Back-Contact cell technology
A first attempt at benchmarking the reliability and performance of BC modules

Jean-Nicolas JAUBERT
Director of China Operations
Kiwa PVEL

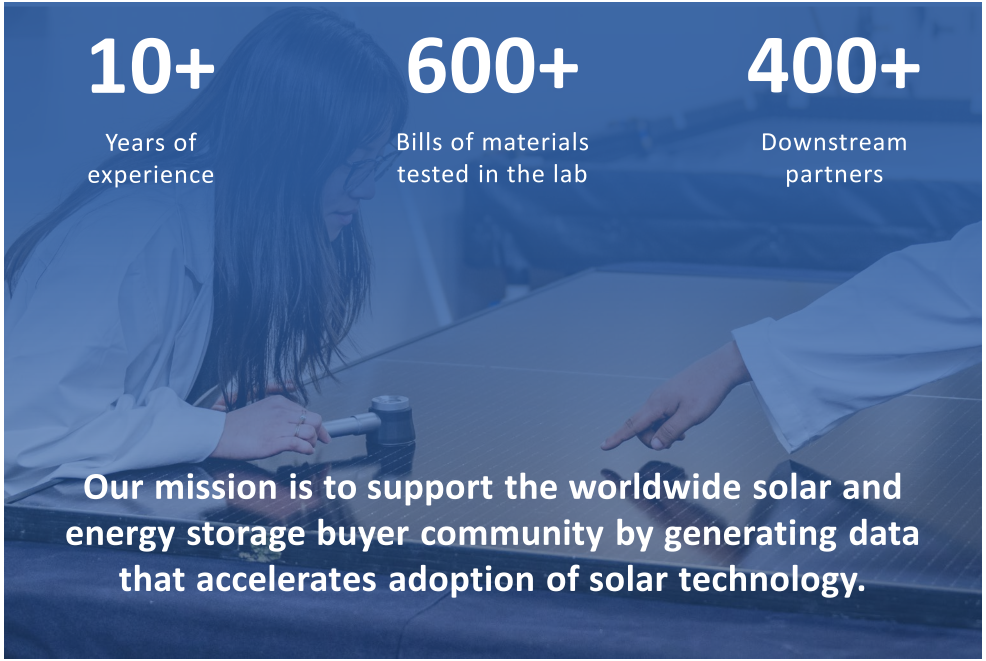
11/22/2024, Zhuhai BiFi Workshop

We
Create
Trust

Outline

- A first attempt at XBC module reliability benchmark:
  - PQP (Product Qualification Program), a unique benchmark tool
  - Methodology & market trends
  - 2024 Scorecard vs XBC reliability results
  - Diving into Failure Modes: what to expect for XBC designs?
- Quick glance at XBC performance metrics
- Wrap-up

Kiwa PVEL is the Independent Lab of the Downstream Solar Market



10+
Years of experience

600+
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.

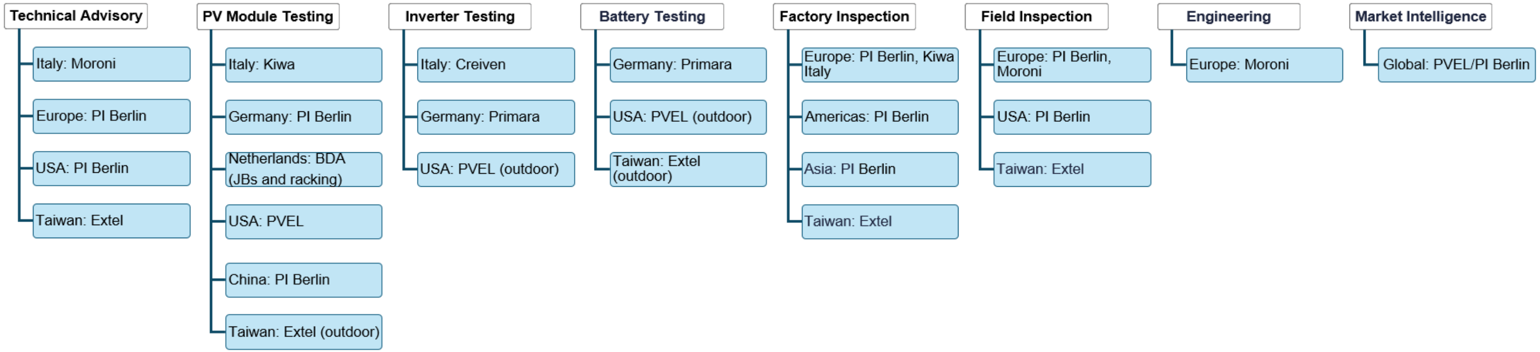
Services at a glance

- Extended reliability and performance testing for PV modules
- Batch testing of PV modules
- Outdoor testing at PVUSA, an iconic grid-connected research site
- Data services for PV buyers and investors

See more details at kiwa.com/pvel

Kiwa Overview

- Kiwa is a global testing, inspection and certification (TIC) company, founded in 1948.
- Headquartered in Rijswijk, the Netherlands with more than 10,000 employees, working in over 37 countries. Kiwa is primarily active in renewable energy, construction, manufacturing, fire safety, medical devices, food & water.
- Kiwa's solar businesses at a glance:



- Kiwa's mission is to create trust by contributing to the transparency of the quality, safety and sustainability of products, services and organizations as well as of personal and environmental performance.

kiwa PVEL

The annual PV Module Reliability Scorecards lists top performing manufacturers and insights from Kiwa PVEL's PQP.

Visit www.scorecard.pvel.com

TOP PERFORMER 2024 kiwa PVEL PV MODULE RELIABILITY SCORECARD

- The 2024 PV Module Reliability Scorecard was released on June 5, 2024.
- >35,000 unique IP addresses from over 160 countries have accessed the 2024 Scorecard.
- New for the 10th Edition:
  - New Top Performer category for hail: modules that didn't experience glass breakage (or major visual defects/wet leakage failures) with ≥40 mm hail.
  - Higher bar for LID+LETID Top Performers.
  - Better recognition of manufacturers who are Top Performers in multiple categories.
  - Deep dive into Kiwa PVEL's industry leading IAM test.

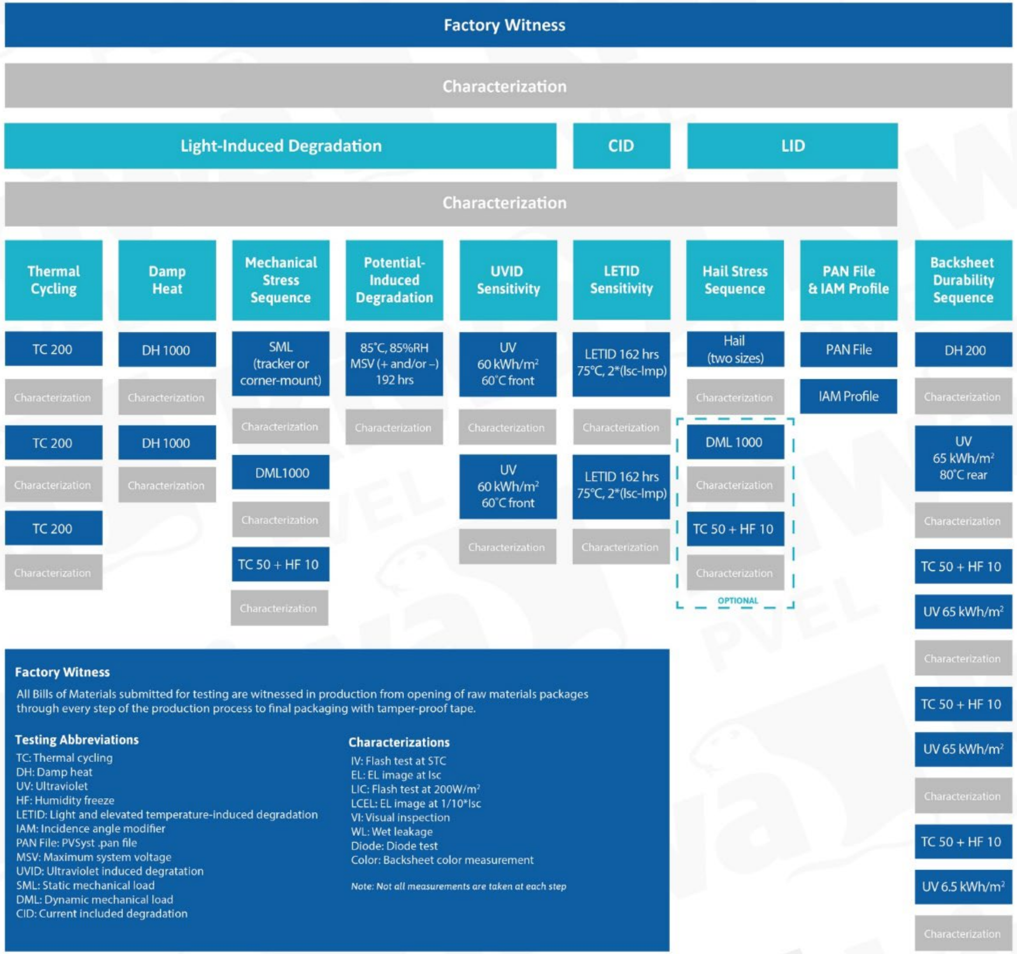
kiwa PVEL

Methodology: 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.

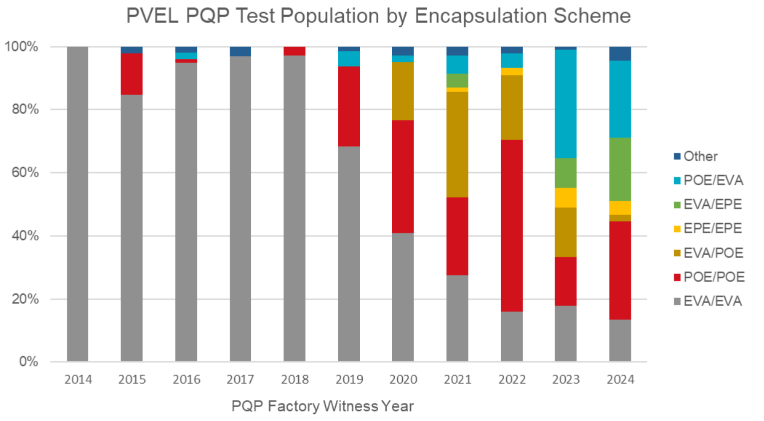
Learn more about the current version of the PQP test plan at kiwa.com/pvel/pqp.

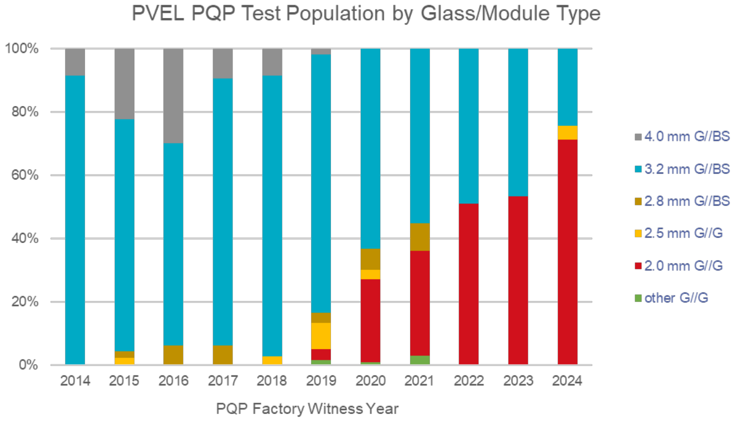


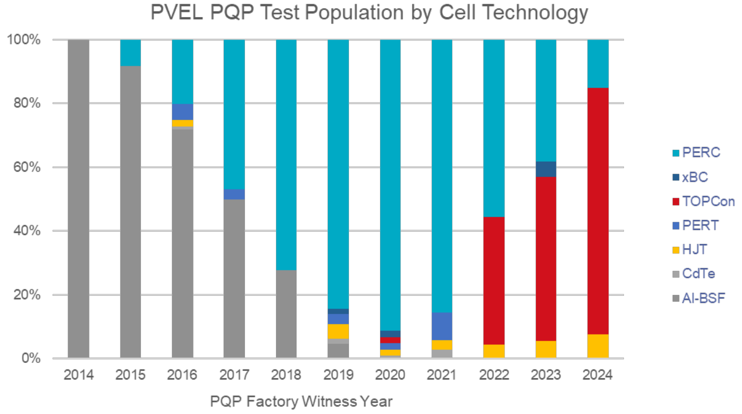
kiwa PVEL

Methodology: PQP Test Population Trends

- Our data benchmark uses the entire PQP population over the 2021 Q3 – 2024 Q3 period.
  - Growing share of G//G module construction (>70% in 2024).
  - Effervescent diversification in encapsulation strategy.
  - Growing share of TOPCon modules (>75% in 2024), limited number of HJT and xBC BOMs.





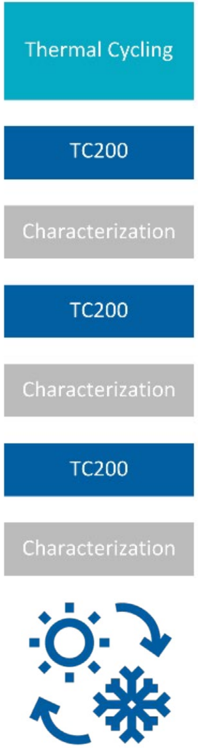


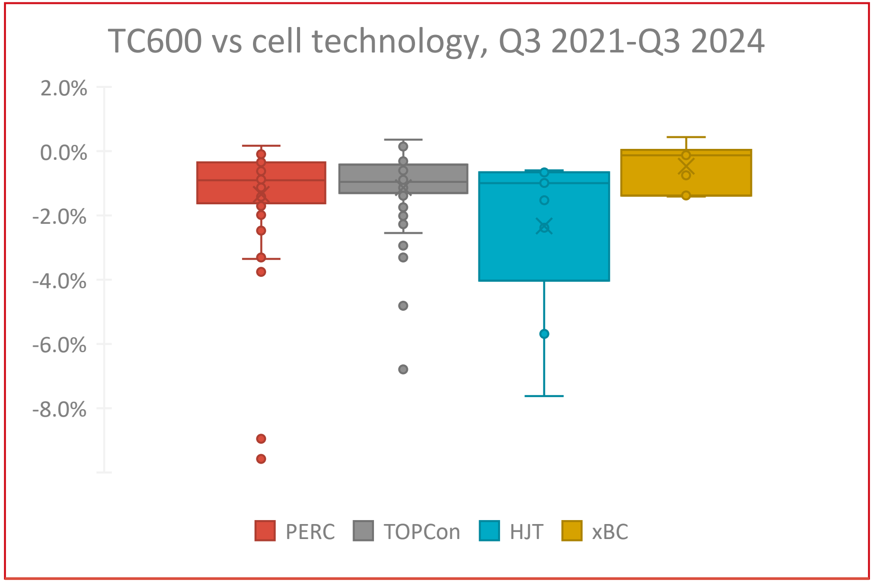
Benchmark of xBC Technology in Historical PQP Test Results

kiwa PVEL

We Create Trust

Thermal Cycling Results



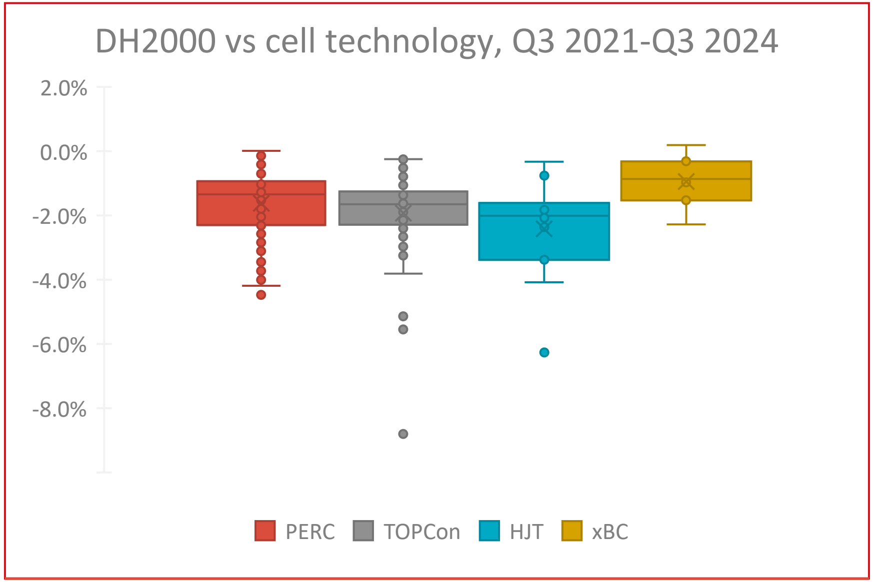


	PERC	TOPCon	HJT	xBC
P50	-0.90%	-0.95%	-0.99%	-0.13%
P90	-3.06%	-2.20%	-6.07%	-1.39%
Count	64	64	9	7*

- Modules are subjected to 600 temperature cycles from -40°C to +85°C.
  - Identify cell soldering issues, failed diodes, burnt connectors, or j-box open solder bonds.
- Pmpp degradation post-TC600:
  - Similar median degradation ~1.0% for incumbent PERC and n-type technologies.
  - Larger spread for HJT, but outliers observed for all technologies.
  - xBC designs seems to outperform, with median degradation ~0.1% and no failures observed until today.

* For xBC BOMs, coverage date extends to 2020 Q1

Damp Heat Results



	PERC	TOPCon	HJT	xBC
P50	-1.35%	-1.65%	-2.01%	-0.86%
P90	-3.05%	-2.93%	-4.08%	-1.83%
Count	80	86	11	7

- Module are subjected to +85°C and 85% relative humidity for 2000 hours.
  - Reveals cell sensitivity to corrosion, delamination and j-box insulation issues.
- Pmpp degradation post-DH2000:
  - Overall, incumbent PERC performs better with median degradation ~1.4%, compared to TOPCon ~1.7%, and HJT ~2.0%.
  - Again, outliers observed for each technology, stressing importance of BOM.
  - xBC designs seems to outperform, with median degradation ~0.9% and no failures observed until today.

Damp Heat Results – G//B vs G//G, does it matter?

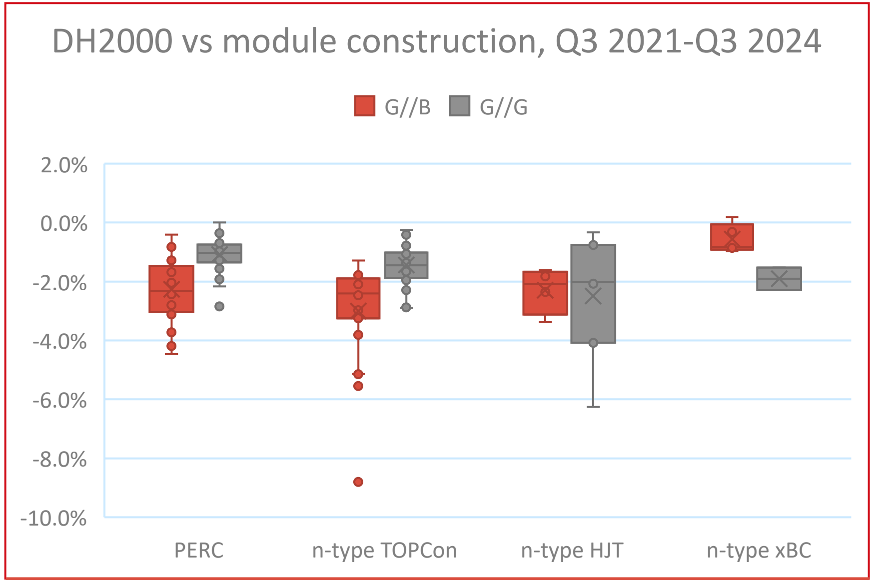
Damp Heat

DH1000

Characterization

DH1000

Characterization



	PERC	TOPCon	HJT	xBC
P50 (G//B)	-2.3%	-3.0%	-2.3%	-0.6%
P50 (G//G)	-1.1%	-1.4%	-2.5%	-1.9%
Count	36/44	27/59	4/7	5/2

- Power Pmpp degradation ~2 times lower for G//G module construction, similar observation for PERC and TOPCon cells.
  - TOPCon cell sensitivity to moisture ingress similar as expected for PERC.
  - High relevance of metallization paste and encapsulation choices
- No clear trend for HJT and Back-Contact cells, but limited sample size.
  - Some robust G//G construction with water ingress prevention measures did perform poorly.

kiwa PVEL

Mechanical Stress Sequence Results

Mechanical Stress Sequence

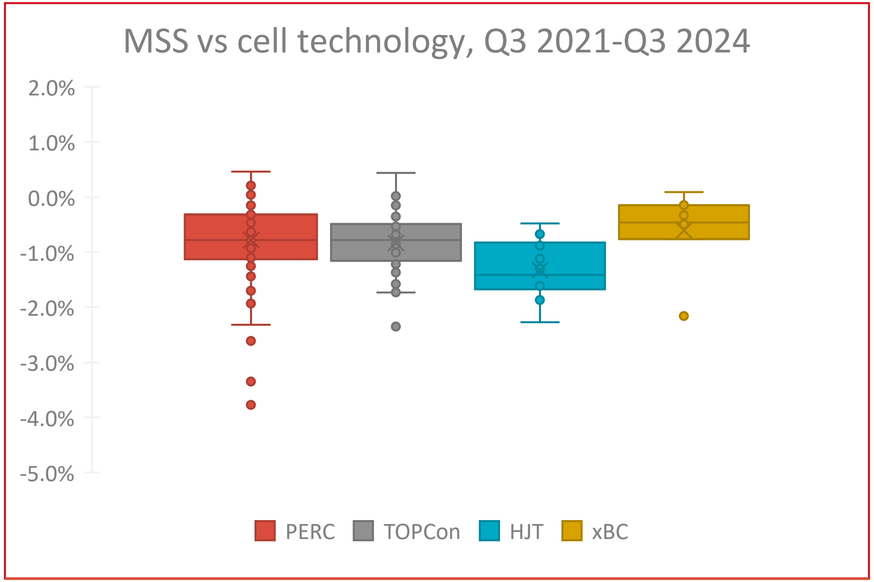
SML
(tracker or corner mount)

DML1000

Characterization

TC50 + HF10

Characterization



	PERC	TOPCon	HJT	xBC
P50	-0.78%	-0.78%	-1.41%	-0.46%
P90	-1.63%	-1.50%	-1.91%	-1.32%
Count	89	89	10	7

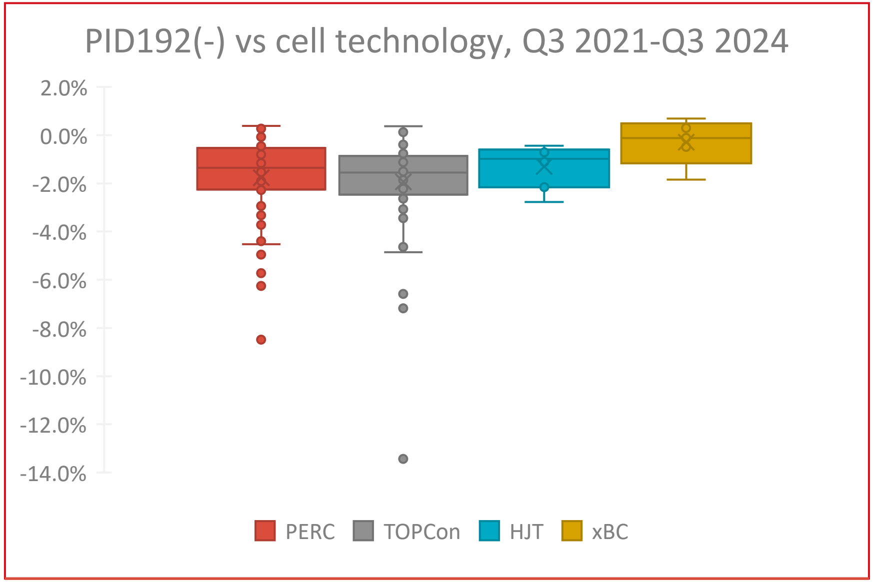
- Static ML followed by DML test with 1,000 cycles of loading at ±1,000 Pa.
  - Reveals mechanical strength of the cell and interconnects interface, structural stability of glass and frame.
  - 4-point clamp mounting (2400Pa) until 2023, tracker mounting (1800Pa) since 2024.
- Pmpp degradation post-MSS:
  - Similar mechanical performance for PERC, TOPCon and xBC technologies, P50 < 1.0%.
  - HJT modules slightly underperforming, with difference mostly driven by final TC50/HF10 stress exposure.

Potential Induced Degradation Results

Potential Induced Degradation

85°C, 85% RH
MSV (+ and -)
192 hours

Characterization



	PERC	TOPCon	HJT	xBC
P50	-1.36%	-1.56%	-0.98%	-0.12%
P90	-4.06%	-3.17%	-2.28%	-1.31%
Count	76	79	9	5

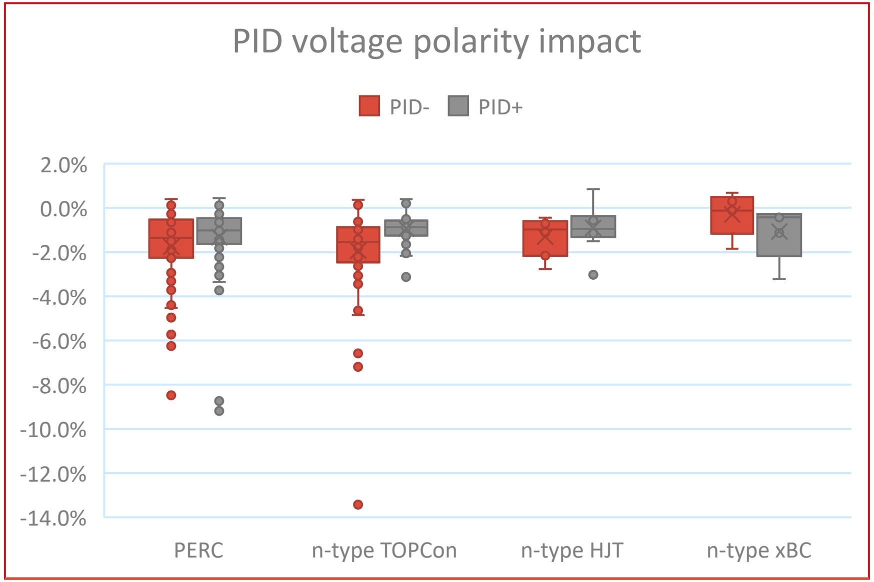
- Modules are subjected to +85°C, 85% relative humidity and maximum system voltage [(-) or (+)] for 192 hours.
- Pmpp degradation post-PID(-):
  - Similar performance for PERC and TOPCon.
  - Multiple occurrences of PID-p (polarization) draw down P90 results.
  - Better performance of HJT (median loss 1.0%) and xBC (median loss 0.1%) BOMs, without any observed outliers.
  - HJT degradation mostly driven by FF-Rs, hinting to different degradation pathway.

Potential Induced Degradation Results – Voltage polarity impact

Potential Induced Degradation

85°C, 85% RH
MSV (+ and -)
192 hours

Characterization



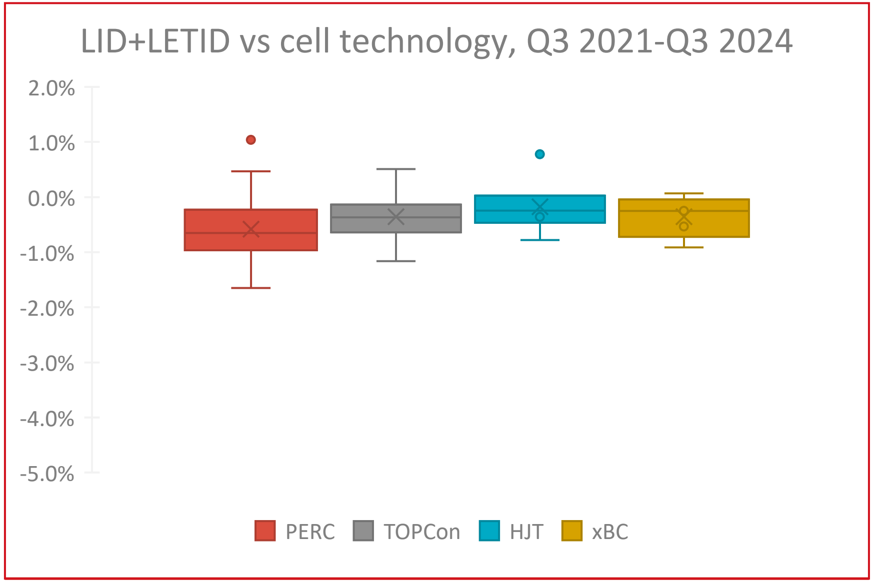
	PERC	TOPCon	HJT	xBC
P50 (PID-)	-1.4%	-1.6%	-1.0%	-0.1%
P50 (PID+)	-1.0%	-0.9%	-1.0%	-0.4%

- Pmpp degradation post-PID:
  - PID(+) degradation in general lower for both PERC and TOPCon.
  - Reduced occurrences of PID-p for TOPCon in PID(+) testing, possibly higher resistance of n-type designs.
  - Back-contact BOMs tested showing slightly higher sensitivity in PID(+).

kiwa PVEL

LID and LETID Results

- LID
- Light Soaking ≥ 40 kWh/m²
- Characterization
- LETID Sensitivity
- LETID 162 hrs 75°C, 2* (Iscp- Imp)
- Characterization
- LETID 162 hrs 75°C, 2* (Iscp- Imp)
- Characterization



	PERC	TOPCon	HJT	xBC
P50	-0.74%	-0.37%	-0.25%	-0.25%
P90	-1.46%	-0.75%	-0.57%	-0.76%
Count	58	42	6	5

- LID: 17 modules exposed outdoor to >40kWh/m² light-soak.
- LETID: 2 modules are subjected to 75°C with a low current injected for 324 hours.
- Pmpp degradation post-LID+LETID:
  - Worst performance for PERC (Ga doped),with ~0.4% median loss, twice high than TOPCon.
  - HJT and xBC mostly insensitive to LID and LETID (median loss ~0.3%) BOMs, no observed outliers.

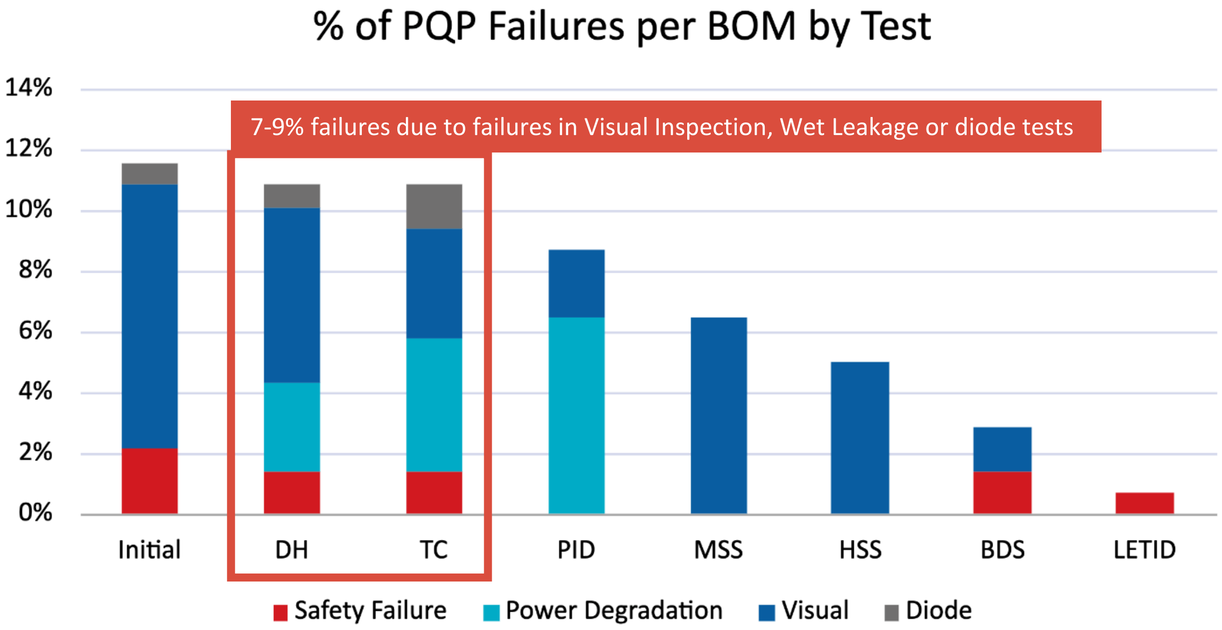
Diving into Failure Modes

kiwa PVEL

We Create Trust

Failure statistics from 2024 Scorecard

- Significant share of failures being “technology agnostic”, i.e. equally relevant for Back-contact designs

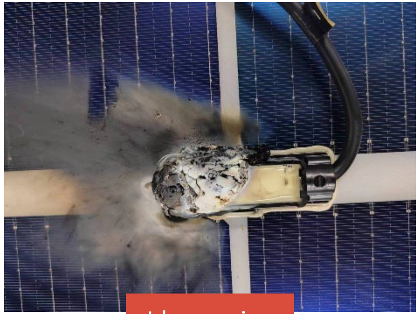


Thermal Cycling Failure Modes

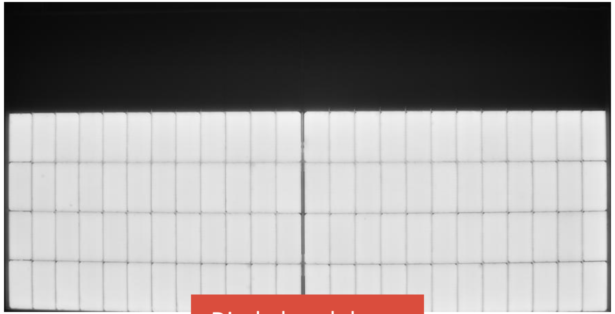
- Thermal Cycling
- TC200
- Characterization
- TC200
- Characterization
- TC200
- Characterization

*Non-exhaustive list

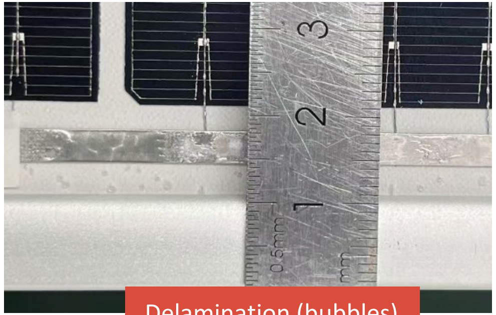
Failure Mode*	Description	xBC specific?	Observed in PQP
Burnt connector	Increased contact resistance due to fretting, or connector mismatch	No	Yes
J-box open solder bond (arcing)	Improper j-box design or sub-quality soldering process	No	Yes
Diode thermal breakdown	Thermal failure of diode, when switching between forward and reverse conditions. J-box design (thermal dissipation) or diode specs issue	No	Yes
Cell-interconnect solder fracture	Improper stress relieve design (adjacent cells or adjacent solder pads)	Yes	Yes
Parasitic leakage current	Current crowding between Metal Wrap Through holes and bulk	Yes (MWT)	No
Cell string solder bond failure	Improper stress relieve design or sub-quality soldering process	Yes	Yes
Delamination	Material compatibility or process issue, continuous bubbles path leading to sub-standard creepage distances	No	Yes



J-box arcing



Diode breakdown



Delamination (bubbles)

Thermal Cycling Failure Modes

Thermal Cycling

TC200

Characterization

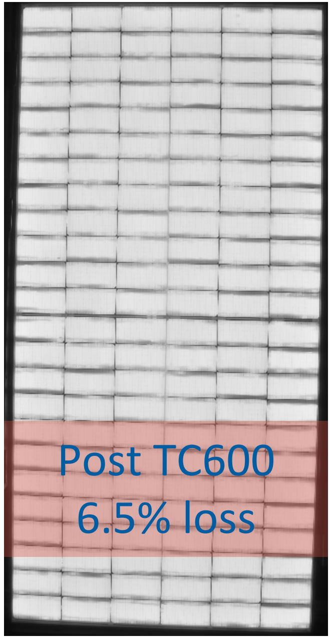
TC200

Characterization

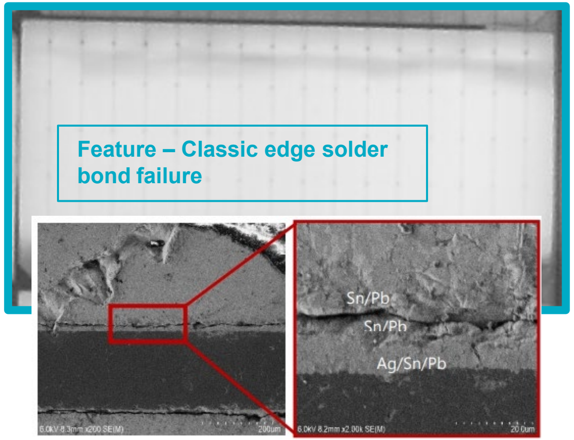
TC200

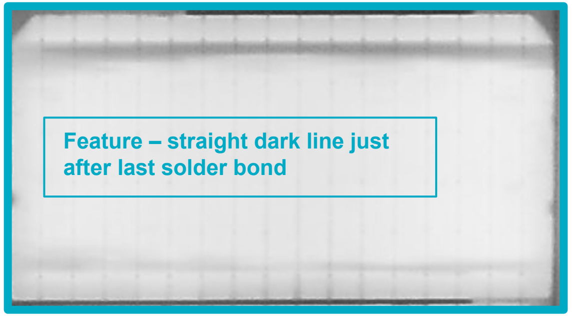
Characterization

Failure Mode	Description	xBC specific?	Observed in PQP
Cell-interconnect solder fracture	Improper stress relieve design (adjacent cells or adjacent solder pads)	Yes	Yes



- Two common signatures observed post-TC for front contact cell designs:
  1. Facture in cell edge solder bonds (between adjacent cells)
  2. Interruption of metallization fingerprints at proximity of cell edge solder bonds



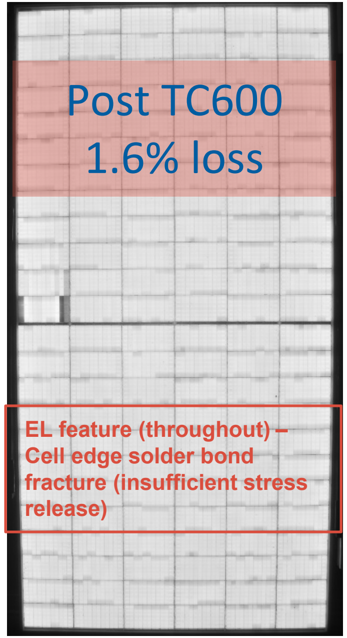


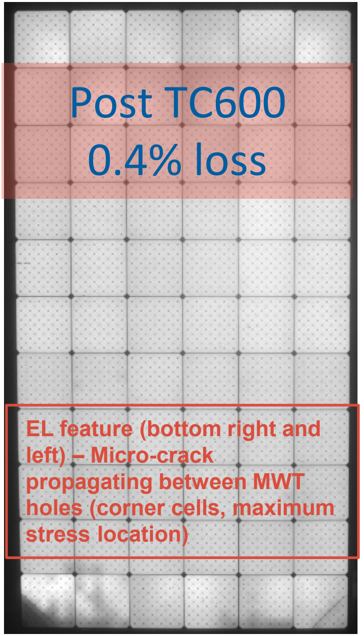
kiwa PVEL

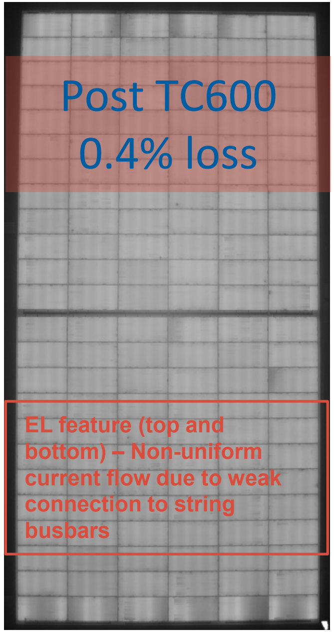
Thermal Cycling Failure Modes – xBC specific examples

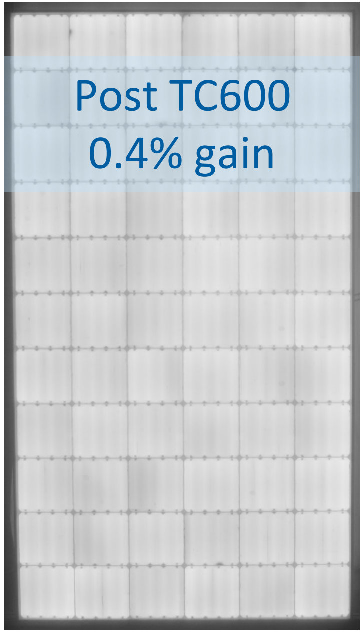
- Thermal Cycling
- TC200
- Characterization
- TC200
- Characterization
- TC200
- Characterization

Failure Mode	Description	xBC specific?	Observed in PQP
Cell-interconnect solder fracture	Improper stress relieve design (adjacent cells or adjacent solder pads)	Yes	Yes









Damp Heat Failure Modes

Damp Heat

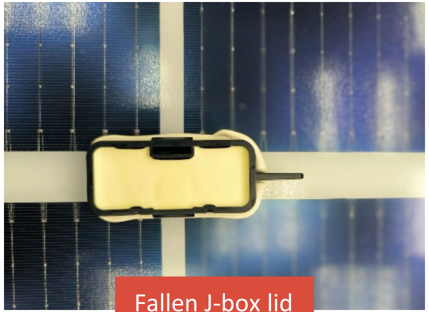
DH1000

Characterization

DH1000

Characterization

Failure Mode	Description	xBC specific?	Observed in PQP
Cell metallization corrosion (fingers)	Reaction of lead oxide with acetic acid from encapsulant, usually happening at the cell edge, led to disconnection of fingers from Si	Possibly	Yes
Cell metallization corrosion (busbars)	Chemical of galvanic corrosion of fingers and busbars connection	No	Yes
Delamination	Material compatibility or process issue, continuous bubbles path leading to sub-standard creepage distances	No	Yes
Encapsulation material yellowing	Material incompatibility or encapsulation recipe (instable additives)	No	Yes
Glass ARC coating degradation	Damages of glass ARC due to moisture	No	Yes
Loss of cell passivation (thermal activation of defect centers)	Increase in front or rear surface recombination under temperature stress, various mechanisms (i.e. LID, LETID…)	No	Yes
Backsheet bubbles and cracking	Degradation of mechanical properties (i.e. adhesion intra-layers)	No	Yes
Junction box or connector swelling		No	Yes



Fallen J-box lid

Glass/encapsulant delamination

Encapsulant yellowing

kiwa PVEL

Damp Heat Failure Modes

Failure Mode	Description	xBC specific?	Observed in PQP
Cell metallization corrosion (fingers)	Reaction of lead oxide with acetic acid from encapsulant,	Possibly	Yes
Cell metallization corrosion (busbars)	Chemical of galvanic corrosion of fingers and busbars connection	No	Yes

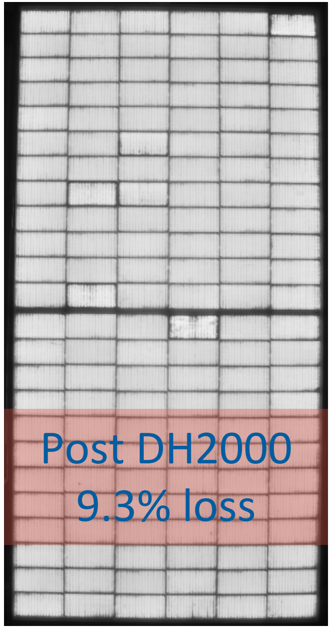
Damp Heat

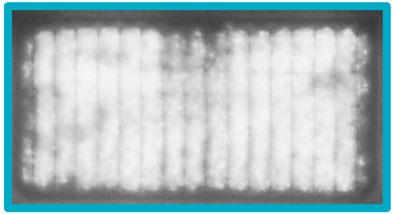
DH1000

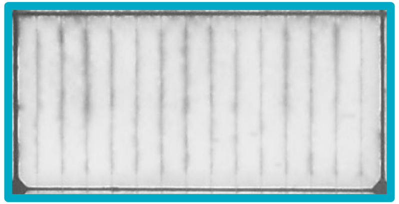
Characterization

DH1000

Characterization







- Three common corrosion signatures observed post-DH for front contact cell designs:
  1. Corrosion of cell fingerprints around cell perimeter (observed on module perimeter for G//G designs), typical for PERC/TOPCon.
  2. Electro-chemical corrosion of cell fingerprint at the connection with busbars, involving solder flux.
  3. Darkening between busbars, possibly due to corrosion of ITO layer (HJT specific) or damages on rear metallization (TOPCon), possibly involving contaminants.

kiwa PVEL

Damp Heat Failure Modes – xBC specific examples

Failure Mode	Description	xBC specific?	Observed in PQP
Cell metallization corrosion (fingers)	Reaction of lead oxide with acetic acid from encapsulant,	Possibly	Yes
Cell metallization corrosion (busbars)	Chemical of galvanic corrosion of fingers and busbars connection	No	Yes

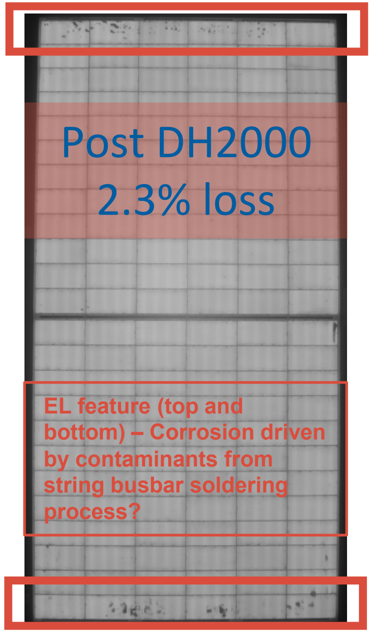
Damp Heat

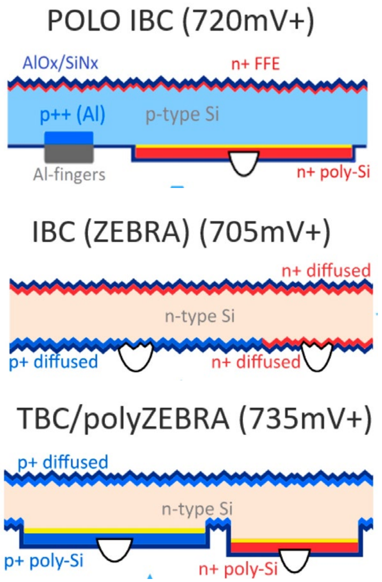
DH1000

Characterization

DH1000

Characterization





- Three common corrosion signatures observed post-DH for front contact cell designs:
  1. Corrosion of cell fingerprints.
  2. Electro-chemical corrosion of finger/busbars connections.
  3. Contaminants-driven corrosion mechanisms (Na+).
- Expect the same corrosion modes possible for xBC cells depending on topology, observed modes 2&3 in past projects, to lesser extent.

kiwa PVEL

Damp Heat Failure Modes – xBC specific examples

Damp Heat

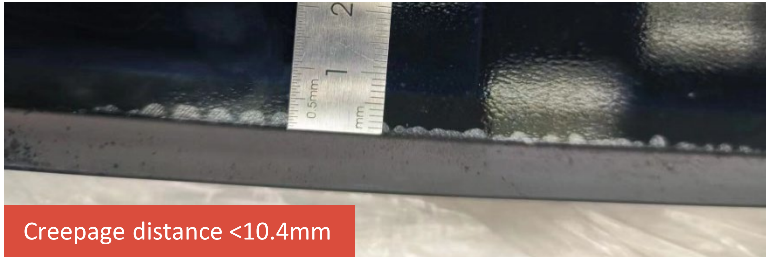
DH1000

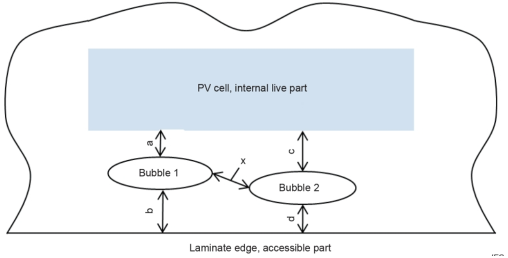
Characterization

DH1000

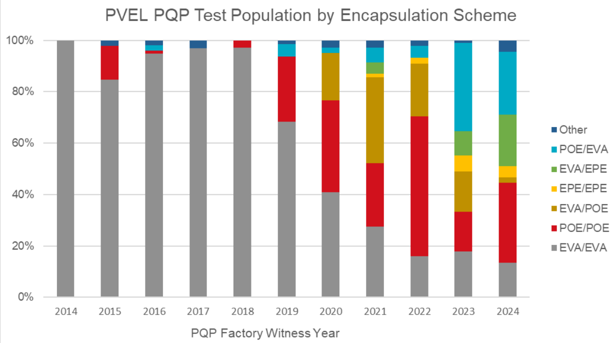
Characterization

Failure Mode	Description	xBC specific?	Observed in PQP
Delamination	Material compatibility or process issue, continuous bubbles path leading to sub-standard creepage distances	No	Yes





- Highly sensitive n-type cell designs require more sophisticated encapsulation strategy.
- Not specific to xBC technology: delamination risk increasingly significant.



Mechanical Stress Sequence Failure Modes

Mechanical Stress Sequence

SML (tracker or corner mount)

DML1000

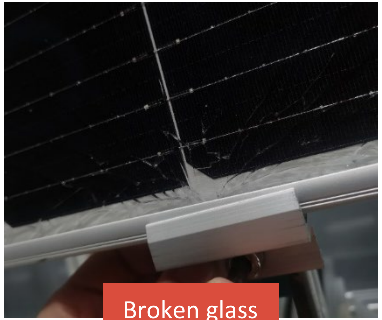
Characterization

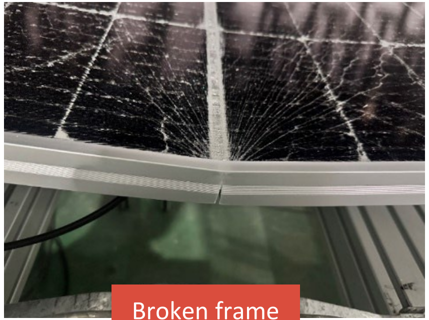
TC50 + HF10

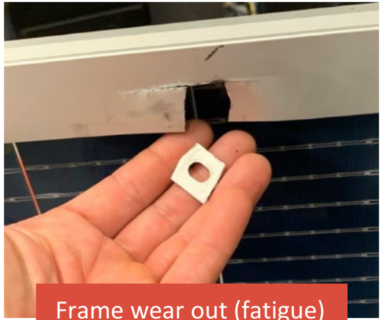
Characterization

*Non-exhaustive list

Failure Mode*	Description	xBC specific?	Observed in PQP
Structural failure, broken glass	Local stress exceeding glass bending strength, or failure upon contact with tracker subjacent structure	No	Yes
Structural failure, broken frame	Local stress exceeding frame yield strength or quality issue	No	Yes
Structural failure, module pulled out from clamps	Installation manual incorrect guidance or design issue	No	Yes
Laminate loss of adhesion	Inappropriate module deflection or quality issue with silicon seal	No	Yes
Cell micro-crack	Cell quality or process issue (i.e. PERC holes laser opening)	Possibly	Yes
Delamination	Material compatibility or process issue, continuous bubbles path leading to sub-standard creepage distances	No	Yes
Fatigue failure of mounting points	Too aggressive frame design or inappropriate fastener guidance	No	Yes


Broken glass


Broken frame

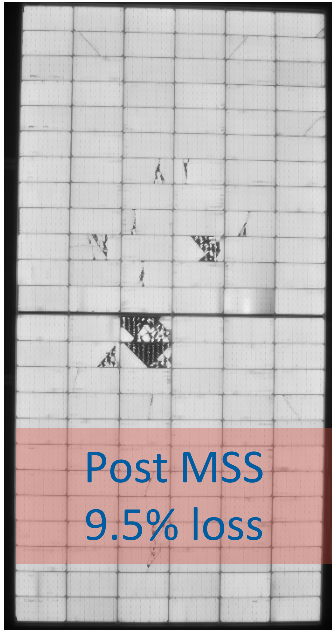

Frame wear out (fatigue)

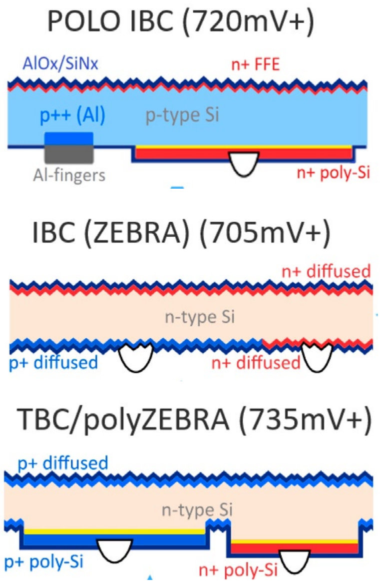

Laminate loss of adhesion

Mechanical Stress Sequence Failure Modes

- Mechanical Stress Sequence
- SML (tracker or corner mount)
- DML1000
- Characterization
- TC50 + HF10
- Characterization

Failure Mode	Description	xBC specific?	Observed in PQP
Cell micro-crack	Cell quality or process issue (i.e. PERC holes laser opening)	Possibly	Yes





- Most common issues in recent years related to structural failures, either frame of glass:
  - Up to 7% BOMs with structural failure.
- Some PERC and TOPCon BOMs with high power loss when mounted on trackers.
- For xBC cells used in G//B construction, careful attention required given the non-symmetry and potential use of laser contact opening processes.

kiwa PVEL

Potential Induced Degradation PID Failure Modes

Potential Induced Degradation

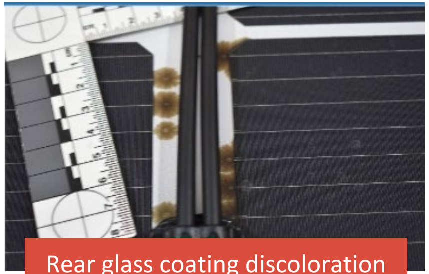
85°C, 85% RH
MSV (+ and -)
192 hours

Characterization

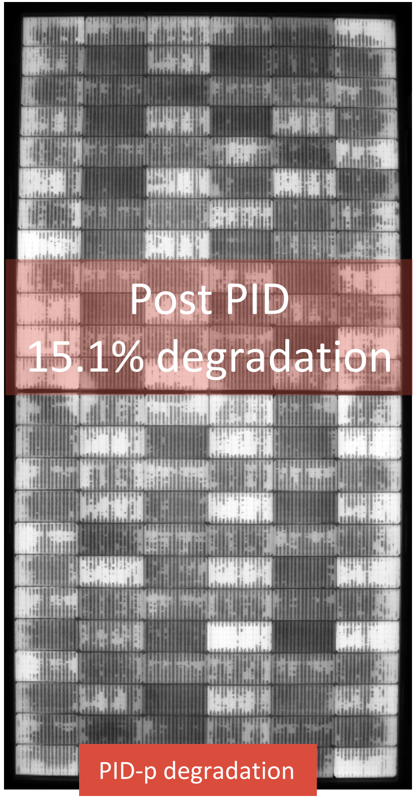
*Non-exhaustive list

Failure Mode*	Description	xBC specific?	Observed in PQP
PID-s shunt creation	Shunting of local pn junction by Na+ ions migrating from glass	No	Yes
PID-p polarization	Decrease of passivation efficacy at interface between passivation stack/silicon, due to charge accumulations in AlOx layer	Possibly	Yes
PID-c corrosion	Hole-like damage to AlOx passivation stack	No	No?
J-box loss of adhesion	J-box silicon sealant to glass adhesion failure	No	Yes
Rear glass white grid discoloration	Chemical reaction between glass enamel coating and string ribbons, black dots	No	Yes

J-box loss of adhesion



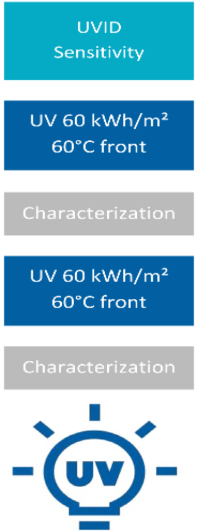
Rear glass coating discoloration

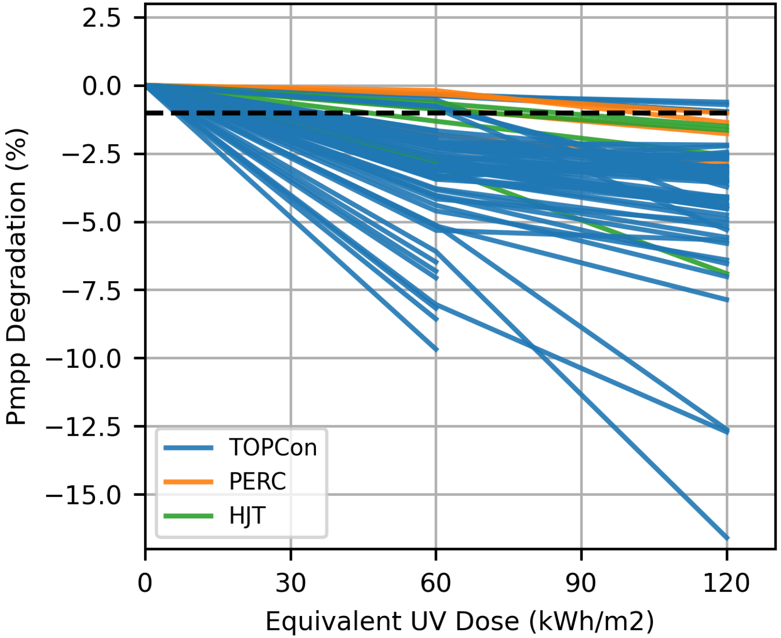


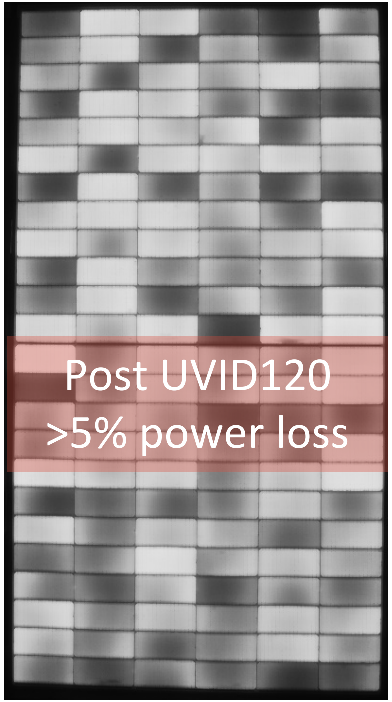
PID-p degradation

- PID-p(+) to remain highly relevant for all n-Type xBC cell structures.

UVID Failure Modes







- More on UVID here: www.kiwa.com/us/en/kiwa/entities/pvel/news/ieee-pvsc-presentation-and-poster/

UVID Failure Modes

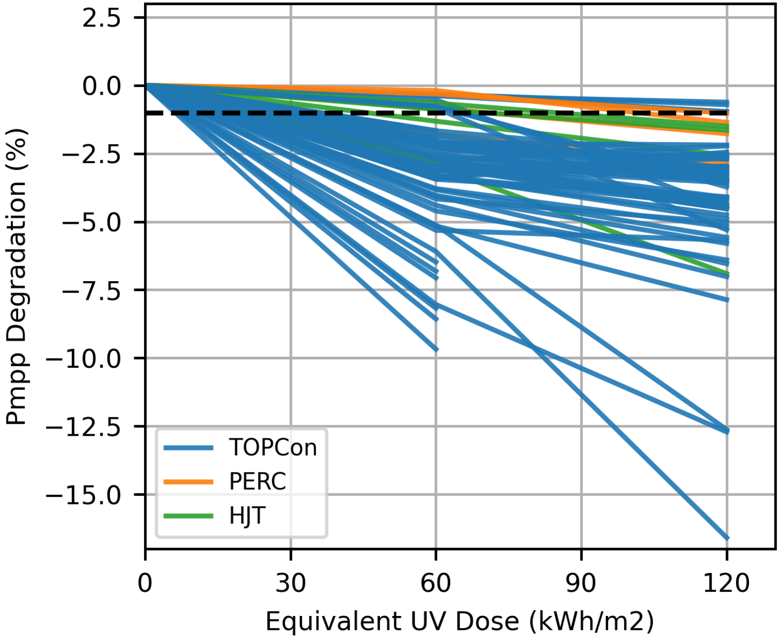
UVID Sensitivity

UV 60 kWh/m² 60°C front

Characterization

UV 60 kWh/m² 60°C front

Characterization



- 33 BOMs evaluated, 2 modules per BOM.
  - 86% were n-type TOPCon modules.
  - Power loss ranged from -0.9% to -16.6%.
  - Only 25% BOMs showed <3% power loss.
  - Voc is the most affected parameter (attributed to passivation loss), followed by Isc and FF.
  - Different UVID failure modes occurring concurrently.
- UVID-stable TOPCon BOMs are possible.
  - Some BOMs show quasi-stabilization after UVID60.
- n-type HJT and p-type PERC modules showed moderate power loss (2-7%), sample size is limited.

- No UVID data on xBC modules yet, but failure mode highly relevant for Back-contact cells, given similar front side passivation stacks being used.

Kiwa PVEL

Quick glance at key Performance Metrics

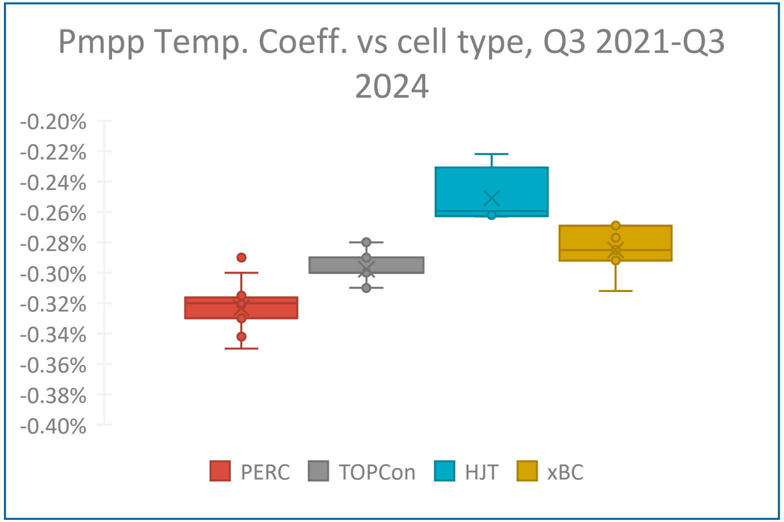
We
Create
Trust

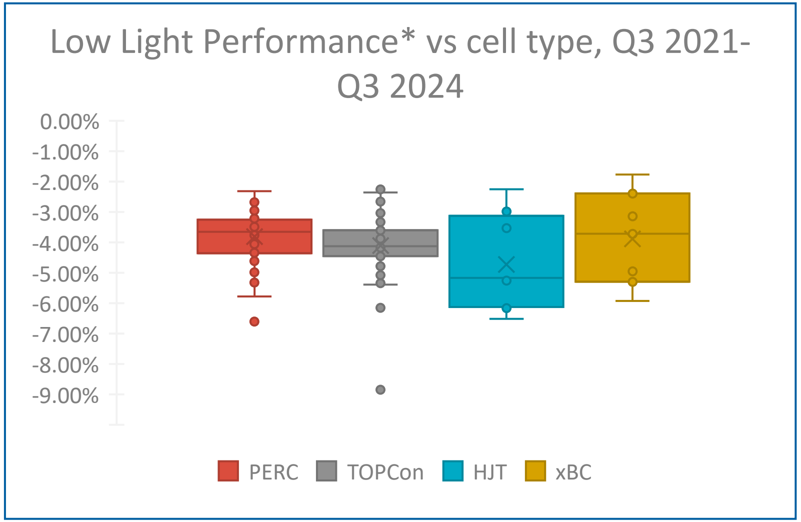
PAN Results

PAN Files & IAM Profile

Pan File

IAM Profile



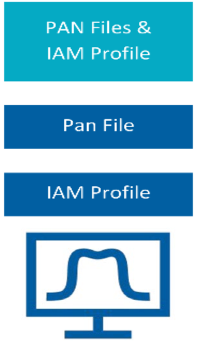


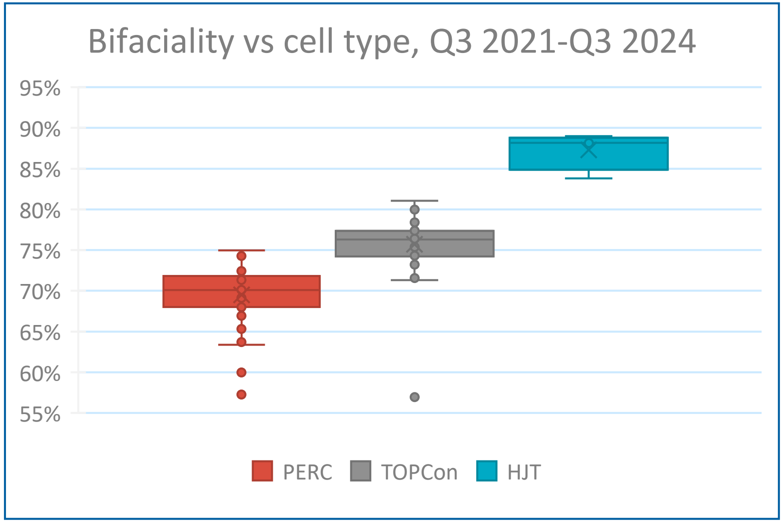
*relative efficiency deviation at 200 vs. 1000 W/m^2

	PERC	TOPCon	HJT	xBC
P50	-0.32%	-0.30%	-0.26%	-0.29%
P90	-0.33%	-0.31%	-0.26%	-0.30%
Count	48	43	4	7

	PERC	TOPCon	HJT	xBC
P50	-3.7%	-4.1%	-5.2%	-3.7%
P90	-4.9%	-4.9%	-6.3%	-5.5%
Count	90	83	8	7

PAN Results (cont.)





	PERC	TOPCon	HJT	xBC
P50	70.1%	76.3%	88.2%	/
P90	65.5%	73.2%	85.1%	/
Count	55	70	4	2

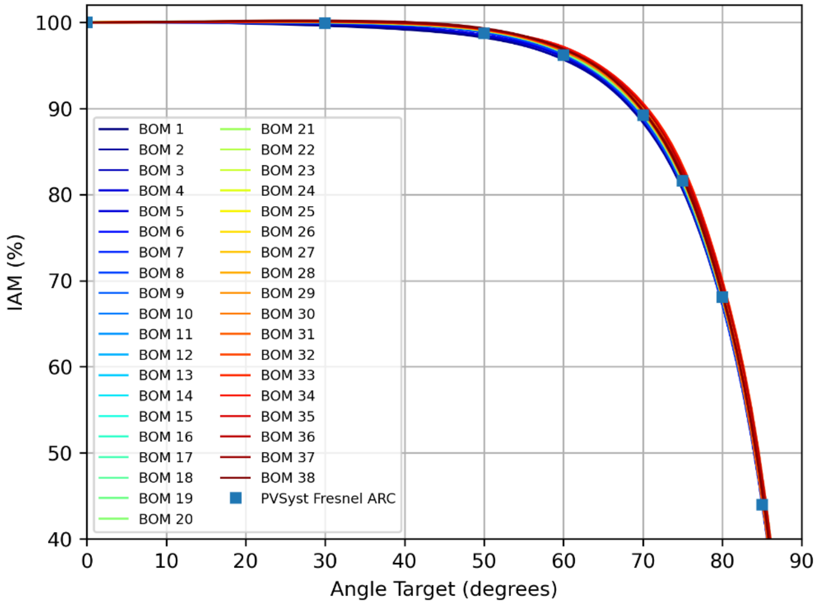
- Modules (3) tested per IEC 61853-1, conditions ranging in irradiance from 100 W/m^2 to 1,100 W/m^2 and in temperature from 15°C to 75°C.
  - Median Pmpp temperature coefficients stable: −0.26 %/°C (HJT), −0.30 %/°C (TOPCon), −0.32 %/°C (PERC), **xBC comparable to TOPcon**.
  - Median low-light relative efficiency (200W/m^2): comparable results for PERC and **xBC (96.3%)**, decreasing trend for TOPCon (95.9%). Large variations for HJT (median 94.9%).
  - Bifaciality factor: PERC results consistent with general datasheet values (median 70.1%), TOPCon aggressive (76.3% / 80% datasheet), HJT conservative (88.2% / 85% datasheet). **Only two xBC results, widely different (39% vs 69%)**.

IAM Results

PAN Files & IAM Profile

Pan File

IAM Profile



- Modules (3) tested per IEC 61853-2, to assess performance losses under 0-85° incidence angles.
  - A typical module outperforms the PVsyst Fresnel ARC default by a median of 0.17%.
  - The highest performing BOM had a modelled energy yield 0.52% higher than the lowest performing BOM.
- Glass sun-facing front structure (texturing, ARC layer design) drives IAM performance, cell technology impact secondary at best.
- **No significant difference in IAM behavior for xBC modules**.

Takeaways

kiwa PVEL

We Create Trust

Takeaways

- BC modules have potential to be Top Performers in each PQP reliability/performance metrics!
  - Power losses for all BC module BOMs tested so far **below <2.5%, no critical failures** (Visual, Wet Leakage).
  - Sample size still very limited as market is mostly driven by TOPCon.
- Most of the known critical failure modes of PERC/TOPCon technologies remain relevant for BC structures.
  - Cell resistance to PID-polarization, various corrosion mechanisms, and thermo-mechanical stresses driven by similar design (i.e. stress relieve connection), process and BOM decisions (i.e. passivation stack, metallization pastes..)…
  - UVID degradation to be monitored due to increased sensitivity (passivation stack with AlOx layers).
- Potential for new failure modes exists as specific materials/processes are introduced (i.e. insulation pads, new metallization paste chemistries).
- Performance and LCOE wise, IAM, temperature coefficients and low irradiance performance are expected to be inline with TOPCon. For high bifacial gain applications, BC module bifaciality factor still lower than TOPCon, but not far behind!

We Create Trust

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