The Race to PV Cell **Quality & Compliance**

Why PV module buyers are focusing on upstream due diligence to manage quality amongst ever-evolving market influences

kiwa

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Introduction

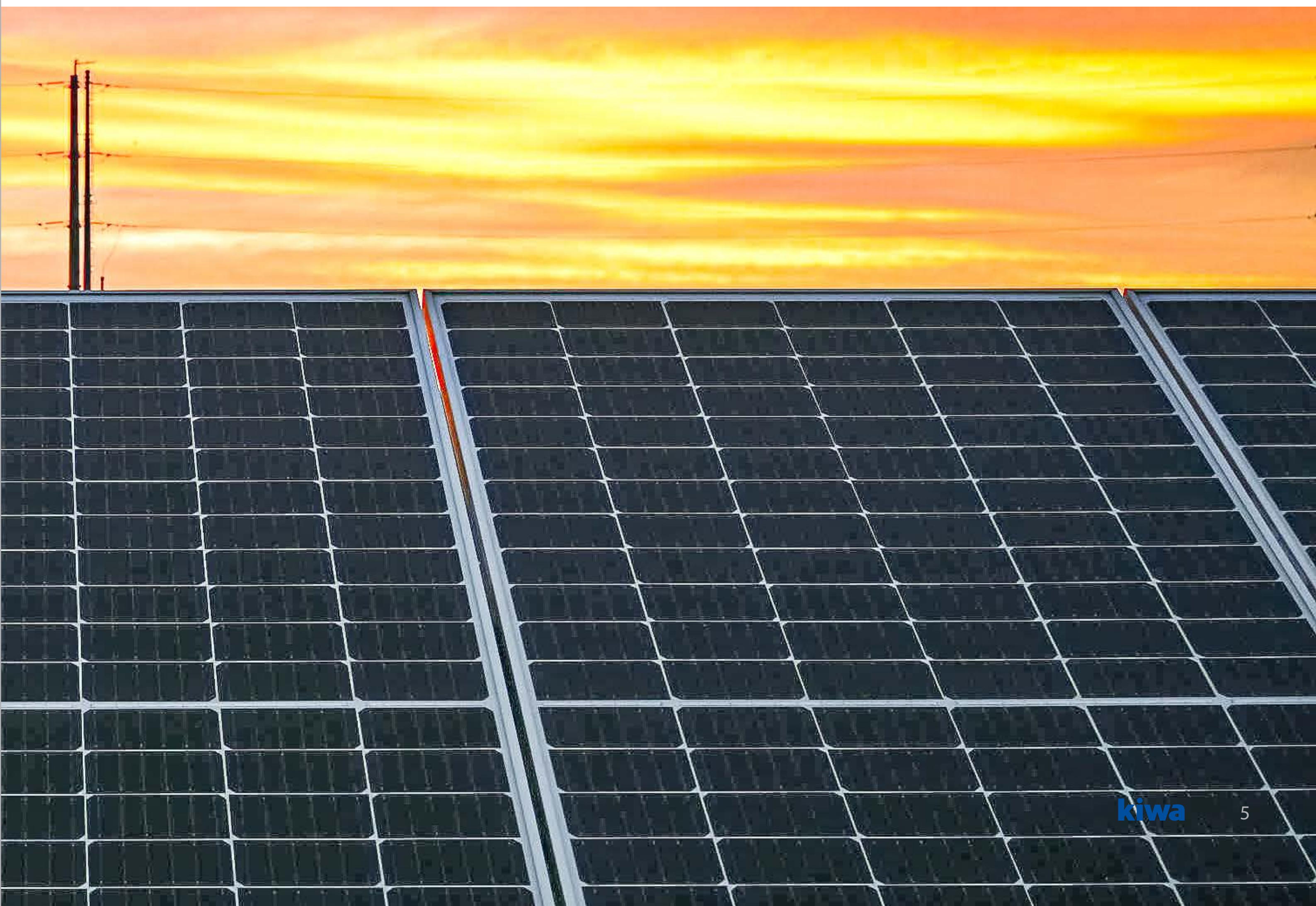
Photovoltaic (PV) cell manufacturing has undergone a gloal transformation and expansion, leading to an increased focus from module buyers and system owners. This evolution is driven by recent rapid shifts in policy compliance requirements, heightened traceability needs for supply chains, widespread adoption of new cell architectures, transition to larger wafer formats, and the diversification of production capabilities and experience levels, which collectively is reshaping the market. These developments have amplified the risks associated with PV module quality, long-term reliability, and regulatory compliance.

Regulatory changes have accelerated global manufacturing diversification. In the United States, measures such as the One Big Beautiful Bill Act (OBBBA), International Emergency Economic Powers Act (IEEPA) tariffs, and active Antidumping and Countervailing Duties (AD/CVD) petitions have catalyzed the construction of new cell factories globally. In Africa, early-stage facilities are emerging in countries such as Egypt and Ethiopia, aiming to bypass tariff exposure and capture regional market share. In the US, domestic content and foreign entities of concern (FEOC) provisions are driving the ramp-up of domestic facilities. Asia remains the core of PV cell production, but capacity expansion is now coupled with technological upgrades. High-throughput n-type cell manufacturing in these regions includes integrating larger wafer formats, multi-busbar interconnections, and

advanced metallization techniques. These innovations require new process equipment, operator retraining, and elevated quality assurance protocols to maintain product performance during this rapid scaling phase.

Today's **buyer risk** profile is defined by the simultaneous growth of global manufacturing capacity, the need to demonstrate compliance across multiple regulatory requirements, and the imperative to ensure quality into buyer's final PV modules.

The convergence of **regulatory pressures and technology transitions** underscores the **importance of upstream due diligence**, and PV module buyers are responding with targeted quality assurance actions to reduce project risk. The strategy to mitigate risk is to strengthen upstream quality management by leveraging cell factory audits, expanded bill of material (BOM) supply chain traceability assessments, and module reliability testing. This whitepaper provides an executive overview followed by expanded technical exhibits on these key risks and quality management mitigations. As more industry stakeholders assess their own cell management strategies, Kiwa's goal is to provide the industry with an overview of the quality risks within PV cell manufacturing, how market influences are increasing focus on cell diligence, and outline the tools buyers can implement to reduce quality and compliance risks in their PV module procurement and project development.



Executive Summary

The PV industry faces rising risks as new technologies, shifting cell production to emerging regions, and stricter U.S. regulations like the OBBBA converge. Cell-level traceability, reliability, and process control are now critical, as even small design or sourcing changes can significantly impact module quality and compliance. Safeguarding performance and bankability requires rigorous quality assurance frameworks that integrate audits, traceability, and continuous reliability testing. The following sections provide a detailed discussion of these factors.

Market Influences & Policy Pressures

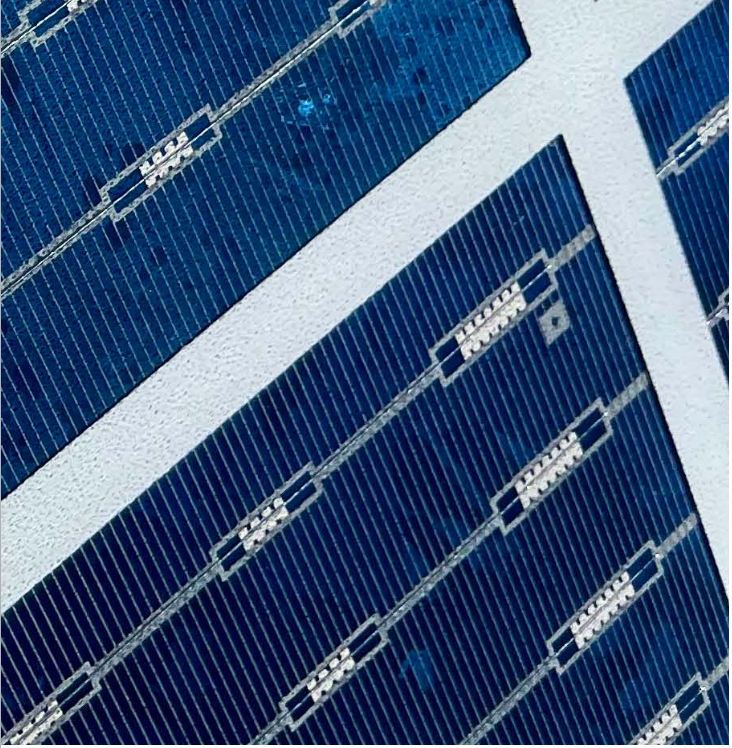
Buyers are now focusing on PV cells because policy, quality, and compliance requirements point upstream from the finished module to its most critical subcomponent. In the past, diligence centered on the final PV module; today, incentive eligibility depends on verifying the origin and compliance of the cell and its inputs.

For U.S. buyers, OBBBA has fundamentally changed the compliance landscape for PV project stakeholders by tying federal tax incentives to strict prohibitions on "material assistance" from foreign entities of concern. Within the PV module, the cell represents the most consequential component in compliance to these polices. Cells have a significantly increased weighting in the estimated FEOC % compliance requirements (see Figure 1). This has elevated PV cell-level traceability from a best practice to a legal and financial imperative. At the same time, manufacturing is shifting toward new hubs in Africa and the Middle East to capture tariff advantages. While promising for cost and tariff management, these regions often present wide variability in process maturity, quality systems, and workforce capability—making rigorous supplier qualification, factory auditing, and traceability assessment essential.

> *"Success now depends on proactive due diligence at the cell level."*

In this environment, **buyers must adopt multi-tiered quality assurance strategies** that combine BOM traceability, verification of material and cost flows, and independent cell-factory audits—particularly for new or rapidly scaling facilities. These measures are essential to secure project bankability, mitigate latent defect risk, and ensure compliance with evolving domestic content and trade policies. In short, success now depends on proactive technical due diligence at the cell level, not only to manage regulatory exposure but to guarantee the performance and reliability expected from system owners.

For more, see Market Influences & Policy Pressures in Annex below.



Evolving Cell Architecture

The rapid evolution in cell architecture underscores a critical point: the lifecycle of PV technologies is becoming increasingly compressed. This raises the risk of early-stage reliability issues which may remain undetected until large-scale production and field deployment.

Manufacturing TOPCon and HJT cells demands substantial modifications to existing PERC production lines—or complete replacement of equipment—due to different process requirements. These changes introduce potential for increased process-related defects and highlight the need for updated process control, training and quality measures. Given these challenges, quality assurance must go beyond standard factory checks. Rigorous process validation, in-line characterization, and independent factory audits are essential to catch defects early. These measures safeguard long-term performance and maintain the bankability of solar assets in an environment of rapid innovation and heightened technical risk.

For more, see Cell Architecture in Annex below.

Wafer Size Progression

In addition to evolving cell types, over the past decade, the PV industry has experienced a significant shift toward larger silicon wafer formats. This transition aims to reduce manufacturing costs and enhance module power output, thereby improving overall system economics.

Larger wafers, especially when coupled with reduced thickness, are more prone to mechanical damage such as microcracks, edge chipping, and scratching during handling, processing, and transport. The increased surface area also demands tighter process uniformity, more precise alignment, and improved materials handling systems to avoid yield losses.

During cell production, maintaining uniform high yield rates across larger surface areas of M10 and G12 wafers presents additional complexity. Cell lines, process controls, and people originally working with smaller wafers (M3 and M6) often required significant upgrades, training or entirely new equipment to accommodate larger formats. This wafer size evolution highlights the critical need for advanced process control, equipment precision, and robust quality assurance frameworks to ensure that performance gains are not offset by increased defect rates or field reliability risks.

For more, see Wafer Size Progression in Annex below.

Manufacturing Quality

Cell manufacturing is rapidly expanding beyond traditional hubs into emerging regions such as Africa, the Middle East, and parts of Southeast Asia. This geographic diversification aims to mitigate tariff exposure, reduce logistics costs, and meet surging global demand. However, the rise of new facilities introduces significant variability in manufacturing maturity, process discipline, and sub-tier supplier transparency. These factors heighten the risk of non-conformance, making structured oversight—such as BOM-level traceability and independent factory audits—essential for ensuring compliance with federal incentives and maintaining long-term performance integrity.

As highlighted in Kiwa PI Berlin's 2025 PV Manufacturing Quality Report, factory audits reveal that new facilities have a higher rate of major non-conformities than mature manufacturers, driven by weak process control, limited operator training, and incomplete quality systems. Material handling issues—such as using unqualified suppliers or expired inputs—are also common during rapid scale-up. These gaps highlight the critical need for **regular qualification and verification audits** to enforce best practices and reinforce upstream quality assurance.

For more, see Managing Manufacturing Quality in Annex below.

Production Process Risks & Defect Categorization

Maintaining long-term cell efficiency and reliability requires rigorous control of process parameters, environmental conditions, and material integrity. Audit data from Kiwa PI Berlin shows that quality findings cluster (Figure 8) into four critical categories: inadequate process control, weak quality management systems (QMS), unreliable testing and labeling, and insufficient material qualification. Each of these areas introduces latent risks that, if unchecked, can compromise module performance and operational life.

The majority of audit findings—41%—originate from **process control deficiencies**, reflecting the extreme sensitivity of cell manufacturing steps

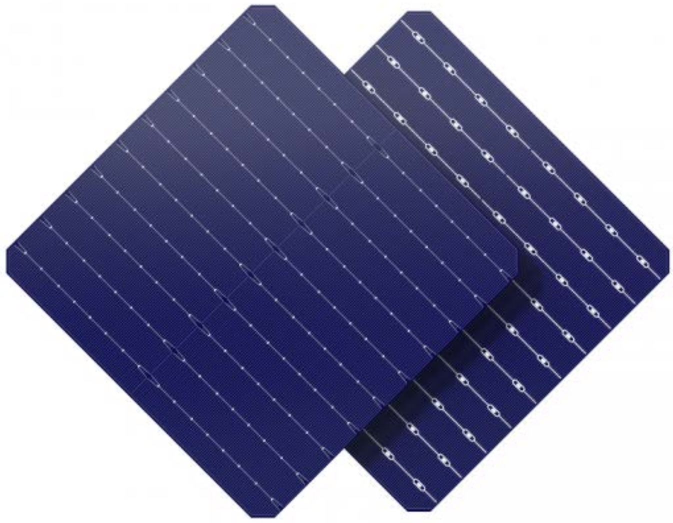


Image: SunveoSolar.com

to variations in temperature, chemical concentration, vacuum levels, and deposition times. Even minor deviations can cause reliability issues that routine checks like electroluminescence (EL) imaging or flash testing fail to detect. QMS weaknesses represent the second most common issue, driven by missing SOPs, poor calibration protocols, and inadequate supplier oversight—problems often concentrated in newer factories or emerging markets where quality culture is still developing.

Additional gaps stem from unreliable testing practices and weak material management. Improper calibration of flash testers and reference cells leads to mislabeling and inaccurate power ratings, a problem corroborated by Kiwa PVEL's findings and Fraunhofer ISE's published data showing rising discrepancies between declared and measured power output. Similarly, inadequate incoming inspection and storage practices for raw materials elevate the risk of introducing defects early in production.

TOPCon and HJT amplify these risks due to their reliance on ultrathin passivation layers and intricate multi-material interfaces. These advanced designs are highly sensitive to micro-defects that may escape detection during standard module assembly. When undetected, these flaws can accelerate field degradation, increase failure rates, and reduce long-term energy yield. Consequently, **system owners must closely evaluate failure modes linked to cell-level weaknesses** to mitigate long-term performance risk.

For more, see Production Process Risks in Annex below.

Reliability Testing Insights

Kiwa PVEL's Product Qualification Program (PQP) has consistently shown that even minor changes in PV cell architecture, materials, or process controls can significantly affect module reliability and energy yield. Recent testing cycles highlight vulnerabilities such as UV-Induced Degradation (UVID), especially in n-type technologies like TOPCon. While module-level mitigations (e.g., UV-blocking encapsulants) exist, most manufacturers rely on cell-level solutions. However, unless process upgrades are consistently applied across full-scale production, reliability risks remain.

Recent PQP results illustrate how variations in cell BOM, design, process and material sourcing lead to performance disparities:

- UVID120: A PQP retest achieved an 80% power loss reduction (6.5% → 1.3%) via improved anti-reflective coatings and passivation.
- Thermal Cycling (TC600): Identical-rated modules from different cell suppliers showed losses from 0.3% to 3.3%.
- Damp Heat (DH2000): Two nearly identical BOMs from the same manufacturer—produced within three months and differing only in cell model—showed contrasting results: 1.5% loss for the first BOM vs. 3.8% loss for the second.
- Potential-Induced Degradation (PID): Two similar TOPCon BOMs from the same manufacturer diverged sharply: 1.6% loss for BOM-1 vs. 7.2% for BOM-2 due to cell BOM and process differences.

For more, see Reliability Testing Insights in Annex Below.

Conclusion

& Recommendations

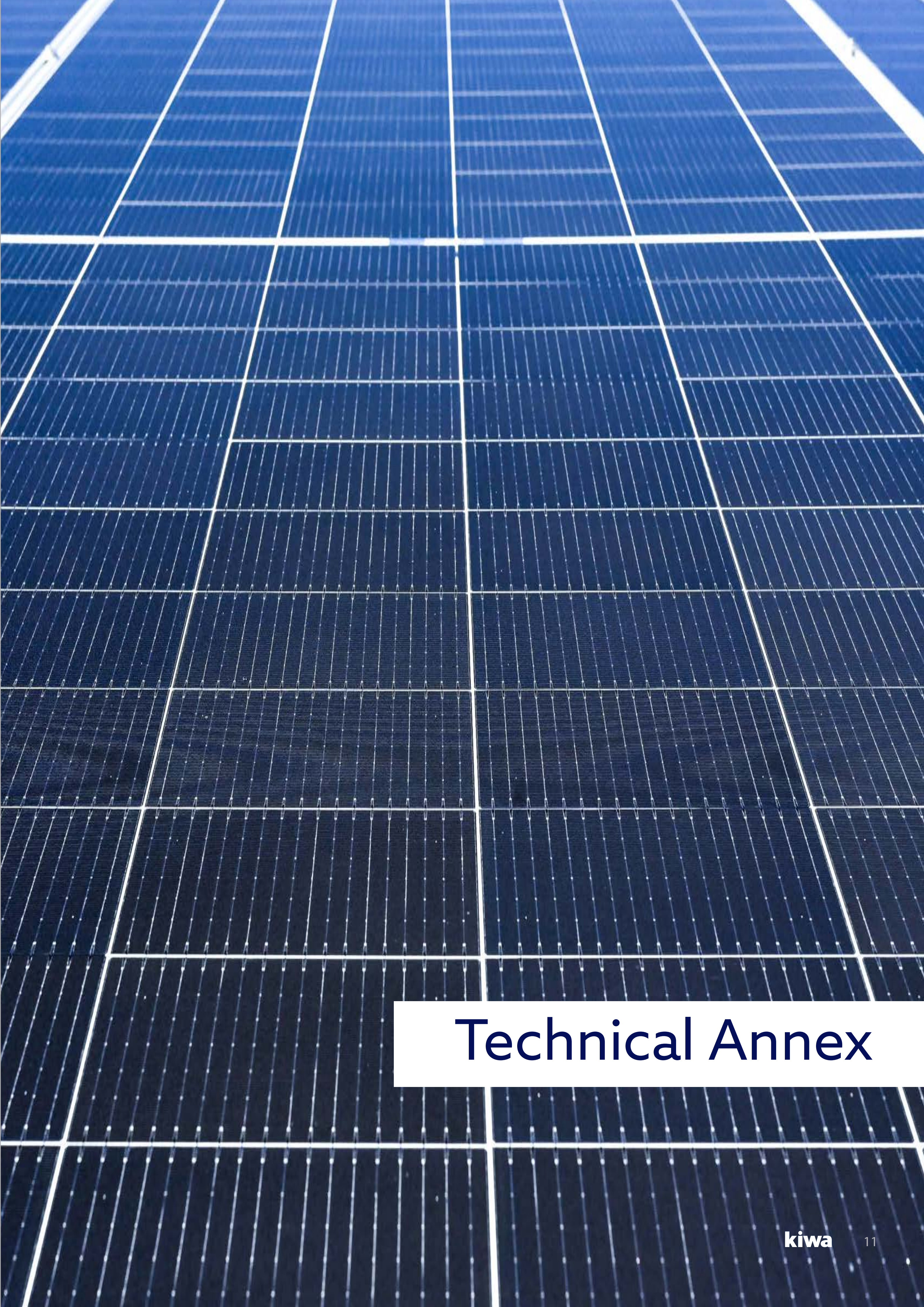
Cell manufacturing for advanced technologies demands precise handling, robust supply chain oversight, and stringent traceability to ensure compliance with evolving regulatory and quality requirements. In response, **PV module buyers are implementing targeted quality assurance measures to mitigate technical and financial risks**. Kiwa recommends the following best practices:

- Comprehensive BOM-Level Traceability and pre-qualification testing through the PQP: Increase visibility into subcomponent suppliers, and material origins, and performance of BOM combinations to ensure authenticity and compliance.
- Verification of Supplier Declarations: Independently confirm manufacturer statements regarding sourcing policies and cost allocations rather than relying solely on self-reported data.
- Independent Cell-Facility Audits: Conduct on-site audits at cell production sites to evaluate process control, operator competency, and quality system implementation.
- End-Product Reliability Testing: Perform batch-level and extended reliability tests on finished PV modules to validate mechanical integrity, electrical performance, and long-term durability.
- Engage an experienced technical advisor prior to and throughout the PV module procurement process. Early involvement ensures that procurement decisions are aligned with the overall project strategy, regulatory requirements, and financial objectives.

The rapid adoption of advanced PV cell technologies—such as TOPCon and HJT—along with larger wafer formats, has introduced both higher efficiency potential and increased manufacturing complexity. Manufacturing innovations, combined with global supply chain diversification and rapid capacity scaling, amplify the risk of latent defects that may escape detection in standard module-level inspections. PV cells, as the keystone component of a module, require careful upstream quality management to safeguard both technical performance and financial viability.

Leading buyers are mitigating these risks through structured, multi-phase cell factory audit programs. Initial qualification audits validate process stability and control capabilities, followed by recurring verification audits to ensure ongoing compliance and closure of corrective actions. When paired with robust BOM-level traceability and finished-module reliability testing, this approach strengthens upstream quality oversight, enforces standardized manufacturing practices, and scales across diverse sourcing portfolios. Audit findings consistently highlight areas for improvement—including process control gaps, materials handling deficiencies, and equipment calibration issues—which, if addressed, directly enhance cell performance and long-term module reliability.

Though PV projects face increasingly complex cell technologies and supply chains, strong global demand and the unmatched cost-competitiveness of solar power continue to drive the energy transition forward. Even in the absence of incentives, declining LCOE and robust project economics are pushing developers to adopt advanced technologies, scale production, and innovate in quality assurance. By **leveraging rigorous auditing, traceability, and reliability testing**, the industry can confidently navigate challenges while delivering long-term, bankable solar assets that accelerate the world's shift toward sustainable energy.



Technical Annex

Policy Pressures Increase Upstream Diligence

PV project developers and investors face heightened compliance requirements to manage ongoing regulatory and market influences. In the U.S, the OBBBA now ties tax credit eligibility to strict prohibitions on "material assistance" from foreign entities of concern, making PV cell–level traceability a critical regulatory and financial requirement. Many in the industry feel Treasury guidance will reinforce the diligence of cells as by assigning the highest material weight to PV cells in the domestic-content calculation framework, a single origin failure can jeopardize an entire project's Investment Tax Credit (ITC) qualification. While the industry awaits precise guidance, IRS Bulletin 2025-8[II.]. offers interim guidance on component-level cost allocations used for compliance, which was originally developed in response to domestic content eligibility.

For US buyers, the compliance landscape is further complicated by overlapping regulations, including the Uyghur Forced Labor Prevention Act (UFLPA), Section 232 investigations, and IEEPA-based tariffs. These measures intensify scrutiny on polysilicon and PV cell sourcing while driving manufacturing shifts to emerging hubs in Africa and the Middle East. While these regions provide tariff advantages, they also introduce variability in manufacturing maturity and quality systems—making rigorous qualification and oversight essential.

Against this backdrop, PV cells have become the pivotal checkpoint where regulatory compliance, supply chain transparency, and technical reliability converge. To address escalating risks, buyers must implement robust, multi-tiered quality assurance strategies—integrating full BOM traceability, verification of material and cost flows, and rigorous third-party cell factory audits, especially at new or rapidly scaling facilities. These actions are not optional; they are essential to safeguard project bankability, mitigate failure risks, and maintain compliance with evolving trade and domestic content policies.
Figure 1. US Domestic Content BOM Assigned Cost Percentages.

Polysilicon supply chains have historically been under regulatory scrutiny, particularly under measures like the UFLPA, which mandates upstream traceability from polysilicon through to modules . Consequently, manufacturers have enhanced traceability systems, instituted rigorous supplier qualification protocols, and restructured sourcing networks away from high-risk regions.

Anti-Dumping and Countervailing Duties (AD/CVD) tariffs are further accelerating regional diversification of cell manufacturing. In July, the issue was opened on India, Laos, and investigation . Luckily, the industry has gone through this for the original targeted countries of Vietnam, Malaysia, Thailand, and Cambodia and has a general roadmap of how to respond. In addition, announcement of the Section 232 investigation on polysilicon adds another dimension—national security concern, potentially intensifying scrutiny of polysilicon and PV cell sourcing. Simultaneously, International Emergency Economic Powers Act (IEEPA) based tariffs are driving geographic diversification of manufacturing operations. In response, investments are flowing into emerging hubs across Africa and the Middle East—

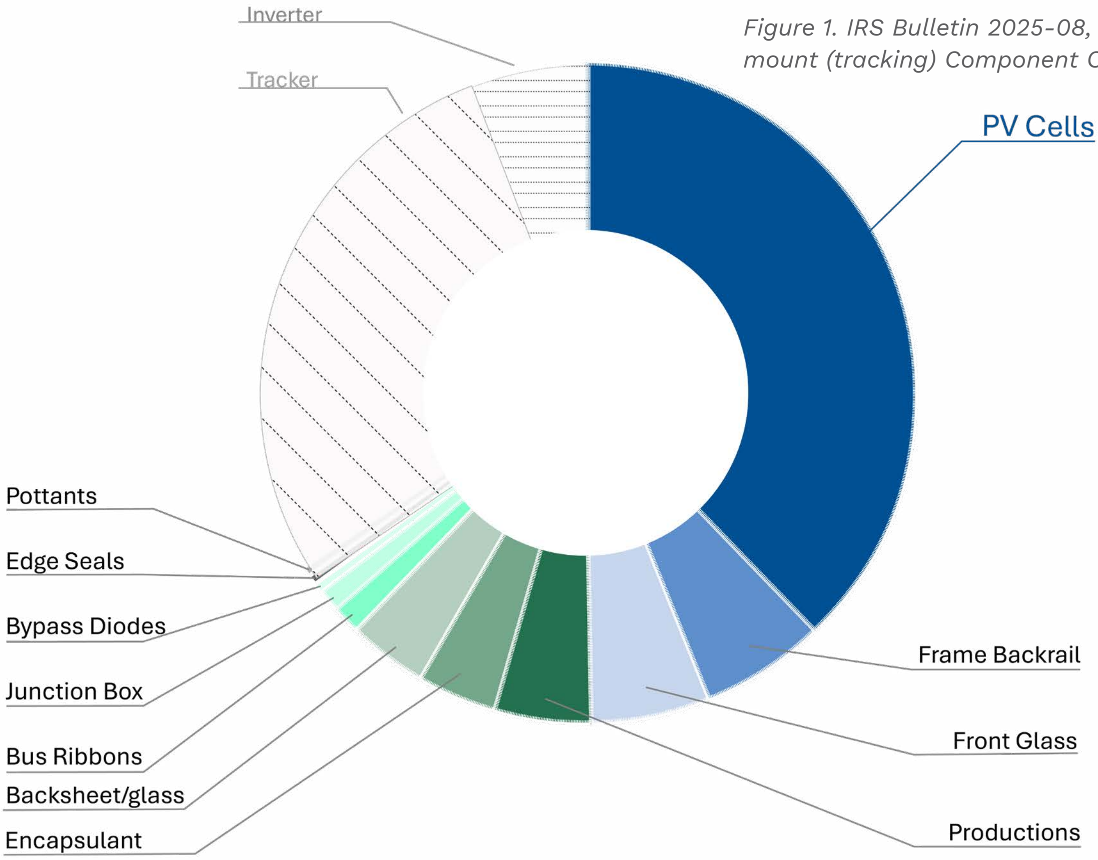


Figure 1. IRS Bulletin 2025-08, Ground-mount (tracking) Component Cost Ratio

in countries such as Ethiopia, Morocco, Egypt, and Oman—to create tariff-advantaged PV cell supply alternatives. This expansion brings challenges, including varied manufacturing maturity levels, quality control complexity, and increased compliance oversight.

Collectively, these market and policy dynamics have redefined the PV cell as a strategic compliance checkpoint—where supply chain complexities, regulatory oversight, and technical performance intersect. Buyers increasingly require factory-level qualification audits and independently verified quality programs, particularly in emerging regions, to mitigate ramp-up risks and ensure long-term reliability.

Under this regulatory environment, cell-level traceability is non-negotiable. Developers, investors, and EPCs must adopt a robust strategy encompassing:

- Comprehensive BOM-based supply chain traceability of subcomponent suppliers and origins.
- Verifying supplier declarations with cost allocations aligned to domestic-content and FEOC rules.
- Independent routine cell factory quality audits manufacturing facilities—especially in newer production locations—to continuously verify process integrity.
- Finished PV module batch & reliability testing to verify ongoing performance and BOM consistency

Stakeholders who proactively invest in detailed technical due diligence, end-to-end supply chain mapping, and independent quality verification are best suited to mitigate risks related to both regulatory compliance and sustainable module performance.Buyers are increasingly adopting multi-layered strategies that combine BOM-level traceability, verification of supplier cost allocations, and independent cell-factory audits—particularly for newer production sites. Proactive investment in these measures ensures not only compliance but also the long-term performance integrity required for bankable solar assets.

Evolving Cell Architecture

Technology

Ongoing buyer demand trends indicate an accelerating transition in silicon solar cell technologies, with TOPCon leading the shift. Its architectural similarity to the well-established PERC design has allowed manufacturers to repurpose existing infrastructure and leverage process expertise, enabling rapid scale-up. Industry forecasts suggest TOPCon could command close to 60% market share within the next decade[i]—a trajectory that may surpass the pace of the earlier Al-BSF to PERC transition, as evidenced by recent announcements from major manufacturers.

Emerging Risks

This swift evolution highlights an important reality: the technology lifecycle for PV cells is compressing, increasing the likelihood that reliability concerns remain undiscovered until after large-scale deployment. The industry has seen this before—Light and Elevated Temperature Induced Degradation (LETID) emerged unexpectedly in PERC modules, causing unforeseen performance losses in the field. Similar concerns are now surfacing for advanced architectures such as TOPCon and HJT, with test results indicating potential UV-Induced Degradation (UVID). The enhanced surface passivation and novel material interfaces that enable higher efficiency may

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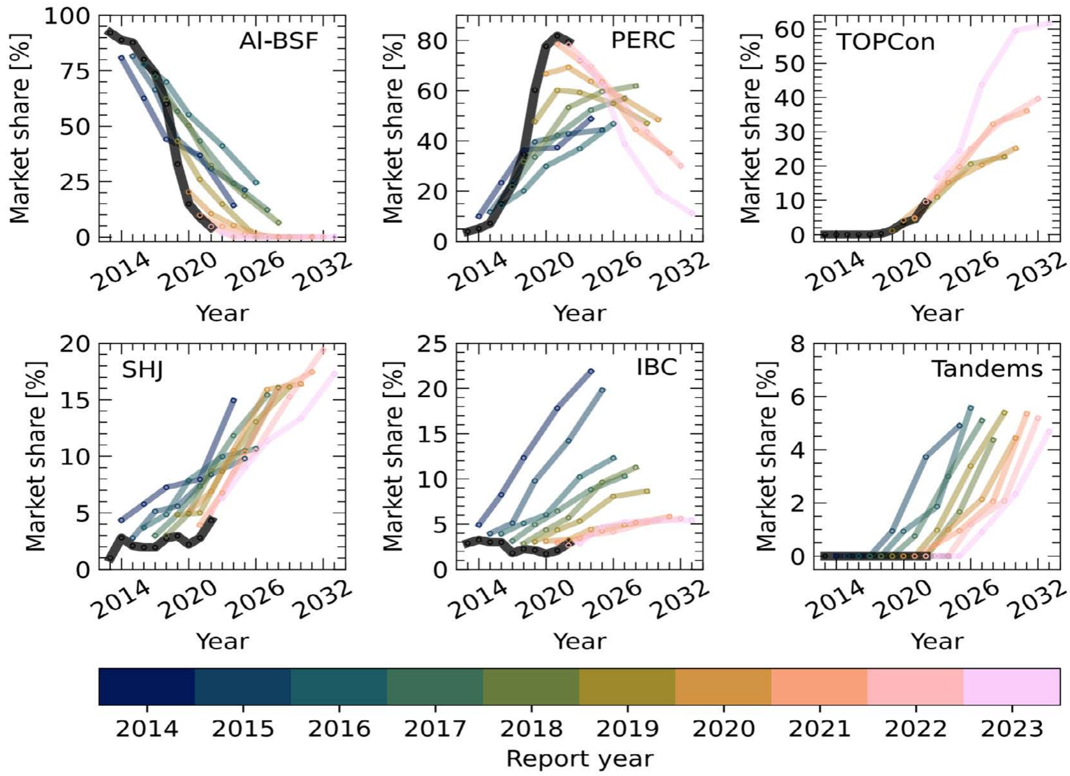


Figure 2. Market share by Technology Type[i]

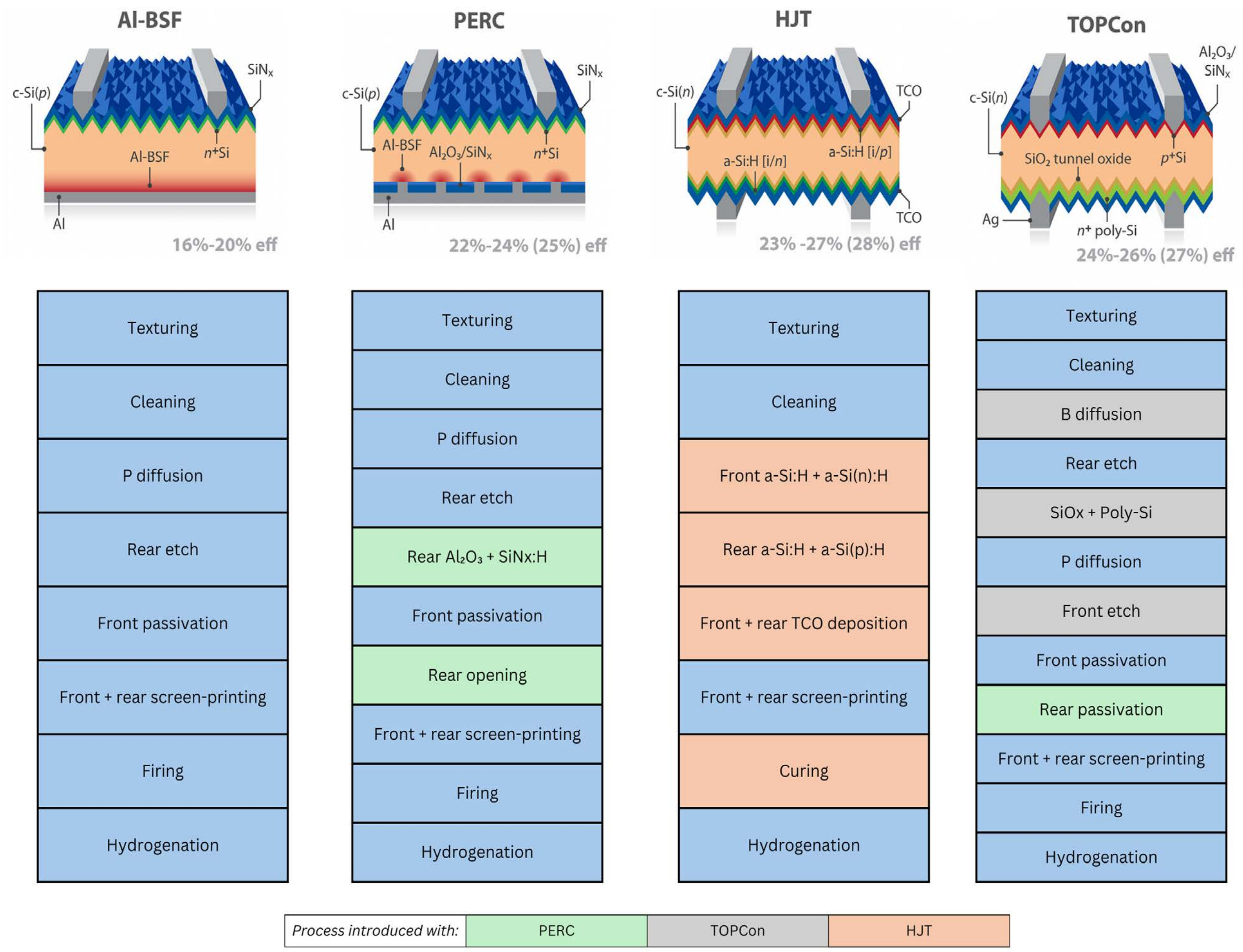


Figure 3. Overview of silicone solar cell architectures and production sequences[I, IV.]

introduce new failure modes under prolonged UV exposure.

These developments underscore the need for rigorous quality control frameworks that go beyond standard factory due diligence. Comprehensive process validation, combined with thorough cell-factory audits throughout production, is essential to minimize the risk of defects. Such vulnerabilities can manifest under real-world operating conditions, potentially causing performance losses, reduced module lifetimes, and increased warranty claims—ultimately jeopardizing system performance and project bankability.

PV cell architectures—such as PERC, TOPCon, and HJT—are fundamentally dependent on precise material control, engineered process design, and thorough in-line and post-process characterization in shaping the long-term performance, stability, and reliability of the final solar cell, as well as its integration into PV modules operating under real-world stress conditions.

Wafer Size Progression

Transition to Larger Wafer Formats

Over the past decade, the PV industry has undergone a fundamental shift toward larger silicon wafer formats, driven primarily by the pursuit of lower manufacturing costs and higher module power output. This trend reflects a broader strategy to improve system-level economics through enhanced energy yield per square meter and reduced balance-of-system (BOS) costs.

Up until around 2015, the M0 format (156.0 mm × 156.0 mm) dominated as the industry standard. Incremental refinements led to the M2 format by 2018, offering marginal improvements in chamfering and thickness without major process disruptions. However, beginning in 2019, the push for greater efficiency accelerated, ushering in a new era of large-format wafers:

- G1 (158.75 mm) introduced modest gains with minimal retooling requirements.
- M6 (166 mm) marked the first significant leap toward standardized large formats around 2020.
- M10 (182 mm) and G12/M12 (210 mm) emerged shortly thereafter, enabling ultra-high-power modules designed for advanced architectures such as PERC, TOPCon, and HJT.

By 2023–2024, M10 and G12/M12 have become dominant across high-efficiency cell production lines, reshaping the utility-scale PV market by supporting higher power classes and improved energy density.

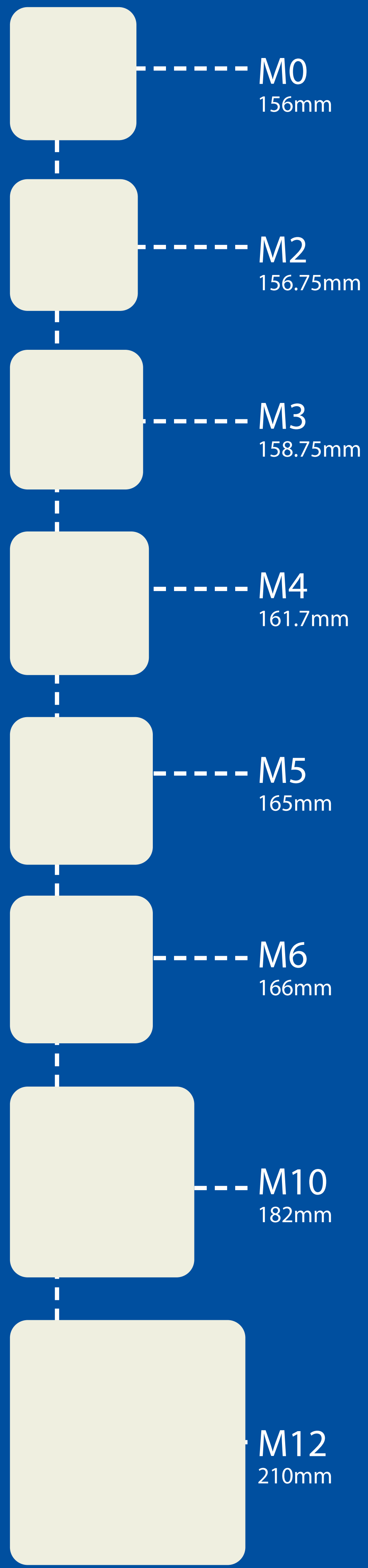


Figure 4. Wafer sizing

Operational Challenges

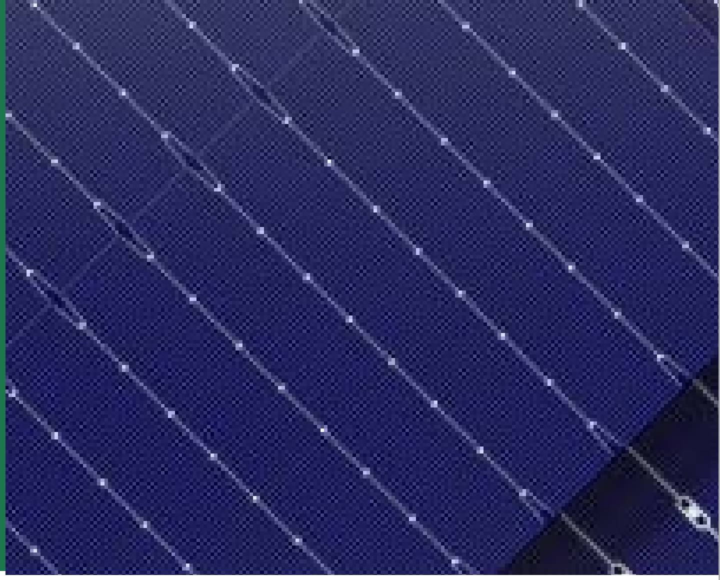
While the benefits of larger wafers are clear, this transition introduces new manufacturing and reliability challenges. Larger wafers—often paired with reduced thickness to minimize material costs—are inherently more susceptible to mechanical stress, leading to an elevated risk of microcracks, edge chipping, and surface scratches during handling and processing. Their increased surface area also necessitates tighter process uniformity, improved alignment accuracy, and advanced materials handling solutions to maintain production yields. Moreover, production lines originally designed for M6 or smaller wafers frequently required extensive upgrades or even full reconfiguration to accommodate M10 and G12/M12 formats. These modifications must ensure that throughput and electrical performance are maintained without compromising reliability.

Quality Assurance Implications

The evolution toward larger wafer sizes underscores the critical need for enhanced process control, precision equipment, and comprehensive quality assurance frameworks. Without these measures, the performance gains from larger wafers risk being offset by increased defect rates and latent field reliability issues—factors that could significantly impact long-term project performance and bankability.

The PV industry has undergone a fundamental shift toward larger silicon wafer formats, driven primarily by the pursuit of lower manufacturing costs and higher module power output..."

Managing Quality



Regional Dynamics

Global solar cell manufacturing is undergoing rapid geographic diversification, with new facilities emerging in regions such as India, the US, Africa and the Middle East to mitigate tariff exposure and optimize logistics. While this expansion provides greater supply flexibility, it also introduces variability in manufacturing maturity, quality systems, and sub-tier supplier transparency. These dynamics amplify the need for structured oversight. Independent factory audits, BOM-based traceability programs, and verified supplier certifications at the cell level are no longer optional—they are critical safeguards to ensure technical integrity, compliance with federal incentive programs, and long-term asset reliability.

As illustrated in Figure 5, audit results indicate a higher incidence of non-conformities in newly established facilities such as Indonesia and India compared to long-standing manufacturers such as in Malaysia. Common root causes include insufficient process control, inadequate operator training, and incomplete implementation of quality management frameworks. Emerging hubs, while instrumental in meeting global demand, often lack the institutional knowledge and stable supply chains characteristic of mature markets, necessitating enhanced diligence measures. Cell factory audits can give buyers improved qualification tools for cell suppliers, and provide targeted quality management over time.

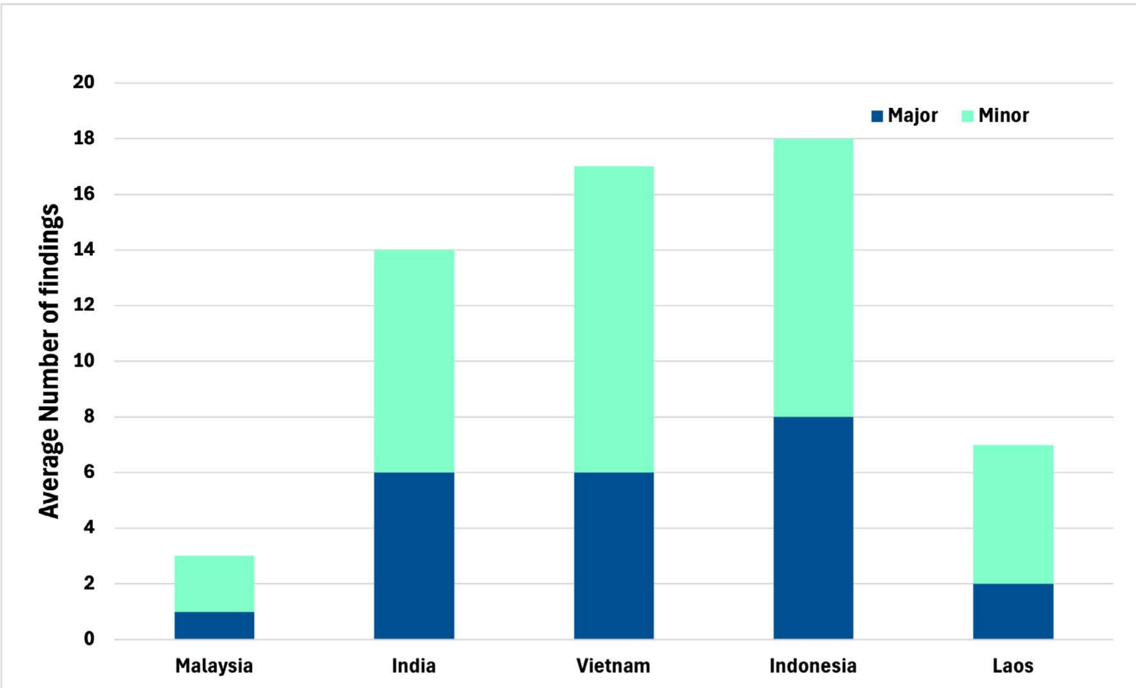


Figure 5. Regional Variability

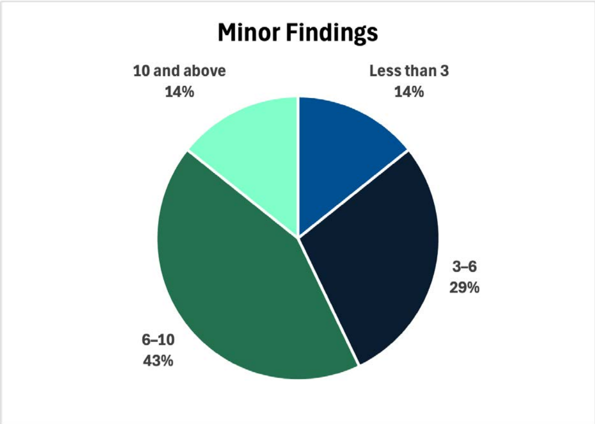


Figure 6. Minor Findings

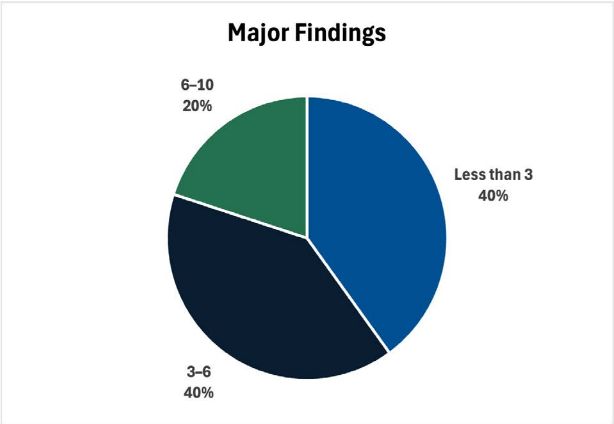


Figure 7. Major Findings

Cell Factory Audits

Kiwa PI Berlin conducts comprehensive cell factory audits globally, applying deep expertise in quality management and traceability for critical PV and BESS equipment. These audits evaluate critical risk areas across the full production lifecycle, ensuring alignment in supplier management, and employing quality control measures.

Figures 6–7 provide a detailed breakdown of the findings categorized as major and minor defects observed during factory audits. The analysis reveals that 40% of factories reported 3–6 major findings, while 20% recorded 6–10 major findings. The minor defect category also shows a significant number of findings, with over 85% of audited factories reporting more than three minor issues.

Given the high sensitivity of solar cell production to any process deviations, these results highlight significant challenges within solar cell manufacturing lines. Several of the observed findings, particularly in the major category, pose potential risks to end-module safety, reliability, and performance.

The significant number of both minor and major findings further underscores the importance of thorough production due diligence, including comprehensive factory audits, to mitigate risks and ensure consistent product quality.

In-factory cell quality assurance (QA) differs from module QA by focusing on large production batches that may not be assessed into the buyer's product. Differing from module product oversight and pre-shipment inspection programs, buyers are increasingly adopting a multi-audit strategy: beginning with a cell factory qualification audit to validate process stability and quality control capability, followed by regular verification audits to ensure controls remain effective and corrective actions are closed. This approach strengthens upstream quality management, enhances BOM traceability, and scales effectively for extended production runs across projects or portfolios.

Production Process Risks

Findings Categorization

Maintaining long term cell efficiency and reliability demands a comprehensive understanding of where quality risks originate in the production process. Cell manufacturing requires cleanroom classification (ISO Class 5–7), strict environmental controls (e.g. humidity, temperature), and critical process parameter control such as chemical concentration, processing time, and vacuum levels, to ensure consistency. Figure 8 breaks down Kiwa PI Berlin's factory audit finding data at cell manufacturers globally. Top audit findings are categorized into four critical areas:

1. Inadequate process control management, where even minor parameter deviations can lead to latent failures;
2. Deficiencies in quality management systems (QMS), particularly in emerging manufacturing regions;
3. Unreliable testing and labeling ractices, including improper calibration and lack of standardized metrology;
4. Weak material qualification and control, which can introduce defects early in the production cycle.

Process Control

As shown in Figure 8, the majority of quality findings—41%—originate from production process control, underscoring its critical role in defect prevention. Each step in cell fabrication is highly sensitive to variations in temperature, doping levels, gas flow, deposition time, and material purity. Even minor deviations can lead to latent reliability issues that escape routine factory checks like EL imaging or flash testing, only to emerge later as field degradation.

Quality Management System

The second most prevalent issue involves deficiencies in QMS frameworks for 25% of quality findings. Common gaps include missing SOPs, inadequate calibration protocols, and weak implementation of quality control plans and supplier oversight.

These shortcomings are especially pronounced in newer factories or emerging manufacturing regions, where operational maturity and quality culture are still evolving. A robust QMS is essential for consistent production, process monitoring, and meeting performance KPIs.

Testing & Characterization

Improper calibration of flash testers and reference cells is a recurring issue, leading to inaccurate power ratings and mislabeling of cells, resulting in 21% of findings. Some manufacturers lack trace-

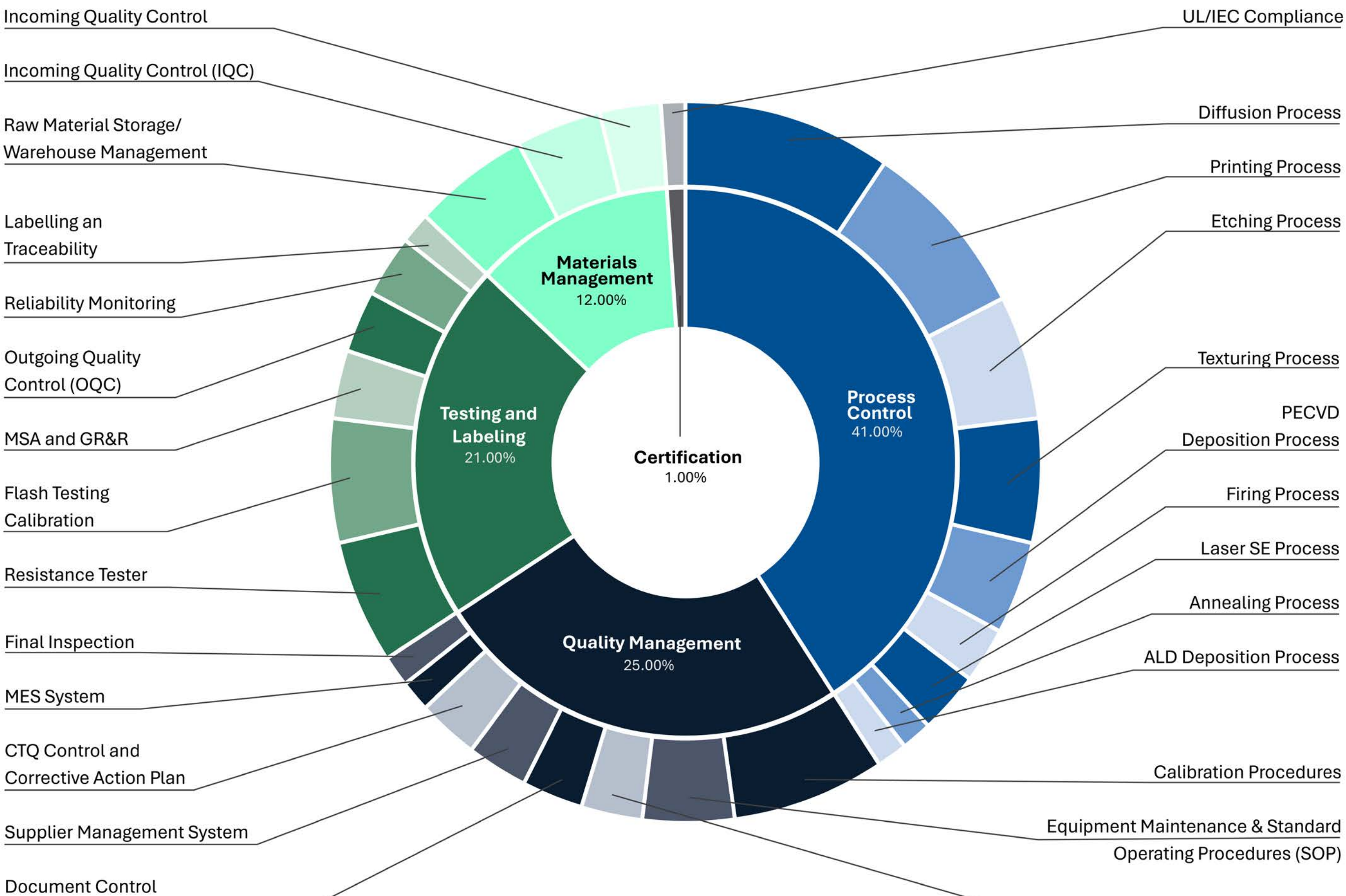
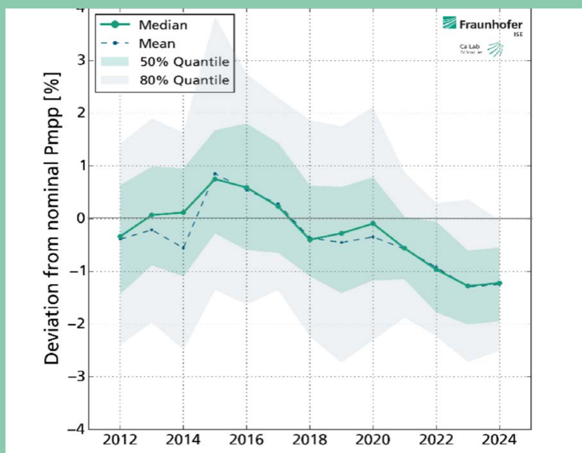


Figure 8. Deviation from reported rated power

able calibration procedures, which cause unreliable electrical measurements. Fraunhofer ISE[III]. data revealed that the average discrepancy between declared and measured PV module power values has increased in recent years. Until 2016, modules typically exhibited slightly higher measured power values compared to the manufacturer's labels. However, since then, a negative trend has emerged, particularly between 2020 and 2024. By 2024, FISE reported an average negative deviation of approximately 1.2%, indicating that measured power values were consistently lower than those declared by manufacturers — a trend that undermines system performance forecasting and buyer confidence.

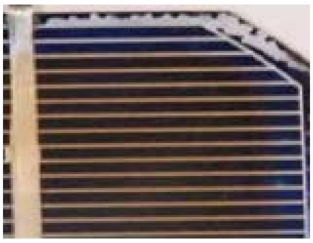
Additional gaps include the absence of engineering-based test protocols such as sheet resistance and four-point probe testing, which are vital for validating doping uniformity and film thickness. Furthermore, several production lines lack ongoing reliability testing and comprehensive outgoing quality control (OQC), increasing the risk of defective cells entering downstream processes and compromising module-level durability.

Material management accounts for 12% of observed findings. Issues include inadequate incoming inspection procedures, poor raw material sourcing controls, and substandard storage conditions. These weaknesses elevate the risk of introducing defects early in production, which may propagate through subsequent steps or manifest during field operation. A robust material qualification system is essential to safeguard long-term cell performance and reliability.

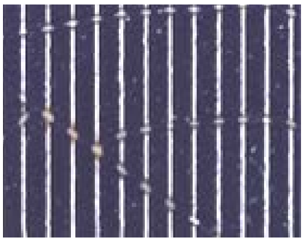


Deviation from reported rated power found in Fraunhofer ISE measurements.[III]

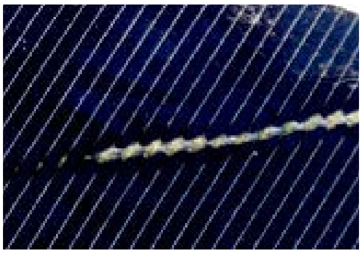
Defect Categorization



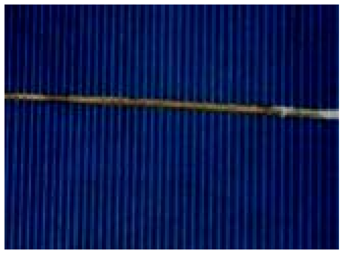
Edges Delamination



Snail track



Snail track with delamination



Discoloration and corrosio

Hidden Defect Risk

Cell-related risks are especially pronounced for TOPCon and HJT, where performance hinges on ultrathin passivation layers and complex multi-material interfaces. These designs introduce additional sensitivity to micro-defects that are often undetectable during PV module assembly. When **such defects bypass factory controls, they can manifest as accelerated field degradation**, higher failure rates, and ultimately lower energy yield. For this reason, system owners should understand the primary failure modes tied to cell-level issues, which commonly include:

a) Interface defects and poor interlayer adhesion: Reduce passivation effectiveness, leading to higher recombination losses and reduced open-circuit voltage (Voc).

b) Delamination and void formation: Causes local recombination, reduces carrier lifetime, and can lead to hotspots or local performance loss.

c) Non-uniform passivation quality: Causes localized recombination, leading to reduced fill factor (FF) and inconsistent power output across the module.

d) Elevated surface and bulk recombination: Lowers carrier lifetime and short-circuit current (Isc), directly reducing energy yield.

e) Microcracks and mechanical weaknesses: Lead to inactive cell areas, increased series resistance, or even electrical isolation of cell regions, reducing overall module efficiency.

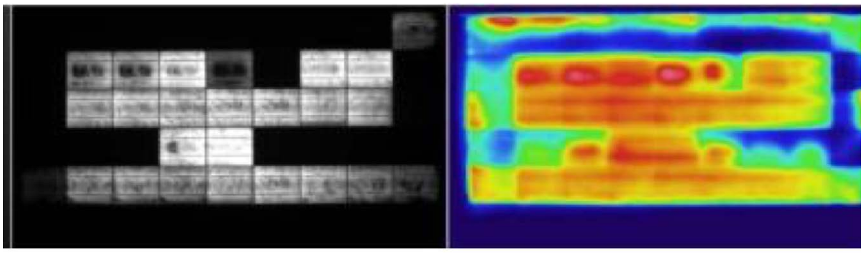
f) Pinholes or layer discontinuities: Cause leakage currents or localized shunting, which degrade module performance and may result in hotspot formation.

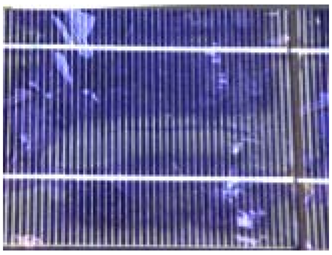
g) Contamination-induced shunting or leakage currents: Result in efficiency loss, higher dark current, and potential long-term degradation due to corrosive or conductive paths.

h) Laser-induced damage or improper edge isolation: Can create electrical shorts or hotspots, affecting module safety and performance stability.

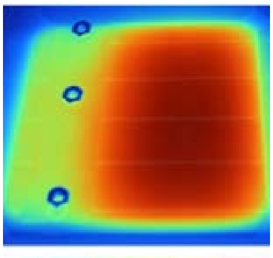
i) Patterning or alignment defects: Lead to incomplete contact formation or electrical mismatch, lowering power output and yield.

j) Hydrogen blistering or outgassing: Causes physical instability in the layer stack and can lead to delamination, loss of passivation, and module

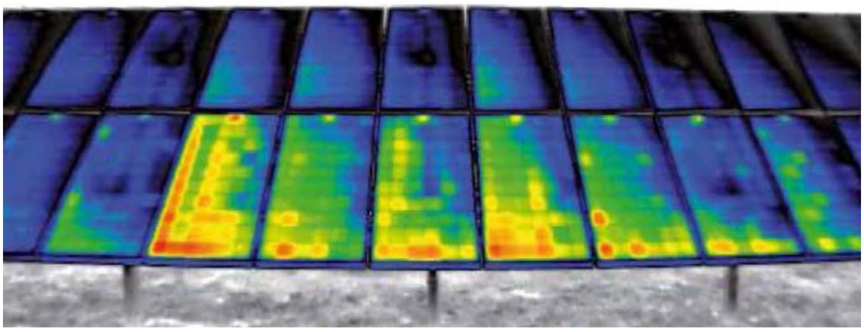




n of fingers and busbars



Hotspot



PID

Image References: Classification of cell cracks provides more legal certainty, Fraunhofer Center for Silicon Photovoltaics. Report IEA-PVPS T13-30:2025

reliability concerns.

k) Incomplete doping profiles: Weaken the electric field and reduce carrier collection, lowering both Voc and overall module power.

l) Metal paste diffusion or spiking: Introduces shunting paths through the cell, degrading fill factor and increasing the risk of local heating or early failure.

Such cell defects can contribute to field-related degradation phenomena including PID, LETID, and UVID— all of which pose significant threat to module performance and long-term reliability. Advanced cell architectures – PERC, TOPCon, and HJT—have significantly increased the complexity of cell production processes. Unlike traditional aluminum back surface field (Al-BSF) cells, which follow a relatively straightforward process, these high-efficiency technologies concerns which are detailed and described in Table 1.

Process Step	PERC	TOPCon	HJT	Defects & Risks
Wafer Cleaning & Texturing	✓ Wet or plasma etch	✓ Wet or plasma etch	✓ Wet or plasma etch	Incomplete cleaning → surface contamination, poor passivation, reduced efficiency
Emitter Formation	✓ Thermal diffusion	✓ Thermal diffusion	✗	Non-uniform diffusion → cell mismatch, poor shunt resistance
Surface Passivation	✓ AlOx/SiNx stack	✓ Tunnel oxide + Poly-Si	✓ a-Si:H layers	Defective passivation → high recombination, lower Voc and efficiency
Tunnel Oxide Deposition	✗	✓ (thermal oxidation)	✗	Thickness variation → tunneling failure, passivation loss
Poly-Silicon Deposition	✗	✓ LPCVD/PECVD	✗	Poly grain boundary issues → higher recombination, instability
Intrinsic a-Si:H Deposition	✗	✗	✓ (PECVD)	Thickness non-uniformity → passivation loss, optical absorption
Doped a-Si:H Deposition	✗	✗	✓ p+/n+ a-Si:H (PECVD)	Poor doping control → asymmetry in carrier collection, loss in fill factor
Transparent Conductive Oxide (TCO)	✗	✗	✓ ITO/AZO (sputtering)	TCO cracking or delamination → series resistance, adhesion failure
Metallization	✓ Screen printing + firing	✓ Screen printing + firing	✓ Low-temp curing or plating	Paste overflow, poor contact → shunting, cell-to-cell variation
Firing / Annealing	✓ High-temp (~750–800°C)	✓ High-temp (~750–800°C)	✗ Low-temp (<250°C)	Over-firing → metal spiking; under-firing → poor contact, increased resistance
Edge Isolation	✓ Laser/chemical etch	✓	✓	Incomplete isolation → edge shunting, leakage current
Final Cleaning & Inspection	✓	✓	✓	Missed defects → undetected microcracks, contamination, or warping

Table 1. Process steps and defect risks

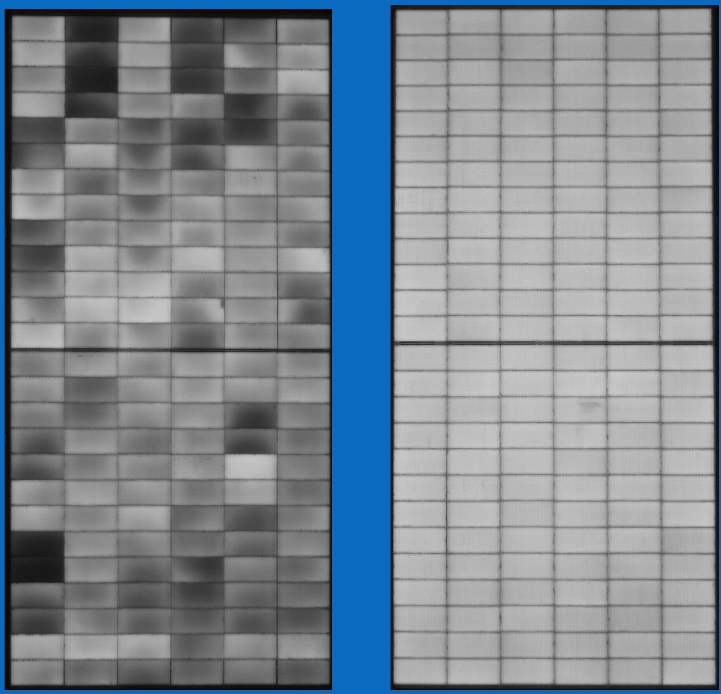


Figure 9
Left: Initial post-UV120 result (6.5% power loss).
Right: Retest post-UV120 result (1.3% power loss).

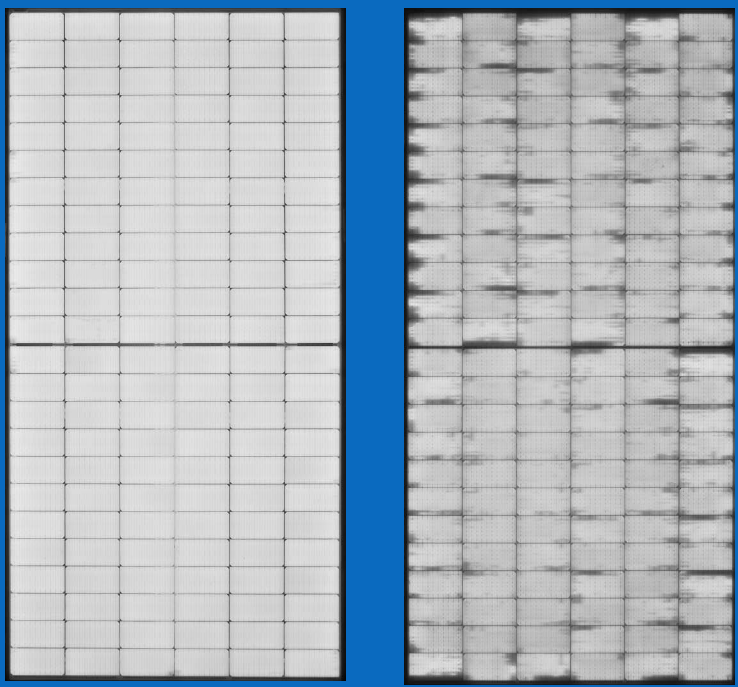


Figure 10
Left: Project 1's post-TC600 result (0.3% power loss).
Right: Project 2's post-TC600 result (3.3% power loss).

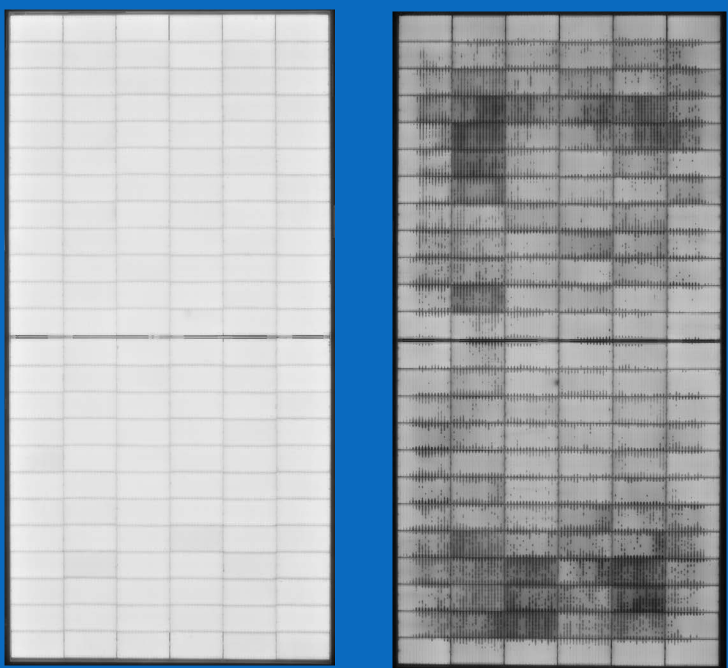


Figure 11
Left: BOM 1's post PID192(-) result (1.6% power loss).
Right: BOM 2's post-PID192(-) result (7.2% power loss).

Reliability Testing Insights

Since the introduction of the Product Qualification Program (PQP) in 2012, Kiwa PVEL's extended reliability and performance testing has consistently revealed how even subtle cell-level changes can significantly influence module durability and energy yield. Recent test cycles underscore that material selection, cell architecture, and process quality control remain critical determinants of long-term reliability.

One prominent area of focus is UVID, a key challenge emerging alongside the rapid adoption of n-type cell technologies. While UVID risk can be mitigated at the module level through UV-blocking or downshifting encapsulants and specialized glass, most TOPCon manufacturers rely on cell-level solutions. As shown in Figure 9 a recent PQP retest illustrates this point: the initial test recorded 6.5% power loss after UV120. The manufacturer then submitted new samples for a retest, which resulted in reducing power degradation to just 1.3%, an 80% improvement likely achieved by employing enhanced anti-reflective coating (ARC) and passivation process controls. While promising, this highlights a persistent risk: process upgrades must be consistently deployed across full-scale production, not just on PQP test samples.

Thermal cycling (TC) testing offers another example of the variability introduced by cell-related changes. One tested module demonstrated excellent TC600 results with only 0.3% power loss and a defect-free EL image (Figure 10). However, a subsequent BOM submitted by the same manufacturer under the same model and power class—this time with a different cell supplier as well as an alternative flux and encapsulant—recorded 3.3% power loss and clear evidence of cell metallization and soldering defects within the EL image.

The PQP's damp heat (DH) test provides more essential module reliability data and can often be used to distinguish reliable cells/BOMs from those needing improvements. Such as in this DH example, where two nearly identical BOMs from the same manufacturer—produced within a three month period and differentiated only by cell model number, flux, and frame sealant—yielded significantly different outcomes: the first achieved 1.5% power loss after DH2000, earning it a PV Module Reliability Scorecard Top Performer in that test, while the second had over twice the degradation with an average power loss of 3.8% following DH2000.

In this final example in Figure 11, potential induced degradation (PID) can also be significantly impacted by the cell's BOM and manufacturing process. Here, two very similar TOPCon BOMs from the same module manufacturer, both using the same front-side POE and rear-side EVA encapsulant produced sharply divergent results: 1.6% power loss for BOM-1 (making it a Scorecard Top Performer) versus 7.2% while BOM-2, which showed signs of PID-polarization throughout its EL image.

Given the cell's impact to module performance and reliability, Kiwa PVEL requires full PQP retesting for any cell manufacturer change, with the exception of the Backsheet Durability Sequence (BDS) test. Modifications to wafer thickness or metallization do not necessitate a complete retest but still trigger targeted PQP sequences as outlined in the Kiwa PVEL PQP – BOM Test Requirements. These retesting policies reflect a core principle: even incremental changes at the cell level can propagate into significant reliability risks, making robust testing and retesting protocols indispensable for quality benchmarking.

Kiwa PVEL PQP - BOM Test Requirements

New Material / Change in Material Specifications* / Etc.	TC	DH	MSS	PID	LID/LETID	UVID	HSS	PAN	IAM	FE	BDS
Cell[1]	X	X	X	X	X	X	X	X	X	X	
Cell Metallization	X	X									
Wafer Thickness	X[2]		X				X[2]				

1. Cell: Retests are not required for cell width and/or length changes within ±2 mm if there are no reductions to the cell-to-cell or creepage distances, but TC and MSS required if cell-to-cell distance decreases and DH and MSS required of creepage distance decreases; all 'new cell' tests required if cell width and/or length changes by >2 mm.
2. Wafer thickness: TC and MSS required if change to a ≥10% thinner wafer; MSS and HSS required if change to a ≥10% thicker wafer.

About Kiwa PI Berlin

Kiwa PI Berlin is a leading technical advisor and risk manager focused on quality assessment of PV and battery storage equipment. Kiwa PI Berlin provides technical diligence, procurement, and quality assurance services in the lab, factory, and field for a range of solar installers, project developers, utilities, and investors. We independently verify qualify, reliability, and performance through our direct relationships with PV module, inverter, BESS, and transformer manufacturers.

Kiwa PI Berlin has office locations in Germany, the USA, Spain, and China, and operates IEC 17025–accredited test laboratories in Berlin and Suzhou that evaluate PV module performance and reliability.

About Kiwa PVEL

Kiwa PVEL is the leading reliability and performance testing lab for downstream solar project developers, financiers, and asset owners around the world. As part of the larger Kiwa Group, Kiwa PVEL's integrated services for the solar supply chain offer technical solutions for mitigating risk, optimizing financing and improving solar and energy storage systems performance throughout the project lifecycle.

For over a decade, Kiwa PVEL's Product Qualification Program (PQP) has been globally recognized for replacing assumptions about PV module performance with quantifiable metrics. Related data and consulting services offered by Kiwa PVEL provide vital procurement intelligence to a network of downstream solar buyers. Visit kiwa.com/pvel and kiwa.com/solar to learn more.

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