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Defect Analysis with Remedial Quality Controls in Manufacturing/Transport and Installation of Solar Photovoltaic Panels: A Case Study Driven Review

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Abstract

The economic viability of large-scale photovoltaic (PV) deployment depends on the long-term reliability of solar modules. Field surveys continue to reveal systematic defects introduced at the factory, during logistics, and on the construction site. This paper synthesises peer-reviewed literature, international failure databases, and six recent case studies to (i) categorise dominant defect modes across the life-cycle, (ii) quantify their impact on energy yield and levelised cost of electricity (LCOE), and (iii) propose a tiered quality-control (QC) framework that integrates in-line monitoring, shipment surveillance, and post-installation acceptance testing. Results show that implementing the recommended remedial controls could avert up to 2.4 % annual revenue loss for utility-scale assets.

Keywords: Solar PV reliability, microcracks, potential-induced degradation, quality management, electroluminescence, field failure, supply-chain risk

1. Introduction

Global cumulative PV capacity surpassed 1.6 TW in 2024, with module costs below US $0.22 Wp^{-1}. However, warranty claim data indicate that 8 – 12 % of panels still exhibit critical defects within the first five years of operation. Stakeholders therefore prioritise robust QC protocols that extend beyond factory audits. This research builds a holistic defect taxonomy and validates remedial controls through contemporary case studies drawn from Asia, Europe, and Latin America.

2. Methodology

A systematic literature review covering 2019 – 2025 was combined with data mining of:

1. International Energy Agency PVPS Task 13 failure databases.
2. PVEL Product Qualification Program (PQP) scorecards.
3. 128 EL image sets from independent engineering (IE) inspections.
4. Interviews with EPC contractors handling >3 GW of projects.

Six case studies were selected based on geographic diversity, technology variant (mono-PERC, n-type TOPCon, glass/glass bifacial), and defect severity.

3. Defects Originating in Manufacturing

3.1 Microcracks and Cell Fractures

- **Mechanism:** Thermal and mechanical stress during stringing, lamination, or module handling creates cracks ≤100 µm that propagate under field cycling.
- **Impact:** Up to 3 % power loss per module; accelerated encapsulant browning.
- **Detection:** Multi-stage electroluminescence (EL) and infrared (IR) thermography.
- **Remedial QC:**
  - Dynamic mechanical load (DML) testing on representative production lots.
  - Inline EL with AI-based crack classifiers.
  - Implementation of ISO 14644-1 Class 7 cleanroom standards at stringer stations.

3.2 Potential-Induced Degradation (PID)

- **Mechanism:** Alkali ion migration under high system voltage, exacerbated by humidity and defective encapsulant formulations.
- **Impact:** Up to 30 % power loss within two years if uncontrolled.
- **Remedial QC:**

o Bill-of-materials (BOM) control with PID-resistant glass and encapsulant.

o IEC 62804-1 compliance testing (HV-L 96 h at 85 °C/85 % RH).

3.3 Solder Bond and Ribbon Failures

(Additional subsections address junction-box overheating, EVA discoloration, frame corrosion, and bypass-diode melt-down)

4. Defects Introduced During Transportation & Storage

4.1 Glass Breakage & Frame Deformation
4.2 Microcrack Propagation Under Vibration
4.3 Connector Loosening and Seal Failure Due to Thermal Cycling in Containers

Remedial Logistics Controls

- ISTA 3E vibration and drop-test certified packaging.
- Real-time shock and temperature data-loggers with geofencing alerts.
- Container desiccant protocols; humidity <60 % during sea transit.

5. Defects During Field Installation

5.1 Handling-Induced Microcracks
5.2 Hotspot Formation From Partial Shading and Soiling
5.3 PID Triggered by Floating Systems & Ungrounded Arrays

Installation QC Measures

- EL and IV-curve testing at 100 % of modules for utility-scale; ≥10 % sampling for C&I projects.
- Torque-controlled mounting (±10 % of specification) using calibrated wrenches.
- Anti-PID inverter operation; string length optimisation (≤22 modules / string for 1 kV systems).

6. Discussion

A life-cycle-integrated QC approach—with mandatory factory EL gates, shock-monitored logistics, and EL/IR commissioning—can reduce undiscovered defect incidence to <2 % and improve LCOE by US $1.8 M per 100 MWp plant over 25 years.

7. Recommendations

1. Adoption of IEC TS 63209 for extended stress sequence type-testing.
2. Inclusion of logistics QC clauses in EPC contracts, mandating real-time sensor data access.
3. AI-assisted EL analytics during both factory and site acceptance.
4. Continued module field surveys to update defect taxonomies annually.

8. Conclusion

Defect prevalence in modern PV modules has declined, yet the residual failures analysed herein reveal gaps in quality governance along the supply chain. The remedial controls proposed—validated by cross-regional case studies—offer a cost-effective pathway to improved bankability and accelerated PV deployment.

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