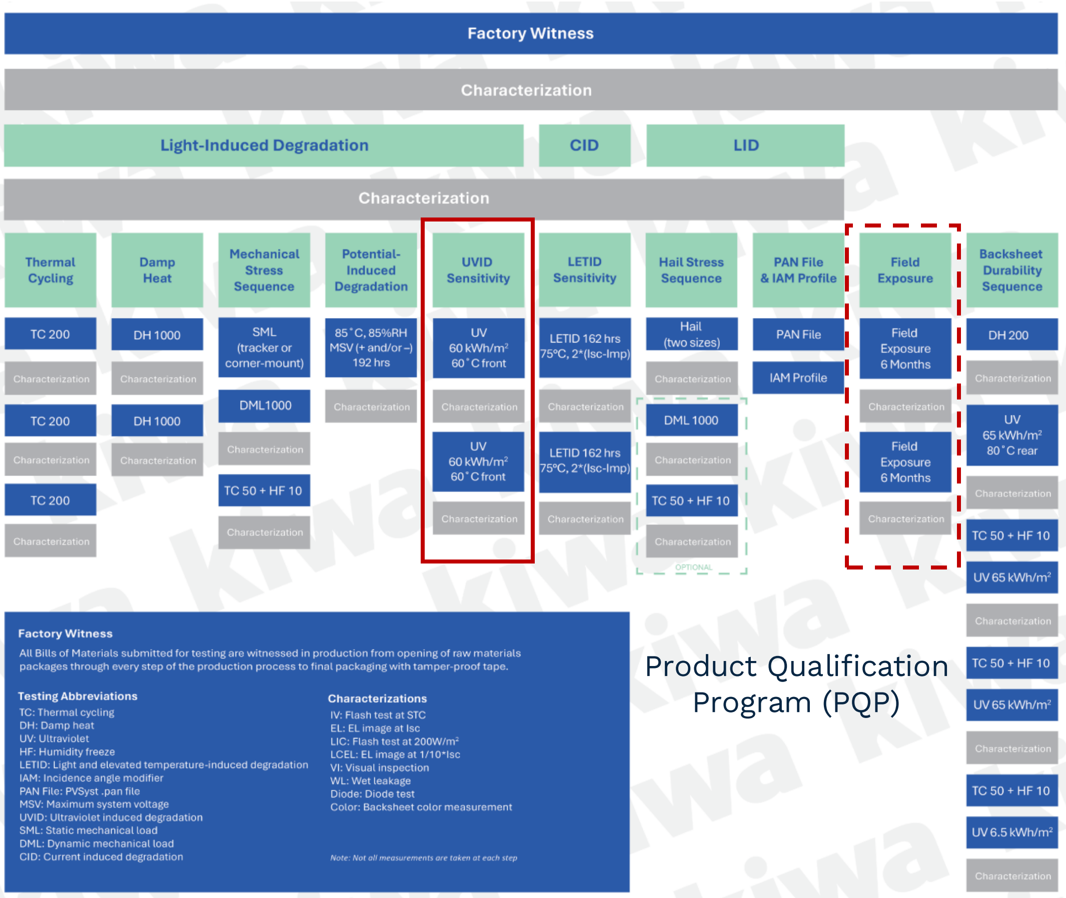
About Kiwa PVEL

- Independent lab for PV Module **Performance and Reliability Testing.**
- Headquarter test lab at Napa, US and a sister company at Suzhou, China.
- Developed PQP test sequences, updated every 2 years.
- Releases PV Module Scorecard every yr. 11th ed released on June 4, 2025.

Oral presentation:
June 12 (Thurs), 1:45 pm

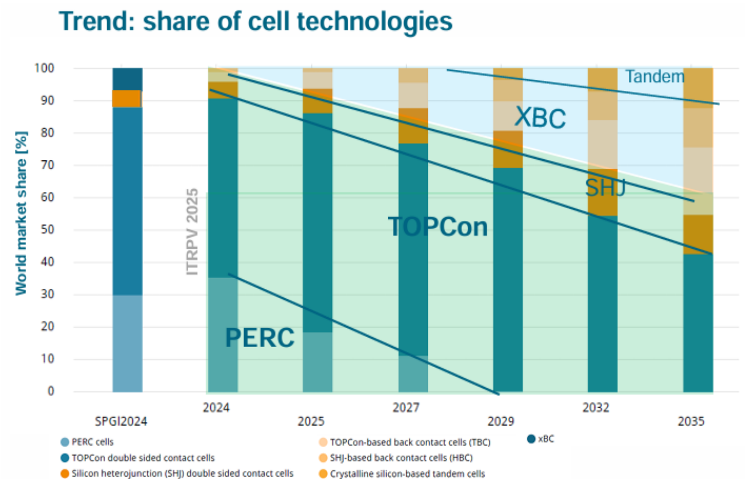
Understanding Solar Module Test Failures: Key Takeaways from Kiwa PVEL's PV Module Reliability Scorecard

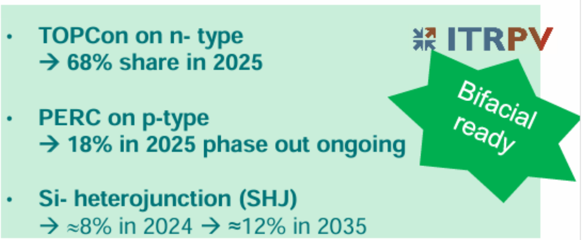


Product Qualification Program (PQP)

N-Type Modules and Growing UVID Concern

- Rapid growth of n-type silicon cell topologies (**TOPCon**, HJT, xBC, ...)
  - Higher efficiency due to better metallization scheme and improved passivation quality.
  - UV transparent encapsulants for current/ power gain.
- Marketed with improved first year (1%) and annual degradation rates (<0.4%).
  - Kiwa PVEL's testing shows resiliency to LID and LETID.
- Higher **vulnerability to UV-induced degradation (UVID)** due to increased cell sensitivity to UV radiation (280-360 nm).
  - Negative impact on energy yield, reliability and bankability.





Source: ITRPV 2025

Kiwa PVEL's UVID Testing

- Testing large-size industrial modules.
- UV Testing with **front-side exposure**.
- Exposure dose **120 kWh/m²** of UV (280-400 nm) **when using metal-halide lamps** or 55 kWh/m² when using UV fluorescent lamps.
  - New UV chambers can accommodate 8 large-size modules (max. 2.7 m x 1.6 m), with turnaround time of 1 month.
- Equivalent to **1-2 years of outdoor exposure**.
- Module temperature 60°C ± 5°C, under short-circuit condition.
- Characterization include visual inspection, front and rear I-V at STC, high & low-current EL, wet leakage current test.

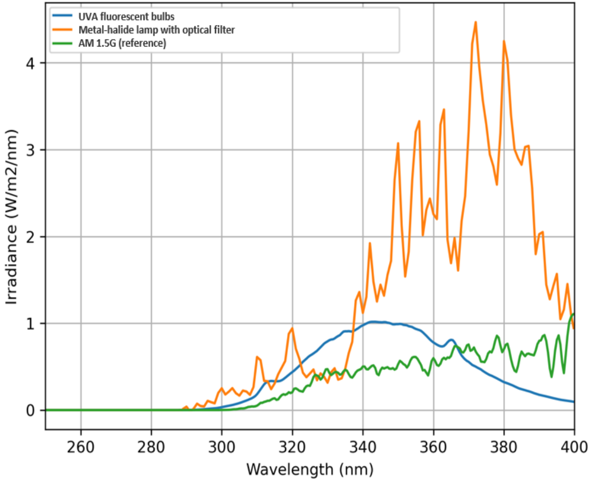
UVID Sensitivity

UV 60 kWh/m² 60°C front

Characterization

UV 60 kWh/m² 60°C front

Characterization

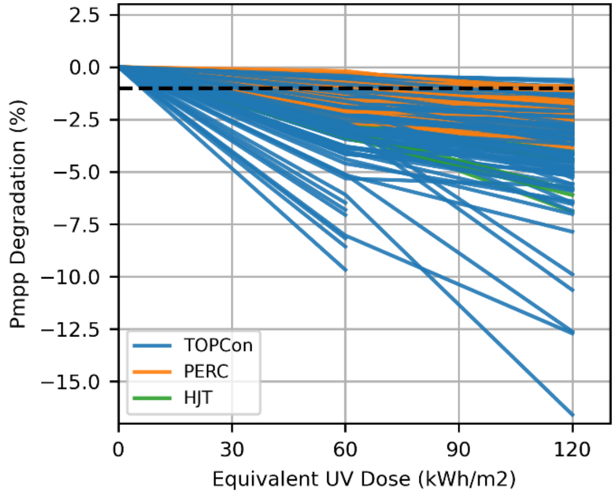


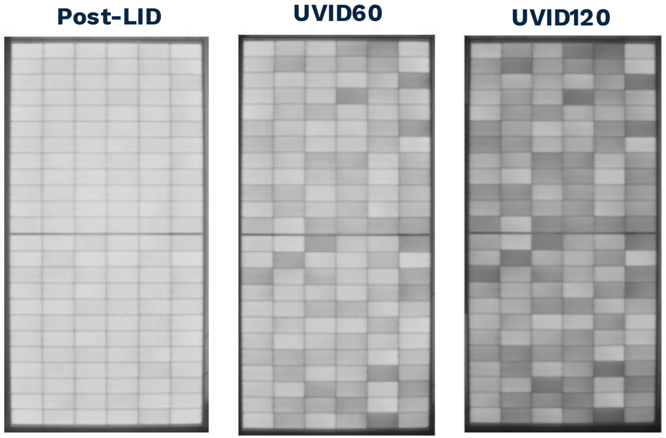
UVID Test Results

- Largest "public" dataset:
  - Total **211 modules** (~105 BOMs) evaluated.
  - 82% TOPCon modules.

- **N-type modules more susceptible to UVID**.
  - TOPCon and HJT modules showed a broad range of susceptibility (0.6% to 16.6%), indicating the variability in bill of materials, cell architecture, and process non-uniformities.
  - More than 50% TOPCon showed power deg >5%.
  - UVID-stable TOPCon BOMs are available.
  - Some BOMs show quasi-stabilization after UVID60.

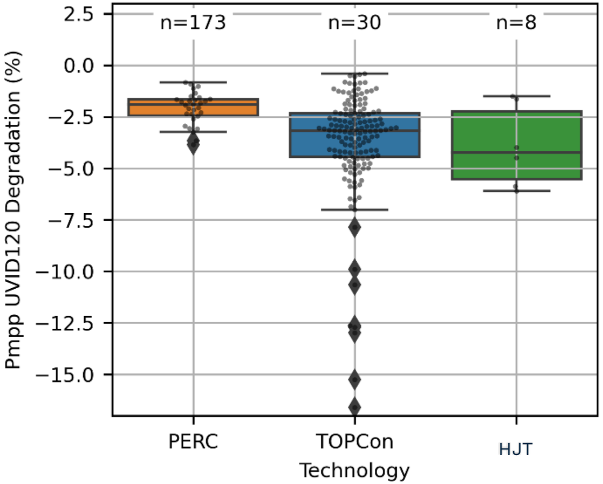
- Characteristic **"Checkerboard" pattern** in EL images.
  - Similar to PID or LETID sensitive modules.
  - Testing based on one-cell sample is not sufficient.

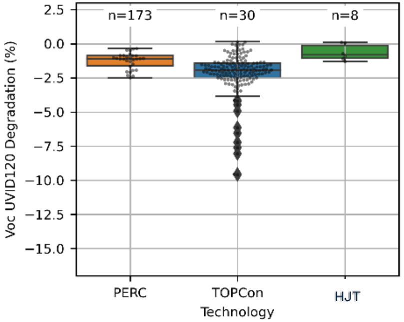


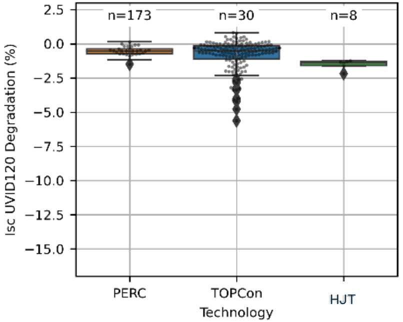


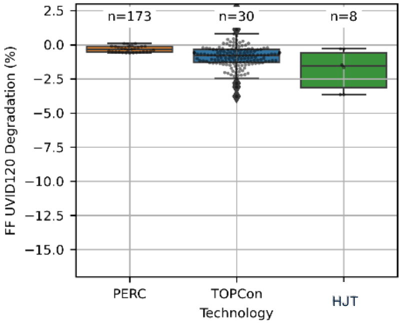
Degradation Pathways

- UVID mechanisms vary by cell types.
  - **TOPCon** BOMs show 0.6% to 16.6% deg, median 3.1%.
    - **Voc most affected** → cell anti-reflective coating or passivation degradation
    - Greater Isc & FF losses in few BOMs → mismatch loss
  - **HJT** BOMs show 1.5 to 6%, median 4.2% (limited samples).
    - **Isc and FF losses are significant** → front TCO/a-Si interface degradation
    - Voc is fairly stable
  - PERC BOMs show lower deg, median 2.2%.







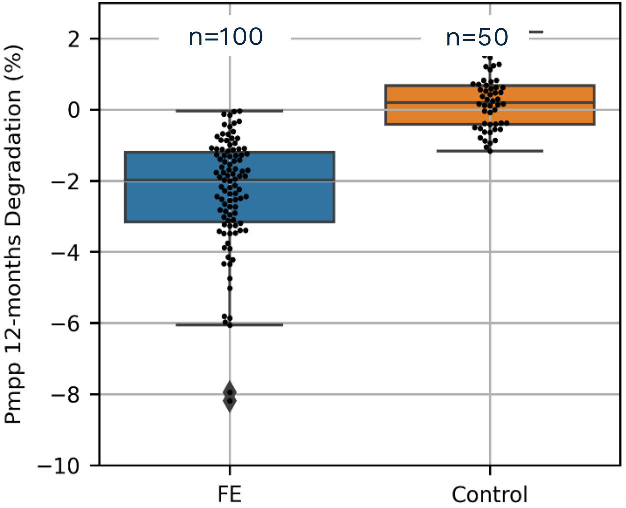


Field Degradation

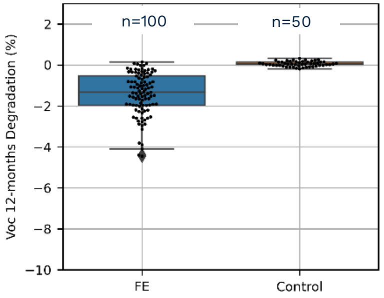
- PQP's optional field exposed (FE) modules performance under MPP are evaluated after 1-year of deployment at Davis test site, CA.

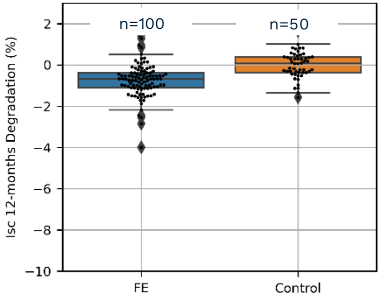
- Total 50 BOMs. 2 test modules and 1 control per BOM.

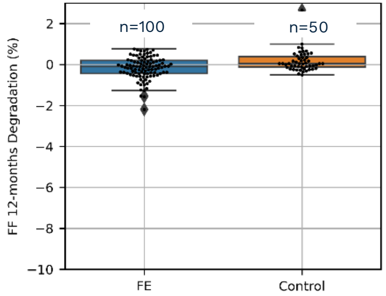
- Significant degradation (**median 2%, highest 8%**) in fielded modules after 1 year of installation in Davis, CA.
  - **Mainly due to UVID**. Higher Voc loss and checkerboard pattern in test modules.
  - Control modules exhibited stable performance.
  - Combined LID and LETID Pmpp loss <1%.



Davis, US (also known as PVUSA)



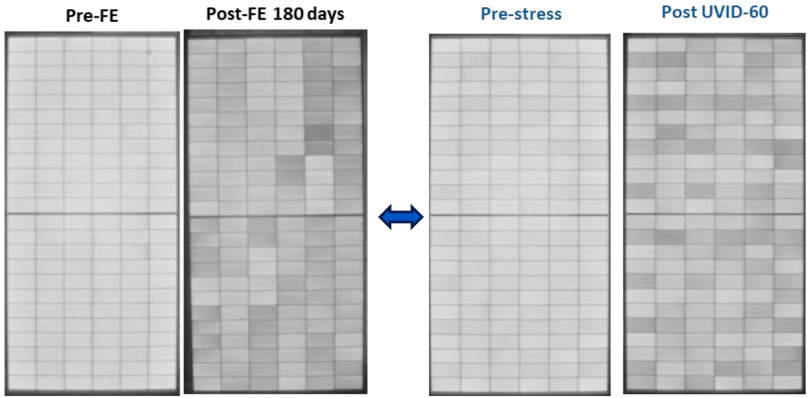


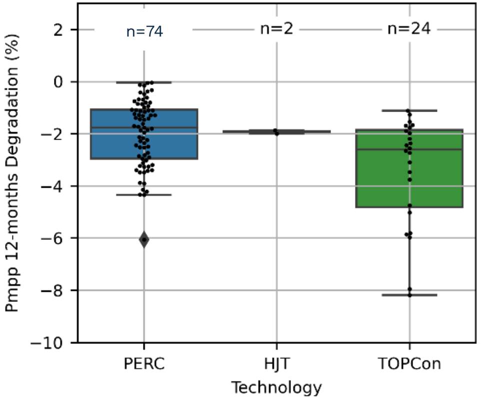


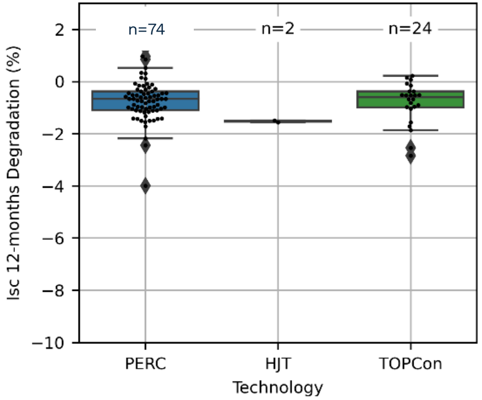
Comparison Field and Lab Testing

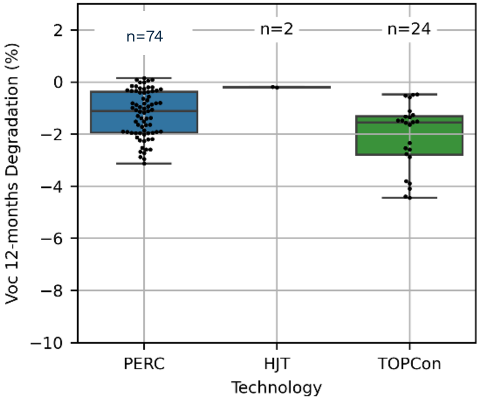
- Like chamber test, TOPCon FE modules degraded dramatically after 1-year.
- Similar checkerboard patten in FE module.
- **UVID is a real field-reliability problem.**

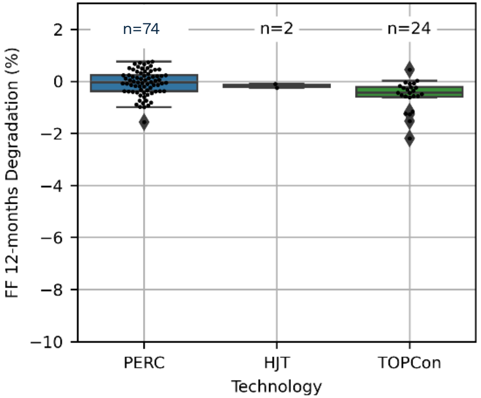
Outdoor field exposure | Indoor chamber test





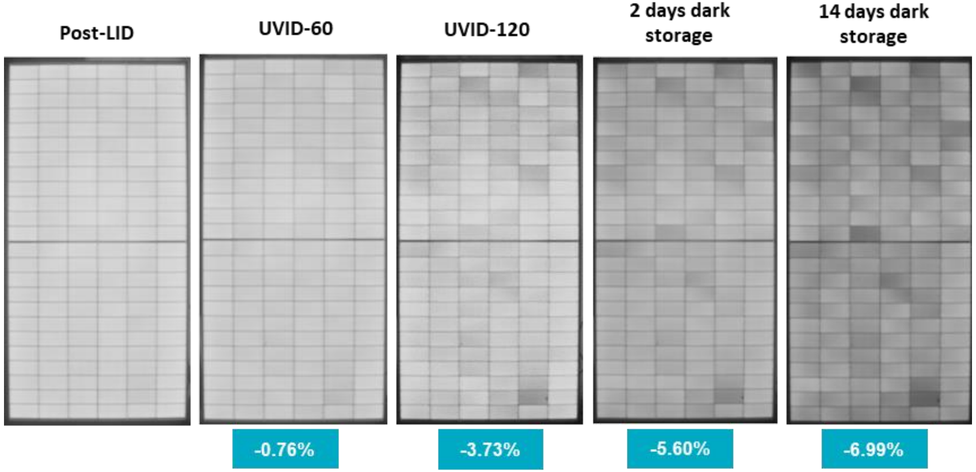






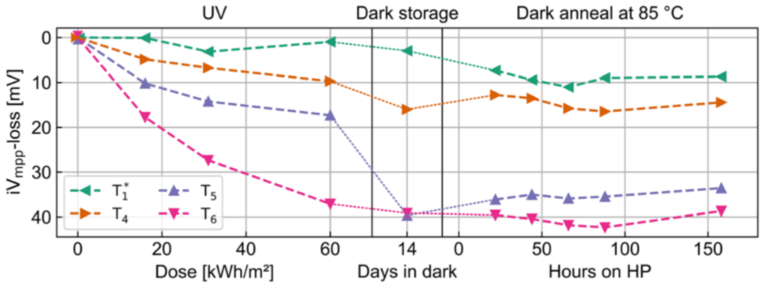
Dark Degradation and Metastability Issues

- Signs of metastability observed in some UVID-stressed and field-exposed modules when stored in the dark.
  - **Significant power loss** and pronounced checkerboard pattern observed.
  - Degradation upto 1%/day in worst scenario.

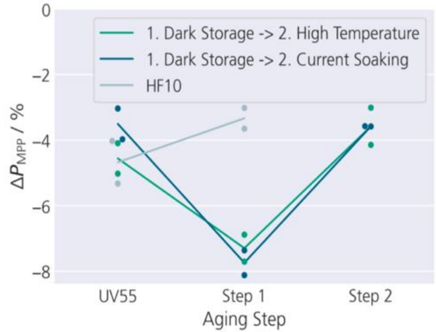


Other's work

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



[2] Module deg under dark storage. Effect reversed by high T or current injection.

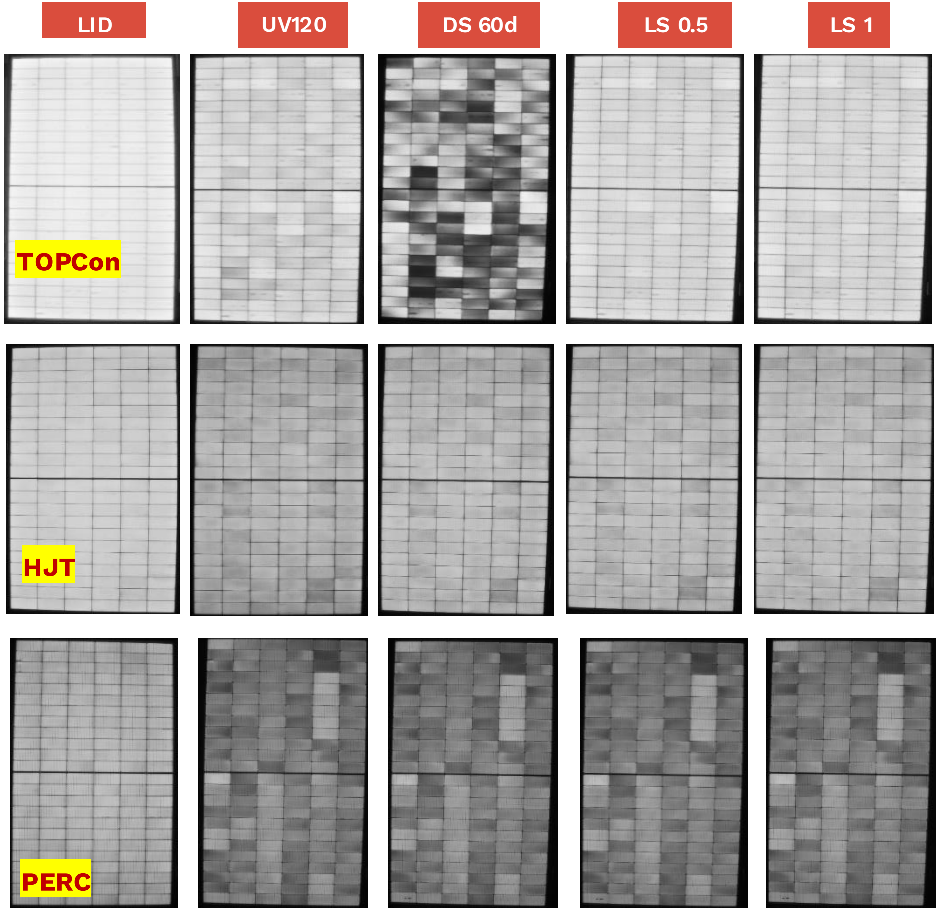


[1] Thome et. al. Solar RRL (2024), 8, 2400628
[2] Gebhardt, P., Kräling, (2024), Prog Photovolt Res Appl.

Post-UVID Stabilization

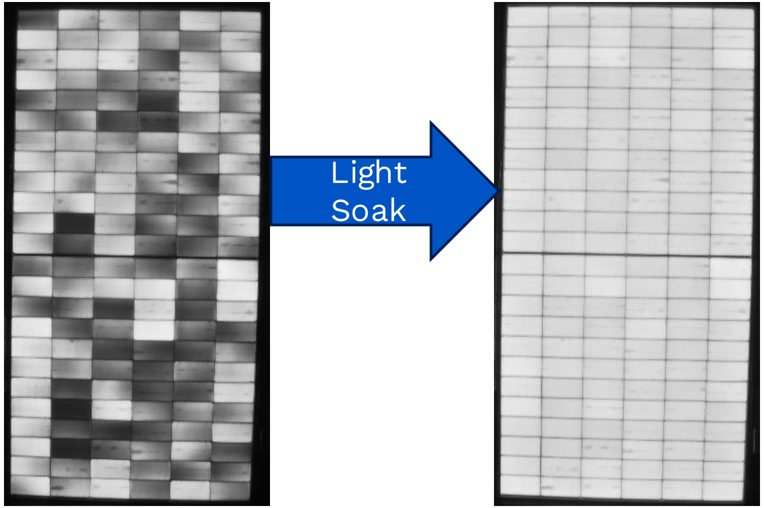
- Dark storage (DS) degradation extent
  - PERC (minimal), HJT (moderate), **TOPCon (extensive)**.
- **Stabilization under full spectrum light soak (LS), partial recovery only**
  - PERC - No obvious degradation or recovery.
  - HJT - Obvious recovery but at slower rate.
  - **TOPCon - Fast and effective recovery**.

Pmax	Bad PERC	Good PERC	Bad TOPCon	Good TOPCon	Tier1 TOPCon	HJT
LID	0.0%	0.0%	0.4%	-0.1%	-0.1%	0.1%
UVID 120	-3.0%	-1.9%	-5.6%	-1.4%	-4.4%	-4.5%
Dark Storage	-3.8%	-2.3%	-12.3%	-2.6%	-12.1%	-6.3%
LS 0.5kWh/m²	-3.8%	-2.4%	-5.7%	-2.4%	-5.0%	-6.0%
LS 1kWh/m²	-3.7%	-2.3%	-5.6%	-2.3%	-4.9%	-5.5%



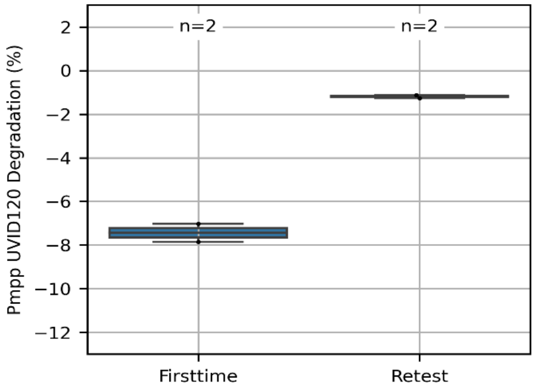
Kiwa PVEL’s New Stabilization Procedure

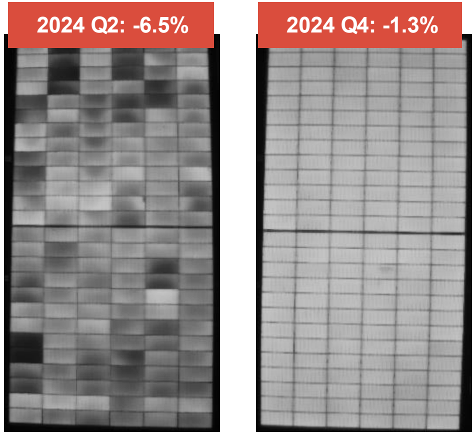
- Modules flashed within 48 h after test completion.
- If not, modules subjected to a full-spectrum light soak
  - Light source requirement:
    - Intensity over 500 W/m^2, indoors or outdoors.
    - Class CCC light source, at least 4% UVA (320-400 nm).
  - **c-Si modules (PERC, TOPCon, HJT): At least 0.5 kWh/m^2 of light, total dose not to exceed 2 kWh/m^2.**
  - CdTe modules: no light-soak requirement (different stabilization procedure).
  - Light soak under open-circuit.
- **Module flashed within 4 hours** after removing from light soaking.



UVID Mitigation at Cell Level

- First project tested in 2024 Q2, retest in 2024 Q4 with same BOM.
- From worse to best-in-class.
  - Original samples - Pmpp degradation 6.5% (average), strong checkerboard pattern.
  - Retest samples degraded by only 1.4% (average), no EL defects.
- Cell design improvements (not disclosed by manufacturer)
  - Most likely due to **front cell ARC/passivation layer process controls.**
- Several other projects with similar excellent results after recent UVID retests



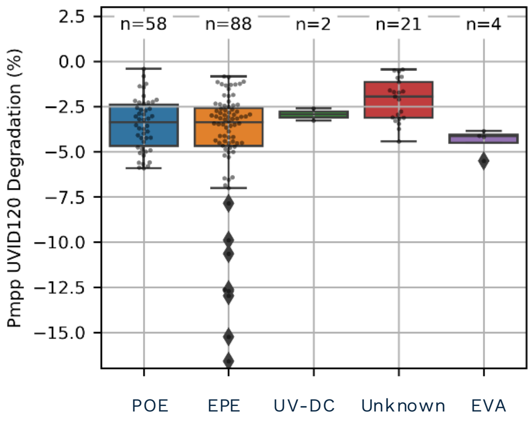


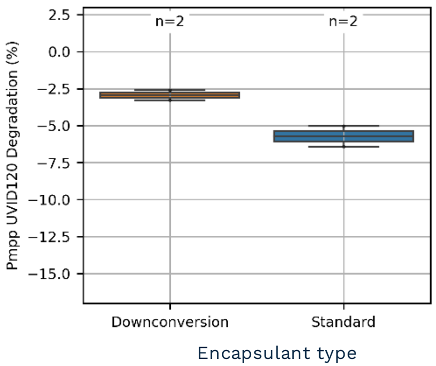
UVID Mitigation at Module Level

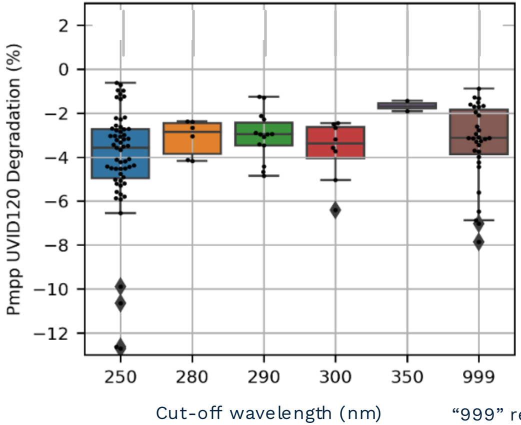
- **Additives and UV cut-off wavelength are critical** for UVID.

- Front encapsulant trends
  - EPE and POE are mainstream encapsulants.
    - EPE showing higher degradation.
  - Cut-off wavelength varies 220 to 380 nm.
    - **Higher degradation below 350nm cut-off**.

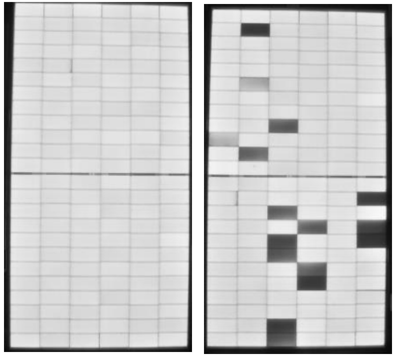
- **UV down-conversion encapsulants are emerging.**
  - UVID effects can be mitigated
  - Other reliability issues may trigger, need to be tested.





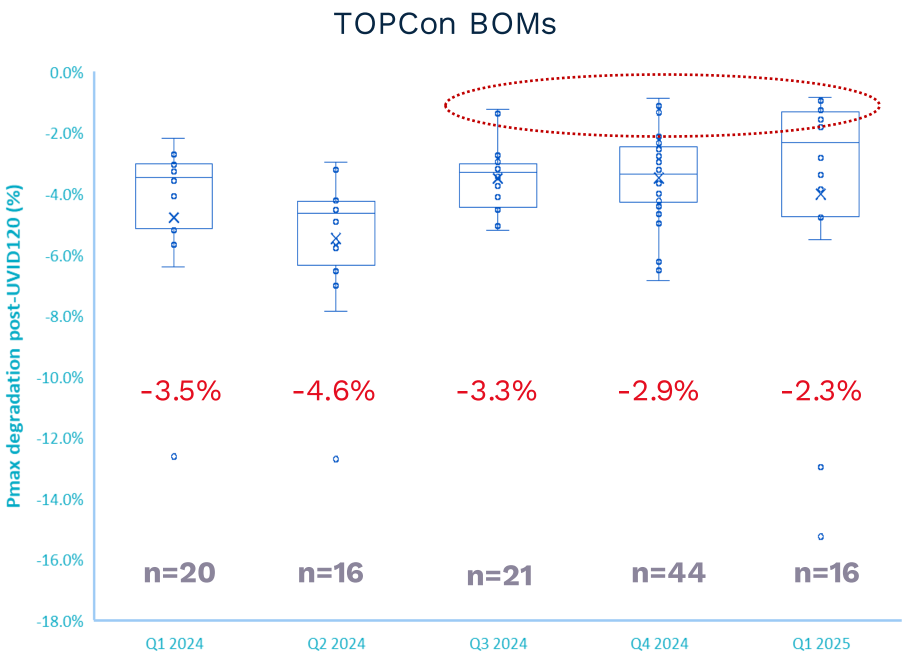


“999” refers to Unknown



Key Takeaways

- UVID is a new **reliability concern for n-type** modules and observed in the field.
- UVID is likely driven by a combination of UV-transparent encapsulants and thinner anti-reflective coatings on cells.
- **Front cell ARC/passivation layer process controls and better encapsulant additives** selection can help in mitigating UVID.
- Recent UVID testing showed **lesser modules are exceeding power loss >5%.**
- TOPCon and HJT modules after UVID and field exposure exhibited dark storage degradation.
  - **Full spectrum light soak** (indoors or outdoors) stabilize the modules.



Thank you!

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