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Performance Assessment of Photovoltaic Modules: A Comprehensive Review

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Abstract

Performance assessment of photovoltaic (PV) modules has evolved from simple power-rating measurements under standard test conditions to a multidimensional field encompassing energy rating, degradation analysis, reliability testing, and climate-specific evaluation. This paper synthesizes evidence from international standards (IEC 61853), field studies across diverse climatic zones, and comparative technology assessments to examine the state of the art in PV module performance evaluation. The evidence reveals a fundamental gap between laboratory ratings and real-world performance: modules rated at Standard Reporting Conditions (SRC: 1000 W/m^2, 25°C) rarely operate under these conditions outdoors, necessitating alternative metrics including Performance Ratio (PR), Performance Test Conditions (PTC), and energy rating methodologies . Field studies in India document annual power degradation rates ranging from 0.8% to 4.0% over 21 years of exposure in composite climatic zones, surpassing typical warranty limits, yet indicating considerable reuse potential for modules with up to 25% performance loss . Temperature effects are profound: in Indian tropical conditions, elevated module temperatures caused output power drops of 7.6% to 15.2% during summer months, while soiling contributed additional losses of 0% to 10.2% before rainfall events restored performance . A 200 kWp rooftop plant in Prayagraj achieved a Performance Ratio of 71.0%, reflecting combined losses from thermal effects (6%), soiling (4.5%), and inverter efficiency (2.5%) . Comparative technology studies in desert climates reveal significant variability: heterojunction (HJT) modules exhibited degradation of up to 8.73% over three years despite favorable temperature coefficients, while one TOPCon model degraded by only 0.14%, highlighting the dependence of reliability on design and manufacturing choices . The paper identifies critical gaps in standardized energy rating implementation, long-term degradation prediction, and climate-specific performance modeling, and recommends a multi-metric assessment framework integrating laboratory characterization, outdoor monitoring, and advanced imaging diagnostics.

Keywords:

photovoltaic modules, performance assessment, Performance Ratio, energy rating, degradation, IEC 61853, soiling, temperature effects, India

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1. Introduction

Performance assessment of photovoltaic modules is the foundation upon which solar energy projects are financed, warranted, and optimized. A module's rated power—measured under Standard Reporting Conditions of 1000 W/m^2 irradiance and 25°C cell temperature—serves as the commercial benchmark, yet this single number conveys little about how the module will perform in the field, where irradiance varies from zero to over 1000 W/m^2, cell temperatures routinely exceed 50°C, and soiling, shading, and spectral variations impose additional losses . The gap between laboratory rating and outdoor reality has driven the development of more sophisticated assessment methodologies: energy rating standards (IEC 61853), field performance metrics (Performance Ratio, final yield), and degradation analysis protocols.

The stakes are particularly high in India, which aims to achieve 500 GW of non-fossil fuel capacity by 2030, with approximately 280 GW expected from solar . As of 2015, India's installed solar capacity reached approximately 110 GW. The performance of these installations—their actual energy yield, degradation rates, and lifetime—determines the return on investment and the viability of future deployment. Field evidence from Indian conditions is essential because the country's composite and tropical climates impose stresses that differ substantially from the temperate conditions where most PV technologies were developed and tested.

This paper examines the methodologies, metrics, and empirical findings that constitute the current state of PV module performance assessment. It addresses both the technical frameworks (standards, metrics, measurement techniques) and the field evidence from diverse climatic zones, with particular attention to Indian studies. The objective is to provide a comprehensive synthesis that identifies what is known, what remains uncertain, and what assessment practices are most appropriate for different applications and climates.

2. Definitions

Standard Reporting Conditions (SRC) / Standard Test Conditions (STC): The reference conditions for PV module power rating: irradiance of 1000 W/m^2, spectral distribution AM 1.5G, and cell temperature of 25°C. Nameplate power (Wp) is measured under these conditions.

Performance Test Conditions (PTC): A more realistic rating condition: 1000 W/m^2 irradiance, 20°C ambient temperature, and 1 m/s wind speed. PTC ratings are typically 10–15% lower than SRC ratings and better predict field performance .

Performance Ratio (PR): The ratio of actual energy output to the theoretical output based on nameplate rating and in-plane irradiance. PR accounts for all losses (temperature, soiling, inverter, wiring, mismatch) and serves as a key figure of merit for system performance .

Energy Rating: A methodology for predicting module energy output across a range of irradiance and temperature conditions, as specified in IEC 61853. Unlike single-point power ratings, energy ratings characterize performance under realistic operating spectra .

Degradation Rate: The annual percentage loss of module power output over time, typically expressed as %/year. Measured through repeated I-V curve tracing or power measurements under controlled conditions.

Soiling Loss: The reduction in energy output due to accumulation of dust, dirt, and particulate matter on the module surface. Measured as the percentage difference between cleaned and uncleaned performance .

3. Need for the Study

Three considerations establish the imperative for this review.

First, the divergence between laboratory ratings and field performance has direct financial consequences. Modules that meet nameplate specifications under SRC may underperform substantially in hot, dusty, or humid climates. A 200 kWp plant in Prayagraj achieved only 71.0% PR, with thermal effects alone accounting for 6% loss . Without accurate performance assessment, investors cannot price risk, and system designers cannot optimize configurations for local conditions.

Second, the Indian evidence base is fragmented across technologies, climates, and methodologies. Studies exist on monocrystalline modules in composite climates , rooftop systems in tropical conditions , bifacial performance in central India , and comparative technology assessments in deserts . A synthesis that identifies consistent patterns and context-specific variations is needed.

Third, international standards for energy rating (IEC 61853) are complex and have not been widely implemented in Indian practice. Simplified procedures developed by laboratories offer alternatives, but their accuracy and applicability to Indian conditions require assessment .

4. Aims and Objectives

This paper aims to provide a comprehensive synthesis of PV module performance assessment methodologies and empirical findings, with emphasis on field evidence from Indian and comparable climates.

Objectives:

1. To review the technical frameworks for PV performance assessment, including SRC/PTC ratings, Performance Ratio, and IEC 61853 energy rating.
2. To synthesize field evidence on temperature, soiling, and degradation effects across climatic zones.
3. To compare performance and reliability of different module technologies (monocrystalline, bifacial, HJT, TOPCon, PERC) based on field studies.
4. To identify gaps between standardized testing and real-world performance.
5. To propose a practical assessment framework for Indian conditions.

5. Hypothesis

H1: Field-measured Performance Ratios in Indian conditions are systematically lower than the values implied by nameplate ratings, with thermal and soiling losses accounting for the majority of the gap.

H2: Degradation rates vary significantly by technology and manufacturer, with some modules exceeding warranty limits within the first decade of operation.

H3: Simplified energy rating procedures can approximate IEC 61853 outcomes with acceptable accuracy for preliminary system design in Indian climates.

6. Literature Search

The literature on PV module performance assessment spans standards documentation, field studies, and comparative technology evaluations.

Standards and Methodologies. The IEC 61853 standard provides the framework for energy rating, characterizing module output as a function of irradiance, module temperature, angle of incidence, and spectral distribution . Parts 1 and 2 address performance testing; Part 3 (Committee Draft at the time of the reviewed source) describes energy rating calculations. Because the full standard is complex, several laboratories have developed simplified procedures using only in-plane irradiance and module temperature, ignoring angle of incidence and spectral effects . The DERlab Association has developed a common procedure for long-term energy yield measurements under outdoor conditions.

Performance Ratio and Field Metrics. Performance Ratio (PR) measures system energy efficiency by comparing actual output to potential output. It is simple to use and can be adjusted for temperature and bifacial modules, but is influenced by environmental factors including high DC-to-AC ratios and curtailment . Differences in how temperature-corrected PR and bifacial adjustments are applied underscore the need for standardized definitions .

Temperature and Soiling Effects in India. A Nature study of rooftop PV in composite climatic conditions recorded output power drops of 7.6% to 15.2% due to elevated module temperatures during June. Soiling losses ranged from 0% to 10.2%, with cumulative loss reaching 10.2% before rainfall events restored performance to near 100% . Average soiling loss was 0.43% per day before rainfall and 0.26% per day after. Rooftop systems demonstrated 2.27% higher cumulative power than ground-mounted systems due to improved convective cooling .

Long-Term Degradation in India. A 21-year field study of monocrystalline silicon modules in composite climatic zones found annual power degradation rates of 0.8% to 4.0%, surpassing typical warranty limits. Despite degradation, modules with up to 25% performance loss showed potential for reuse in low-voltage applications. Area requirement analysis indicated that accommodating 25%-degraded modules would require approximately 36% more land than non-degraded modules at 30° latitude .

Comparative Technology Performance. A three-year field experiment in Qatar's desert climate compared PERC, TOPCon, and HJT modules. HJT modules exhibited the highest degradation (8.73% over three years), while one TOPCon model degraded by only 0.14%—the lowest of all modules. Another TOPCon model showed substantial degradation, indicating high variability dependent on design and manufacturing . Bifacial HJT and TOPCon modules demonstrated

superior specific energy yield compared to PERC, particularly in summer; the gap narrowed in winter. Temperature-corrected PR analysis showed heat-related performance loss of 9.89% for one TOPCon model and 5% for an HJT model . A separate study in the Atacama Desert found HJT modules outperformed PERC under high-temperature conditions, with average effective operating hours of 5.8 versus 5.5 kWh/(kWp·day), and HJT lost 3.5% of EOH to thermal effects versus 5.5% for PERC .

Bifacial Performance in Central India. A study at IIT Bhilai (May–August 2015) compared monofacial and bifacial monocrystalline modules, finding quantifiable PR enhancement for bifacial modules attributable to rear-side energy yield. The study emphasized the influence of seasonal variability, irradiance, and module temperature on performance .

System-Level Assessment. A 200 kWp grid-connected rooftop plant in Prayagraj achieved 71.0% PR, with losses from thermal effects (6%), soiling (4.5%), inverter efficiency (2.5%), and atmospheric attenuation typical of monsoon conditions. The system comprised 363 monocrystalline modules (550 Wp each) with two 80 kW inverters .

7. Research Methodology

This review employs a **systematic narrative synthesis** of standards documentation, peer-reviewed field studies, and conference proceedings on PV module performance assessment.

Sources. The analysis draws upon: (1) IEC 61853 standard descriptions and simplified energy rating procedures ; (2) PR methodology and standardization discussions ; (3) Indian field studies including the 21-year degradation assessment , the Nature soiling and temperature study , the IIT Bhilai bifacial comparison , and the Prayagraj 200 kWp plant assessment ; (4) comparative technology studies from desert climates ; and (5) IEA-PVPS Task 13 reports on performance and reliability .

Analytical Framework. The review is organized by assessment dimension: (a) **rating methodologies** (SRC, PTC, energy rating); (b) **field performance metrics** (PR, yield, losses); (c) **degradation and reliability** (long-term studies, technology comparisons); and (d) **environmental factors** (temperature, soiling, climate).

Limitations. The review is constrained by the predominance of specific technology and geographic contexts in available studies. Indian field data, while growing, remain limited relative to the diversity of climates and module types deployed. Measurement methodologies vary

across studies, complicating direct comparison. The review does not conduct original experimental work.

8. Strong Points: Robust Methodologies and Consistent Findings

Standardized Frameworks Enable Comparison. The IEC 61853 standard and the PR metric provide common languages for performance assessment across laboratories, manufacturers, and field installations . Despite implementation challenges, these frameworks enable meaningful comparison of modules tested in different locations and by different organizations.

Field Evidence from India is Accumulating. Studies from composite climatic zones , tropical monsoon conditions , and central India provide geographically specific data that inform system design. The 21-year degradation study is particularly valuable for understanding long-term performance in Indian conditions, documenting degradation rates that exceed warranty limits but still permit secondary use .

Temperature and Soiling Impacts Quantified. The Nature study provides granular data on the magnitude and temporal dynamics of temperature and soiling losses in Indian conditions: 7.6–15.2% thermal losses and 0–10.2% soiling losses, with rainfall restoring performance . These data enable more realistic yield predictions for system designers.

Technology Comparisons Reveal Trade-offs. The Qatar study demonstrates that no single technology dominates across all metrics: HJT showed superior specific energy yield and lower heat-related losses but higher degradation; TOPCon showed high variability, with one model achieving the lowest degradation and another among the highest . These findings caution against blanket technology recommendations.

9. Weak Points: Limitations and Knowledge Gaps

Gap Between Laboratory and Field. The fundamental limitation of PV performance assessment is that SRC ratings do not predict field performance. Modules rated at 1000 W/m^2 and 25°C rarely operate under these conditions; in Indian summers, cell temperatures routinely exceed 60°C, reducing output by 10–15% . While PTC and energy ratings address this gap, their adoption in Indian procurement and warranty practices remains limited.

Incomplete Degradation Understanding. The 21-year Indian study found degradation rates of 0.8–4.0% per year, but the mechanisms driving this variability are not fully characterized . The

Qatar study's finding of high inter-model variability in TOPCon degradation—from 0.14% to substantially higher—indicates that manufacturing quality, not just technology class, determines reliability . Predictive models for degradation remain underdeveloped.

Measurement Uncertainty and Standardization. The ScienceDirect review acknowledges that "existing methods for characterizing PV system performance are subject to substantial uncertainty" . Differences in how PR is calculated—temperature-corrected versus uncorrected, bifacial-adjusted versus not—create comparability problems . The absence of standardized reference materials and round-robin testing for field performance assessments hinders progress.

Limited Coverage of Emerging Technologies. Most Indian field studies focus on monocrystalline silicon. Data on TOPCon, HJT, and perovskite-silicon tandems in Indian conditions are scarce. The Qatar study provides desert-climate data , but Indian monsoon and composite climates impose different stresses (humidity, dust, variable irradiance) that require dedicated investigation.

Soiling Modeling Limitations. While the Nature study documents soiling rates and rainfall cleaning effects , predictive models for soiling in different Indian regions remain inadequate. The interaction between soiling, humidity, and wind is complex and site-specific.

10. Current Trends

Shift Toward Energy Rating and Climate-Specific Assessment. The limitations of SRC ratings are increasingly recognized, driving interest in IEC 61853 energy ratings and climate-specific performance characterization . IEA-PVPS Task 13 has published reports on climatic rating of modules and optimization for different climates .

Bifacial Technology Assessment. Bifacial modules are gaining market share, and assessment methodologies are evolving to account for rear-side irradiance. Studies in central India and desert climates document quantifiable PR and yield enhancements, though the magnitude depends on albedo, mounting height, and climate.

Advanced Diagnostic Imaging. Electroluminescence (EL), photoluminescence (PL), and lock-in thermography (LIT) are increasingly used for spatially resolved assessment of degradation and defects . EL imaging, standardized under IEC TS 60904-13, is the most widely applied method for module characterization.

Long-Term Field Studies and Reuse Assessment. The 21-year Indian study exemplifies a trend toward understanding end-of-life performance and reuse potential . As the first generation of utility-scale PV installations approaches retirement, assessing degradation and secondary use options becomes critical for circular economy considerations.

Real-Time Monitoring and Digital Twins. IEA-PVPS Task 13 has published reports on digitalization and digital twins in PV systems , reflecting movement toward continuous, data-driven performance assessment rather than periodic offline testing.

11. History

The assessment of PV module performance has evolved alongside the technology itself, from simple power measurements to sophisticated multi-dimensional characterization.

Early Era (1950s–1980s): Single-Point Ratings. The first PV modules, developed for space applications, were rated by their maximum power under specific illumination. As terrestrial applications emerged following the oil crises of the 1970s, the need for standardized ratings became apparent. The establishment of SRC (1000 W/m^2, AM 1.5, 25°C) provided a common benchmark, enabling commercial transactions and technology comparison. However, the limitations of single-point ratings for predicting field performance were recognized early.

Standardization and Field Testing (1990s–2000s). The IEC 61215 and 61646 standards for module qualification established testing protocols for design qualification and type approval. The IEC 61853 standard for energy rating was developed to address the gap between SRC and field performance, characterizing module output across irradiance and temperature matrices . Field testing programs, including those coordinated by IEA-PVPS Task 2, began systematically collecting performance data from grid-connected and stand-alone systems . These programs revealed that annual final yields varied widely (100–1200 kWh/kW for stand-alone systems) and that performance ratios for off-grid domestic systems ranged from 0.2 to 0.6 .

Degradation and Reliability Focus (2010s–present). As the first large-scale PV installations aged, attention shifted to degradation and lifetime performance. IEA-PVPS Task 13 was established to address performance and reliability, producing reports on degradation and failure modes, service life estimation, and assessment of performance loss rates . Advanced characterization techniques—EL, PL, LIT—became standard tools for diagnosing degradation mechanisms . In India, the 21-year degradation study represents a milestone in long-term field assessment .

Climate-Specific and Technology-Diverse Assessment (2018s–present). The most recent phase is characterized by recognition that performance is climate-specific and technology-dependent. Studies in desert climates , tropical monsoon conditions , and composite zones provide evidence that a single set of performance parameters cannot characterize all deployment contexts. The emergence of TOPCon, HJT, and perovskite technologies demands new assessment protocols that capture their distinct degradation modes and temperature responses.

12. Discussion

The evidence assembled in this review supports a clear conclusion: **PV module performance assessment must move beyond nameplate ratings toward multi-metric, climate-specific, and time-dependent characterization**. The SRC rating, while necessary for commercial transactions, explains little about field performance. The metrics that matter—Performance Ratio, final yield, degradation rate—vary substantially by climate, technology, and system design.

The Temperature Penalty in Indian Conditions. The finding that thermal effects reduce output by 7.6–15.2% during Indian summers and contribute 6% to total PR losses in Prayagraj quantifies a penalty that is often underestimated in system design. The Qatar study's temperature-corrected PR analysis, showing heat-related losses of 5–9.89% depending on technology , confirms that thermal management is not a secondary concern but a primary determinant of energy yield in hot climates. Modules with lower temperature coefficients (HJT) show advantages in desert conditions , but the Indian evidence base on comparative temperature coefficients is limited.

Soiling as a Dynamic and Manageable Loss. The Nature study's documentation of soiling losses accumulating to 10.2% before rainfall, then dropping to near zero after heavy rain , illustrates both the magnitude of the soiling penalty and the potential for natural mitigation. In regions with regular rainfall, cleaning schedules can be optimized based on seasonal patterns. In arid regions, soiling losses can be much higher—up to 70% in extreme desert environments according to the literature reviewed .

Degradation Variability and Warranty Implications. The 21-year Indian study's finding of 0.8–4.0% annual degradation, exceeding typical warranty limits , has significant implications for asset valuation and warranty enforcement. The Qatar study's finding that one TOPCon model

degraded by only 0.14% over three years while another showed substantial degradation indicates that manufacturing quality and design choices, not technology class alone, determine reliability. This variability complicates the use of generic degradation assumptions in financial modeling.

The Bifacial Advantage. The IIT Bhilai study provides empirical evidence of quantifiable PR enhancement for bifacial modules in central Indian conditions . The magnitude depends on albedo, which varies by ground cover and season. The Qatar study confirms superior specific energy yield for bifacial HJT and TOPCon compared to PERC, particularly in summer . Bifacial technology thus offers a pathway to higher energy density per unit area, though the additional cost and complexity of system design must be weighed against the gain.

Methodological Standardization as an Unmet Need. The ScienceDirect review's acknowledgment of "substantial uncertainty" in performance characterization and the PR definition inconsistencies noted by pv magazine indicate that the field lacks the standardization necessary for rigorous comparison. The IEC 61853 standard exists but is complex and incompletely implemented . Simplified procedures offer practical alternatives but require validation against the full standard for Indian conditions.

13. Results

Performance Ratio and Losses. A 200 kWp plant in Prayagraj achieved 71.0% PR. Loss breakdown: thermal 6%, soiling 4.5%, inverter 2.5%, atmospheric attenuation (monsoon) remainder . Temperature-corrected PR analysis in Qatar desert: heat-related losses 5% (HJT) to 9.89% (TOPCon) .

Temperature Effects. Indian summer conditions: output power drops of 7.6% to 15.2% due to elevated module temperatures . Rooftop systems showed 2.27% higher cumulative power than ground-mounted due to improved convective cooling .

Soiling Losses. Indian composite climate: 0–10.2% monthly soiling loss, average 0.43%/day before rainfall, 0.26%/day after. Heavy rainfall (>10 mm) restored performance to near 100% .

Degradation. 21-year Indian monocrystalline field exposure: 0.8–4.0% annual power degradation. Modules with up to 25% loss showed reuse potential for low-voltage applications . Qatar desert three-year study: HJT degradation 8.73% (highest), TOPCon 0.14% (lowest among tested), highlighting inter-model variability .

Technology Comparison. Atacama Desert: HJT average EOH 5.8 kWh/(kWp·day) vs. PERC 5.5; HJT thermal loss 3.5% vs. PERC 5.5%; HJT bifacial gain +3.5% vs. PERC +2% . Qatar: bifacial HJT and TOPCon showed superior specific energy yield vs. PERC, especially summer; gap narrowed in winter .

Bifacial Enhancement. IIT Bhilai: quantifiable PR enhancement for bifacial modules attributable to rear-side yield under central Indian seasonal variability .

14. Conclusion

The performance assessment of photovoltaic modules has matured from a narrow focus on nameplate ratings to a multidimensional field encompassing energy rating, field performance metrics, degradation analysis, and climate-specific characterization. The evidence assembled in this review demonstrates that **field performance is systematically and substantially lower than laboratory ratings in Indian and comparable climates**, with thermal and soiling losses accounting for the majority of the gap.

The 200 kWp Prayagraj plant's 71.0% PR, with 6% thermal and 4.5% soiling losses , and the Nature study's documentation of 7.6–15.2% thermal losses and up to 10.2% soiling losses , provide quantified evidence of the penalties that system designers must anticipate. The 21-year degradation study's finding of 0.8–4.0% annual degradation indicates that long-term performance may fall short of warranty expectations, though reuse potential exists for degraded modules.

Technology comparisons reveal that no single module type dominates across all metrics. HJT modules show advantages in temperature coefficients and bifacial gain but exhibited the highest degradation in one desert study . TOPCon performance varies widely by manufacturer, with one model achieving the lowest degradation and another among the highest . Monocrystalline PERC remains competitive with appropriate design .

The path forward requires three developments. **First**, adoption of energy rating methodologies (IEC 61853 or validated simplified procedures) in procurement and system design, moving beyond SRC ratings. **Second**, climate-specific performance databases that enable accurate yield prediction for Indian conditions across technology types. **Third**, standardized degradation assessment protocols that can identify underperforming modules early and inform warranty enforcement.

The assessment of PV module performance is not merely a technical exercise; it determines whether solar energy delivers on its economic and environmental promise. Accurate, climate-specific, multi-metric assessment is the foundation of that delivery.

15. Suggestions and Recommendations

For System Designers and Investors:

1. **Use PTC or energy ratings, not SRC alone, for yield prediction.** Apply a temperature derating factor appropriate to the site's climate (5–15% for Indian conditions) and account for soiling losses based on local rainfall and dust patterns.
2. **Prioritize temperature coefficient in module selection for hot climates.** Modules with lower temperature coefficients (typically HJT and some TOPCon products) offer higher energy yield in Indian summers, partially offsetting higher upfront costs.
3. **Consider bifacial modules where albedo permits.** Empirical evidence from central India and desert climates supports quantifiable gains, but the benefit depends on ground cover and mounting configuration.

For Researchers:

4. **Conduct comparative technology studies in Indian monsoon and composite climates.** The evidence base is dominated by monocrystalline silicon; TOPCon, HJT, and tandem technologies require dedicated assessment under Indian conditions.
5. **Develop and validate simplified energy rating procedures against IEC 61853 full characterization.** Practical tools for Indian system designers are needed .
6. **Standardize PR calculation methodologies.** Temperature correction and bifacial adjustment should follow consistent definitions to enable cross-study comparison .

For Policymakers and Standards Bodies:

7. **Mandate energy rating disclosure in public procurement.** Requiring IEC 61853-based energy ratings alongside SRC nameplate ratings would improve transparency and enable better-informed purchasing decisions.
8. **Support long-term field monitoring infrastructure.** The 21-year Indian study demonstrates the value of sustained observation; similar programs for emerging

technologies would provide data essential for degradation modeling and warranty enforcement.

16. Future Scope

1. **Climate-specific energy rating datasets for India.** Systematic collection of performance data across the country's diverse climatic zones (hot-dry, hot-humid, composite, cold, moderate) for multiple module technologies.
2. **Degradation modeling and prediction.** Development of physics-based or data-driven models that can predict degradation trajectories from accelerated stress tests, validated against long-term field data.
3. **Bifacial and tandem technology assessment.** As bifacial and perovskite-silicon tandems enter the market, independent field studies are needed to validate manufacturer claims and characterize performance under Indian conditions.
4. **Soiling prediction and cleaning optimization.** Machine learning models that integrate weather forecasts, dust deposition physics, and economic cleaning costs to optimize maintenance schedules.
5. **Advanced diagnostic integration.** Combining EL/PL imaging with I-V curve analysis and thermal imaging for comprehensive, non-destructive module health assessment in field settings .
6. **Reuse and circular economy assessment.** The 21-year Indian study's finding of reuse potential for degraded modules warrants further investigation into second-life applications, testing protocols, and market development.

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