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# Comparative Assessment of Crystalline-Silicon PV Technologies (PERC, TOPCon, HJT, IBC): Encapsulant Selection, Reliability Testing (PID, DH, UVID, LeTID, Hot-Spot, TC, HF), and Cost–Efficiency Trade-offs

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## Abstract

We present a comparative study of four crystalline-silicon photovoltaic (PV) cell architectures—PERC, TOPCon, HJT, and IBC—integrating module-level performance ranges, manufacturing cost orientation, and reliability testing aligned with IEC standards. We analyze efficiency (20.5–24.5%), temperature coefficients, bifaciality, and indicative $/W costs, and propose a bill-of-materials (BOM) decision framework using encapsulants EVA, EPE, and POE for glass–glass (GG) and glass–backsheet (GB) packages. We include a standardized test matrix for PID (IEC TS 62804-1), Damp Heat (DH), UV preconditioning (UVID), LeTID (IEC TS 63342), Hot-Spot endurance, Thermal Cycling (TC), and Humidity Freeze (HF). Charts compare efficiency, cost, LCOE, and retained-power trajectories for GG vs GB. Results indicate TOPCon as the near-term cost–performance default, HJT as a premium option in heat- and space-constrained contexts, and IBC as the high-efficiency frontier; encapsulant choice (POE/EPE) materially reduces PID and moisture-driven risks, especially in GG bifacial modules.

***Keywords:*** TOPCon; PERC; HJT; IBC; Encapsulant; EVA; POE; EPE; PID; LeTID; IEC 61215; Reliability; LCOE; Bifacial; Glass–Glass; Glass–Backsheet

## 1. Introduction

Crystalline-silicon (c-Si) technologies dominate PV, with module efficiency advancing beyond 22% and N-type architectures displacing legacy PERC. Contemporary adoption centers on TOPCon, HJT, and back-contact (IBC), each with distinct process and reliability considerations. This report consolidates public data (2024–2026) and IEC-aligned test methods to guide material selection and qualification in hot/humid climates.

## 2. Methods

Performance ranges were synthesized from industry technology guides and trend reports. Cost orientation reflects directional $/W ranges observed in China-centric manufacturing. Reliability test parameters follow

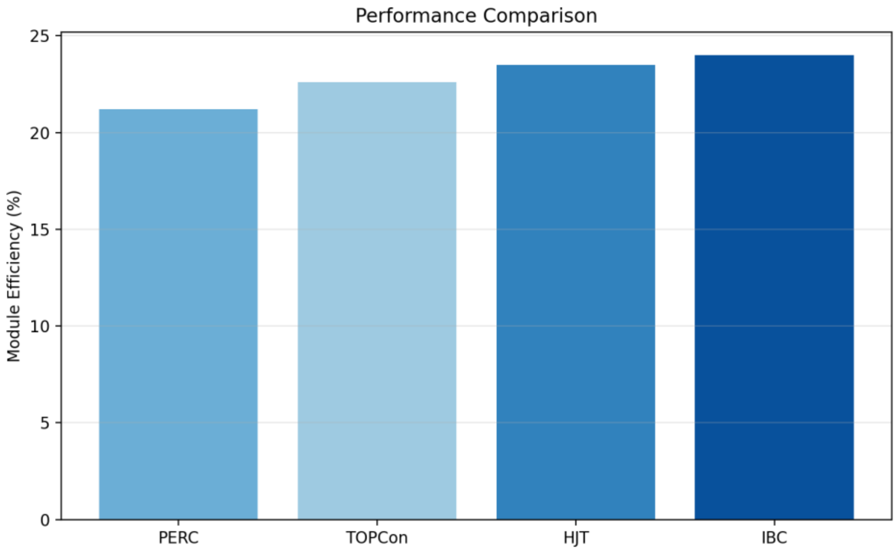
IEC 61215 and IEC TS 62804-1/IEC TS 63342. LCOE and retained-power charts were computed under hot-site assumptions; efficiency and cost charts use reported ranges.

## 3. Technology Overview

PERC: mature, low cost, higher LID/LeTID susceptibility. TOPCon: tunnel oxide passivated contacts, higher efficiency and bifaciality, reliable field behavior. HJT: heterojunction stacks, lowest temperature coefficients, high bifaciality, BOM-dependent reliability. IBC: rear contacts eliminate shading; premium process complexity.

## 4. Performance and Cost

Module efficiency ranges: PERC ~20.5–22%; TOPCon ~21.5–23.8%; HJT ~23–24%; IBC ~23–24.5%. Temperature coefficients: PERC −0.34 to −0.40%/°C; TOPCon −0.30 to −0.32%/°C; HJT ~−0.25%/°C typical. Bifaciality: PERC ~70%, TOPCon 80–90%, HJT up to ~95%. Indicative $/W ordering: PERC < TOPCon < HJT < IBC.



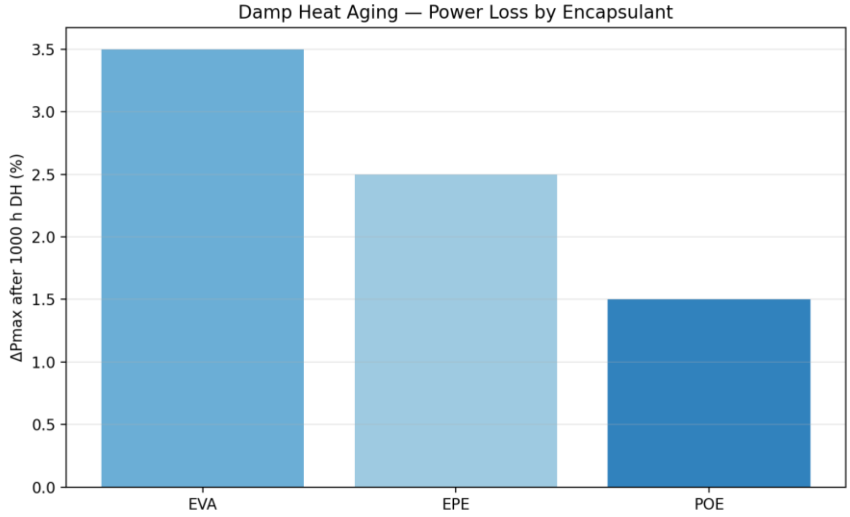

## 5. LCOE and Reliability (GG vs GB)

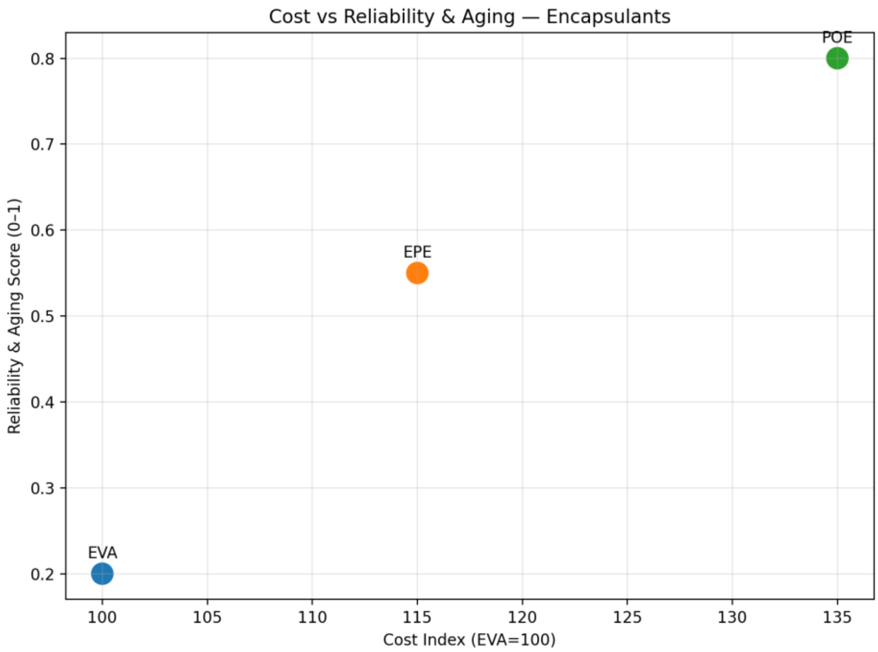
LCOE comparison under hot-site assumptions shows TOPCon minimizing LCOE owing to near-PERC cost with improved temperature and bifacial performance; HJT approaches/overcomes TOPCon where temperature and bifaciality dominate. Retained-power trajectories favor GG packages across technologies.

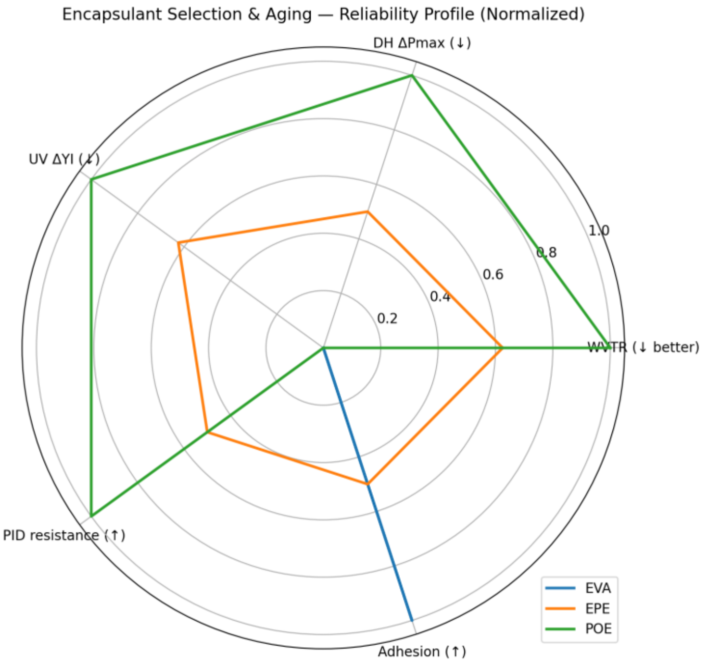
| Technology | LCOE Ranking | Long-Term Reliability | Best Packaging |
|---|---|---|---|
| **TOPCon** | ★ **Best** | ★ **Excellent** | **Glass-Glass + POE/EPE** |
| **HJT** | Good (premium) | BOM-dependent | GG + POE |
| **IBC** | High (premium) | Excellent (if GG+POE) | Glass-Glass |
| **PERC** | Lowest upfront but highest LCOE | Moderate | Glass-Backsheet (EVA/EPE) |

## 6. Encapsulant Selection and Aging

EVA: strong adhesion/clarity; moderate WVTR; acetic-acid formation under DH/UV can corrode metallization/TCO—mitigate via gel ≥80%, UV stabilizers, robust backsheets and edge seals. POE: low WVTR; no acid formation; higher electrical insulation; reduces PID and moisture risks—preferred for GG and n-type modules. EPE: co-extruded EVA-POE-EVA; balances barrier and adhesion; useful when processability with EVA outer layers is desired.



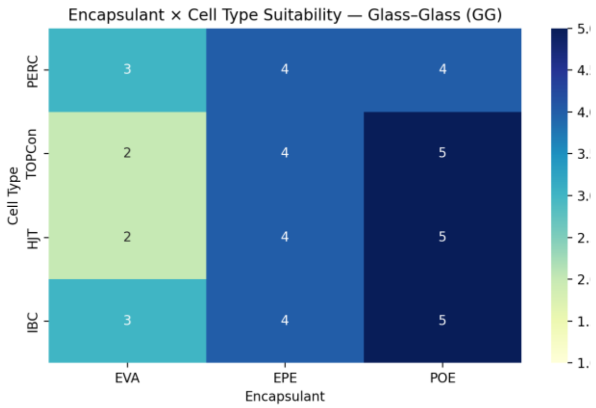






## 7. Encapsulant–Cell Combinations

| Cell Tech | EVA | EPE | POE | Notes |
|---|---|---|---|---|
| PERC | Viable (GB/GG), cost-leading | Improved barrier | High barrier (harsh climates) | EVA acceptable with robust backsheets; choose POE/EPE for coastal/high-voltage sites |
| TOPCon | Acceptable (GB) | Strong default | Preferred (GG bifacial) | POE/EPE mitigate PID/polarization and corrosion; GG benefits from low WVTR |
| HJT | Use with strong UV stabilization | Strong | Preferred | BOM-sensitive under DH; POE/EPE recommended |
| IBC | Acceptable (premium | Strong | Preferred | Premium GG + POE common for high-efficiency |

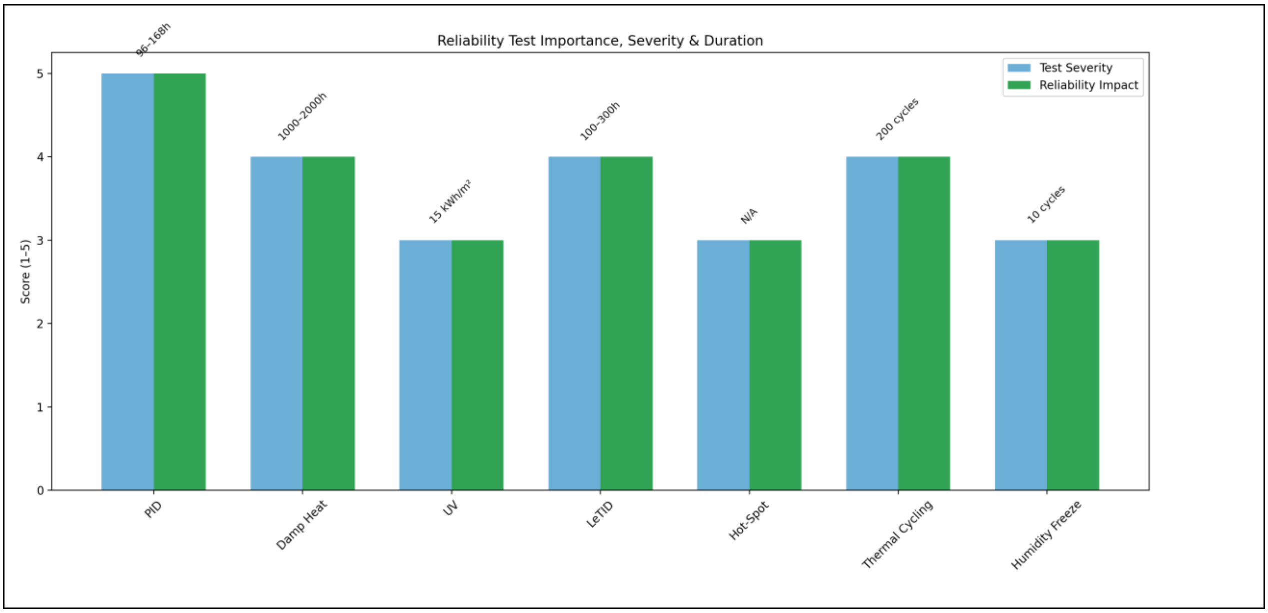
BOM) builds




## 8. Reliability Test Methods and Parameters

| Test | Objective | Key Parameters | Applies To | Primary Metrics | Standard |
|---|---|---|---|---|---|
| PID | High-voltage sensitivity (PID-s/p/c) | 85°C/85% RH, ±1000 V, 96–168 h; dark & UV variants | All | ΔPmax, EL/PL, insulation resistance | IEC TS 62804-1:2025 |
| Damp Heat (DH) | Moisture/thermal aging | 85°C/85% RH, 1000–2000 h | All | ΔPmax (<5%), EL/visual | IEC 61215 MQT 13 |
| UVID (UV) | UV susceptibility/yellowing | 15 kWh/m$^2$ @ 60–70°C | All | YI, ΔPmax | IEC 61215 MQT 10 |
| LeTID | Light + elevated temperature degradation | 1 sun @ 75–85°C, 100–300 h; current injection variants | PERC, TOPCon, some HJT | ΔPmax(t), recovery residual | IEC TS 63342; draft IEC 61215-2 MQT23 |
| Hot-Spot | Bypass/defect heating robustness | Partial shading; thermal imaging | All | Max cell temp, damage | IEC 61215 MQT 18 |

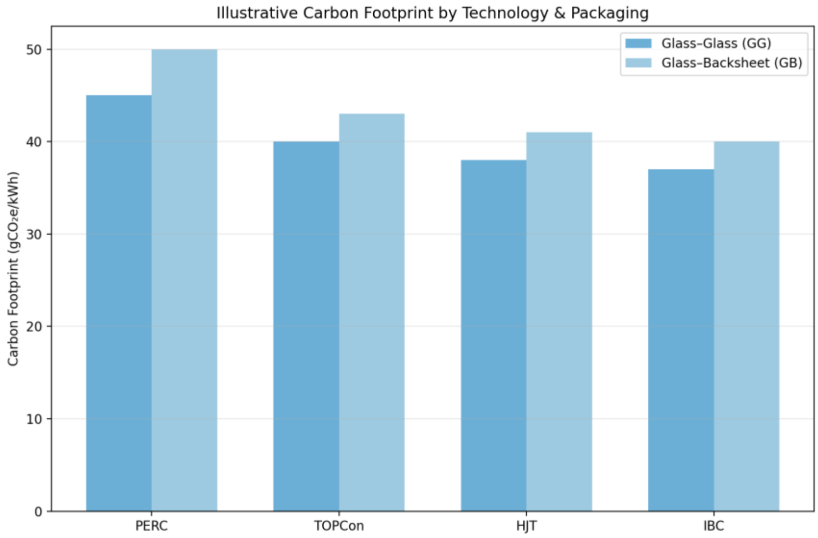
| | | | | | |
|---|---|---|---|---|---|
| Thermal Cycling (TC) | Interconnect fatigue/microcracks | −40↔+85°C, 200 cycles | All | ΔPmax (<5%), EL | IEC 61215 MQT 11 |
| Humidity Freeze (HF) | Freeze-thaw moisture stress | 10 cycles (85/85↔−40 °C) | All | ΔPmax, delamination | IEC 61215 MQT 12 |

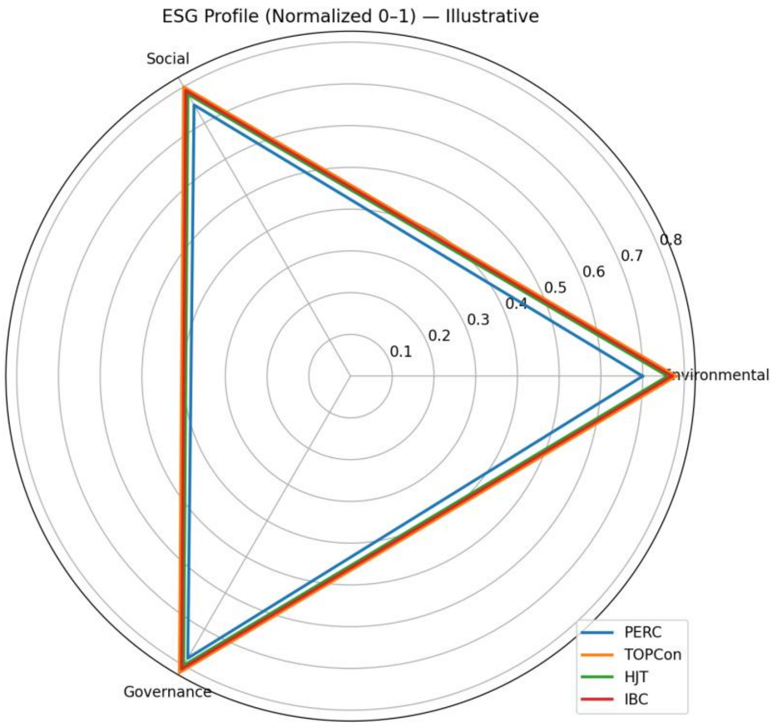



### Test duration (text labels above each bar)

Using durations from IEC standards and industry testing:

| Test | Duration / Exposure |
|---|---|
| **PID** | **96–168 hours** @ 85°C/85%RH & ±1000 V (IEC TS 62804-1:2025) |
| **Damp Heat** | **1000–2000 hours** @ 85°C/85%RH (IEC 61215 MQT 13) |
| **UV** | **15 kWh/m²** @ 60–70°C (IEC 61215 MQT 10) |
| **LeTID** | **100–300 hours**, 1 sun @ 75–85°C (IEC TS 63342 / MQT23 draft) |
| **Hot-Spot** | N/A (bypass diode + hotspot thermal response test) |
| **Thermal Cycling** | **200 cycles** from −40 → +85°C (IEC 61215 MQT 11) |




## 9. Discussion

Results support TOPCon as the most favorable near-term LCOE choice, with HJT/IBC reserved for premium yield scenarios. Encapsulant selection measurably affects PID susceptibility and moisture-driven degradation; POE/EPE are preferred for GG bifacial and n-type modules. DH/UV outcomes emphasize BOM sensitivity, particularly for HJT in GB structures. Market trends indicate TOPCon capacity dominance through mid-2020s with continued metallization cost reductions.

## 10. Conclusion

For hot/humid deployments, align cell technology and encapsulant choice to reliability test evidence: prioritize TOPCon with POE/EPE in GG bifacial designs, and apply comprehensive IEC-aligned PID/LeTID/DH/UV/TC/HF screening. This approach reduces risk, stabilizes yield, and improves bankability.

## Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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