TOPCON RELIABILITY

Part 2

Ensuring Robust Reliability in the Era of TOPCon PV

2026

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Biography

Edgard Abou Kheir

Electrical Engineer, Leveraging a master' s degree from the Lebanese University (Faculty of Engineering, Branch 2) and 8 years of experience with a proven track record in the solar energy sector. Previously, as a Project Manager at Phoenix Energy (Indevco Group), he led diverse C&I solar projects, from initial costing and procurement to design, execution, commissioning, and customer training. Currently, Technical Service Manager for the MENA Region for Jinkosolar.

In this role, he provides pre-sales support, navigates contract negotiations, and participates in organizing events including marketing updates with technical part. Additionally, he manages product lines and delivers customer training sessions, ensuring clients stay current on industry trends and technologies.

Ameera Al-Amayrah

Ameera Al-Amayrah is the Research Team Lead at Solarabic DMCC, with over 9 years of experience in the renewable energy sector across the MEA region. She specializes in market intelligence and advisory work spanning solar PV, energy storage, and green hydrogen, translating complex data into clear, decision-ready insights.

Dr. Dhanup S. Pillai

Dr. Dhanup S. Pillai is an Electrical with a master' s degree in Power Electronics and Drives and a PhD in Photovoltaic (PV) Systems. He is currently a Scientist with the Energy Center at the Qatar Environment and Energy Research Institute (QEERI), where he also serves as the Scientific Manager of the Outdoor Test Facility (OTF). Dr. Pillai' s expertise centers on field-based performance assessment, reliability evaluation, and operational validation of PV systems under real-world conditions, particularly in harsh desert environments.

His work encompasses outdoor benchmarking of PV modules and inverters, fault detection and protection strategies, system-level reliability analysis, performance optimization methods, and the evaluation of robotic cleaning technologies. He has led and delivered applied research programs exceeding USD 3 million in total value in collaboration with global PV manufacturers, developers, and O&M stakeholders. Dr. Pillai has co-authored numerous peer-reviewed scientific publications in high-impact journals and international conferences, including influential contributions on PV system protection, fault diagnosis, and field performance evaluation. Since 2018, he has been a member of the Institute of Electrical and Electronics Engineers (IEEE), and an inventor of several PV-related innovations

Topcon market overview in the region – Ameera Al-Amayrah

The global solar industry is in a rapid transition, with n-type TOPCon technology now leading the market. This section provides a concise overview of this shift, its implications for the MENA region, and the critical importance of long-term reliability.

1.1 The Rise of a New Standard: TOPCon's Journey to Dominance

The timeline below illustrates the rapid evolution of TOPCon technology, from its emergence in R&D to its current market-leading position and future projections.

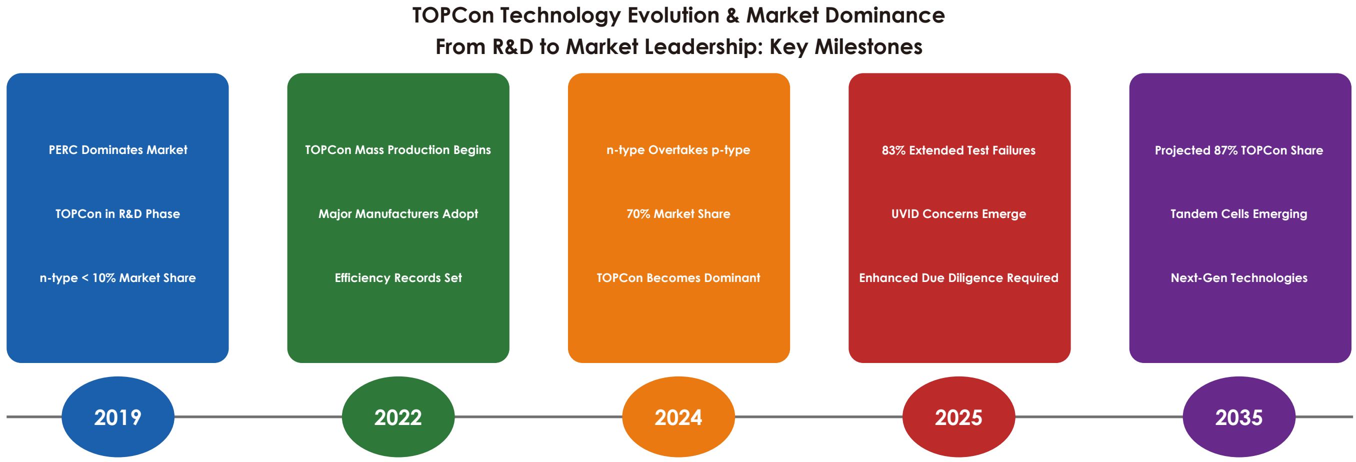


Figure 1 TOPCon technology evolution timeline Source: ITRPV, Kiwa PVEL

The provided timeline highlights the meteoric rise of TOPCon technology, transitioning from an R&D-focused alternative in 2019 to the industry's dominant standard by 2024. This journey was marked by a rapid scale-up in mass production starting in 2022, which allowed TOPCon to effectively overtake p-type PERC in market share.

Looking ahead to 2035, TOPCon is projected to maintain a commanding 87% market share, even as next-generation tandem cell technologies begin to emerge.

1.2 Market Snapshot: N-type Global Shipment

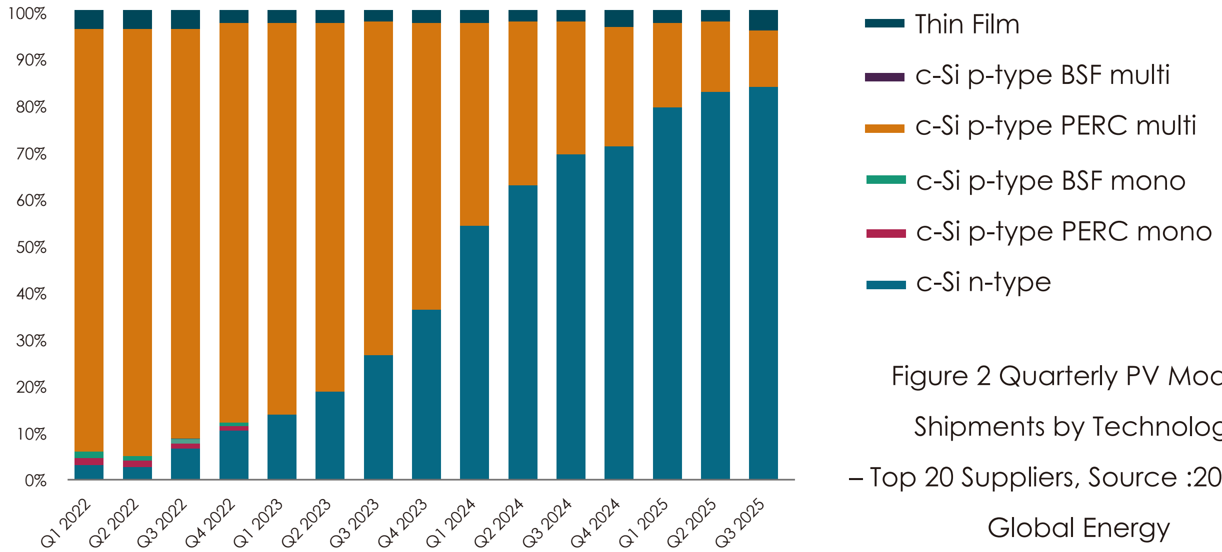


Figure 2 Quarterly PV Module Shipments by Technology – Top 20 Suppliers, Source :2025 S&P Global Energy

Building on the latest quarterly shipment trends from S&P Global Energy, the global solar PV industry is clearly moving through a rapid — and increasingly irreversible — technology transition. The chart highlights a structural shift in the technology mix of the top 20 module suppliers, where n-type has expanded from a marginal position in early 2022 to become the new industry baseline by 2024–2025. [2]

1.3 MENA's Solar Boom: Ambitious Goals Meet New Technology

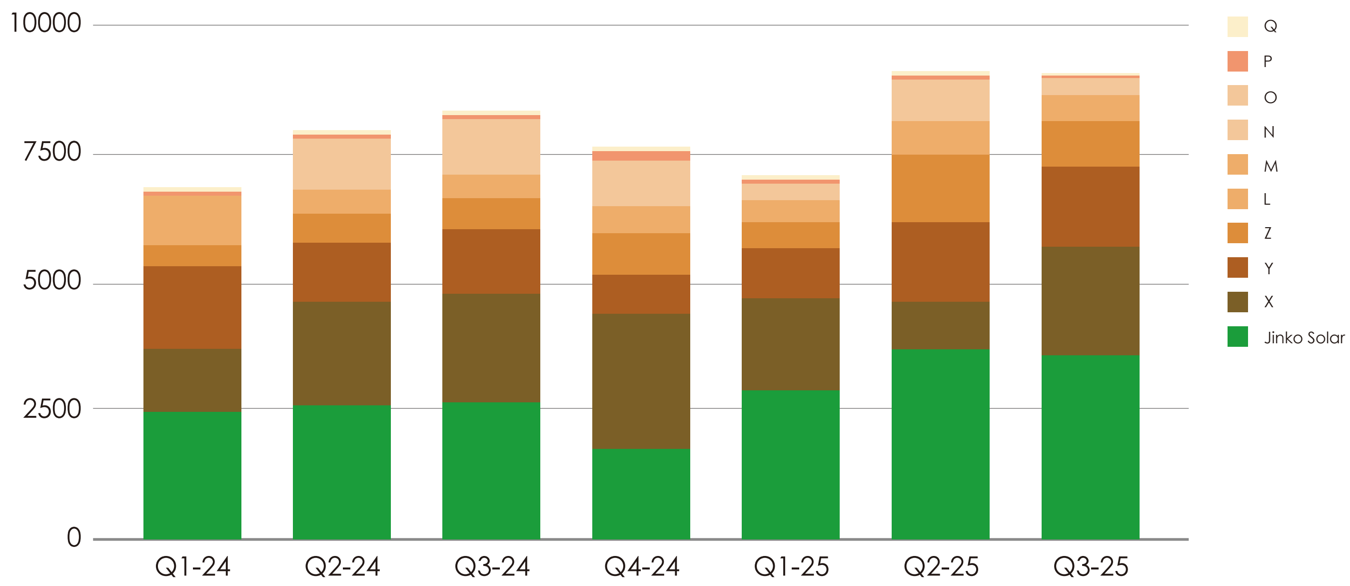


Figure 3 Total Shipment for MEA Region (MW)

Source: 2026 S&P Global Energy

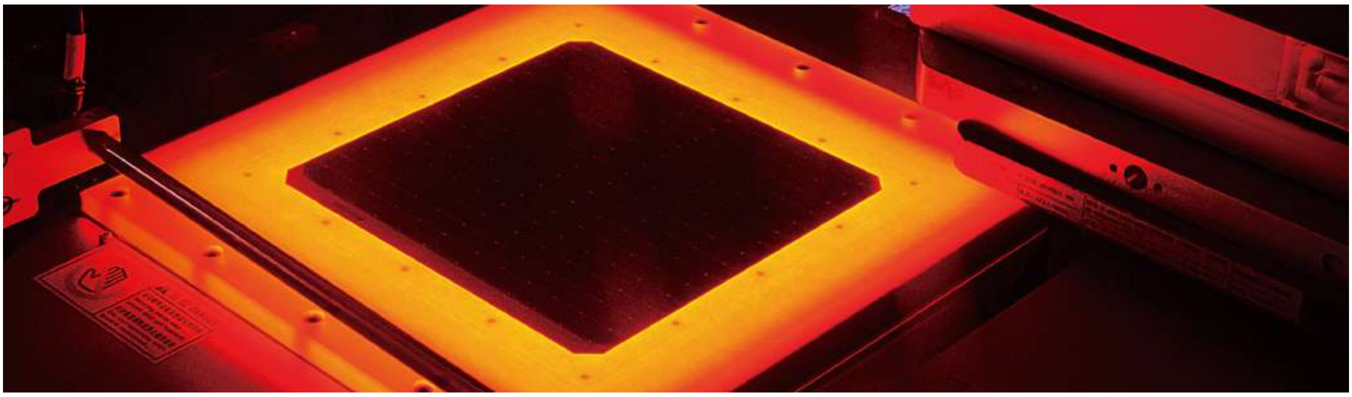
JinkoSolar's global leadership is even more pronounced in the strategically critical and environmentally demanding Middle East & Africa (MEA) region. The company is the undisputed #1 supplier, consistently capturing over a third of the market share among top-tier manufacturers.

In the first three quarters of 2025 alone, JinkoSolar shipped 10.1 GW to the MEA region, a 38.10% increase over the last three quarters of 2024. This accelerating growth saw its market share among top suppliers climb from 29% to over 40%, a powerful indicator of the trust it has earned from the region's largest developers for their giga-scale projects in harsh desert conditions.

TOPCon modules performance in Excessive Reliability Tests (PVEL , RETC, and 3xIEC) – Jinkosolar

2.1 Introduction

As advanced photovoltaic (PV) technologies like TOPCon, HJT, and BC continue to push the boundaries of efficiency and performance, their long-term reliability has become just as critical as their initial power output. High efficiency by itself is not sufficient; investors, developers, and asset owners require assurance that modules will maintain performance over 25–30 years of PV plant operation as any premature degradation or reliability issues will significantly impact the Levelized Cost of Energy (LCOE) and the overall bankability of the PV project.
To address this, reliability testing through standards like IEC, and more rigorous independent programs such as PVEL's PV Module Reliability Scorecard and RETC's Accelerated Stress Testing, has become a cornerstone of technology evaluation. These tests go beyond baseline certifications, exposing modules to harsher conditions such as damp heat, thermal cycling, potential-induced degradation (PID), and ultraviolet (UV) stress. For emerging high-efficiency technologies like TOPCon, HJT, and BC, these tests are particularly important, since new materials, architectures, and encapsulation methods may behave differently under long-term stress compared to conventional PERC.



2.2 Overview of Testing Programs

The PVEL Scorecard is based on the PV Module Product Qualification Program (PQP), which subject's modules to reliability tests that exceed IEC standards. Manufacturers are recognized as "Top Performers" for excelling in categories such as thermal cycling (TC600), damp heat (DH2000), potential-induced degradation (PID), mechanical stress (MSS, HSS), and lightinduced degradation (LID and LETID). PVEL also evaluates PAN files, low□light performance, and incidence angle modifier (IAM), which feed directly into yield modeling.
The RETC PVMI 2025 applies its "Thresher Test" methodology, designed to push modules far beyond qualification standards. RETC assesses reliability, performance, and quality across a range of categories including thermal cycling, damp heat, static and dynamic mechanical loading, hail testing, ultraviolet-induced degradation (UVID), LID/LETID, and PAN-based performance ratios. Manufacturers can earn "High Achiever" or "Overall Highest Achiever" distinctions.
The term "3× IEC" refers to extended reliability testing where the duration or cycles of key IEC sequences (such as damp heat and thermal cycling) are tripled. While often used by manufacturers in marketing material, these tests are not standardized across laboratories and must be carefully reviewed for conditions and acceptance criteria.

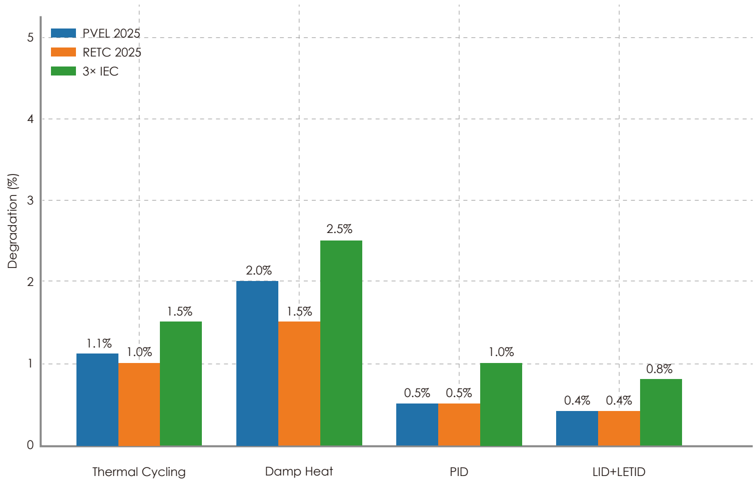


Figure 4 TOPCON modules degradation comparison

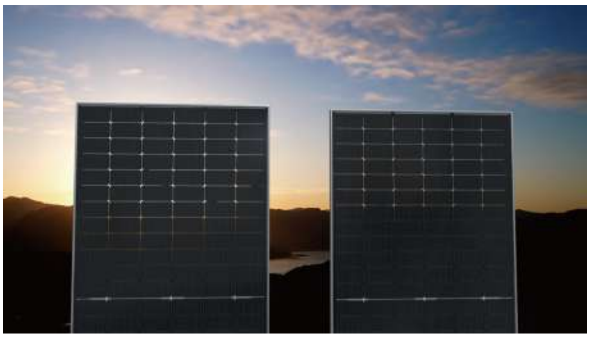
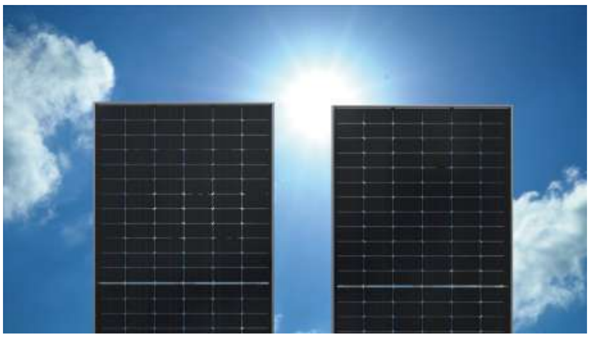
Chart Key Outcomes

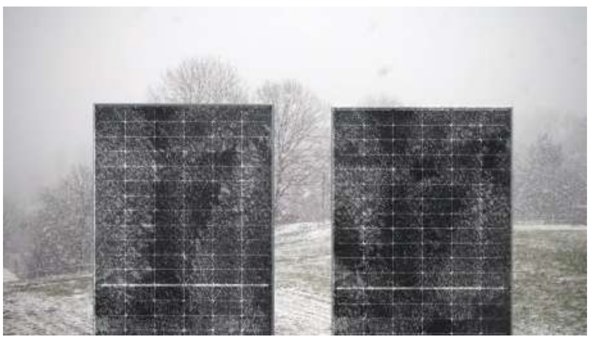
-The 2025 testing cycle reinforces TOPCon as a bankable technology with advantages over PERC, HJT and BC in both reliability and performance. Thermal cycling, PID resistance, temperature coefficient, and bifacial gains are clear strengths

-The TOPCon cell technology, besides its dominance in the market, has shown great performances in the reliability tests such as TC, DH, PID and LID+LETID, as shown by the chart above, where average degradation didn't exceed 2.5% after extensive tests.

-TOPCOn continues to show compelling advantages besides the total transparency in the reliability tests, a key factor that differentiates this cell technology from others, like BC. Although many major companies are adopting BC as their mainstream cell technology, when it comes to reliability matters, they prefer to send samples implementing the TOPCon cell technology, a key point confirming how the market is confident about the reliability of TOPCon.

-Despite that BC cell technology was commercially available since 2022, but we didn't see much of its history with reliability, a major challenge that raises the concern for BC compared to TOPCOn when it comes to evaluating the most performant and reliable PV modules, mainly for Utility Scale projects.



Winning the Desert race TOPCON VS TBC – Edgard Abou kheir

3.1 Introduction: The Desert Code Standard

The first part of the whitepaper covered the main tests that are conducted under what is called the "Desert Code Standard" which was developed by GCC lab in Saudi Arabia that is an important benchmark to consider stricter than IEC and designed for PV modules installed in the desert. This protocol is more demanding than standard IEC 61215 certifications to reflect the extreme heat and UV levels in the MENA region.
The desert code was conducted on 2 technologies to compare their reliability and handling the harsh conditions of the desert:
-Type 1: TOPCON Technology from Jinkosolar
-Type 2: TBC Technology (TOPCON Back contact) from another Tier 1 supplier

3.2 Initial Power and STC Conditions Analysis

The initial performance at Standard Test Conditions (STC) reveals distinct characteristics of both cell architectures:

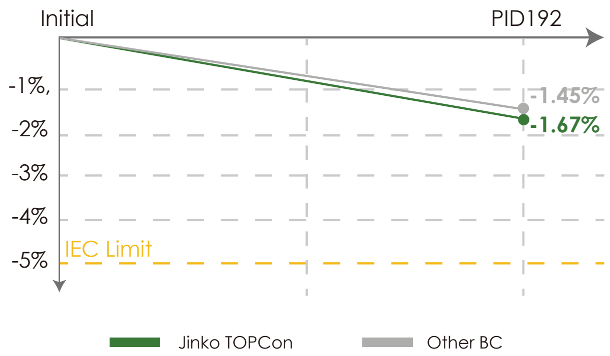
3.2.1Front vs. Rear Power

Metric	**Jinko TOPCon**	**BC Technology**
Label Power	**630W**	640W
Label Bifaciality	**80±5%**	75±5%
Pmax Front [W] – Average front side power of the tested samples	**~631.41 W**	~640.61 W
Pmax Back [W] – Average back side power of the tested samples	**~511.11 W**	~451.42 W
Average Bifaciality of the samples tested (%)	**~80.9%**	~70.5%
Average Fill Factor of the samples tested (%)	**81.35%**	76.31%

3.2.2Analysis:
-While the BC technology has a higher front-side peak power of 10W compared to TOPCON, the Jinko TOPCon module provides ~13.2% more power from the rear side. In high-albedo desert environments, this significantly higher bifaciality often translates to a higher total energy yield (LCOE) despite a lower front-side rating.
-Measured Bifacial factor of TOPCON was aligned with the average bifaciality mentioned in the data-sheet while the measured bifacial factor of BC was under the lower side of the range mentioned in the datasheet
-Jinko TOPCon Maintained a superior Fill Factor of 81.69% while BC Technology Recorded a lower Fill Factor of 76.37%. A higher Fill Factor indicates better internal cell quality, lower series resistance, and a more robust electrical architecture, which is critical for long-term stability under thermal stress.

3.3 Test Results

The modules were subjected to four primary stress sequences to evaluate long-term durability.
3.3.1Potential Induced Degradation (PID)
This test evaluates a module's ability to withstand high-voltage stress between its internal circuits and the frame—a critical factor for long-term safety and performance in utility-scale plants.
·Test Detail:
The modules were subjected to a negative bias of -1500 V for 192 hours at ambient temperature of 85°C and relative humidity of 85%, simulating the maximum system voltage stress under field conditions.
·Results:
Jinko TOPCon: Maintained a high Fill Factor of ~81.56% and passed without any visual or EL defects.
BC Technology: Maintained a Fill Factor of ~76.48% and passed the sequence.
Below graph shows the power degradation after the test with a difference between the 2 technologies less than 0.2%:



Source: Gulf Renewable Lab (GCC)
Figure 5 Degradation values after PID 192h test

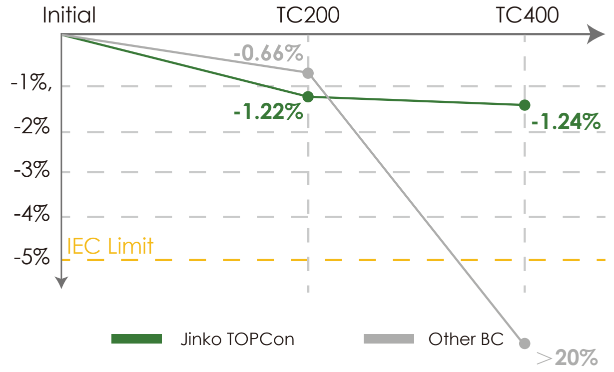
·Analysis: Both technologies showed high resistance to leakage currents, with no significant micro-cracks or shading observed in post-test Electroluminescent (EL) imaging.

3.3.2Thermal Cycling (TC) – 400 Cycles
Designed to simulate the extreme thermal expansion and contraction experienced in desert environ-ments specially between night time and day time.
·Test Detail:
The "Desert Code" standard is more rigorous than the IEC certification, cycling modules between -40°C and +95°C (compared to the standard +85°C) and number of cycles is 400 which is the double of the IEC.

·Results:

Jinko TOPCon: Successfully completed all 400 cycles with a final degradation well within the allowable limits and no impactful EL defects.

BC Technology: Experienced a failure during the final 200-cycle phase (C2). The BC sample module failed both the EL inspection and performance criteria.



Source: Gulf Renewable Lab (GCC)

Figure 6 Degradation values after TC400 test

·Comparison: Jinko's TOPCon architecture demonstrated superior mechanical robustness under extreme temperature swings compared to the tested BC technology.

3.3.3Damp Heat (DH) – 2000 Hours

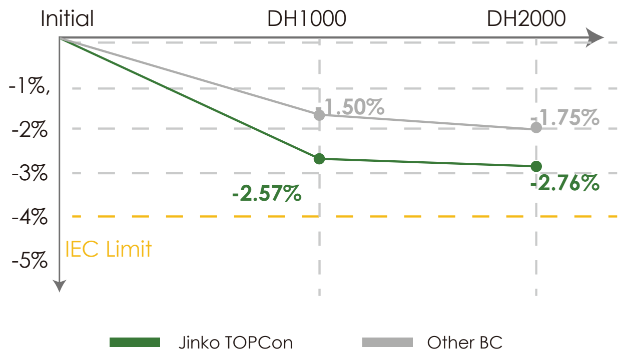
This test measures resistance to long-term moisture penetration and subsequent corrosion.

·Test Detail: Modules were placed in a high-humidity environment (85% R.H.) at 85°C for a total of 2000 hours which is double the time stipulated in the IEC standards.

·Results:

After 1000 Hours (C1): Jinko TOPCon showed 2.57% degradation; BC Technology showed 1.50%.

After 2000 Hours (C2): Jinko TOPCon settled at 2.76%; while BC Technology at 1.75%.



Source: Gulf Renewable Lab (GCC)

Figure 7 Degradation values after DH 2000 test

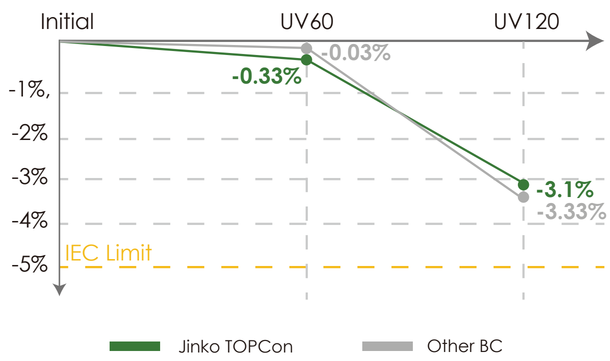
·Analysis: While Jinko had slightly higher initial degradation, both modules passed the 2000-hour mark successfully, staying below the 5% industry failure threshold.

3.3.4UV Exposure Sequence

This sequence assesses the stability of the module's materials under intense solar radiation specially that in the desert the UV radiation is one of its highest in the globe.

· Test Detail: The modules were exposed to a UV dose of 60 kWh/m² (280-320nm) at a module temperature of 70°C, which is 10°C higher than standard certification requirements.

·Results:
Jinko TOPCon: Showed a power degradation of 1.57% post-UV exposure.
BC Technology: Showed a power degradation of 1.52% post-UV exposure.



Source: Gulf Renewable Lab (GCC)

Figure 8 Degradation values after UV120 test

·Analysis: Both modules exhibited excellent UV stability, with no yellowing or delamination observed in visual inspections.

3.4 Technical Recommendations

The Desert code report confirms that while BC technology offers higher front-side peak power, Jinko's TOPCon technology is more robust for extreme desert conditions for the following reasons:

1.Reliability: Jinko successfully passed the extended 400-cycle Thermal Test, whereas the BC technology showed a failure under these high-temperature cycles.

2.Energy Yield: The significantly higher bifaciality (~81% vs ~70%) makes the TOPCon module a superior choice for ground-mounted desert installations with reflective sands.

Electrical Integrity: The higher Fill Factor (81.69%) demonstrates a more efficient and stable cell architecture under load.

TOPCon field tests from the world:

4.1 TOPCon Field Testing in Harsh Desert Climates: Insights from Qatar - Dr. Dhanup S. Pillai

As the photovoltaic (PV) industry transitions from Passivated Emitter and Rear Cell (PERC) toward next-generation cell architectures such as Tunnel Oxide Passivated Contact (TOPCon) and Silicon Heterojunction (SHJ), the central question is no longer laboratory efficiency, but 'can these advanced technologies sustain their laboratory advantages under prolonged exposure to extreme field conditions?' While datasheet performance and IEC-based stress tests indicate strong performance potential, they are not designed to capture the combined, long-duration stress exposure expected during continuous harsh climate operation. In this context, desert environments introduce a unique combination of high irradiance (>1000 W/m²), prolonged module operating temperatures exceeding 65–70 °C, intense ultraviolet (UV) exposure, airborne dust loading, and intermittent humidity ingress, all of which are stressors that interact synergistically and are not fully represented in conventional qualification protocols. Consequently, real-world field validation in harsh climates is essential to distinguish technology-level promises from deployment-ready robustness.

To address the need for climate-resolved field evidence, the Qatar Environment and Energy Research Institute (QEERI) has been operating one of the largest continuously monitored outdoor photovoltaic testing facilities in the Middle East and North Africa (MENA) since 2013. The outdoor test facility (OTF) has been continuously monitoring PV technologies under desert exposure and generating long-term climatic and performance records across multiple cell architectures. The present assessment draws on two independent field datasets: (a) a multi-year dataset of medium-power modules (<450 W), and (b) a more recent deployment of high-power modules (>550 W) installed under fixed-tilt configuration. Both datasets included commercially deployed TOPCon and SHJ modules tested under identical mounting conditions and monitored using state-of-the-art measurement systems.

The comparative field results provide clear differentiation in thermal and performance stability between the two technologies in desert climates. Across both datasets, TOPCon modules maintained consistently higher and more stable temperature-corrected performance ratios (PRs). High-power TOPCon systems achieved specific yields exceeding 6.7 kWh/kWp/day, demonstrating strong energy retention compared with its counterparts. In contrast, SHJ modules exhibited greater variability across both datasets. While medium-power SHJ modules initially performed within expected ranges, the high-power SHJ systems showed elevated operating temperatures under peak irradiance, alongside early performance degradation. Electroluminescence (EL) imaging further confirmed the onset of localized degradation features in selected high-power SHJ modules during the monitoring period.

Figure 9 illustrates the comparative thermal behavior of the high-power TOPCon and SHJ test systems deployed at the OTF. Except for one TOPCon array that operated at comparable peak temperatures, the TOPCon modules generally exhibited lower operating temperatures relative to the SHJ system. Importantly, even under similar or elevated thermal conditions, TOPCon modules consistently delivered superior PR and specific yields compared to SHJ. These findings underscore that thermal behavior alone does not dictate field reliability. Rather, the interaction between cell architecture and bill-of-material (BOM) design plays a decisive role in determining sustained performance under desert stress conditions.

From a technology deployment perspective, the implications are twofold. First, the field evidence indicates that TOPCon architecture demonstrates strong operational resilience under sustained high-temperature, high-irradiance desert conditions, positioning it as a robust successor to PERC for large-scale installations in hot climates. Importantly, this resilience was observed even when operating under comparable peak thermal stress, suggesting architecture-level stability beyond simple temperature effects.

Second, it is important to recognize that no emerging architecture is immune to environment-specific degradation risks. Recent literature has identified potential susceptibility of certain TOPCon configurations to ultraviolet-induced degradation and moisture-related sensitivity, particularly under high UV flux and elevated humidity conditions. These mechanisms are strongly by bill-of-material (BOM) choices, including wafer format, encapsulant chemistry, glass configuration, and cell passivation designs, that collectively determine thermal dissipation, degradation pathways, and stability under UV and soiling exposure. However, such risks are not uniform across geographies and therefore cannot be generalized without context of climate. In arid desert regions, prolonged UV exposure and elevated operating temperatures may place greater emphasis on UV stability and interfacial durability. Accordingly, long-term reliability should be framed not as a binary comparison between technologies, but as a function of architecture–BOM compatibility with the intended deployment environment.

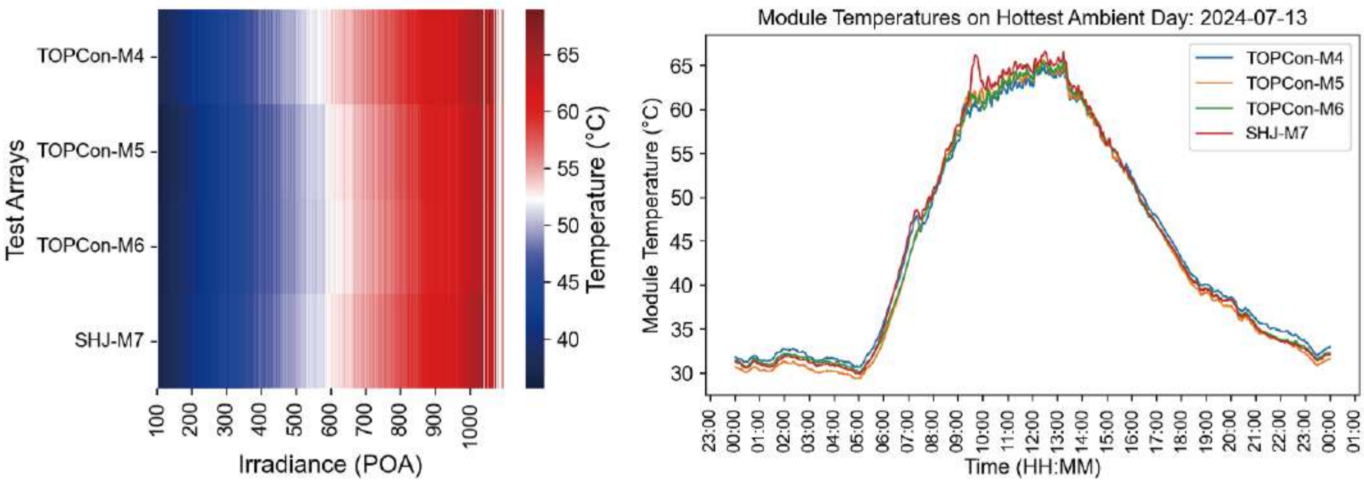


Figure 9 Thermal behavior of high-power TOPCon and SHJ modules (Dataset 2) deployed at QEERI's Outdoor Test Facility. Left: Module operating temperature as a function of plane-of-array (POA) irradiance for individual test arrays (TOPCon-M4, TOPCon-M5, TOPCon-M6,

Taken together, the QEERI's field results provide valuable evidence that TOPCon modules can sustain strong performance stability under prolonged high-temperature, high-irradiance desert operation, while also highlighting the decisive influence of integrated module design on long-term reliability. As advanced cell architecture continues to evolve, climate-resolved field validation must accompany laboratory efficiency improvements to ensure deployment-ready robustness.

For manufacturers and project stakeholders, the message is clear: technology leadership in the next generation of PV modules will be defined not only by peak efficiency, but by architecture–BOM optimization aligned with specific climatic stress profiles. Sustained multi-site field benchmarking across diverse geographies like desert, tropical, coastal, and temperate, will therefore be essential to ensure that next-generation technologies deliver durable, bankable performance at scale.

4.2 TOPCon Field Testing in Middle east: Insights from Lebanon

Against the backdrop of the global solar PV industry's accelerated transition to high-efficiency N-type modules, parking lots, as one of the core application scenarios for distributed PV, feature low installation tilt angles, significant fluctuations in ground reflection, and frequent changes in ambient temperature—all of which place higher requirements on the comprehensive performance of modules. Recently, Jinko Solar conducted a four-month field test (from Jul 29 to Nov 12, 2025) in the Matn District of Mount Lebanon Governorate (east of Beirut, Lebanon). During the test period, the average daily irradiance reached 526.57 W/m², and the average ambient temperature was 22.8℃. The representative meteorological conditions can fully simulate the actual operating environment of PV projects in the Middle East and similar climate zones.

Figure 10 Project picture

4.2.1Project Design

Eight 630W Jinko Tiger Neo modules and eight 640W N-type BC modules were selected for the test. Both module types feature a bifacial dual-glass structure and consistent environmental adaptability. For installation, all modules are arranged at a 5° tilt angle facing southeast, with an installation height of approximately 2.5 meters above the ground. To ensure data accuracy, the two module types are connected to independent Maximum Power Point Tracking (MPPT) systems, completely restoring the system configuration in practical applications. The test system is equipped with high-precision sensing equipment, collecting data at 6-minute intervals to real-time monitor core parameters including DC voltage, current, output power, module temperature, and front-side irradiance. The test period covers from Jul 29 to Nov 12, 2025.

Cell Technology	**Module Power**	**Module type**
Jinko Tiger Neo	630W	Bifacial Dual-Glass
N-type BC	640W	Bifacial Dual-Glass

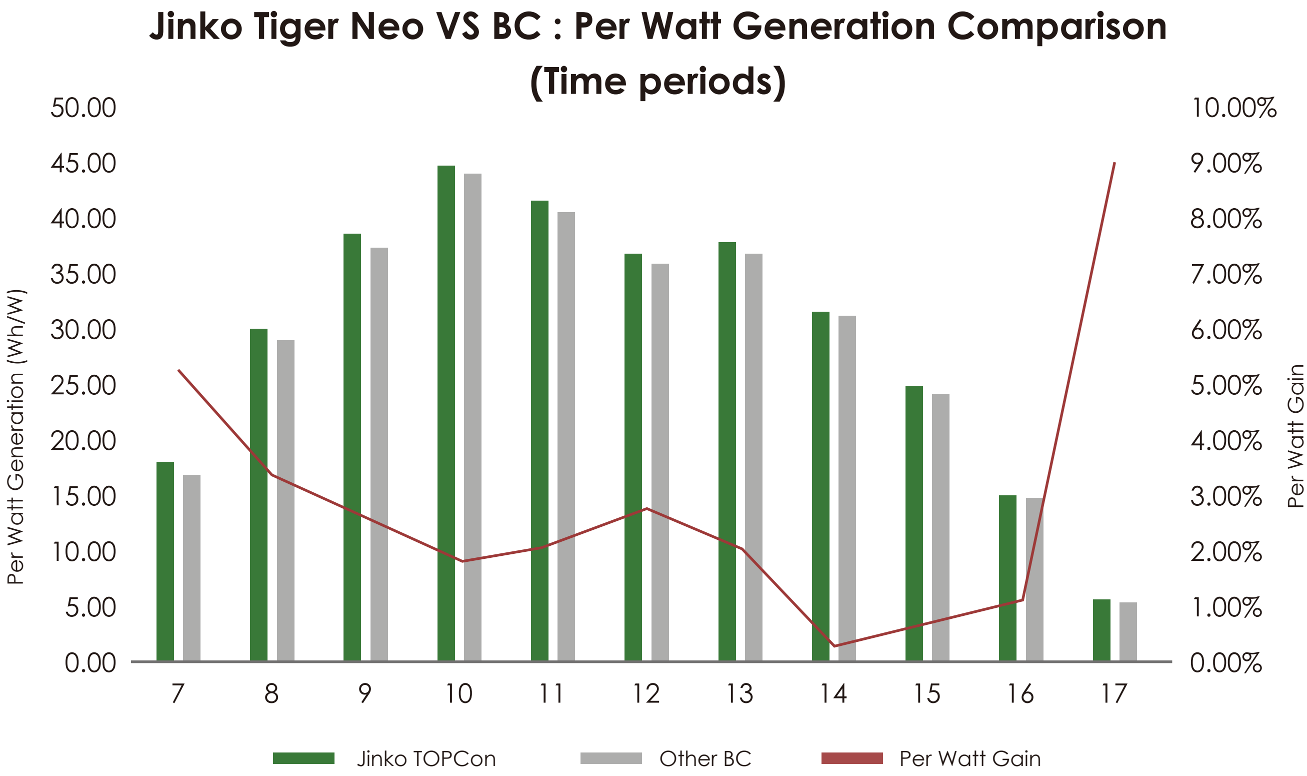


Figure 11 Specific yield comparison

4.2.2Results

Full-cycle field test data from the Middle East parking lot confirms Jinko Tiger Neo modules outperform N-type BC modules in power generation efficiency and environmental adaptability, offering clear guidance for PV parking lot product selection. With a specific yield of 327.22 kWh/kW (vs. 320.08 kWh/kW for BC modules), Tiger Neo achieved a 2.23% average per-watt gain—stable during the high-temperature summer period (Jul 29-Sep 30), underscoring its reliability in heat.

Outstanding Advantages in Early/Late Low-Irradiance and High-Temperature Periods: During the early morning (7:00-8:00) and late afternoon (17:00-18:00) when irradiance intensity is typically in the low-light range of 100-200 W/m², Tiger Neo modules demonstrated exceptional performance. Specifically, their power generation output was 5.21% higher than that of N-type BC modules in the morning, with a yield gain of 8.93% in the late afternoon. The core reason lies in their superior low-light response characteristics.

Significant Performance Improvement in Midday High-Reflection Period: During midday (12:00-13:00), the reduced number of parked vehicles in the parking lot area leads to a marked increase in ground reflection intensity. Leveraging its higher bifacial factor, Tiger Neo modules achieved a 2.75% power generation yield gain—exceeding the daily average level and fully unleashing its performance potential in high-reflection scenarios.

4.3 TOPCon Field Testing in The World: Insights from Italy

Based on the third-party testing, inspection and certification organization, TÜV SÜD Germany, the data analysis of the demonstration project in Basilicata, southern Italy, shows that JinkoSolar's N-Type TOPCon technology Tiger Neo3.0 module has an average power generation gain of 2.04% higher than that of the TBC module.

4.3.1Project Overview

The project is located in Basilicata area (40.42 ° N, 16.16 ° E) in southern Italy, which has both Mediterranean climate characteristics and typical European power plant environmental parameters, with an average annual irradiation of 1,800kWh/m², extreme temperatures exceeding 45 ° C in summer, and significant fluctuations in humidity in winter, which can effectively validate the long-term reliability of the modules under the composite stress of high temperatures, high humidity and fluctuations in irradiation.

Figure 12 Project location

Two different types of modules were installed for this test: JinkoSolar's TOPCon technology modules and TBC-type modules from other manufacturers. Each string consisted of 16 bifacial modules, with the comparative power station installed at an angle of 33 ° on grassland, and the bottom of the modules positioned 1 meter above the ground. The aim was to gain a deeper understanding of the application performance of these two types of modules in different typical climates.

Cell Technology	Module Power	Module Size	Module type
Tiger Neo 3.0	605W	2278x1134mm	Bifacial Dual-Glass
TBC	610W	2278x1134mm	Bifacial Dual-Glass

4.3.2Results

During the testing process, monitoring equipment comprehensively collected a range of key data, including DC voltage, DC current, DC power, DC power generation, module temperature, radiation intensity, total irradiance, ambient temperature, relative humidity, wind speed, wind direction, and atmospheric pressure.

The data shows that during the testing period from July to November 2024, the average daily power generation of Tiger Neo modules was 4.21 kWh/kW, while that of TBC modules was 4.13 kWh/kW, resulting in a power generation gain of 2.04% . This outcome fully demonstrates the significant advantages of JinkoSolar's TOPCon technology modules in efficient power generation.

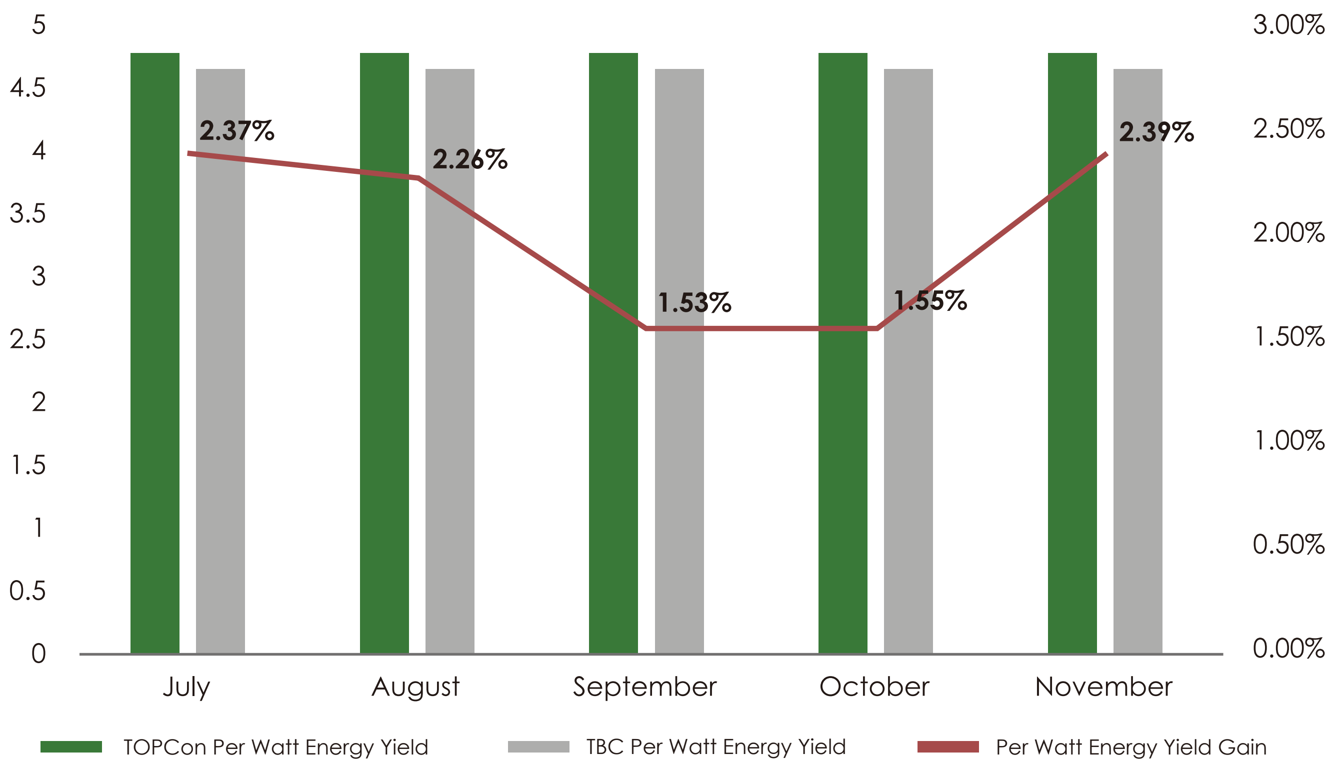


Figure 13 Specific Yield comparison

Sources

1 · *International Technology Roadmap for Photovoltaics (ITRPV), reported in "ITRPV: TOPCon to surpass PERC in coming years," pv Europe, April 2025.*

2 · *Infolink*

3 · *2026 S&P Global Energy*

4 · *Kiwa PVEL*

5 · *Desert code report GRL25-020_R01_Final*