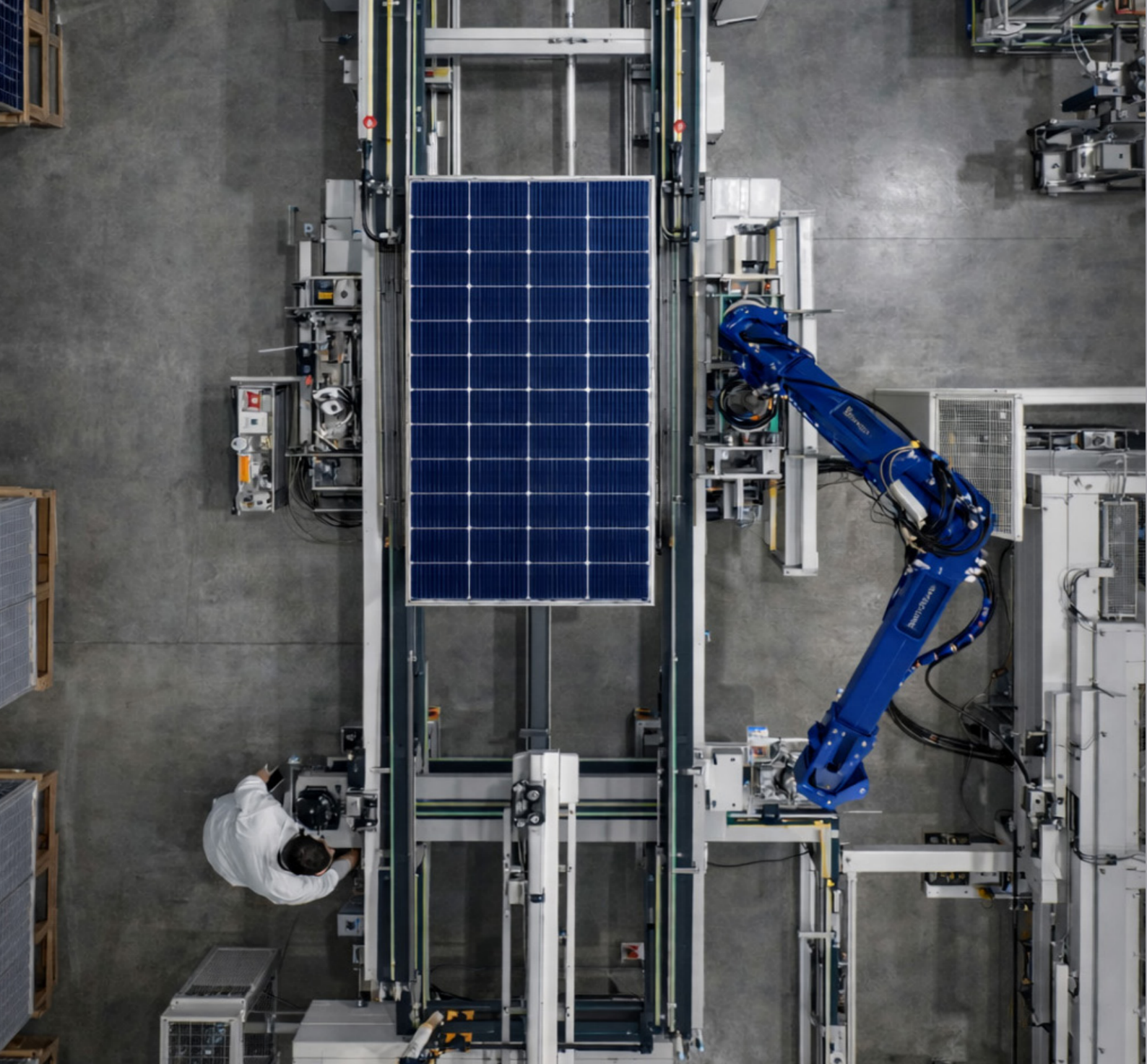


*Trends in
PV Module
Manufacturing
Quality from
Independent
Quality Assurance*

The 2026 **PV Module Manufacturing Quality Report**



kiwa



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Introduction

Across the global photovoltaic (PV) module industry rapid factory expansions, aggressive cost-reduction strategies, and tightening regulatory frameworks are reshaping the manufacturing landscape, while simultaneously amplifying quality risks. Over the past year, Kiwa PI Berlin's in-factory quality assurance and benchmarking data reveal a clear and concerning trend: **non-conformance findings and quality deficiencies are on the rise.**

Building on more than a decade of global quality assurance intelligence, the *2026 PV Module Manufacturing Quality Report* delivers defect categorization of the most critical risk areas observed across production lines and end-of-line module inspections.

This year's findings highlight new defect patterns emerging in high-impact processes. These include: **layup precision, lamination integrity, and junction box assembly**, issues that directly influence module performance, reliability and safety. Batch testing indicates an increase in failures such as potential-induced degradation (PID), highlighting weaknesses in the manufacturer's internal BOM and process controls, which lead to degradation greater than the allowable limit.

Beyond factory-level observations, policy-driven supply chain shifts are introducing wide variability in manufacturing maturity. Across the EU, the Net-Zero Industry Act (NZIA) incentivizes regional production through premium-based tender structures, looking to increase a more diverse supply chain for their countries.

While in the U.S., compliance with Foreign Entity Of Concern (FEOC) provisions increase requirements for bill-of-material (BOM) component traceability, as well as reporting on the manufacturers direct costs. These policies are accelerating geographic diversification toward emerging manufacturing hubs, such as those in Africa and the Middle East. The net impact of this is that new factories produce at a higher defect rate than mature facilities, requiring increased quality diligence.

For buyers and developers, these manufacturing and market dynamics **demand a proactive, data-driven approach to procurement and supplier management.** By leveraging benchmarked quality assurance insights across PV module factories around the globe, procurement experts are able to quickly strengthen their supplier strategies. At first glance, it may seem like quality is back-sliding because of rapid growth, new technology and changing module designs. However, those who integrate robust technical quality assurance diligence during their production can reduce PV plant equipment risk, minimize O&M costs, and strengthen solar PV's position as a backbone of global energy supply.



QUALITY OVER TIME

From 2015 to 2025, Kiwa PI Berlin has observed the impact of technological transitions, manufacturing capacity expansion, and market pressures on product quality across the PV module industry.

Over this period, fluctuations in quality have been driven by both the maturation of existing technologies and the rapid adoption of new ones. As the industry faced emerging challenges (including shifting regulatory policies, increased requirements for supply chain transparency, geographic expansion of manufacturing, and major technology transitions from PERC to TOPCon) defect rates rose notably in 2023 and 2024. As shown in Figure 1, in 2025, the PV module pre-shipment inspection (PSI) non-conformance defect rate reached its highest level at 3.36%. This rise is largely attributed to policy uncertainty in the U.S.

● Percent of BOMs with one or more failures, as reported in the past five PV Module Reliability Scorecards by Kiwa PVEL.

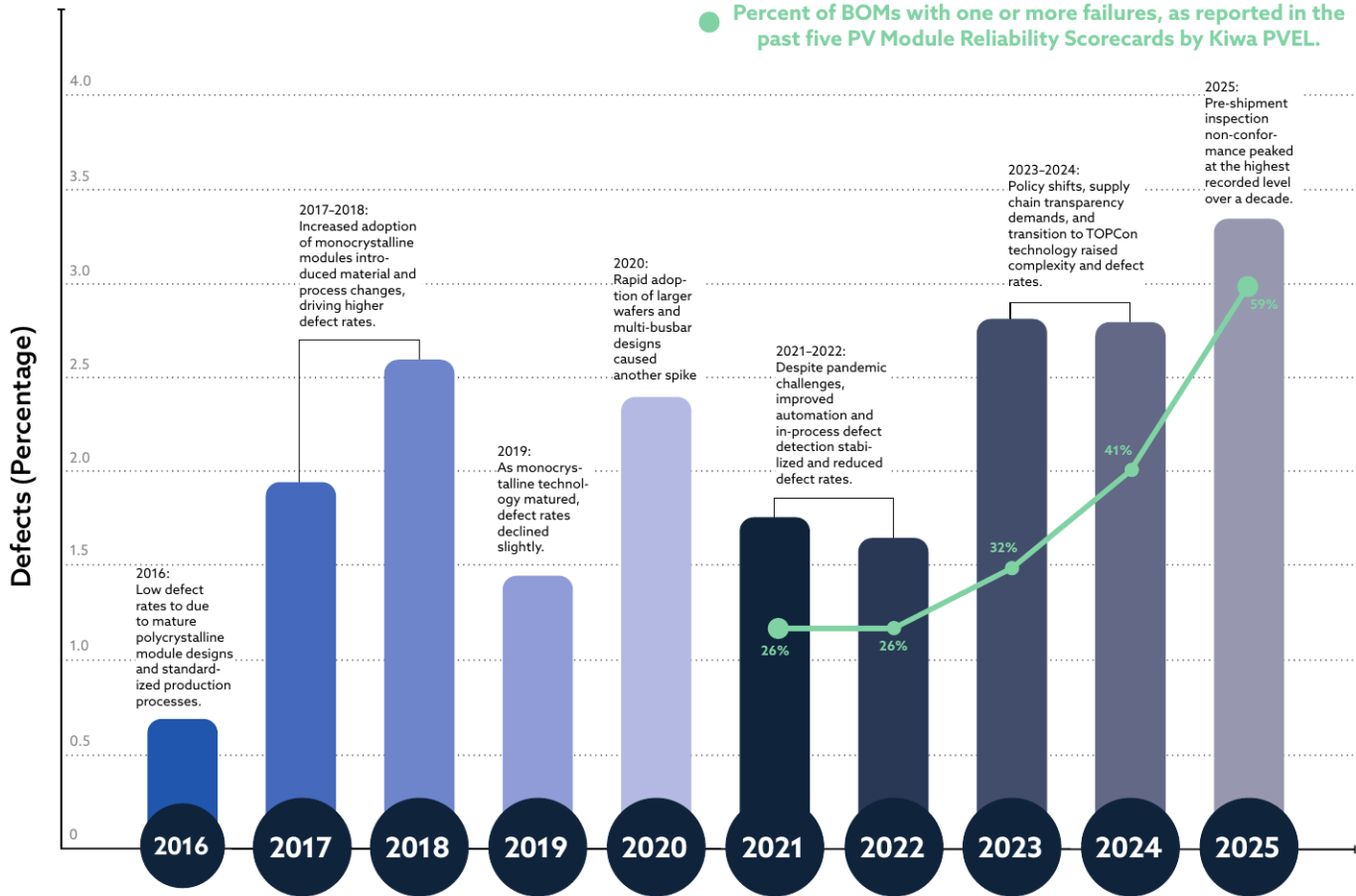


Figure 1: Manufacturing Quality Over Time

solar market including stricter regulatory requirements such as FEOC compliance, increased expectations for supply chain transparency, and the rapid expansion of manufacturing capacity for both PV modules and PV cells in emerging manufacturing hubs such as the U.S. and Africa, where large-scale manufacturing remains relatively nascent.

The increased percentage of BOM testing failures from Kiwa PVEL's PQP and [Scorecard](#) reflects the same trend observed in the factory QA data, as shown in Figure 1. Rising variability in manufacturing processes further compounds these risks. To remain competitive, buyers must strengthen their focus on quality mapping and implement robust controls to ensure their products stand out in the market.

A notable trend in 2025 has been the relocation of manufacturing capacity from Southeast Asia to Africa, driven primarily by the imposition of multiple tariffs on Southeast Asian countries. However, evidence suggests that production ramp-ups in these new regions have faced significant challenges, constrained by inadequate facilities and infrastructure, shortages of experienced engineers and skilled operators, and persistent supply chain disruptions affecting raw materials and equipment spare parts. The uncertainties associated with this shift are expected to persist into 2026 and are likely to continue exerting downward pressure on product quality.

Meanwhile, the solar industry in China is facing intense pricing competition and material costs increases. As profit margins erode, companies have responded by reducing capacity and aggressively cutting operational costs, resulting in layoffs, including the loss of experienced engineers and skilled production personnel. The erosion of technical expertise, combined with unstable production planning, increases manufacturing risk.

Over the past year, a notable area of improvement has been the reduction of defects associated with cell technology.

Findings indicate that cell-related defects in TOPCon production have decreased and are now comparable to those observed in PERC modules, demonstrating measurable improvements in quality (Figure 2). These enhancements are attributed to optimized cell-level design, material modifications, and the accumulation of production expertise and knowledge in manufacturing TOPCon cells.

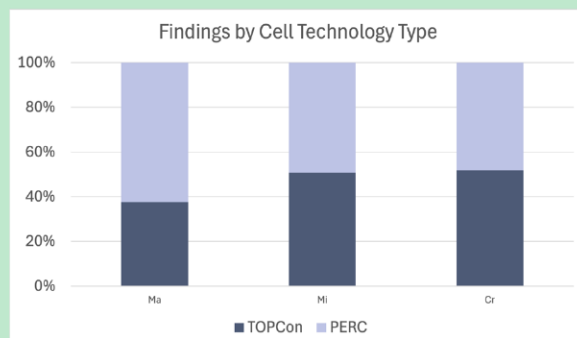


Figure 2: Comparison of cell-related defects findings in TOPCon vs. PERC technologies

Factory Audits

GLOBAL BENCHMARKING

Factory audits are a critical component of due diligence during supplier qualification and remain a crucial tool to evaluate a factory prior to production. Corrective actions implemented as a result of audits play a key role in driving continuous quality improvement throughout subsequent production phases. In 2025, Kiwa PI Berlin conducted 85 benchmarked audits across global PV manufacturing sites, assessing process control, quality systems, and compliance with industry best practices. These audits revealed significant variability in manufacturing maturity, highlighting downstream risks for buyers, investors, and project developers.

Systematic audits provide a transparent, data-driven approach to evaluating supplier performance and mitigating risks from low-quality production. Detailed audit reports enable buyers to move beyond datasheets and certifications, supporting informed supplier selection, AVL development, and risk-based procurement. For investors and project owners, integrating audit results into qualification decisions reduces exposure to long-term operational, performance, and financial risks.

KEY POINTS

- Regional variation matters – U.S. factories show highest critical and major findings; newer regions (Middle East, Africa, Southeast Asia) have a high amount of defects, while Vietnam and Indonesia perform stronger.
- Increase in poor performing factories results with increased severity findings, 21% of factories rated Below Average or Poor; same brand does not guarantee consistent quality across locations.
- High-defect factories should impact quality assurance plan – Multiple major or any critical findings require enhanced inspections and follow-up audits.
- Audit data drives smart procurement – Use benchmarking to build Approved Vendor Lists and reduce long-term reliability and financial risk.

QUALITY RATINGS & FINDINGS

Audit results reveal a wide variation in factory performance. As shown in Figure 3 only a small percentage achieved an Excellent rating, while most fell between Above Average and Average. Notably, 21% were rated as Below Average or Poor, highlighting a persistent risk to long-term reliability that certifications alone may not provide sufficient assurance or fully mitigate.

Non-conformances were classified as Critical, Major, or Minor based on their impact on safety and performance. Kiwa PI Berlin defines a **Critical** finding as one that may create a safety hazard or cause early-life product failure or significant performance loss in the field; **Major** as one that may cause near-term under-performance or more rapid degradation than expected, and **Minor** as one that may cause long-term under-performance or more rapid performance degradation than expected over time.

OVERALL GRADING

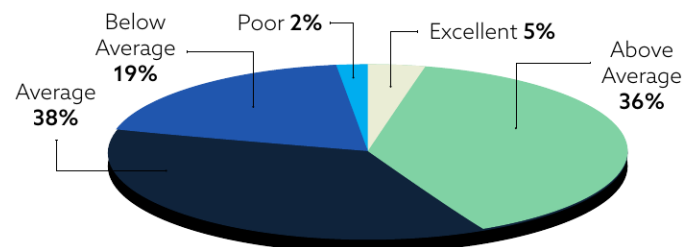


Figure 3: Overall factory results by grade

CASE STUDY

A comparison of audit findings for the same manufacturer operating an established factory in Asia and a newly commissioned U.S. facility illustrates the impact of factory maturity on product risk. Figure 5 summarizes average results from five audits. Despite both sites following the same Quality Management System (QMS), significant variation was observed.

The original factory reported no critical findings and only 2-4 major findings, reflecting stable processes and a mature QMS. Conversely, the U.S. site showed one critical finding, 5-6 major findings, and a notably higher count of minor issues. These gaps underscore common challenges associated with ramp-up, workforce training, process stabilization, and equipment adaptation. Brand consistency does not ensure uniform quality across locations; therefore, routine audits remain essential to confirm compliance, implement corrective actions, and mitigate risks to module reliability, safety, and long-term performance.

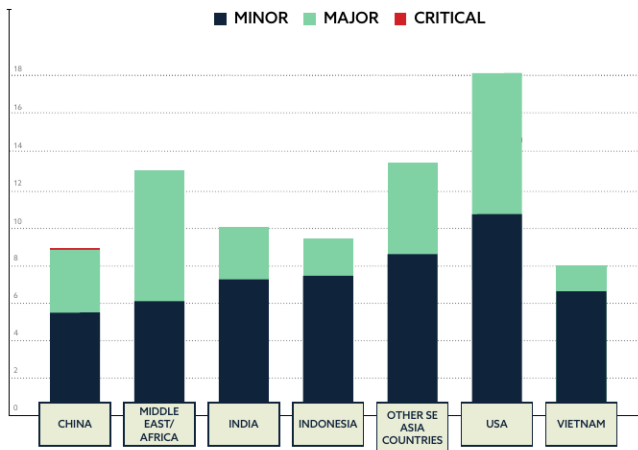


Figure 4: Factory audit findings by category and region

REGIONAL VARIABILITY

A country-level comparison of average findings further highlights regional differences in manufacturing maturity:

- The U.S. stands out with the highest average counts for both major and minor findings, as well as the only region with a notable occurrence of critical findings, indicating that quality is not properly managed.
- Factories in the Middle East, Africa, and other Southeast Asian countries (e.g., Laos, Thailand) exhibit higher average counts of both major and minor findings, reflecting newer manufacturing bases with limited operational history.
- India presents a mixed profile, with moderate findings, suggesting ongoing challenges in process consistency and execution. China shows moderate levels of major and minor findings, consistent with its highly diverse manufacturing base, ranging from advanced Tier 1 facilities to less mature operations.
- Vietnam and Indonesia demonstrate relatively strong performance, with low average counts of major findings and no observed critical findings. This performance reflects more mature production lines, stable workforce training, and well-established quality control systems.

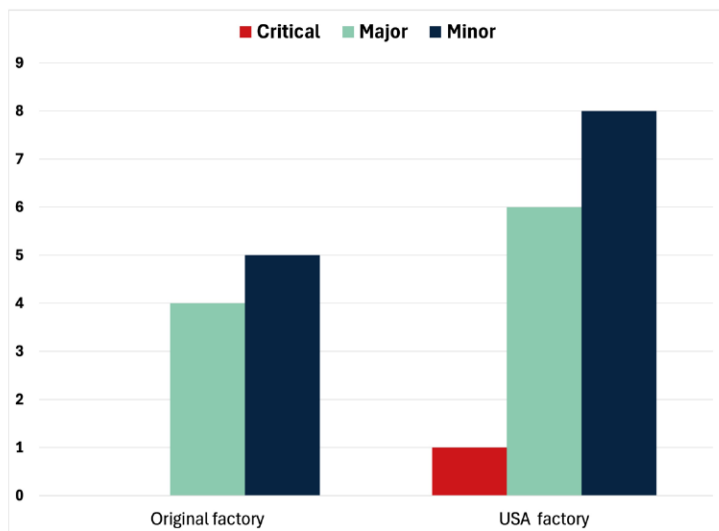


Figure 5: Comparison of findings, original factory vs. U.S. factory

FACTORY AUDIT BENCHMARKING

Figure 6 summarizes audit findings from Kiwa PI Berlin's factory audits over the past year. Each workshop's benchmark rating follows Kiwa PI Berlin's standard methodology, classifying findings by potential impact on product quality, reliability, safety, and end-user risk. Results show wide variation in both number and severity of findings, ranging from fewer than five to thirty per factory, reflecting differences in QMS maturity, process control, and operational discipline.

Using audit findings data as a benchmarking metric enables procurement experts' objective comparison of factories by quality system performance and risk exposure. Factories with high numbers of major and critical findings are considered higher-risk, often correlating with increased field failures, accelerated degradation, warranty claims, and safety issues such as hotspots, insulation breakdown, or fire events. While these products may meet certification at shipment, they are statistically more likely to fail or have poor performance over time. High-risk factories are recommended to undergo increased oversight, PSI, follow-up audits, and verification of corrective actions before product acceptance.

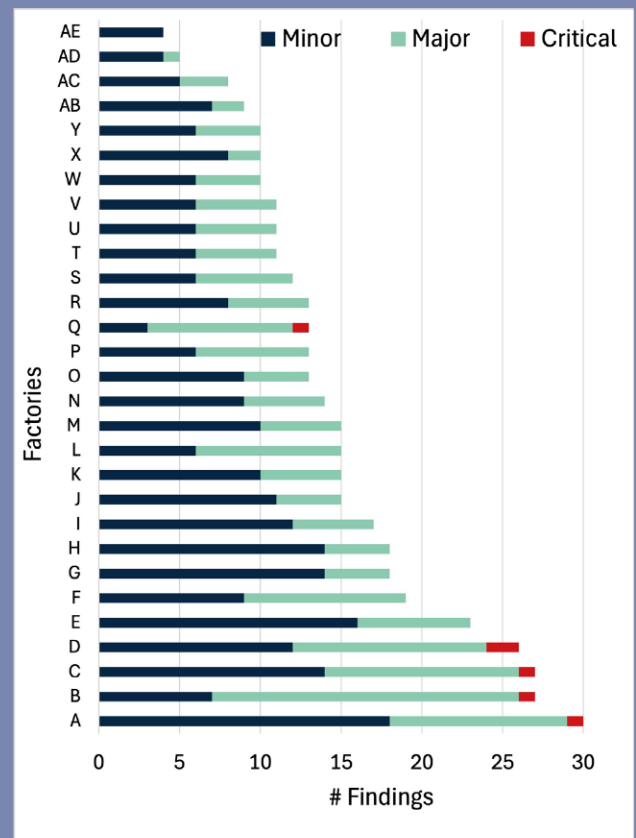


Figure 6: Number of findings by factory.

Production Oversight

Production supervision involves continuous oversight of the entire manufacturing process from initial assembly through final completion, under the guidance of Kiwa PI Berlin's experienced quality assurance engineers. This approach ensures that each stage of production is executed in accordance with defined quality standards. Certain critical assembly processes, such as **cell stringing and lamination**, can have a significant impact on the long-term reliability of PV modules if they are not properly controlled.

As with factory audits, any findings identified during production supervision are classified as critical, major, or minor, depending on their potential impact on module safety, performance, and reliability. All findings are formally reported, and manufacturers are required to implement corrective actions as part of a continuous improvement process. Kiwa's on-site engineers track the status of all findings, monitor open corrective actions through closure, and review the effectiveness and validation of the implemented actions.

Kiwa PI Berlin's engineers have visited and overseen over 5,200 production shifts over the past year. The findings from this comprehensive production oversight have been consolidated to provide an overview of production control practices across PV module manufacturers during this period.

LAYUP PROCESS

The layup process remains a leading category of findings during production oversight. This critical step during assembly involves multiple sequential operations, including glass placement, POE/EVA layering, cell string positioning, cross-conductor soldering, barcode labeling, EVA strip placement, positioning tape application, rear encapsulant and glass placement, and pre-lamination EL testing (see opposite page for process flow).

Due to its complexity, the layup process introduces significant risks such as SOP non-compliance, inadequate monitoring, material control issues, and incorrect equipment settings. Many

KEY POINTS

- Most frequent findings remain in rework, layup, soldering, and junction box (J-box) application - consistent with last year.
- Rework findings decreased from 18.2% to 16.9%, while layup rose slightly to 15.6% and soldering increased to 12.6%.
- Layup issues strongly correlate with PSI defects, including lamination defects (contamination, cracks, bubbles) and cell spacing anomalies.
- TOPCon lines show significant improvement, now comparable to mature PERC lines.
- New production regions, especially the U.S., report higher findings than mature regions and global benchmarks.

final module defects—contamination, cell cracks, spacing errors, bubbles, and delamination originate here, underscoring the need for heightened oversight.

A recurring issue involves equipment qualification or re-calibration after maintenance. Quality teams should verify PV cell string placement accuracy (X, Y, Z axes) and robotic positioning prior to lamination to ensure repeatability within tolerance. Transport after placement is equally critical; vibration or movement before anchoring tape application can displace components, leading to creepage distance violations. Kiwa PI Berlin has documented cases where outer strings shifted under the frame, compromising required clearances.

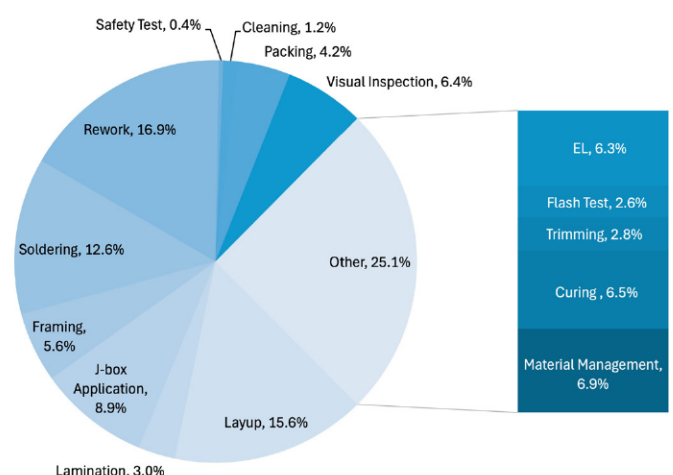


Figure 7: Distribution of oversight findings by process

FACTORY PROCESS

FRONT GLASS PLACEMENT

Front glass is inspected for thickness, dimensions, AR coating defects, contamination, and surface quality. Surface cleanliness is verified through particle and residue checks, followed by automated or manual loading onto the layup table and confirmation of proper glass alignment and positioning.

FRONT POE/EVA PLACEMENT

Front POE/EVA is inspected for roll thickness, gel content, batch ID, and defects. Material is cut to module size using an automatic cutter or pre-cut sheets, placed and aligned on the glass, and verified for proper edge overhang.

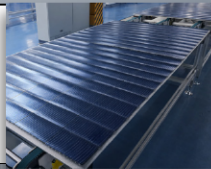


CELL STRING PLACEMENT

Cell strings are verified for correct orientation, including polarity and layout. The strings are placed onto the encapsulant, spacing between strings is adjusted, and cell alignment and squareness are confirmed.

CROSS-CONNECTOR (CC) TO CELL STRING SOLDERING

Cross-connectors are positioned onto the cell strings, followed by soldering and inspection of the solder joints for proper wetting and coverage.



BARCODE LABELING, POE/EVA STRIP PLACEMENT, & POSITIONING TAPE APPLICATION

Reinforcement tape is applied to secure components, followed by placement of pre-cut POE/EVA strips over the cross-connector area. Inner barcode labels are then applied.

REAR POE/EVA PLACEMENT

Rear POE/EVA placement follows the same process steps as the front POE/EVA placement on the module.



REAR GLASS OR BACKSHEET PLACEMENT

Rear glass placement follows the same process as front glass placement, with additional attention to alignment over the cross-connectors through the glass holes. For backsheet placement, the material is cut to module size using an automatic cutter or pre-cut sheets, CC/J-box connection holes are opened, the backsheet is placed and aligned on the glass, and edge overhang is verified.

VISUAL INSPECTION & EL TESTING

Laminate preparation goes through barcode scanning and positioning, followed by in-process visual inspection. The laminate is placed in the EL testing area with proper positioning and electrical connection, EL testing and image acquisition are performed, and defects are identified and evaluated.



Tabbing & Stringing

LAYUP

QA CHECKS

1. Verify correct glass orientation (front vs. rear).
 2. Inspect the glass surface for scratches, stains, and other defects per SOP to prevent quality issues.
 3. Confirm the glass manufacturer, dimensions, and model number match BOM and CDF specifications.
1. Verify the POE/EVA model and manufacturer match BOM and CDF requirements.
 2. Inspect cut dimensions and placement to ensure compliance with factory SOP and prevent edge bubbles, EVA voids, and lamination defects.
 3. Check POE/EVA for incoming material defects, foreign object residues.
 4. Ensure the POE/EVA is placed smoothly and evenly to prevent abnormal cell spacing, cell cracking, misalignment, and post-lamination.
1. Inspect cell string placement for abnormalities per SOP to prevent spacing issues between strings, cells, and glass edges.
1. Measure creepage distance, string spacing, and cell spacing to verify compliance with SOP and drawings and prevent batch deviations.
 2. Inspect backside welding quality for flux residue and foreign object contamination to avoid ribbon misalignment.
 3. Verify ribbon-to-cross-connector overlap meets SOP.
 4. Confirm welding parameters comply with SOP to prevent discoloration and cold solder joints.
1. Verify correct placement of module barcode labels.
 2. Inspect EVA strip position and length to prevent edge bubbles and EVA voids.
 3. Ensure positioning tape is applied per SOP and drawings, including quantity, length, and placement location.
1. Apply the same QA/QC mechanisms used for front POE/EVA placement. Manage materials between front and rear POE/EVA and address added complexity by assessing both locations.
1. Similar QA/QC mechanisms used for front glass or front encapsulant placement.
 2. Manage materials between front and rear glass or backsheet and assess both locations due to added complexity.
 3. Verify alignment and glass edge overhang.
1. Confirm this station is the final checkpoint before lamination and the last opportunity for module rework.
 2. Verify AOI system calibration, settings, and operational status.
 3. Verify EL tester calibration, settings, and operational status.
 4. Confirm operator pass/fail decisions align with factory pre-lamination inspection criteria.

Lamination

Pre-Shipment Inspections & Testing

KEY POINTS

- **Lamination Defects Driving Reliability Failures:** Bubbles and edge delamination are the leading lamination-related defects, posing significant reliability and safety risks. Improper encapsulant storage and inadequate lamination process control are identified as the primary root causes.
- **Rising Creepage Non-Compliance (Cell Spacing):** Cell spacing distance violations, primarily linked to larger wafer formats and new module designs, account for approximately 65% of cell-related defects and pose elevated risks of hot spots, arcing, and potential fire events.
- **Junction Box Defects:** Approximately 60% of junction box defects are associated with sealing and attachment issues. Batch testing has revealed wet current leakage failures following extended thermal cycling, underscoring the need for rigorous BOM validation and robust PSI controls.

In 2025, Kiwa PI Berlin conducted PSI on nearly 160,000 PV modules across 65 manufacturing facilities worldwide. These inspections were performed to evaluate module quality, compliance with inspection criteria (e.g., IV, EL, VI etc.) and technical specifications. Batch-based inspections are conducted on a sample basis according to agreed quality standards and ISO 2859-1:1999. Sampling methodology follows a standard inspection level; all defects identified are documented and evaluated in accordance with the Accepted Quality Limit (AQL). This large-scale dataset provides valuable insights into defect distribution, root causes, and associated risks, while highlighting the importance of rigorous quality assurance in PV module production.

DEFECT DISTRIBUTIONS

The distribution of identified defects during inspections is illustrated in Figure 11. Each segment represents a specific defect category and its percentage of the total defects observed, providing a clear visualization of recurring issues in PV module production. Defects are defined as non-conformances against inspection criteria agreed upon with the buyer or provided by the manufacturer as part of the supply contract.

Analysis of this end-of-line inspection data indicated that the majority of defects originate from key areas, including lamination, cell and string interconnect, cells, frame, and glass, which together account for more than 75% of total observed defects.

Lamination Defects

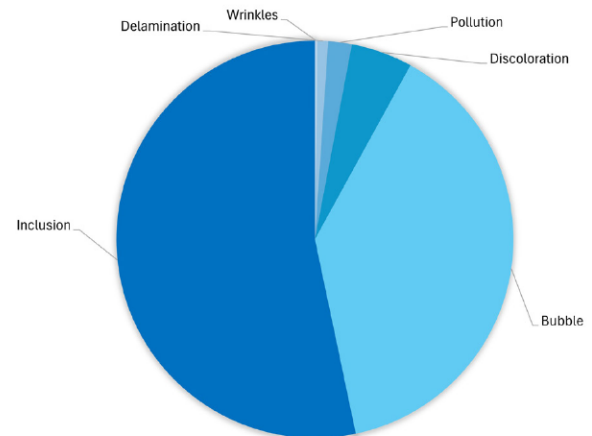


Fig 8: Distribution of lamination defects by type

Cell Defects

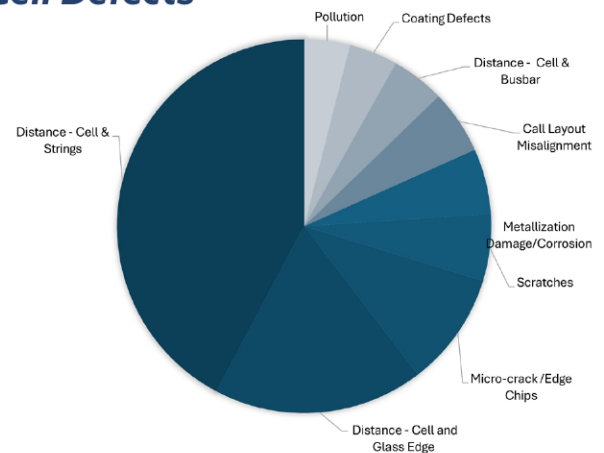


Fig 9: Distribution of cell defects by type

Junction Box Defects

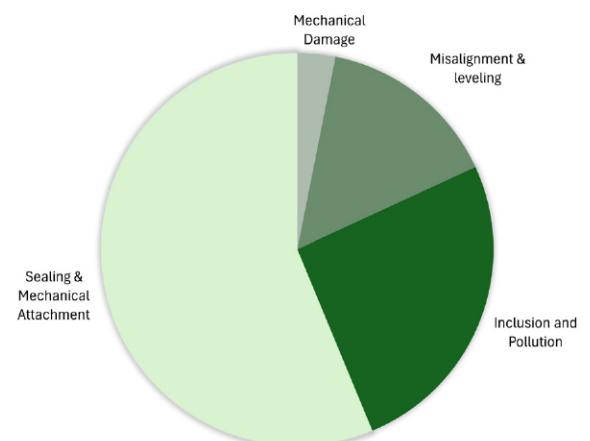


Fig 10: Distribution of junction box defects by type

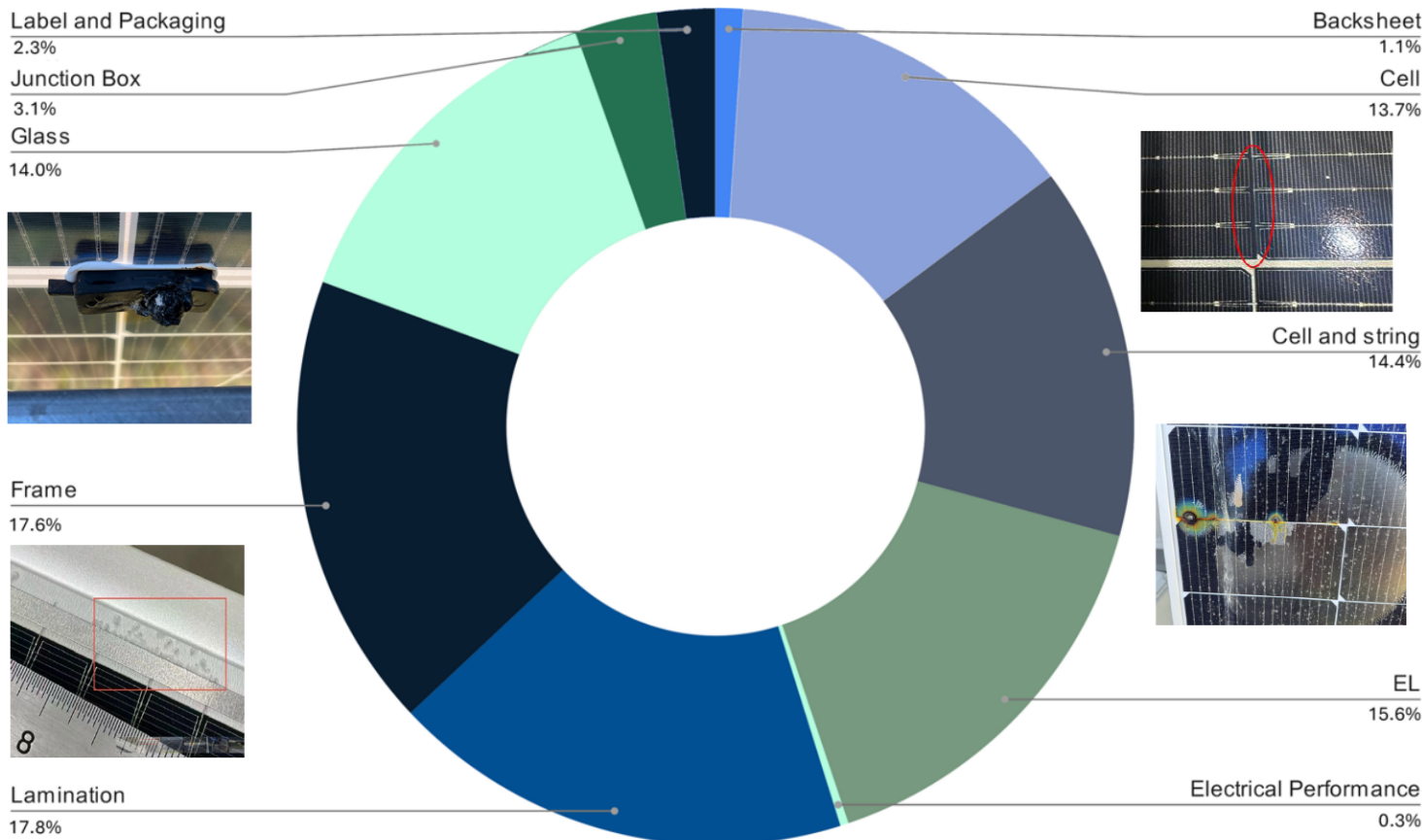


Fig 11: Distribution of pre-shipment defects by type (see breakouts by type in Figs. 8, 9, 10)

LAMINATION DEFECTS

The highest proportion of defects was associated with module lamination, a critical PV module manufacturing step that forms the encapsulation system and is essential for long-term reliability and safety (Figure 8). Consequently, any deviations in materials or process parameters during layup and lamination can introduce significant risks to both users and the PV system performance. A detailed analysis of lamination defects indicates that bubbles are among the most prevalent issues.

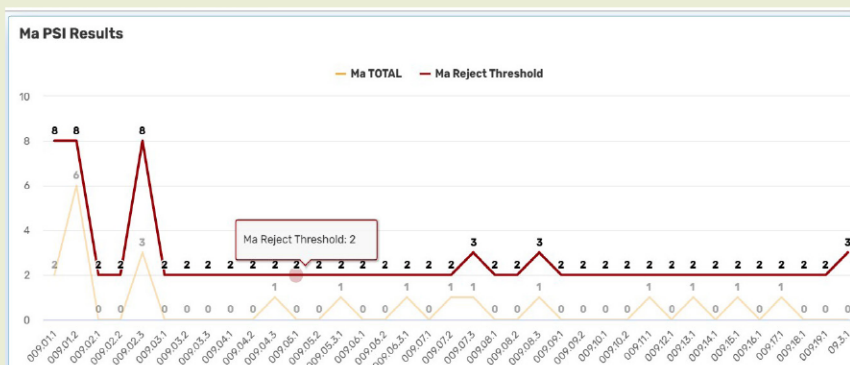
The severity of risk associated with bubbles in PV modules depends on their size, quantity, and location, which can impact creepage distance and safety requirements. Edge-located bubbles can significantly increase the likelihood of delamination. In recent years several fire incidents have identified electrical short circuits as the primary root cause, often originating from edge delamination associated with edge bubbles and weak encapsulation.

The primary root causes of lamination defects are related to both material handling and process control. In multiple cases, it was observed that manufacturers did not follow standard storage conditions for encapsulant materials, which are sensitive to temperature and humidity, nor did they consistently adhere to specified shelf-life requirements, resulting in the use of expired materials. In addition, lamination defects were linked to laminators being operated with parameters outside the specified process limits, particularly with respect to temperature and pressure.

The case study shown on the next page with data from Kiwa PVEL's module testing highlights an example of increased delamination and related testing failures.

PSI - Batch Failure Tracking

Figure 12: Tracking batch inspection data by defect type and quantity provides insight into supplier quality consistency across different projects. The example from Kiwa PI Berlin's dashboard (shown on the right) illustrates module defects identified on a production line throughout the project lifecycle. Capturing and leveraging this data supports improved supplier oversight and overall quality management.



CASE STUDY

For a recent batch testing project performed at Kiwa PVEL's USA lab, a variety of tests were performed on randomly selected modules from several production batches, including potential induced degradation (PID), light induced degradation (LID), light and elevated temperature induced degradation (LETID), static mechanical load (SML) and hail testing.

The most concerning result from this testing was that of modules experiencing delamination following PID testing. While rarely seen at the end production's visual inspection step, delamination/bubbles can appear following climate chamber testing (such as thermal cycling, damp heat, humidity freeze and/or PID). These defects can create a safety risk by forming a potential electrical path from the module's current-carrying parts to the grounded frame, and they are considered a major defect according to IEC 61730 due to the electrical arcing risk they present.

Recent findings from Kiwa PI China Co., Ltd's laboratory in Suzhou, China indicate a notable increase in PID-related batch testing failures, particularly following negative (-) PID stress tests. These elevated failure rates confirm that performance issues are occurring across production for certain projects. The data suggests that some manufacturers' internal quality control processes are not effectively detecting these defects prior to module shipment, creating potential risks for buyers.

The potential root causes for delamination/bubbles can be traced to various cost cutting measures, including the use of thinner encapsulants, laminate edge-pinch on glass//glass modules following lamination, and/or a reduction in lamination time. In this batch testing case, all of the PID samples from batches that used a certain encapsulant showed post-PID delamination, while none of the PID samples from batches using a different encapsulant had signs of delami-

nation. This points to the influence of material selection, and likely lamination recipe, on module reliability.

Delamination has become the most frequent defect to emerge in Kiwa PVEL's Product Qualification Program (PQP) testing in 2025. In the past year, over 10% of BOMs undergoing PQP testing had at least one case of delamination severe enough that it qualified as a major defect. This concerning trend will be further detailed in Kiwa PVEL's 2026 PV Module Reliability Scorecard, forthcoming in Q2 2026.



CREEPAGE DISTANCE DEFECTS

Creepage distance violations remain one of the most significant defect categories identified during pre-shipment inspections. As highlighted in Kiwa PI Berlin's recent [Race to PV Module Quality & Compliance](#) report, the frequency of cell-related defects has increased notably in recent years. This trend is largely driven by the industry's transition to larger wafer formats, advanced cell technologies, and multi-busbar designs, all of which introduce tighter tolerances and greater complexity in maintaining dimensional integrity.

As illustrated in Figure 9, approximately 65% of cell-related defects are linked to creepage distance requirements within the module. These include spacing between individual cells, between cell strings, between cells and the glass edge, and between cells and busbars. Such spacing is critical for meeting safety standards and ensuring electrical isolation under operating conditions.

Inspection data shows these defects are widespread, appearing in products from nearly all major manufacturers and across more than 30 projects. In several cases, modules were found to be non-compliant with UL and IEC standards due to failure to meet minimum creepage distance requirements. These deviations pose serious reliability and safety risks, including increased likelihood of hotspot formation, leakage currents, electrical arcing, and even fire. Kiwa PI Berlin's failure analysis team has investigated multiple field incidents over the past year where inadequate creepage distances were identified as a root cause, leading to module failures and, in some cases, burn damage within DC strings.

To mitigate these risks, cell spacing tolerances must be rigorously validated against IEC and UL 61730 requirements during pre-shipment inspections. Dimensional integrity should be confirmed not only at final assembly but also at critical production stages such as stringing, layup, and auto-bussing. Standard operating procedures (SOPs) for these stations should be reviewed regularly to ensure compliance with design tolerances. Multi-stage verification processes, including automated optical inspection (AOI) and electroluminescence (EL) imaging, are essential for detecting spacing anomalies early and preventing non-compliant modules from reaching buyers.

JUNCTION BOX ASSEMBLY

Junction box soldering and assembly represent another critical module production process. Strict control of materials and process steps is essential, yet recent years have seen a significant rise in field failures linked to junction box assembly and material quality.

As shown in Figure 10, analysis of defect sub-categories shows that approximately 60% of junction box issues relate to sealing and mechanical attachment. These defects pose serious reliability and safety risks: inadequate sealing or poor attachment can allow moisture ingress, leading to corrosion of electrical contacts, bypass diode damage, and increased stress on soldered joints and cable terminations. Modules affected by these failures often exhibit early-stage performance degradation (up to two-third loss in rated power and voltage) along with compromised bypass diode functionality. In severe cases, localized overheating can escalate to thermal run-away and fire hazards.



Additional defects, illustrated in Figure 11, highlight broader challenges in material selection, process control, and equipment calibration. Persistent gaps in inspection and monitoring allow high-risk modules to enter the field, despite the growing number of reported failures.

One common testing failure related to junction boxes is that the module may fail wet leakage testing. Wet leakage testing evaluates electrical insulation per IEC 61215-2:2021 MQT 15, which requires insulation resistance of at least 40 $M\Omega \cdot m^2$. BOMs failing this threshold are reflected in Kiwa PVEL's Scorecard failure statistics.

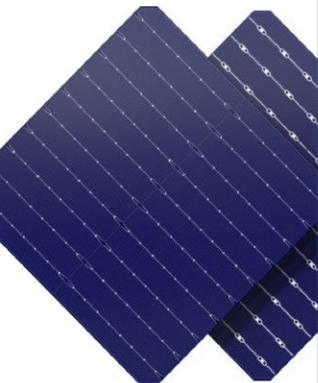
A recent case involved modules failing wet leakage after 600 thermal cycles (TC600). Both tested modules fell below IEC 61215 insulation resistance requirements, with visual inspection revealing cable insulation damage near the junction box entry point. Notably, this defect did not appear during the standard 200-cycle test, underscoring the need for extended reliability testing during BOM qualification. Kiwa PVEL has also documented recurring wet leakage failures linked to poor pottant or adhesive selection and application. Other observed junction box-related issues include covers detaching, bypass diode failures, and melted

or damaged connectors; all of which compromise long-term reliability and safety.



Fig 13.

Conclusion



"The PV industry's continued growth and technological advancement will demand even greater diligence in quality assurance."

PV module manufacturing continues to evolve in ways that increase both opportunity and risk. Variability in factory maturity, rapid technology changes, and expanding global supply chains make consistent quality assurance more important than ever. Buyers who rely on **independent oversight and data driven evaluation are better positioned to secure reliable products** and protect long term project performance.

Factory audit benchmarking, including cell factory audits, continues to demonstrate strategic value in identifying high-risk suppliers. Regional variations in findings highlight the need for tailored oversight, particularly in newer manufacturing hubs where operational maturity is evolving. By leveraging audit data to manage qualified suppliers and enforce corrective actions, buyers reduce exposure to reliability and safety risks while fostering long-term supplier partnerships.

Production oversight and pre-shipment inspections remain essential safeguards against factory process weaknesses. Defect data from layup, lamination, and junction box assembly reinforce the importance of precise process control and material management. PSI data from over 160,000 modules in 2025 revealed defects such as lamination bubbles, creepage distance violations, and junction box failures are concentrated in critical areas. These insights enable buyers to implement targeted QA measures such as multi-stage verification, extended reliability testing, and BOM validation to prevent high-risk modules from entering the field.

Looking ahead, the PV industry's continued growth and technological advancement will demand even greater diligence in quality assurance. The adoption of advanced cell architectures, regional manufacturing incentives, and evolving compliance frameworks will reshape production landscapes. It's a legitimate challenge to manufacture many millions of PV modules in dozens of new and growing factories using hundreds of BOM combinations. By integrating data-driven QA practices into procurement and project execution, stakeholders can not only navigate these complexities but also **strengthen PV's role as a cornerstone of global energy transition**. With collaboration, transparency, and commitment to quality, the industry is well-equipped to deliver safe, reliable, and sustainable solar power for decades to come.



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