The biggest reliability risks facing today's modules

Insights from Kiwa PVEL's PQP testing

Presenter: Jean-Nicolas Jaubert (Kiwa PVEL)
Team: Archana Sinha (Kiwa PVEL), Todd Karin (Kiwa PVEL), Dana B. Kern (NREL)

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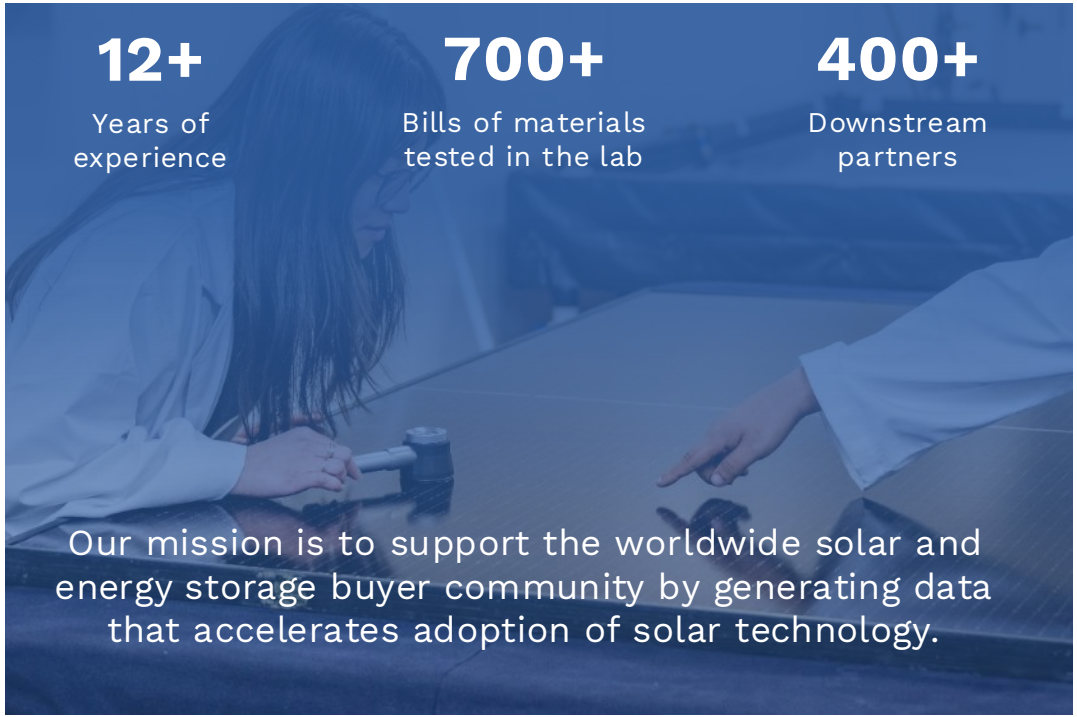


Services at a glance:

- Extended reliability and performance testing for PV modules
- Batch testing of PV modules
- Outdoor testing of PV modules, inverters and energy storage
- Data services for PV buyers and investors

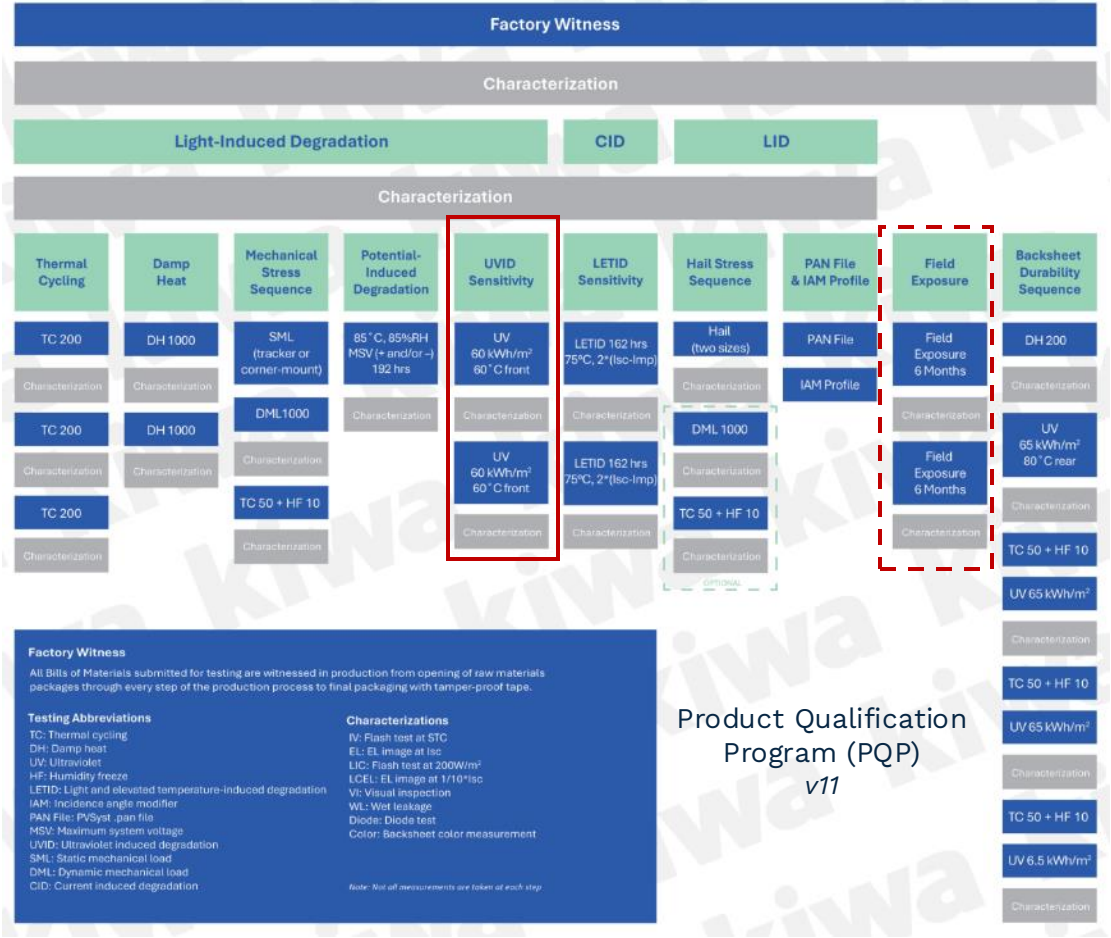
See more details at kiwa.com/pvel

PQP Test Sequence

The PQP evolves every two years based on feedback from Kiwa PVEL's downstream partners, module manufacturers, and the industry's collective understanding of module failure modes and test mechanisms.

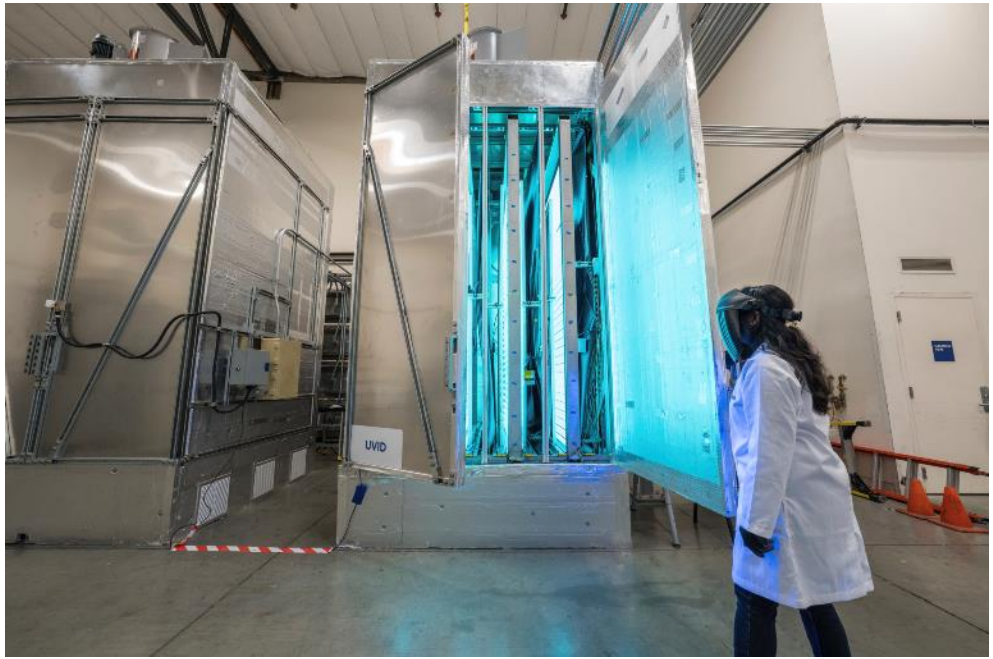
The most recent update introduced the new UVID test and streamlined many of the tests leading to faster execution of PQP projects.

Learn more about the current version of the PQP test plan at kiwa.com/pvel/pqp.



Outline

- UVID most recent results:
  - Indoor accelerated test data
  - Impact of metastability and stabilization
  - UVID mitigation status quo
  - Field Exposure data
- Other risks to keep an eye on:
  - Floppy modules still an issue
  - TOPCon 2.0 upgrade packages
  - Decrease silver content in metallization
  - Creepage distance & delamination risk



Latest UVID results

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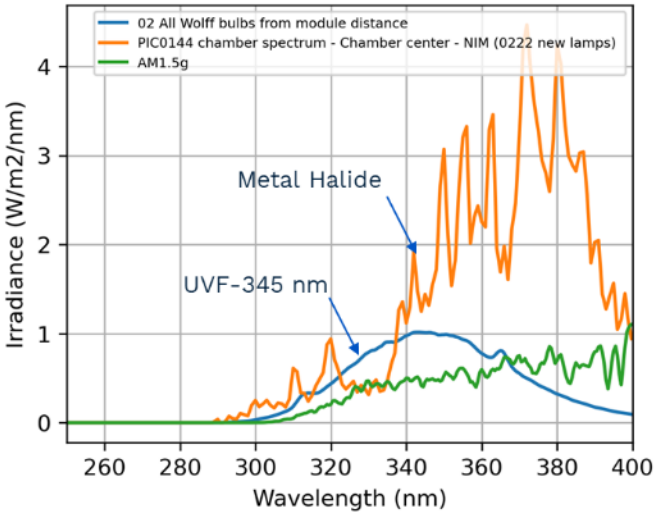
Kiwa PVEL's UVID Testing

- UV Testing with **front-side exposure,** 60°C, short-circuit condition.
- UV exposure dose **120 kWh/m²** of UV (280-400 nm) **when using metal-halide lamps** or 53 kWh/m² when using UV fluorescent lamps.



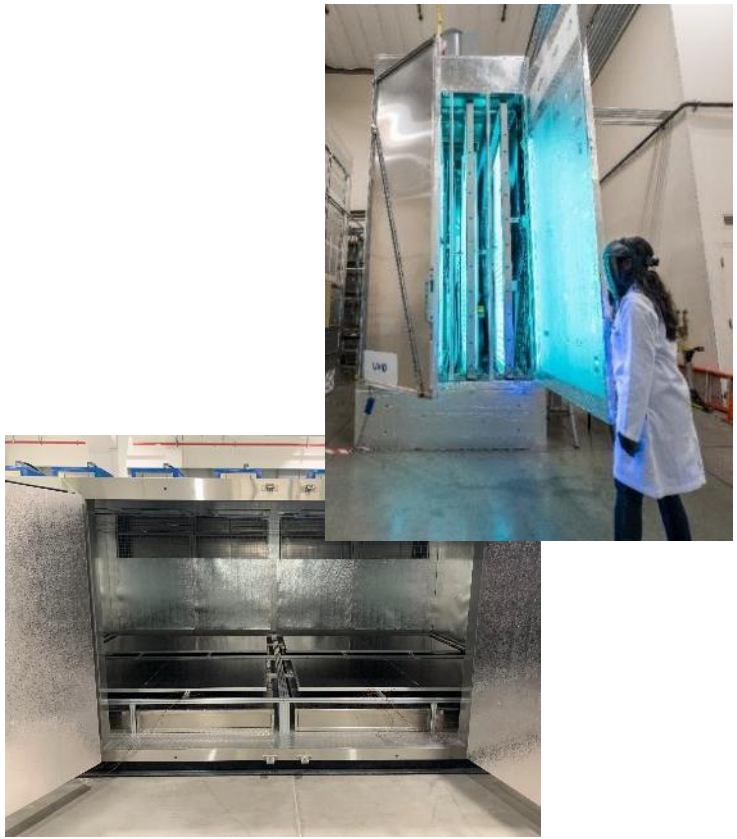
UVID Sensitivity

UV 60 kWh/m² 60°C front

Characterization

UV 60 kWh/m² 60°C front

Characterization

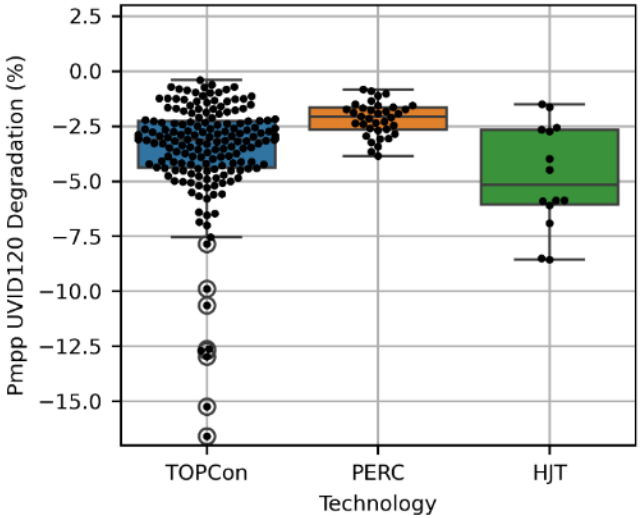


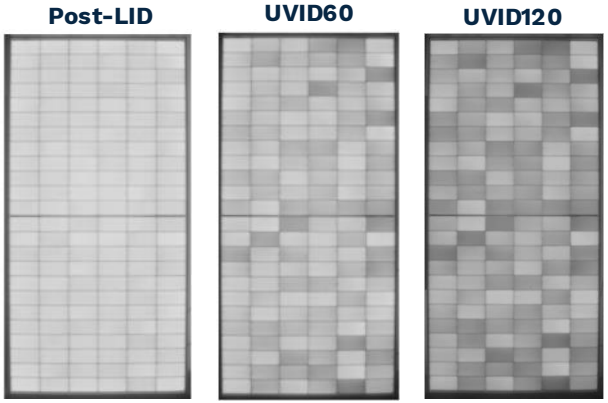
UVID Results at a Glance

- Largest “public” UVID dataset (2024-2025):
  - Total **378 modules** (~189 BOMs) evaluated
  - 77% TOPCon modules, predominant technology
  - Projects started in 2025 have stabilization steps

- **UVID affects all TOPCon, PERC and HJT modules**
  - 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 processes.
  - UVID-stable TOPCon BOMs are available.

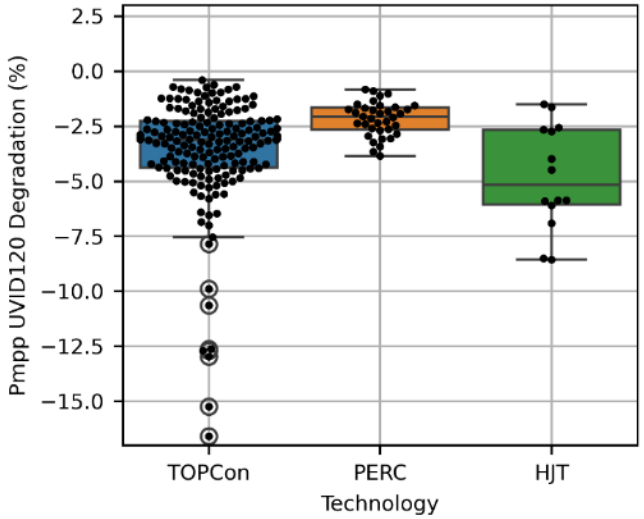
- Characteristic **“Checkerboard” pattern** in EL images
  - Cells degrade randomly within the module, with no distinct pattern with position.

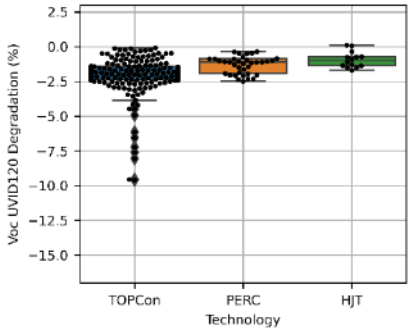


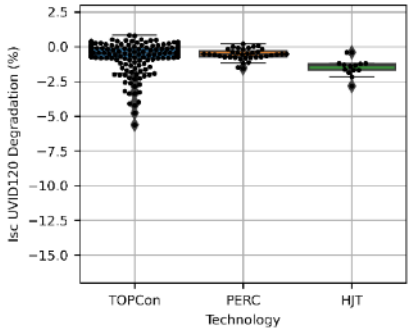


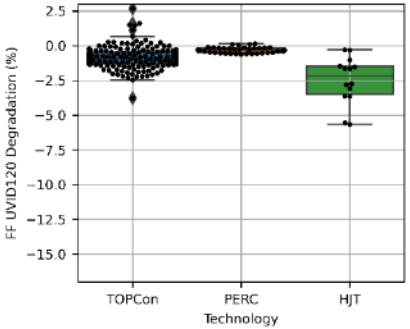
Degradation Pathways

- UVID mechanisms vary by cell types.
  - **TOPCon** BOMs show 0.6% to 16.6% deg, median 3.1%.
    - **Voc most affected** → cell passivation stack degradation [1]
    - 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/Interface degradation [2]
    - Voc is fairly stable
  - **PERC** BOMs show lower degradation, median 2.2%.







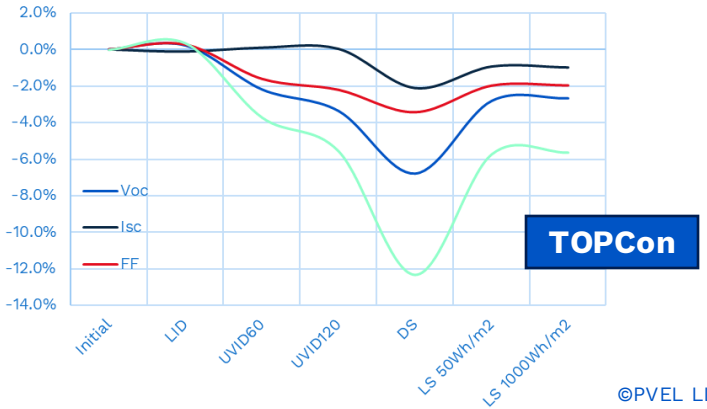


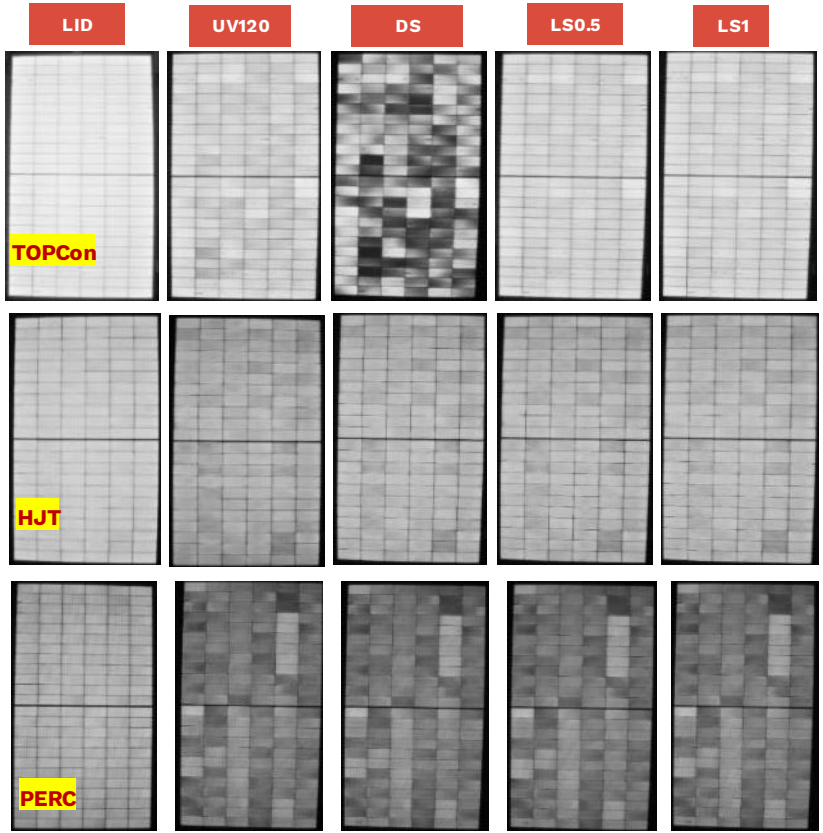
[1] *UV-induced degradation in TOPCon solar cells: Hydrogen dynamics and impact of UV wavelength.* https://doi.org/10.1016/j.solmat.2025.113895
[2] *Solar cell UV-induced degradation or module discolouration: Between the devil and the deep yellow sea,* https://doi.org/10.1002/pip.3725

Dark Storage Metastability & Stabilization

- UVID-sensitive TOPCon modules suffer from dark storage (DS) degradation (metastability).
  - Greater the dark-storage, higher is the degradation.

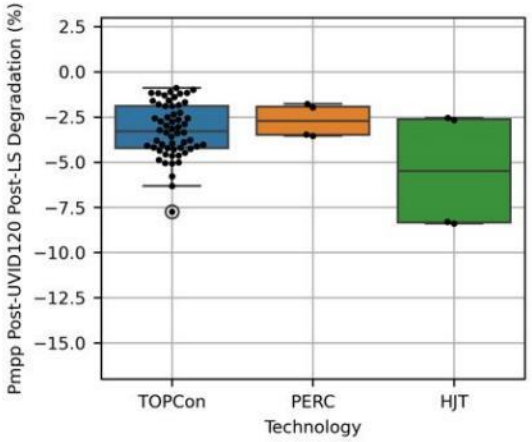
- **This degradation is recoverable under full spectrum light-soak (LS).**
  - TOPCon - Fast and effective recovery (Voc/Isc/FF).
  - HJT - Obvious recovery but at slower rate (FF).
  - PERC - No obvious degradation or recovery.

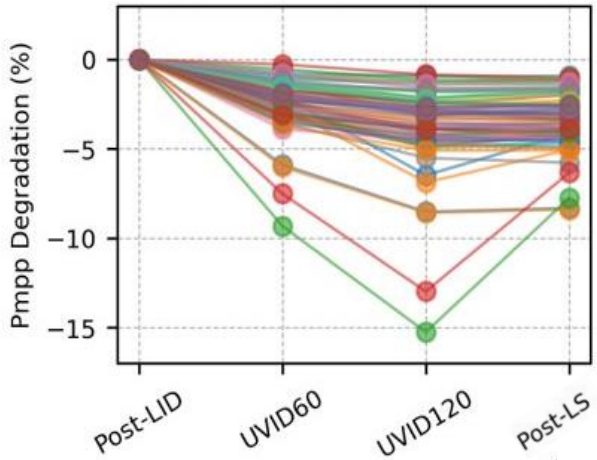


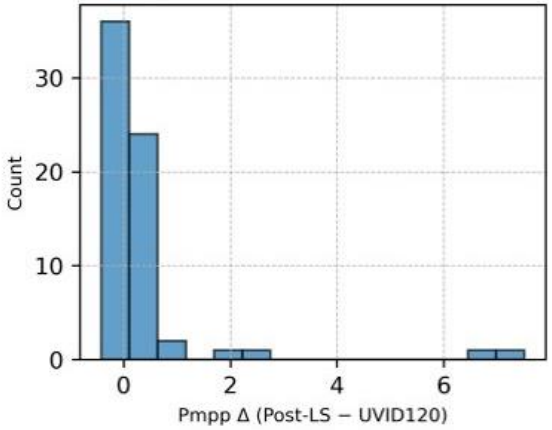


Light Soak Stabilization, How Important is it?

- Characterization window to flash UVID modules is controlled **within 48 hours after test completion**.
- Kiwa PVEL implemented **LS stabilization step post-UVID120** (0.5-1.0 kwh/m^2 full spectrum).
- UVID is still a **major reliability concern**, even when properly handling the metastability.
  - Many test samples not affected by LS (change is <0.4%), but some are very affected.
  - Limiting time from UV chamber to characterization does most of the work for you!







UVID Mitigation & Field Relevance

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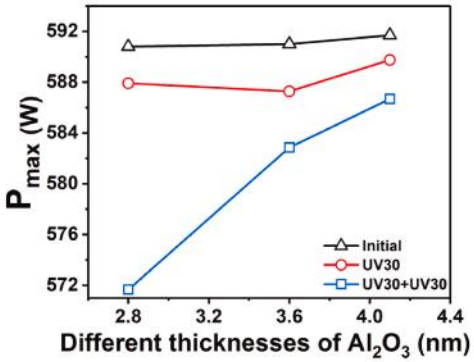
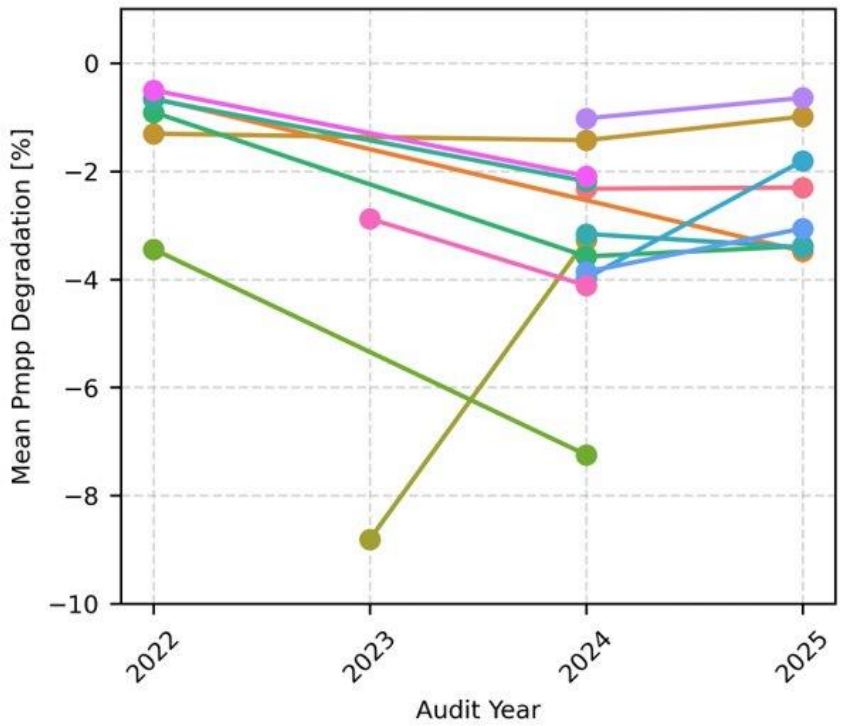
UVID Mitigation at Cell Level

[1] UV degradation analysis of TOPCon cells. https://doi.org/10.1063/5.0247683
[2] UV-induced degradation in TOPCon solar cells: Hydrogen dynamics and impact of UV wavelength. https://doi.org/10.1016/j.solmat.2025.113895
[3] UVID of TOPCon solar cells: Effect of the front passivation Al_2O_3 layer thickness and recovery by different processes. https://doi.org/10.1016/j.solmat.2025.113691

- Many cell suppliers have improved their production quality processes.
  - Each line is an individual cell supplier.
  - Most cell suppliers have better performance in 2025 compared to 2024.

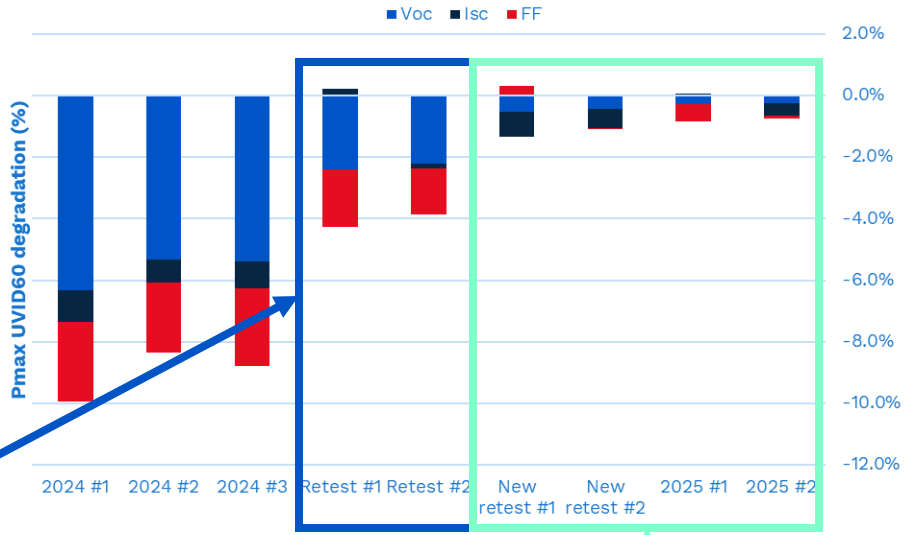
- Cell design improvements: front passivation stack
  - **Front cell ARC/passivation layer process controls** (thicker AlOx, ARC UV-transparence, etc.)





UVID Mitigation at Cell Level – Specific Example

- First project tested in 2024 Q2, UVID60 degradation ~9%!
- Retest in 2024 Q3 with same BOM…***except thicker encapsulant***
  - UVID power loss reduced to ~4%
- Then retest again in 2024 Q4 with same BOM, **improved cell design**
- New project tested in 2025 Q1, same cell production site but different cell size (182→210R).
  - UVID60 power loss reduced to ~1%



Encapsulant thickness
400 → 440 g/m²

3.05	Front encapsulant - area weight (g/mm²)*	≥440

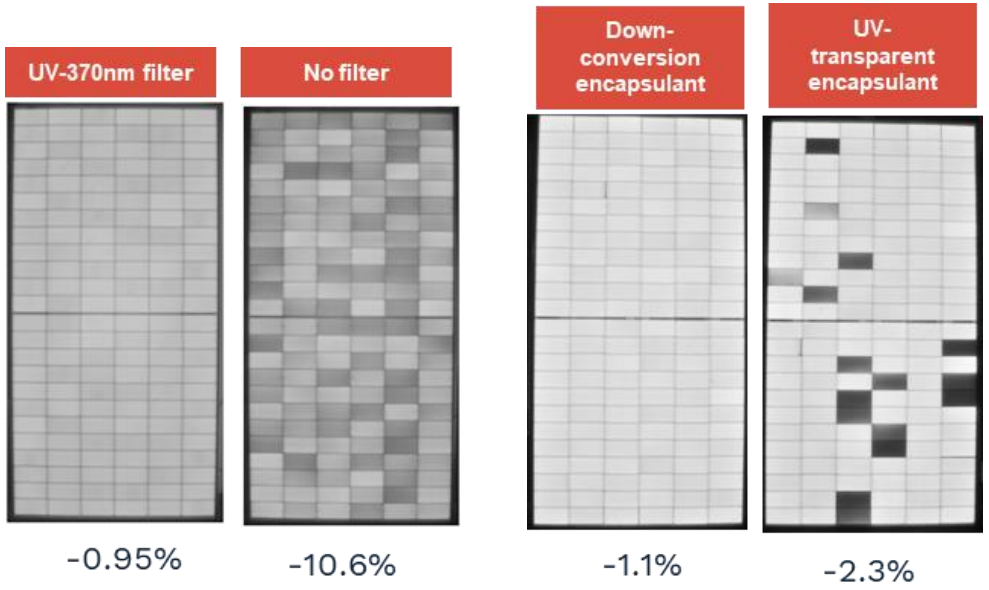
Cell design improvements
(not disclosed by manufacturer)

UVID Mitigation at Module Level

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

- Cut-off wavelength of front encapsulant varies in the range of 220-380 nm.
  - **Higher degradation below 350nm cut-off**.
  - UVID extent can be lowered when tailoring the encapsulant cut-off band.
    - Solutions available from main suppliers but not widely deployed on TOPCon modules

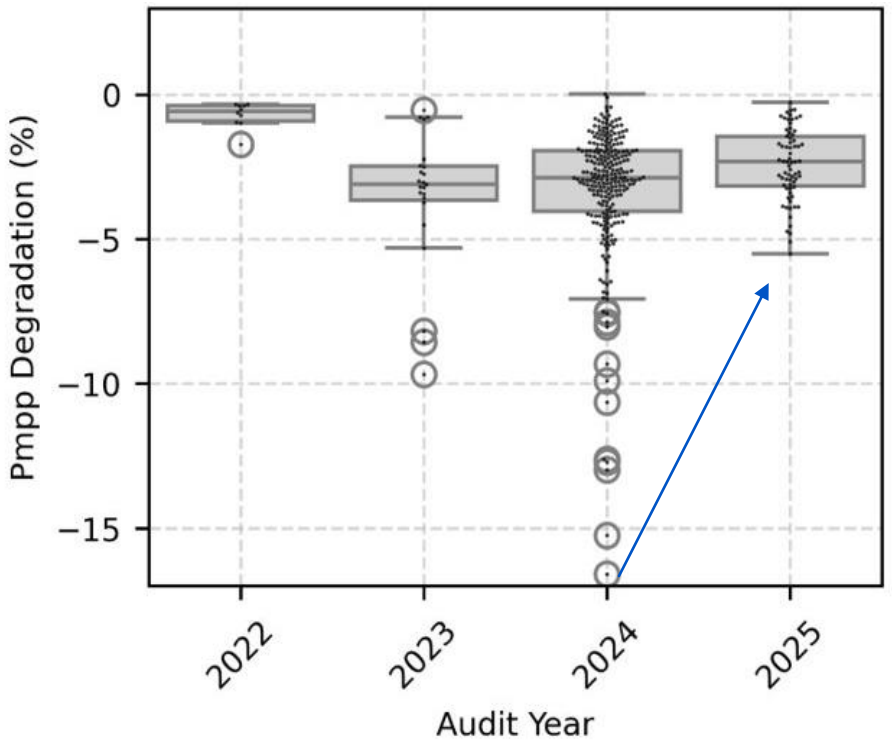
- **UV down-conversion encapsulants.**
  - Currently used in HJT module designs.
  - UVID effects can be mitigated.



UVID Stability is Improving, But is Not Solved!

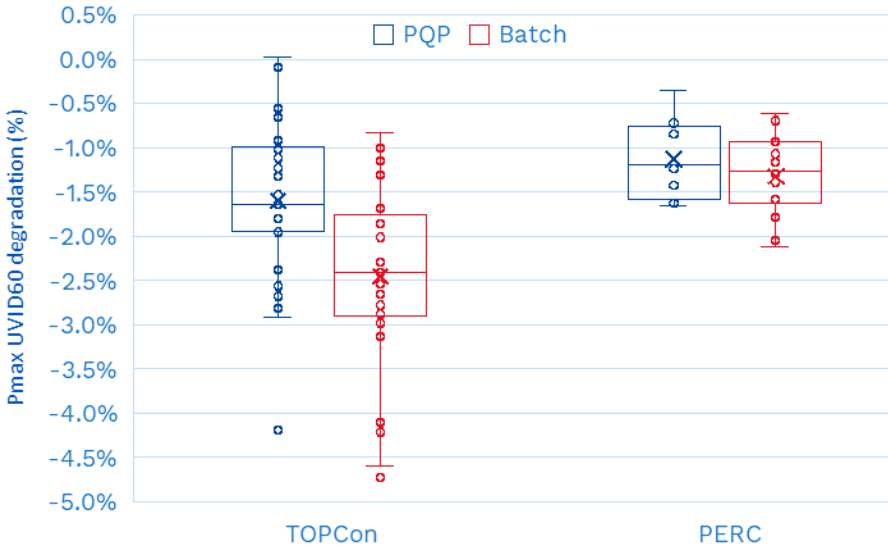
- From 2024-2025, outlier tail disappeared and the median improved.
  - Note: some big outliers are partially a result of dark metastability (LS stabilization from January 2025 onwards)
  - Only TOPCon BOMs shown

- UVID stability has improved, but still only **31% of modules have less than 2% degradation in UVID120**.



UVID Stability is Improving, But is Not Solved! Batch Testing Results

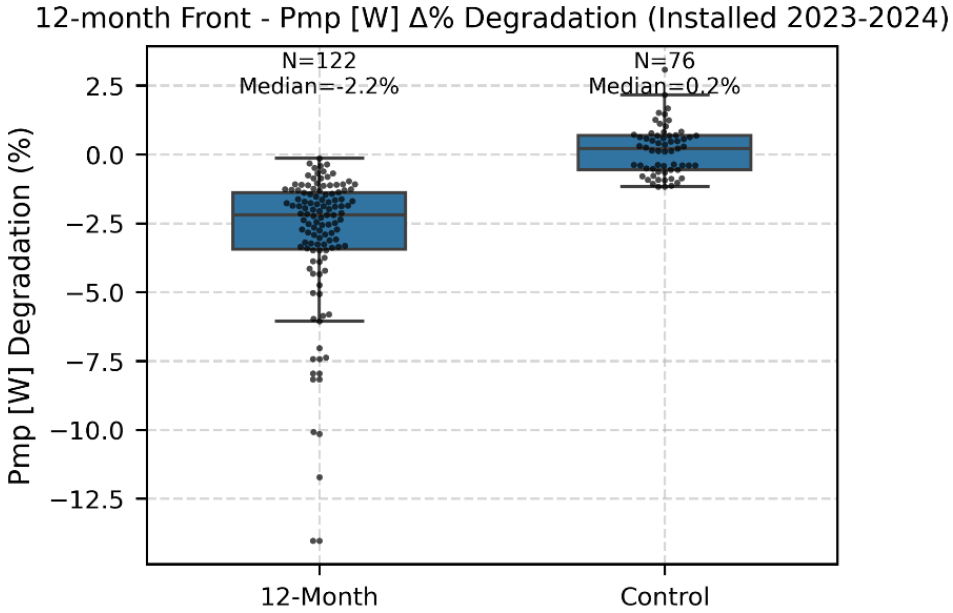
- Downstream customers batch vs manufacturer PQP testing results:
  - Projects tested during 2024 Q4 – 2025 Q3 period
  - TOPCon and PERC, US test lab data only
  - Post-UVID60 Pmax losses
- UVID not yet solved in mass production:
  - **Higher Pmax losses for TOPcon** in batch testing.
  - Both PERC (~1.3%) and **TOPcon (~2.4%) median degradations** exceeding warranties.
- *Open question: how much acceleration factor in lab UVID testing?*



	PQP	Batch	PQP	Batch
Median	-1.6%	-2.4%	-1.2%	-1.3%
Average	-1.6%	-2.4%	-1.1%	-1.3%
Samples	41	45	8	18

Field Exposure (FE) Results at a Glance

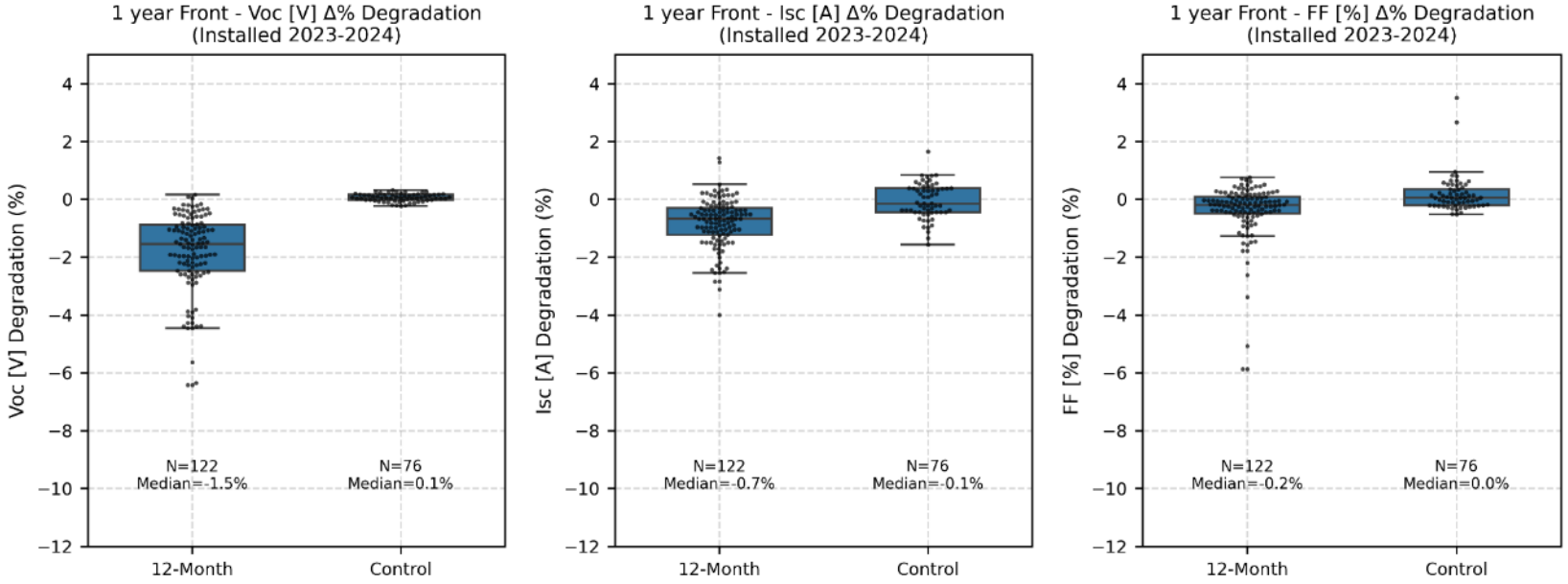
- PVEL performs 1 year outdoor exposure in Davis, CA. Modules installed in 2023 and 2024.
  - TOPCon modules analyzed only.
  - Each project has its own control module kept in dark storage during exposure.
- **1 year Pmp degradation has a median of -2.2%**
  - Combined indoor LID & LETID Pmpp loss <1%.



- Most would **not meet a <1.0% degradation warranty** at the end of year 1.

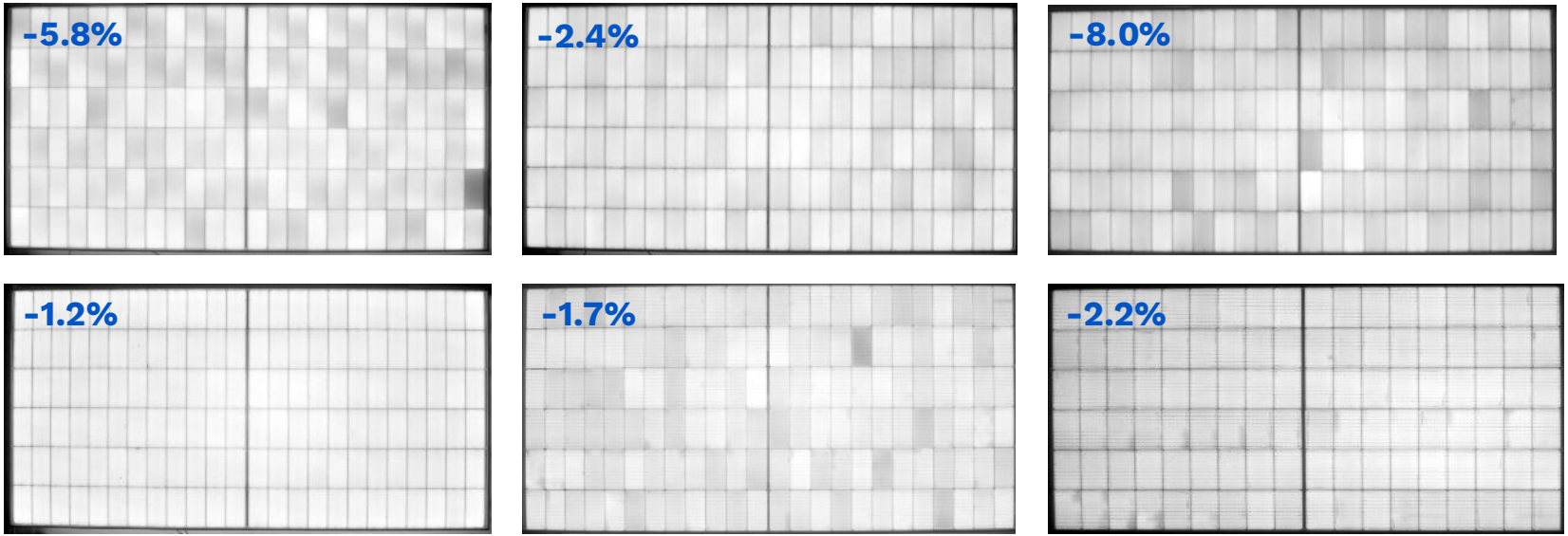
Field Exposure Results, Signs of UVID (Degradation Pathway)

- For most modules: FF degradation is low, Pmpp degradation is primarily driven by Voc degradation, then Isc.
  - Voc degradation is not affected by soiling, and is expected to be very trustworthy.
  - Median Voc degradation: -1.5%!



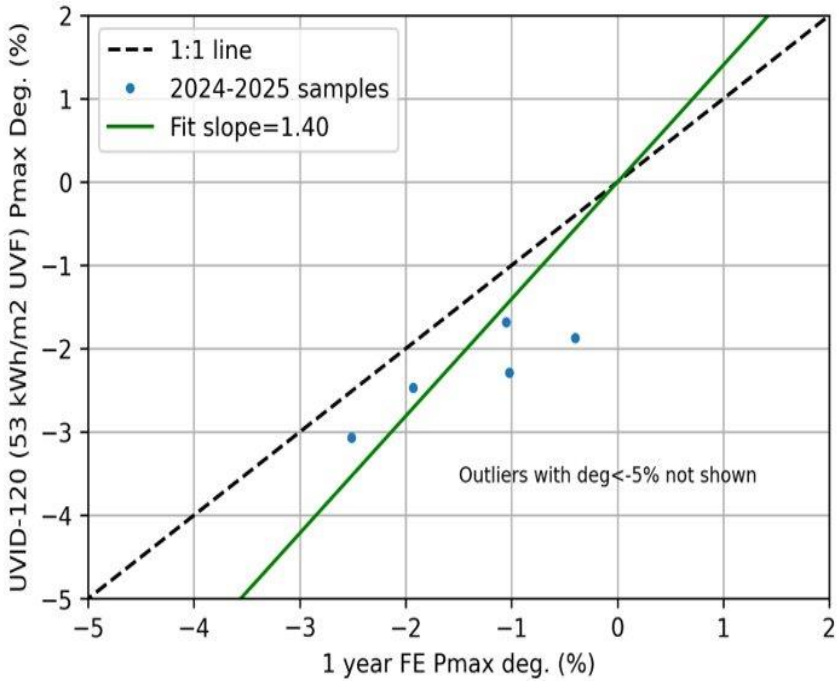
Field Exposure Results, Signs of UVID (Checkerboarding)

- For many modules, UVID signature is clearly visible in EL post 1 year exposure.
  - Somewhat random selection of 6 recent FE projects



Correlation of UVID and FE Degradations

- Each data point on the graph:
  - Average of 2 modules data from UVID120 (55 kWh/m2 of UVF-345nm).
  - Average of 2 modules data from 1 year outdoor exposure in Davis, CA.
  - Only TOPCon, light-soak stabilized BOMs
- Observed higher degradation in UVID testing as compared to field.
- Field data: UVID120 (55 kWh/m2 of UVF) Pmpp Degradation correlates with **1.4 years outdoors in Davis CA**.
- Using light exposure alone, expect UVID120 to be equivalent to 0.5 to 0.7 years.
- *More research on UVID mechanisms necessary!*

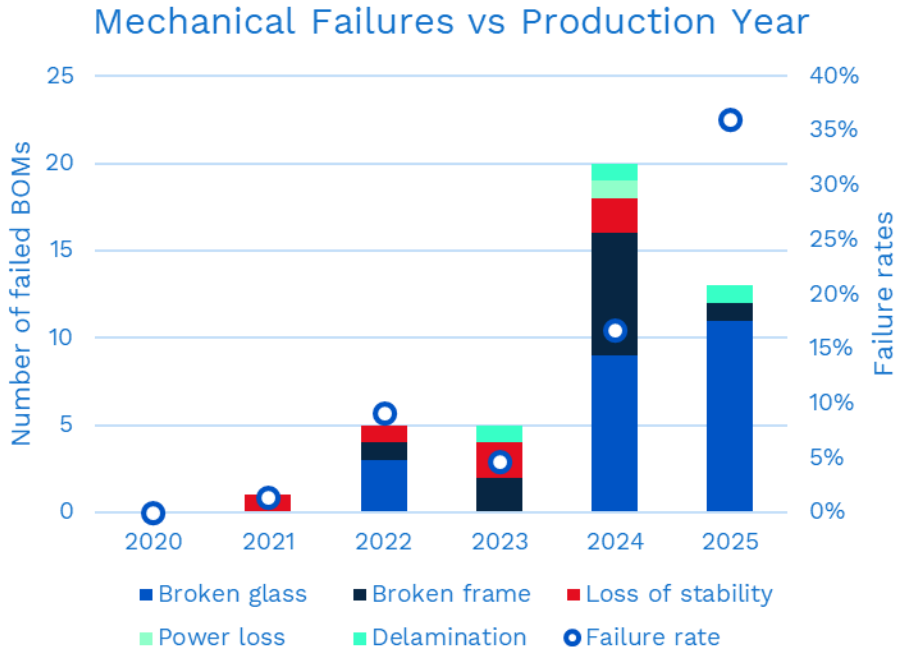


Beyond UVID

Other reliability risks to keep an eye on

#1 Mechanical Breakage Risks at their Highest

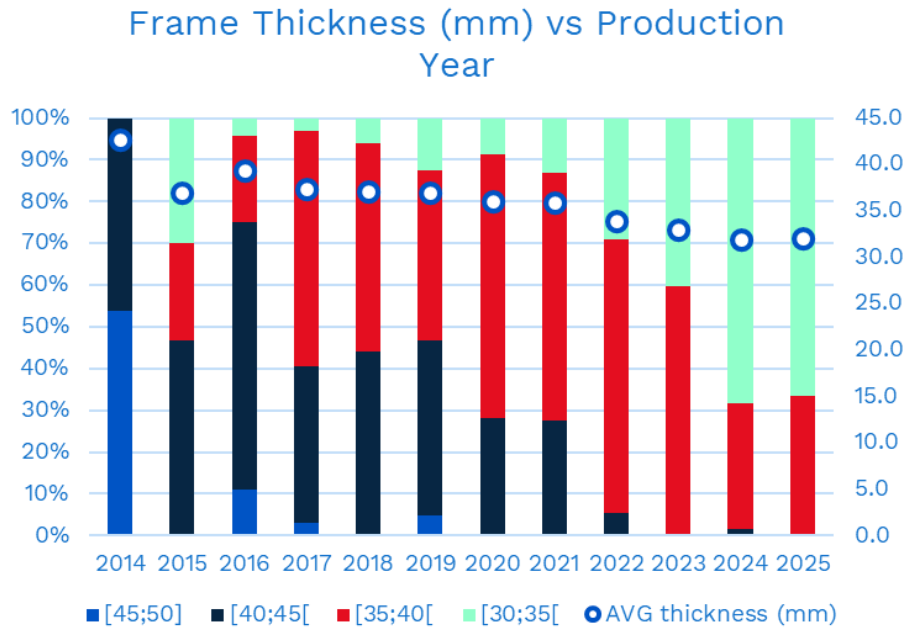
- Steep increase in SML and DML failure rates observed over the past 18 months.
- “Leading” failure mode appears to be glass breakage (front and/or rear) due to pinching.
  - Took over frame failures during 2024-2025 period



Until 2023: 2400Pa, 1/4 length clamp mounting
From 2024: 1800Pa, tracker 400mm mounting

#1 Mechanical Breakage Risks at their Highest

- Steep increase in SML and DML failure rates observed over the past 18 months.
- Frame thickness decreasing trends:
  - Average PQP frame thickness stable 2015 to 2021
  - **Strong acceleration in reduction from 2022** onwards (compounded decrease -12%)
  - Matching industry challenging situation (cost-down)



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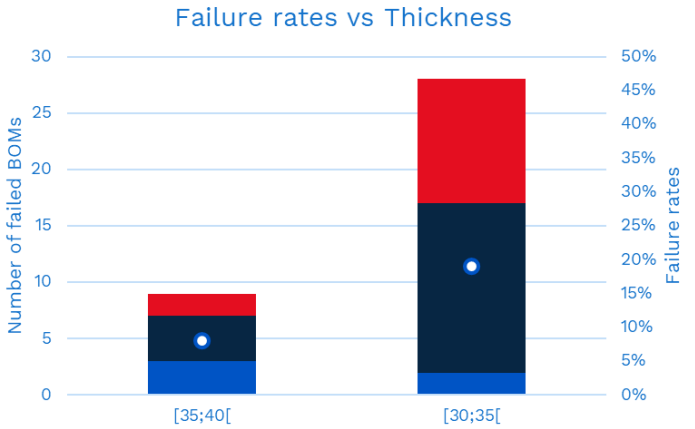
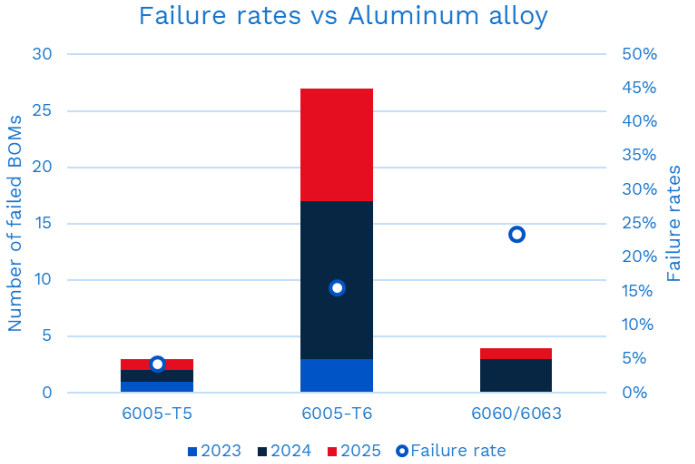
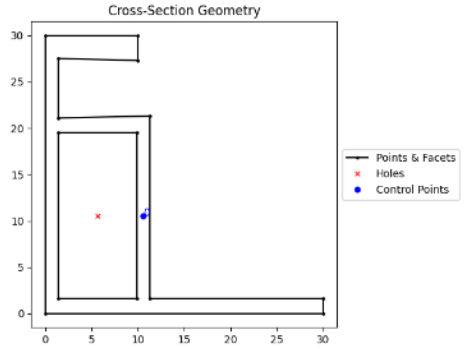
  - Average PQP frame thickness stable 2015 to 2021
  - **Strong acceleration in reduction from 2022** onwards (compounded decrease -12%)
  - Matching industry challenging situation (cost-down)
- Failure rate more than **doubled** when moving **from 35mm to 30mm frame** designs.
  - Transition to stronger 6005-T6 alloy did not help



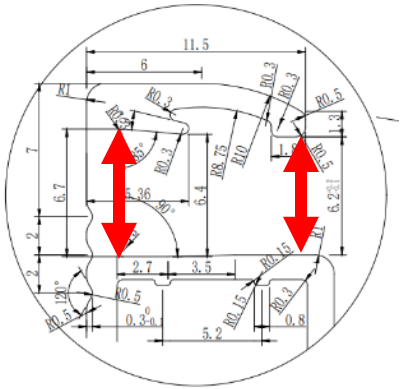


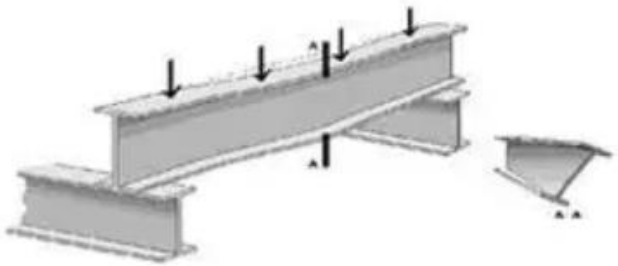
#1 Mechanical Breakage Risks at their Highest – Frame design impact

- Assessment of all 210R BOMs tested during the 2024-2025 period:
  - Same frame thickness, alloy, dimensions
  - Total 16 BOMs analyzed, including 6 failures (37.5%)
- Section modulus (Zx) and Torsion constant (J) calculated from each frame sectional drawings:
  - Zx – Frame ability to resist bending
  - J – Frame ability to resist torsional stress
- Laminate groove thickness range also assessed.



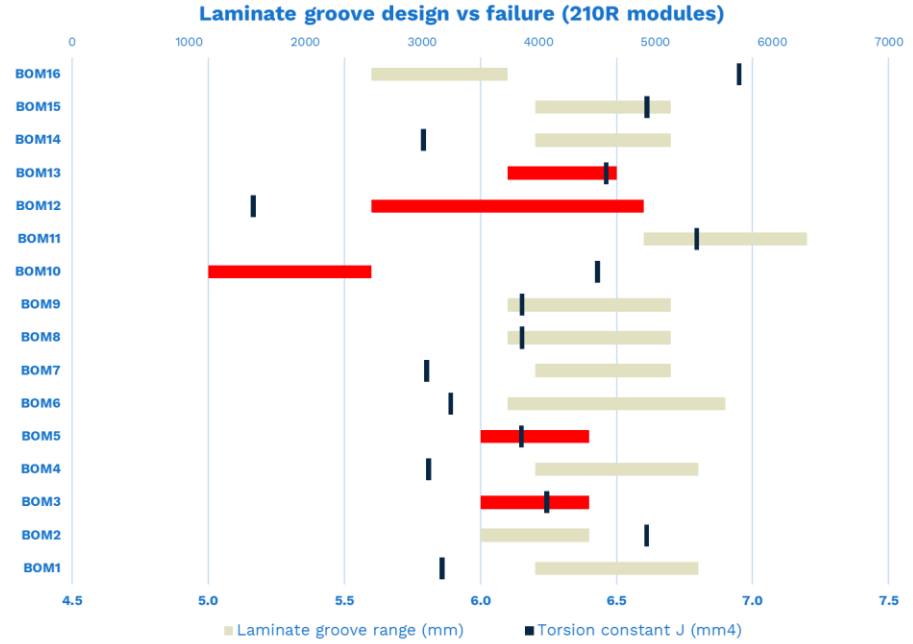
https://sectionproperties.readthedocs.io/en/latest/

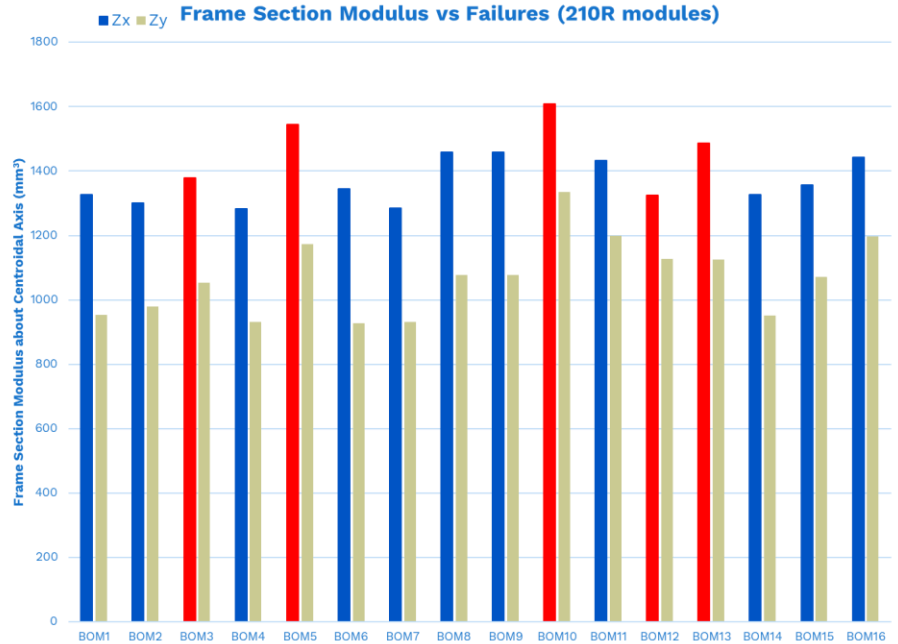




#1 Mechanical Breakage Risks at their Highest – Frame design impact

- Large variations in frame design: groove (5 to 7.2mm), Section Modulus Zx (20%) and Torsion Constant (73%)
- Modules breaking with pinched glass (tagged in **red**) more likely on **thinner grooves, "stiffer" frame**?





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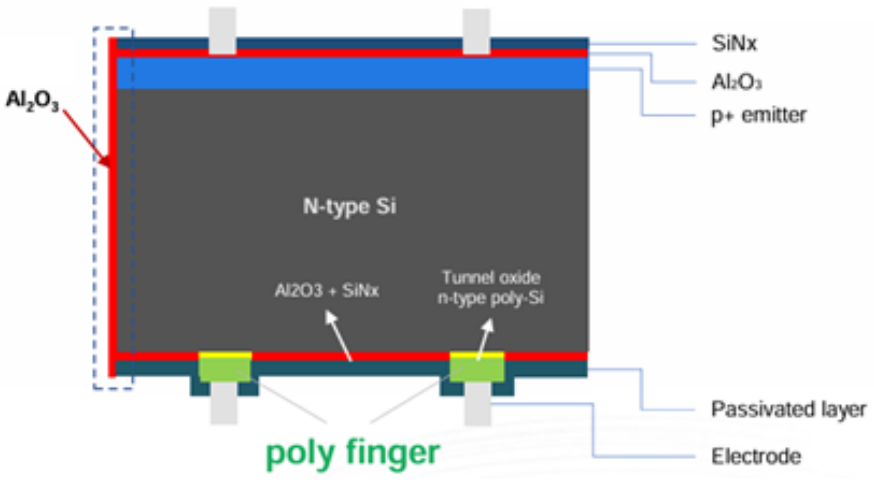
#2 We are Not Done with UVID – TOPCon 2.0 upgrade package

- Harsh competition on-going on module efficiency (TOPCon vs Back-Contact)
- All TOPCon manufacturers introducing high efficiency upgrade package.
  - Expect +15W power increase (G12R-66 cells format), +6% bifaciality
  - Key technology upgrades may include:
    - **Rear poly-finger**
    - Cell edge passivation
    - 0BB “busbar-free” designs
    - Double layer glass ARC
    - Stencil printing for metallization (thinner gridlines)
    - Multi-cut cells (1/3, 1/4)
    - …



Al2O3/SiNx passivation stack replaces tunnel oxide poly-Si

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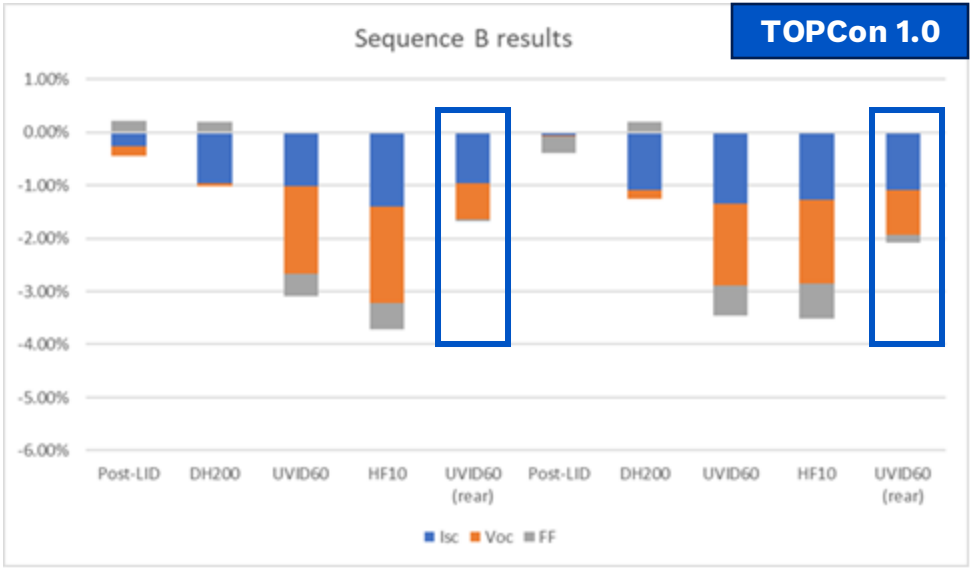
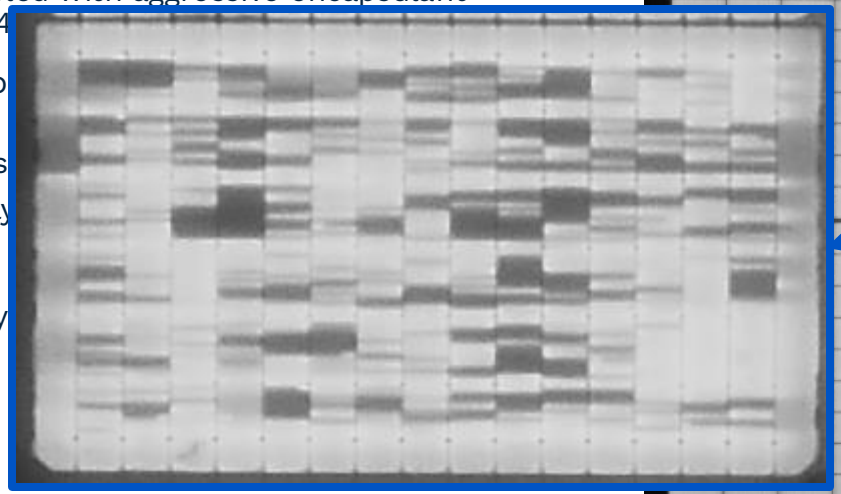
    - Multi-cut cells (1/3, 1/4)
    - …

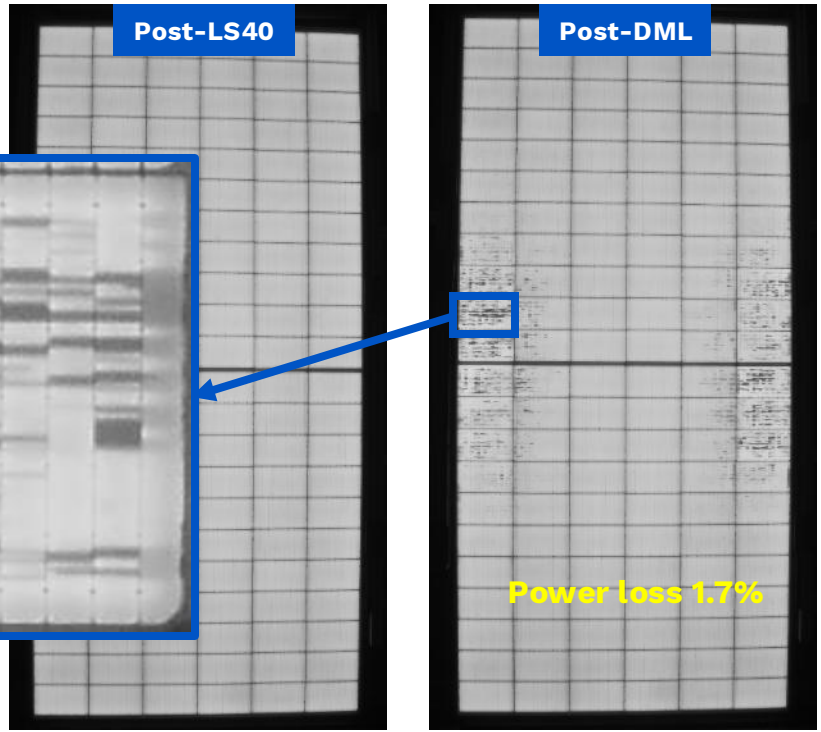


- TOPCon 1.0 generation, rear side UVID exposure was driving recovery (thermal annealing), no extra UVID loss.
- Polyfinger tech may **increase backside sensitivity to UV**.

#3 Quest for low silver content weakens cell metallization

- Increasing number of projects with “strongly” damaged cells post mechanical stress sequence.
  - Reduced cell silver content
  - Sometimes coupled with aggressive encapsulant thickness (here 4
- EL images for wo SML+DML).
  - High stress trans
  - Gridlines partially
- Large power loss
  - Compared to 3-y

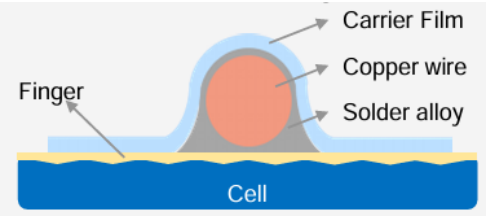




[1] *Degradation Modes of Low Temperature Soldered Wire Interconnects in PV Modules*. P. Hacke and al., EUPVSEC 2025

#3 Quest for low silver content weakens cell metallization

- Some designs part of TOPCon 2.0 upgrade package may **further worsen** the trend.
  - **0BB "busbar-free"**
    - Carrier film approach
    - Adhesive glue approach
  - Stencil printing for metallization (thinner gridlines)



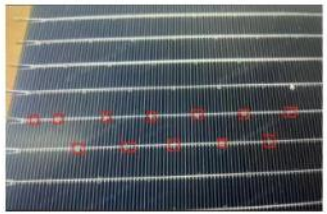
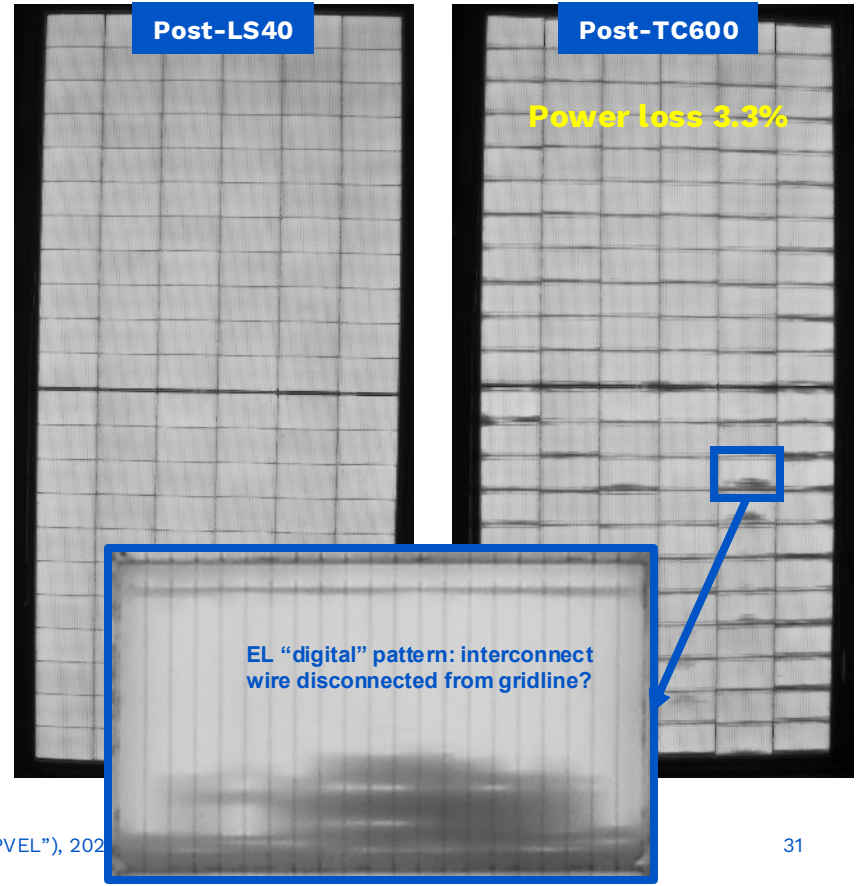
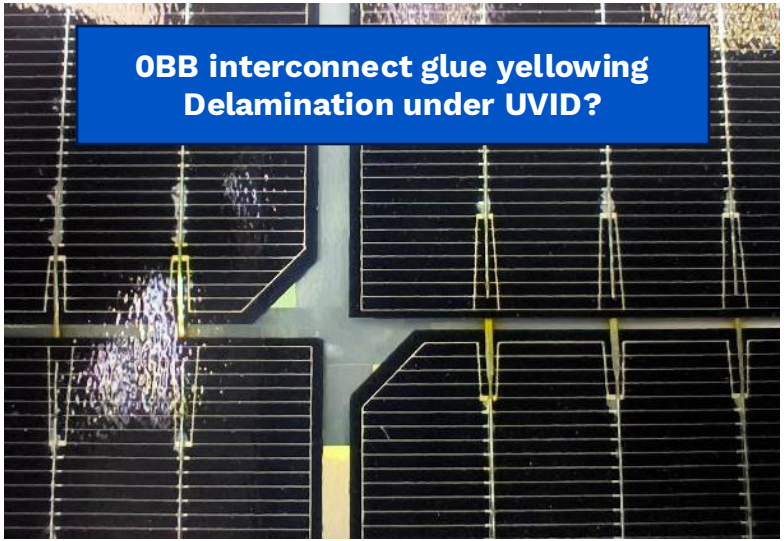


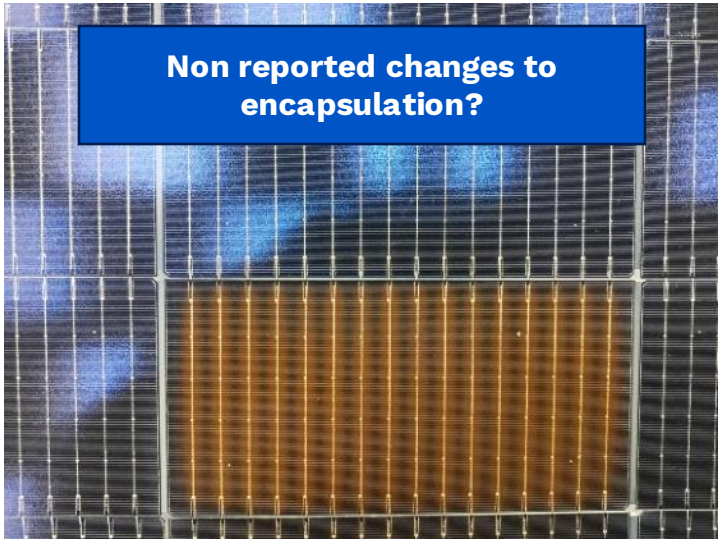
Figure 4-2 Example Image of cell UV glue place



#4 UVID Mitigation at Module Level Create New risks

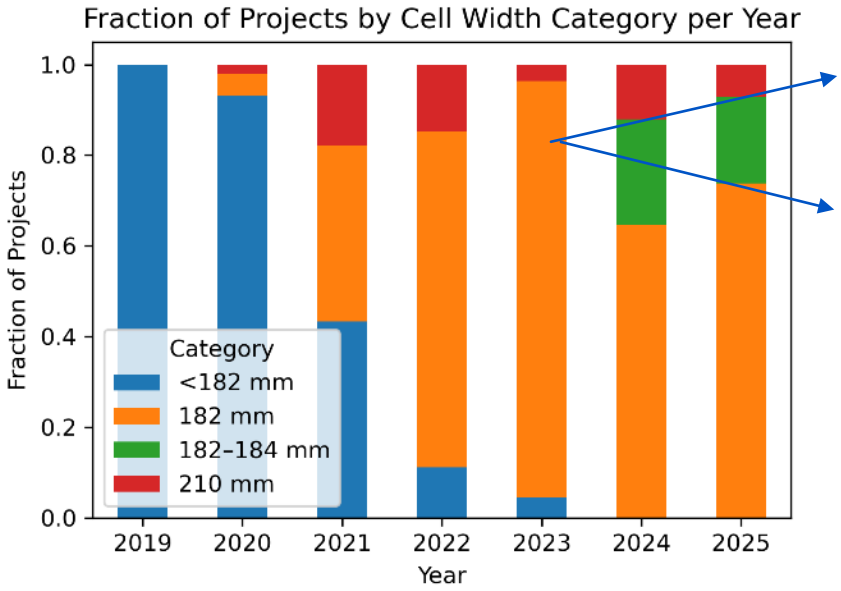
- Encapsulation recipe changes to enhance UVID resistance or enable new interconnection methods can create unexpected chemical reactions with cell and/or interconnection materials:
  - Right picture: **encapsulant browning**, reaction between solder flux and encapsulant on a cell under Hot Spot.
  - Left picture: **yellowing** of 0BB glue dots, discoloration of interconnect, cell/encapsulant **delamination**.

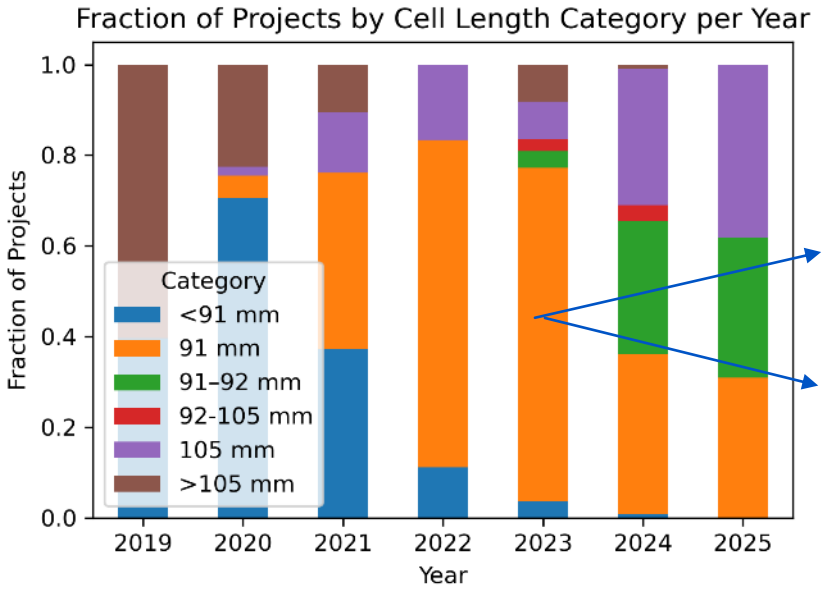




#5 Keep your distances!

- In the last few years, manufacturers are pushing “slightly larger than 182x91 mm” cell size
- Data from PQP test samples.

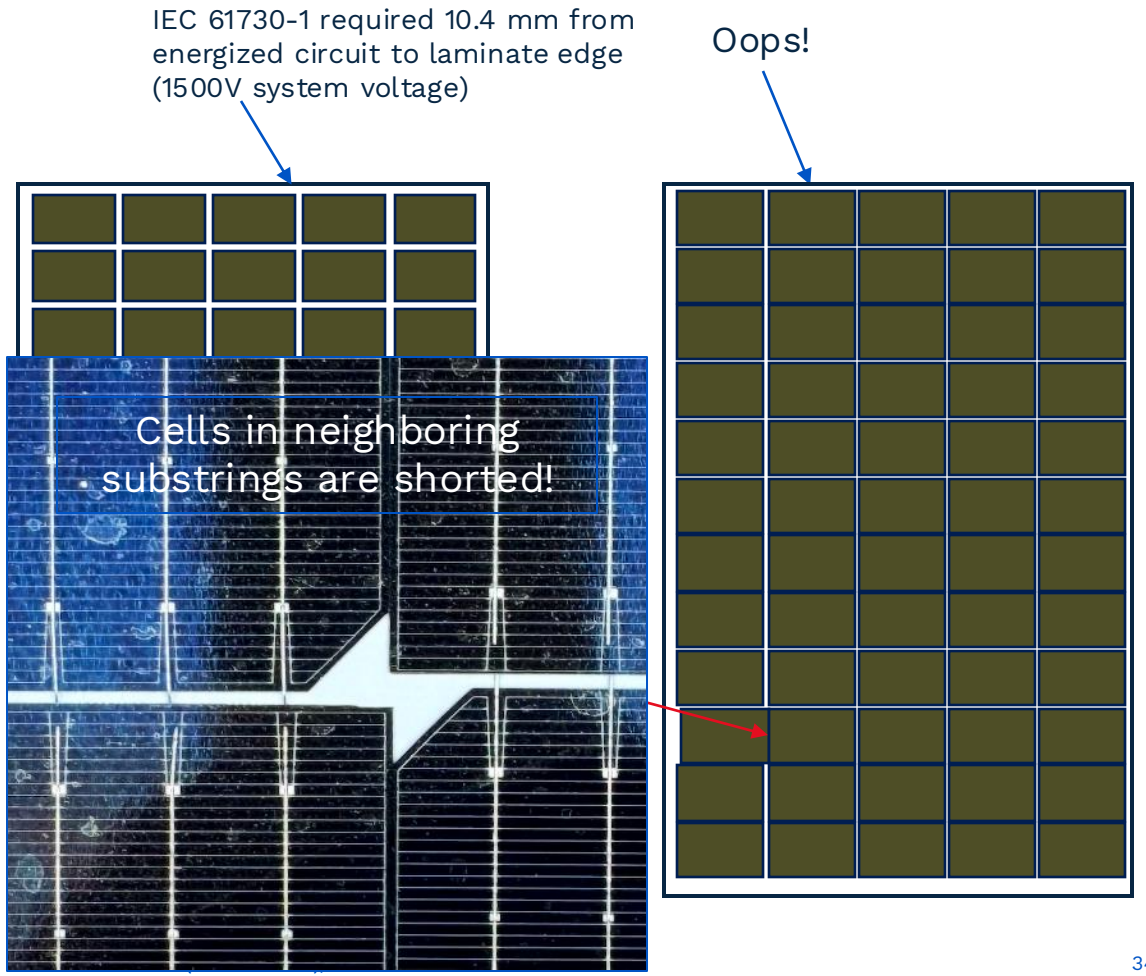




#5 Keep your distances!

- Manufacturers are increasing the size of cells but not changing laminate size.
  - Done to improve module efficiency.
  - Technically possible to achieve the creepage distances but…
  - ~0.2mm tolerances on layout hard to achieve for many manufacturers

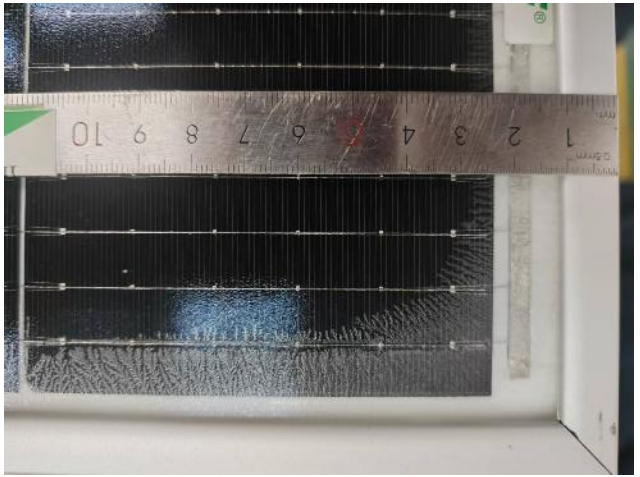
- May create increase **safety risks** in the field:
  - Cell shorting, heating & glass breakage.
  - DC arcing events.

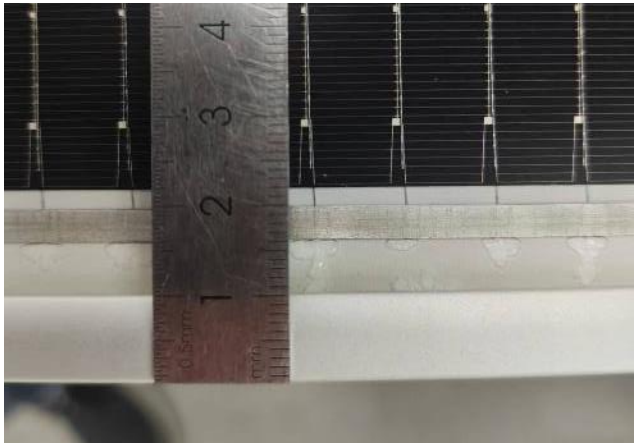


#6 Delamination on the rise

- Significant increase of encapsulant delamination occurrences over v11 PQP.
  - 143 unique BOMs tested over the 2024-2025 period
  - 108 samples with delamination or bubble defects reported
  - ~36% (52 BOMs) with at least one occurrence
  - Included **~11% (16 BOMs) with Major defects**
    - Cluster of bubbles or delamination forming a continuous path between electrical circuit and module edge
    - Failing creepage distance requirements from IEC61730-1
  - Mostly observed post-TC, DH, MSS testing

- Possible root causes, pending further analysis:
  - Reduced encapsulant foil thickness and dimensions
  - Lamination process control issues (lamination time, temp.)
  - Improper solder flux recipe and/or residue cleaning
  - Reduced adhesion of encapsulant to cell surface (HJT)

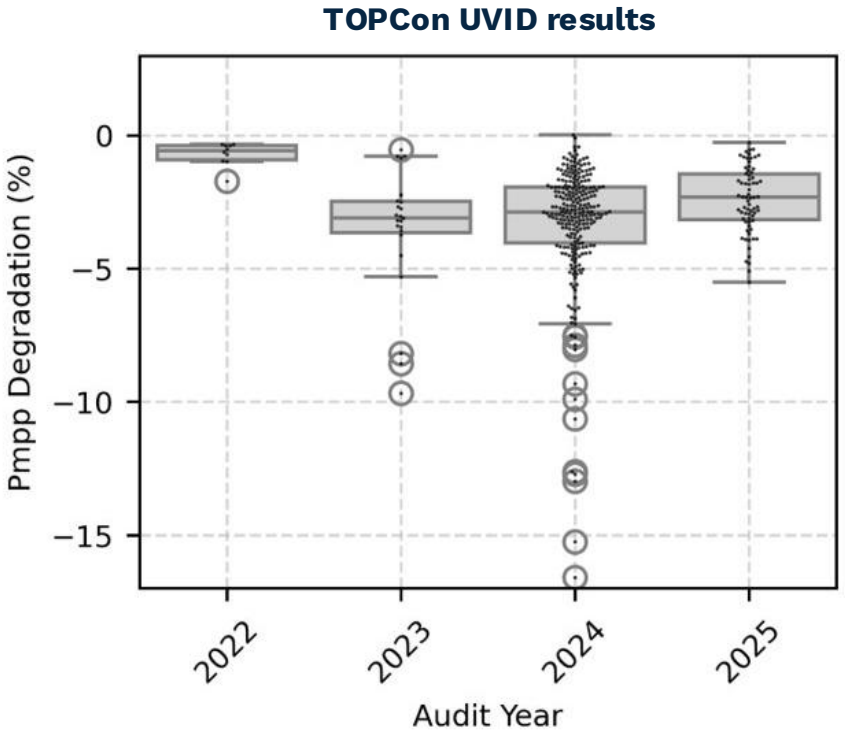




Time to wrap-up

Key Takeaways

- UVID is still **one of the largest reliability concerns** for n-type modules produced today.
  - Data from 1 year field exposure confirms this
  - Likely driven by a combination of UV-transparent encapsulants and thinner passivation stack on cells.
- **UVID stability is improving** as manufacturers learn how to mitigate UVID using better cell process.
- For accurate measurement, **a short light soak under full spectrum** can stabilize the modules from dark storage metastability.
- The industry must **keep in check other reliability risks** as cost pressure remains strong and TOPCon 2.0 efficiency upgrade package is deployed:
  - Frame & cell metallization mechanical strength
  - Encapsulation formulation & lamination process (UVID mitigation, interface adhesion)



Thank you!

Jean-Nicolas Jaubert

creating trust, ***driving progress***

Contact us:
Kiwa PVEL
pvel@kiwa.com
www.kiwa.com/pvel