Performance panel technology for large-scale installations

Maxeon Solar Technologies

Maxeon Solar Technologies White Paper

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About Maxeon Solar Technologies

Maxeon Solar Technologies was launched as an independent company in 2020 following its spin-off from SunPower Corporation. The company continues to build upon a 35+ year foundation of solar technology innovation that began with the founding of SunPower Corporation in 1985.

Maxeon Solar Technologies designs, manufactures and sells solar panels in more than 100 countries around the world. Its flagship solar panels reach record-setting efficiency and unmatched reliability,[1] while its Performance solar panels offer reliability and output superior to conventional solar panels. Maxeon Solar Technologies product lines are deployed at some of the highest-performing solar power plants around the world and are installed on residential and commercial rooftops by a global network of more than 1,200 trusted partners and distributors. MAXEON is a registered trademark in various jurisdictions. See https://corp.maxeon.com/trademarks for more information.

Introduction

The shingled cell Performance solar panel combines 35+ years of materials and manufacturing expertise with conventional p-type mono PERC cells to surpass the performance, reliability, and aesthetics of conventional panels.

Since 2015, more than 7 GW of high reliability Performance panels have been deployed across 60+ countries, making it the leading shingle cell technology on the market today.[2]

The Performance portfolio features high-power panels uniquely suited to reducing the cost structure of solar power plants by using less land, balance of system (BOS) hardware, and labour—all of which contribute to driving down the levelised cost of energy (LCOE) of today's large-scale installations.

Performance panels are designed to work optimally with currently available BOS products, including trackers, inverters, and DC hardware. In addition, Performance panels allow for simple design changes at the factory to better align voltage and current with future BOS product offerings.

The Performance panel capitalises on the insights and experience Maxeon has gained from developing, designing, building, and operating more than 5 GW of power plants across six continents. That knowledge has been instrumental in the continuous innovation of the technology to deliver the production, reliability, and durability required for today's power plant EPCs and developers.

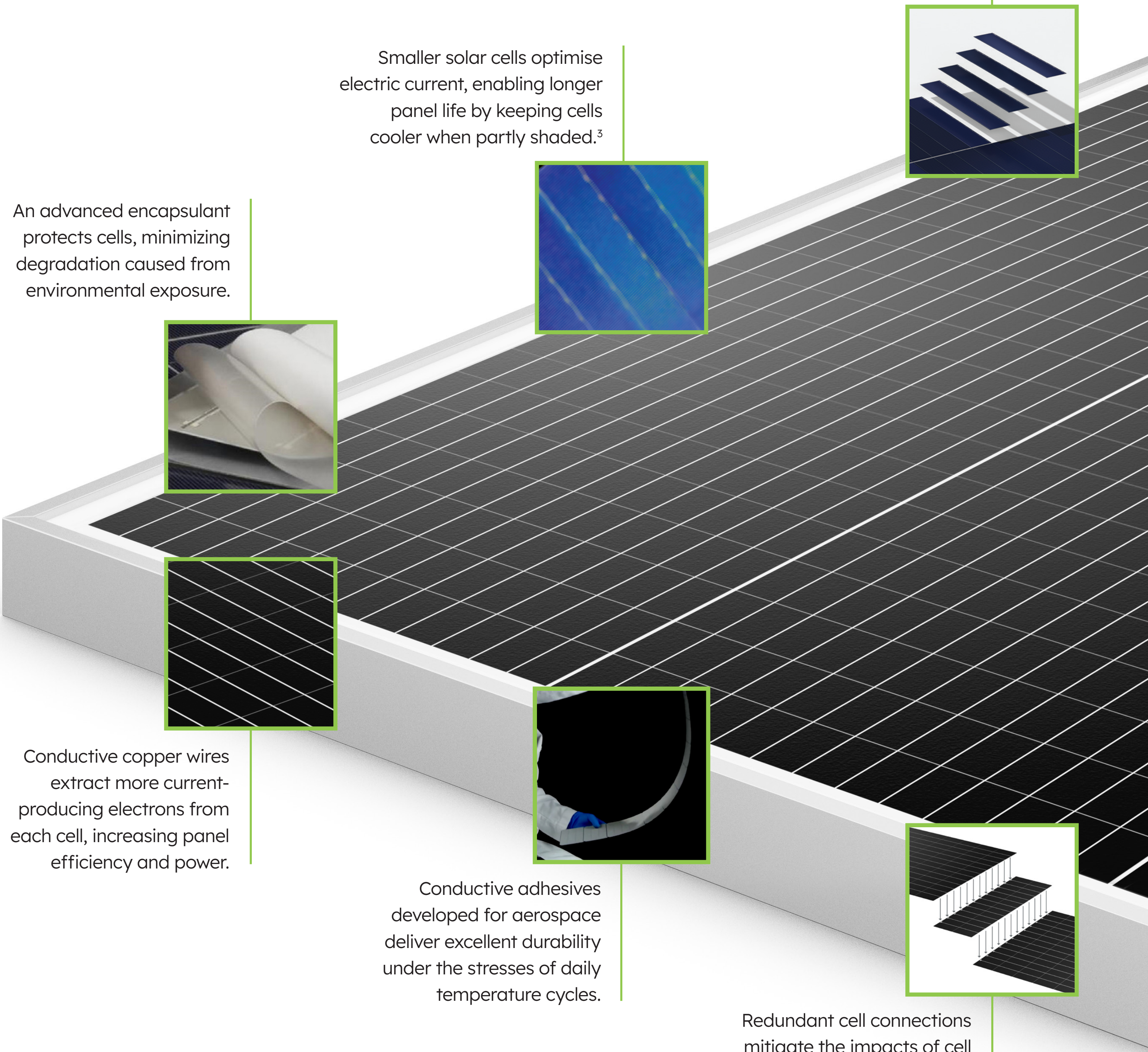
Performance panel core technology advantages

The shingled layout, or hypercell, forms the unique and innovative backbone behind each Performance panel. From its durable electrically conductive adhesive (ECA) to its redundant cell connections, Performance panels offer a variety of production, durability, and reliability advantages over conventional panels.

An innovative shingled cell design shortens paths for electrons to travel to create more energy from each panel.

Smaller solar cells optimise electric current, enabling longer panel life by keeping cells cooler when partly shaded.[3]

An advanced encapsulant protects cells, minimizing degradation caused from environmental exposure.



Conductive copper wires extract more current-producing electrons from each cell, increasing panel efficiency and power.

Conductive adhesives developed for aerospace deliver excellent durability under the stresses of daily temperature cycles.

Redundant cell connections mitigate the impacts of cell cracks on power output by creating flexible paths for continuous electricity flow.

Figure 1: Performance panels are uniquely engineered for more lifetime energy, greater reliability, and better durability over traditional front contact panels.

Electrically conductive adhesive maximises panel durability

The Performance panel eliminates the use of metallic wires for cell connections—designing out one of the major failure modes of conventional cells (figure 2). These metallic connections expand and contract as temperatures rise during the day, and cool at night. This repeated daily stress can cause connections to break and cells to crack. With cracked cells no longer functioning properly, bypass diodes are activated, limiting the amount of power the panel can produce. If the diode fails from continued activation, current will then be forced through the defective cells and ultimately lead to hotspot formation and permanent power loss.

In place of these fragile metallic bonds, the Performance panel uses an advanced electrically conductive adhesive (ECA) originally developed in the aerospace industry. The ECA provides a robust solution with high electrical conductivity. It can adhere to diverse materials, bonding the edge of the front of one cell to the rear edge of the next cell.

This innovative approach increases the number of cell-to-cell contact points, which not only improves efficiency by eliminating spaces between cells, but it also reinforces each connection to withstand the stresses of daily temperature swings and corrosion over time—all while removing toxic lead from the interconnection.

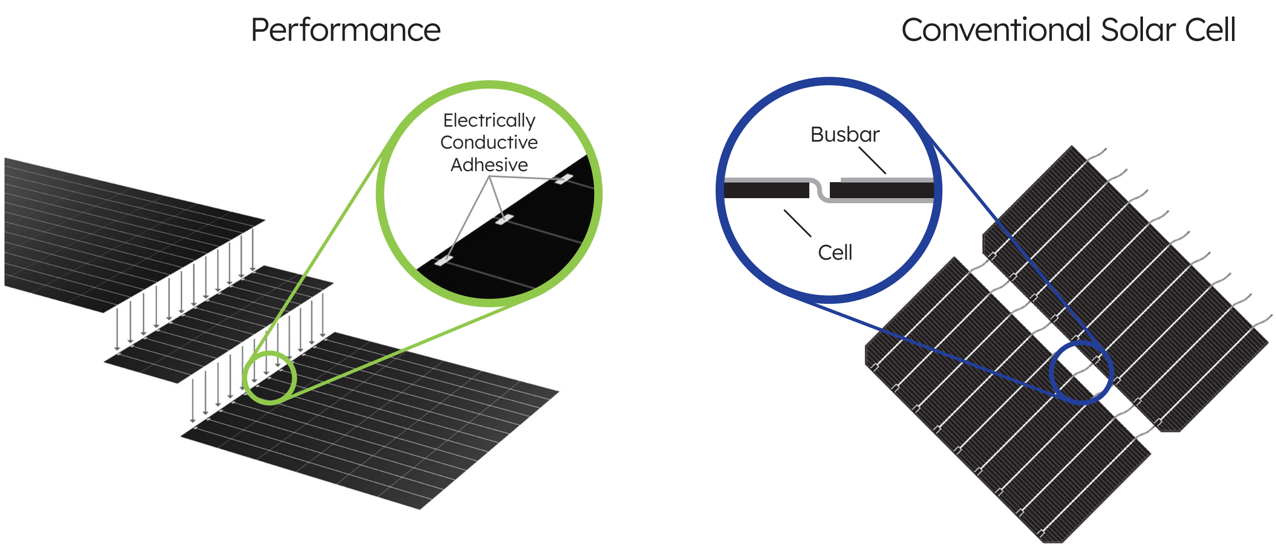


Figure 2: Performance panels eliminate the use of metallic wire cell connections–designing out one of the major failure modes of traditional cells.

A recent study of site inspection results from Dupont demonstrated that one of the predominant panel failure modes can be attributed to the weakness of the cell-ribbon bond on conventional panels (figure 3).[4] Eliminating these connections has been a critical factor in the low claim rate of Performance panels—less than 50 failures per million panels installed globally.[5] In addition, the recent evolution to a glass-glass architecture further strengthens Performance panel resiliency in the field.

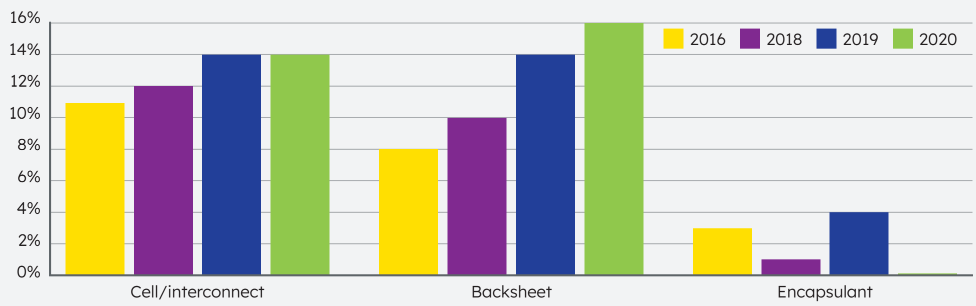


Figure 3: Inspection results from Dupont's Global PV Reliability Field Analysis featuring key causes of panel failure amongst recently installed conventional panels.

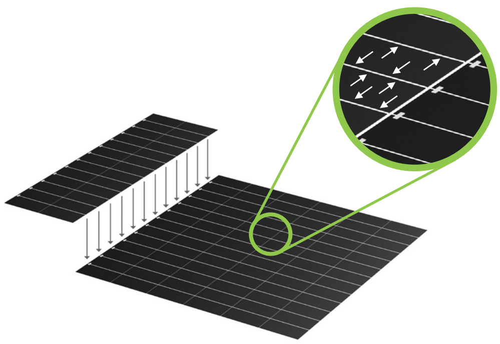
Metal conductive wires optimise current collection

The most recent generation of the Performance panel features the addition of twelve small copper wires soldered to the front of each cell. These conductive wires reduce electrical resistance by shortening the distance current travels via the cell's silver fingers (figure 4a). Charged electrons are provided with more channels by which to exit the cell, thereby increasing the efficiency and power rating of the panel.

In comparison to conventional panels, it is important to highlight that the use of metallic wires on Performance cells does not extend to the cell interconnection. Conventional panels bend metal connections from the front side of one cell, to the rear side of the next. As metals expand and contract from daily temperature swings or become susceptible to moisture-induced corrosion, these cell connections become fatigued. Over time, compromised connections will fail, severely limiting panel output. The Performance panel's use of ECA at the interconnect greatly mitigates the reliability risks resulting from the fatigue of metal-based cell connections in real-world conditions.

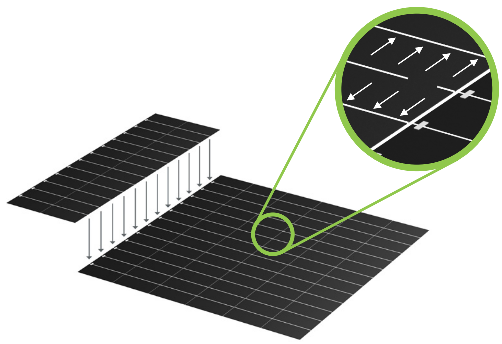
A premium encapsulant and a series of redundant cell connections are additional features that contribute to the superior engineering behind each Performance panel. Should one of the conductive wires be compromised in some capacity, current will still flow freely through the panel via the nearest wire and ECA connection (figure 4b).

As an added benefit, the metal wires used in Performance panels are 30% smaller in diameter than the metal ribbons and busbars typically found in conventional panels. This reduces the stress factor on the wire by 30% while ensuring no material impact to the available surface area of the cell—allowing the cell to absorb the full impact of the sun.



A

Figure 4a: Conductive wires provide more paths for charged electrons to exit the cell and be converted to electricity.



B

Figure 4b: Should a conductive wire break, the charged electrons will continue to flow to the next closest outlet.

Redundant cell connections keep current flowing

Performance panels mitigate the impacts of cell cracks on power output by creating flexible paths for continuous electricity flow. The approach ensures there is no single point of failure throughout the cell (figure 5). In a conventional cell, cracks can propagate until reaching another crack or the ribbon of the cell. As cracks form throughout the cell, they inhibit the flow of current to the conductive ribbons. In the case of the shingled cell Performance panel, the shorter cell length limits the propagation of cracks, isolating cracks to a smaller area of the cell. The highly redundant ECA connections function as a “mesh” to maintain current flow.

Performance

Conventional Solar Cell

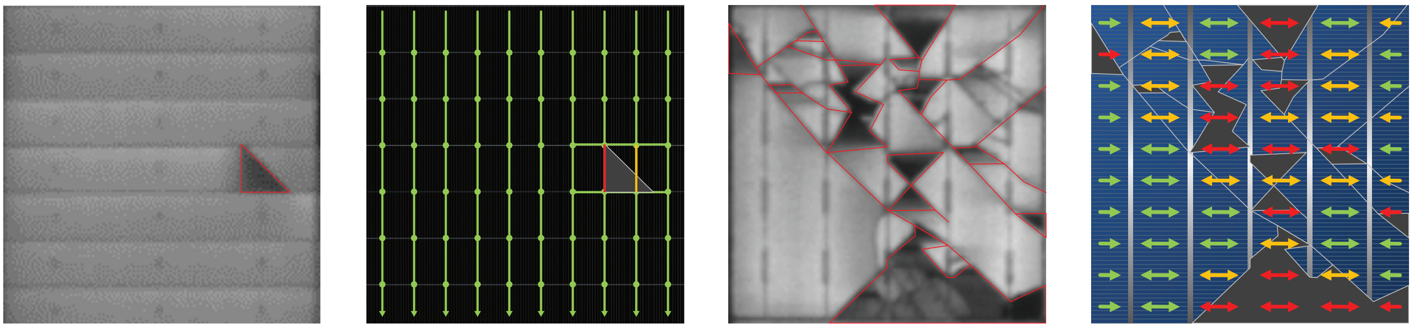


Figure 5: Not only are the smaller cells of the Performance panel less susceptible to breakage, but they confine cracks to a smaller portion of the panel, while maximising energy generation through a series of redundant electrical connections.

Parallel circuitry mitigates the effects of shading and soiling

Landscape orientation (panel)

The parallel cell architecture (hypercell) of the Performance panel ensures optimal performance against shading in landscape-orientation (figure 6). When the bottom of the panel encounters inter-row shade or soiling, the panel loses power in proportion to the amount of shade covering the hypercell. In a scenario where an entire hypercell of a 5-hypercell panel is shaded, only one-fifth of panel power is lost, without activation of the bypass diodes.

In comparison, current flows through conventional panels in a continuous, serial circuit. Any obstruction to this flow, can have detrimental effects on panel operation. Therefore, the panel is typically partitioned into three distinct electrical zones, allowing the panel to bypass obstructions to energy flow should one occur. A linear shadow cast along the bottom of the conventional panel forces one of the bypass diodes to activate, resulting in a 33% power loss.

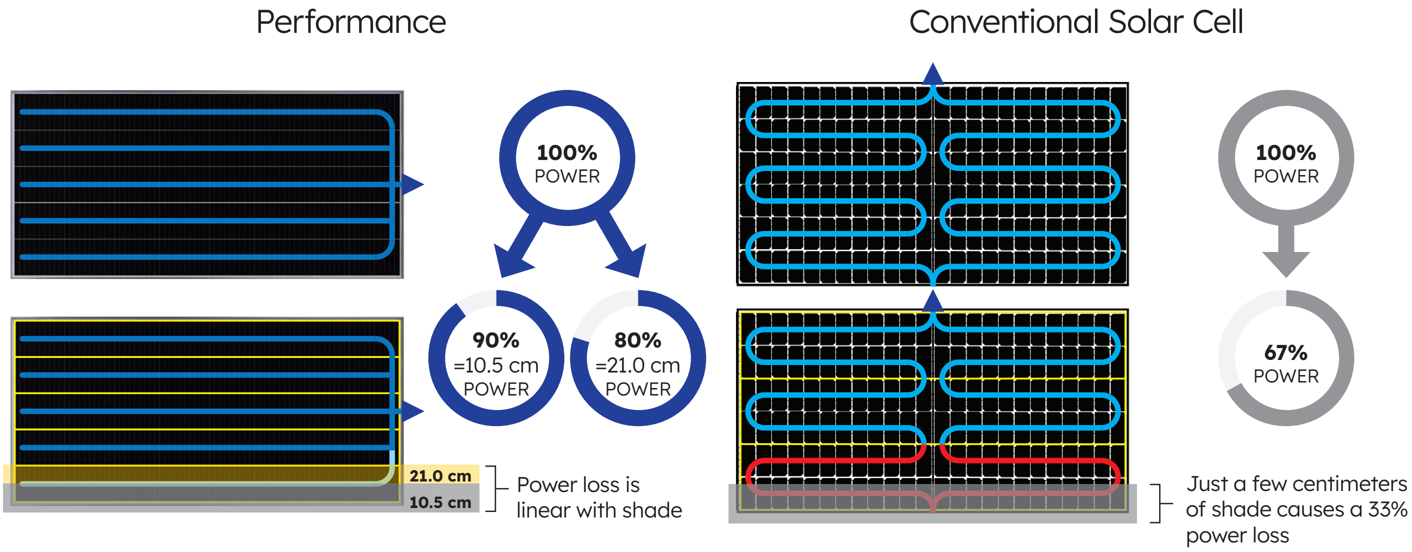


Figure 6: The parallel cell architecture of the Performance panel minimises power loss from shading and soiling in landscape orientation.

Portrait orientation (panel)

Should the Performance panel be installed in a portrait orientation, its shading performance still surpasses that of conventional panels (figure 7). The bypass diodes of the Performance panel are arranged horizontally. When the bottom row cells are shaded in portrait orientation, one of the bypass diodes will activate. In this situation, energy flow is re-routed through the top two-thirds of the panel, resulting in a 33% power loss. For this reason, it is recommended that Performance panels be installed in landscape orientation where possible to maximise energy output.

For conventional panels positioned in portrait orientation, the bypass diodes split the panel in half. Shading the bottom portion of the conventional panel will result in 50% power loss.

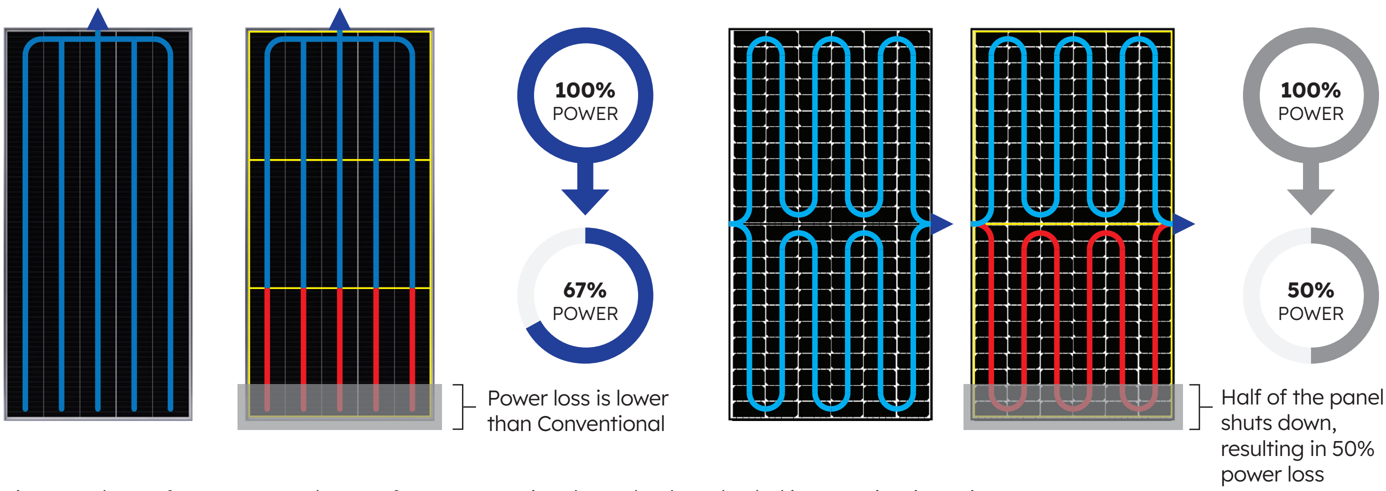
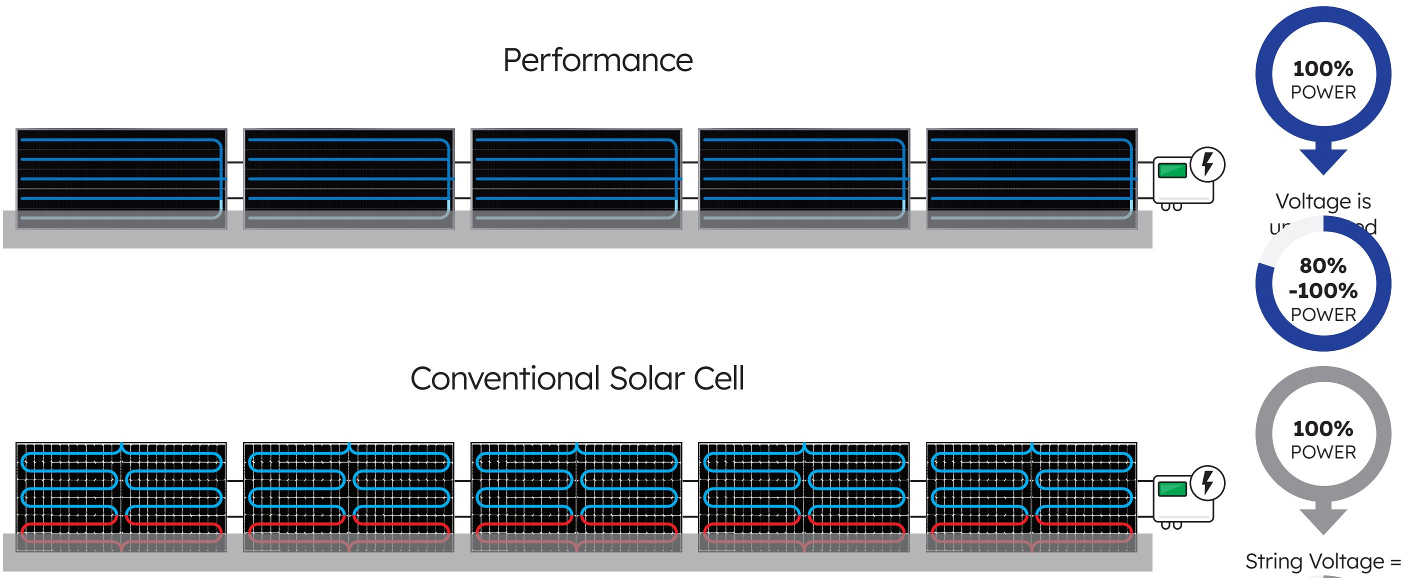


Figure 7: The Performance panel outperforms conventional panels when shaded in portrait orientation.

Landscape orientation (string)

When a string of Performance panels in landscape orientation encounters linear shading across the tracker row, the voltage of the panel remains unchanged (figure 8). This allows inverters to continue operating in their optimal window and maintain peak efficiency.

With the bypass diode activated in the conventional panel, the string operates in a similar fashion, but power is further limited by the electrical configuration of the panel.



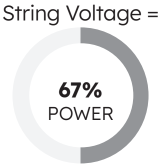


Figure 8: The Performance panel maintains its advantage in shade when consistent linear shadows (i.e., row-to-row shading) impact the entire tracker row in landscape orientation.

Portrait orientation (string)

When a string of Performance panels is in portrait orientation with linear shading across the tracker row, only one-third of each panel is bypassed (figure 9). String power is reduced, but the advantage of the diode configuration allows production to continue. In the case of the conventional panel, the string will continue to operate at 50% power.

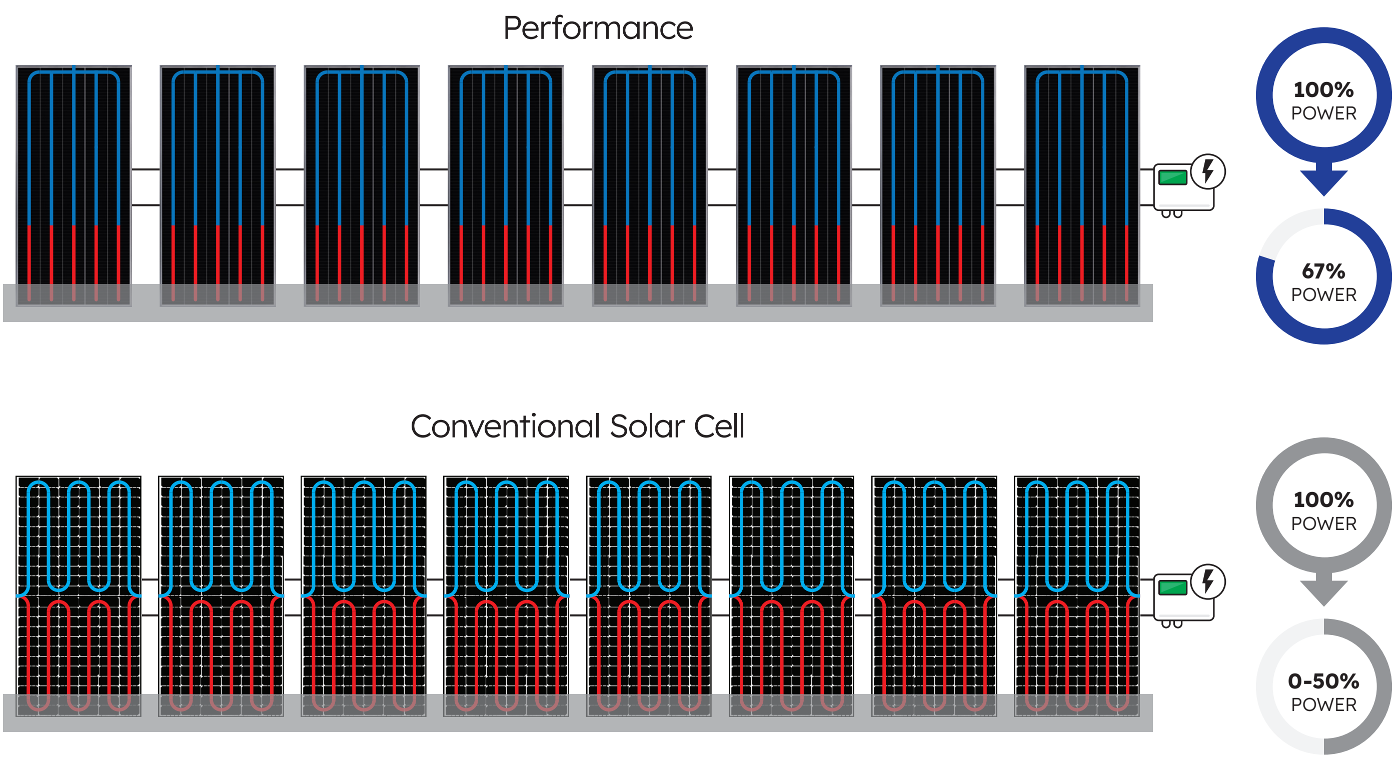


Figure 9: The Performance panel produces more energy than conventional panels when a consistent linear shadow is cast across the entire tracker row in portrait orientation.

Backside shading

The design of the racking system—the quantity, placement, and size of rails—is a common source of rear-side shading in bifacial panels. Albedo is the primary factor that impacts bifacial gain. Based on experiments run at Maxeon's Davis, California R&D lab, it was shown that while a higher albedo does produce higher bifacial gain, the rear irradiance shading impact increases as well.[6] This can cause rear side shading of certain tracker elements to increase due to a larger difference in irradiation between rear-side areas without shade versus those shaded by the racking system. Once again, as with front-side shading, the unique parallel circuitry architecture of the Performance panel minimises the impact of shading. It is suggested that developers contact their tracker OEM for additional information.

Electrical architecture dissipates effects of hotspots

Cell cracks, shading and soiling increase stress on the panel, and can lead to encapsulant browning, backsheet embrittlement, diode failure, and most importantly, hotspots. While hotspots initially reduce panel output, they represent a significant reliability risk to long-term system operation.

Hotspots occur when a portion of a panel, usually a single cell or a spot on a cell, has reduced performance and no longer produces enough current to match neighbouring cells. The solar cell then operates in reverse, consuming power from its neighbours and converting it to heat. The weakest spot on the cell becomes a resistive load, and the cell temperature increases. This effect can be caused by a single event, such as a cell crack, or by regular events such as daily shadows from nearby objects.

In a conventional panel, all of the current must go through the affected cell. The heat dissipation in the weak cell, or hotspot, can be described by P = I * V where the current (Isc) of the panel is available, often as much as 11-18A in panels using larger 182mm and 210mm cells. In the case of panels using larger wafers and full cells, the higher cell current increases the heat dissipation. Slicing the cell in half, reduces the current by half—while slicing the cell into smaller strips, such as the Performance panel, further decreases current.

Independent research has shown that hotspot temperatures are positively correlated with the cell current, meaning higher current panels generate higher hotspot temperatures.[7] As larger cells enter the market, it is becoming imperative that manufacturers adopt some form of cell slicing to mitigate the impact of hotspots. In the case of a full cell panel with a current of 13A and negative bias of 20V, the cell could generate upwards of 250W of heat energy from a single hotspot, which can translate into temperatures well above 150°C, enough to cause permanent damage to the encapsulant and backsheet. It is worth noting here that some panel manufacturers are beginning to include exclusions in their warranties for panels affected by shading.

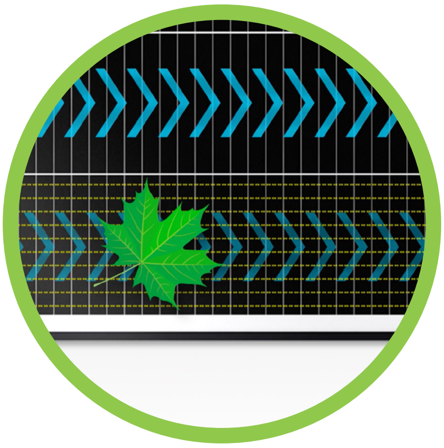


Figure 10: Independent Performance hypercells, backed by redundant connections, offer more tolerance against spot shadows.

Bypass diodes are generally employed to avoid hotspots. As cells go into reverse bias, the substring can be effectively shut down to avoid overheating. However, if cells experience routine shade, soiling or cell cracks, then the cells are consistently pushed into reverse bias which can accelerate diode failure. While IEC 61215 testing does address diode performance, the relatively brief time frame of testing limits insights into the long-term viability of these components. Many solar panels are generally expected to last decades in the field, and that can be a lot to ask of a diode constantly under stress. A field study conducted in 2012, found that for panels over 10 years old, approximately 20% of the diodes had completely failed.[8]

When the cells of the Performance panel are shaded or cracked, the current will take the path of least resistance and be shared by the neighbouring cells (figure 10). The current in any one string is a portion of the operating current of a full cell, greatly reducing the threshold for power dissipation (I * V). As a further mitigating measure, the structure of the Performance panel puts the affected cell in direct physical contact to its neighbouring cells which helps to dissipate hotspot heat. With a lower hotspot temperature in the cell, energy loss is minimised. In a conventional panel, cells are only connected by ribbons, which have little heat transfer capability. Under severe cell cracking or worst-case shading conditions of conventional cells, Performance panels operate at 40-50°C lower temperature (figure 11).[9]

While Performance panels are passively safe, bypass diodes are embedded in their junction boxes to increase energy yield under partial shading should they be required.

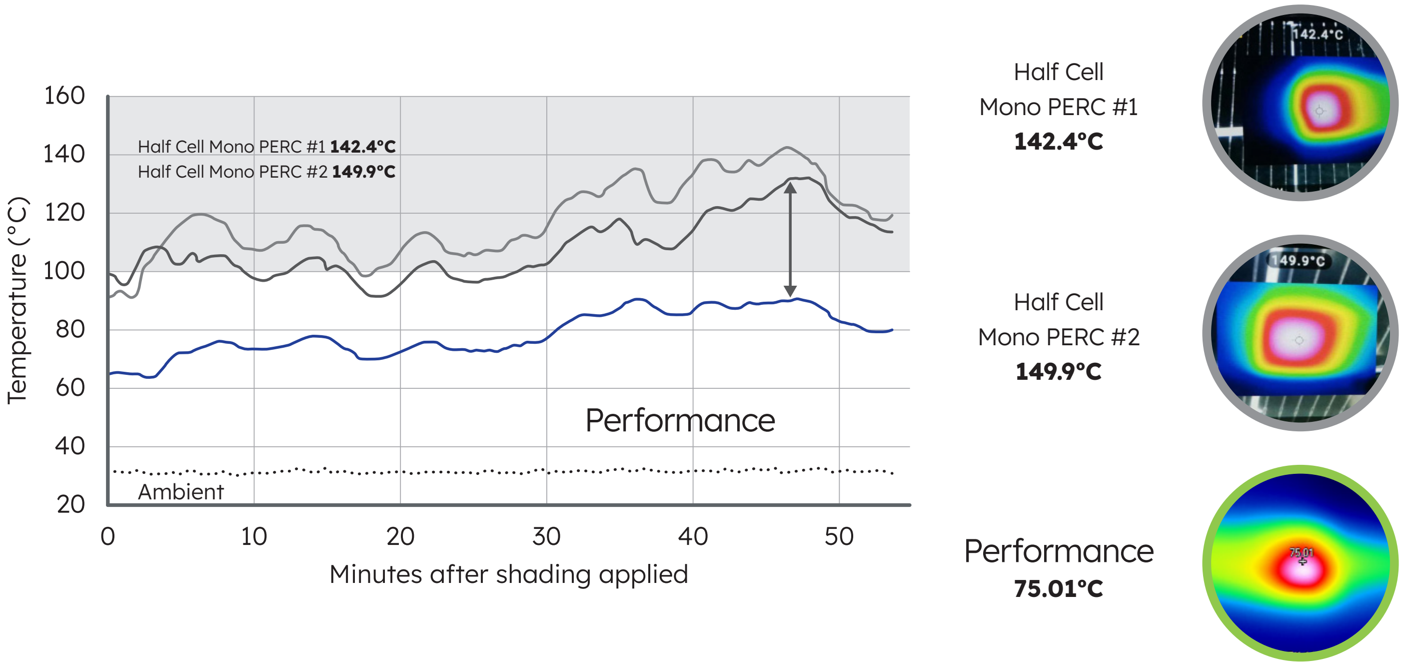


Figure 11: Under severe cell cracking or worst-case shading conditions, Performance panels operate at 40-50°C lower temperature, reducing the risk of temperature-related failures.[9]

LeTID/LID-resistant wafers increase panel power in real-world operation

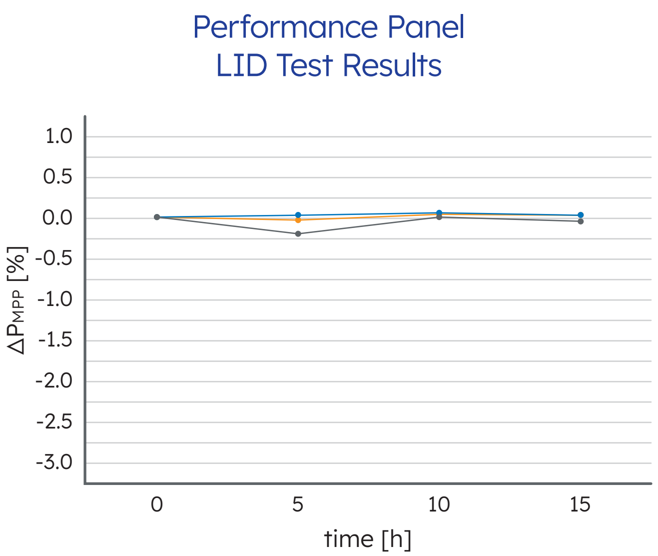
Doping is an important process in wafer manufacturing. Most cells throughout the industry utilise some form of doping to achieve p-type properties in their silicon. Earlier generations of Performance panels used boron-doped silicon, which has been known to be susceptible to light induced degradation (LID). However, more recent generations of Performance panels use an enhanced doping process with LID-resistant wafers to virtually eliminate the effects of LID.

Performance panels with cells from the LID-resistant wafers were sent to Fraunhofer CSE for independent LID and LeTID (light and elevated temperature induced degradation) testing (figure 12). The final report delivered from Fraunhofer CSE states:

- Power changes during LID testing are negligible (50°C, 1000 W/m², 15 kWh/m², IEC 61215 MQT 19)
- In the LeTID test scenario (75°C, 1 A, 702 h) no degradation of panel power (<1 %) is observed
- The tested panels are stable regarding LID and LeTID

The unmitigated effects of LID and LeTID can be detrimental, causing as much as a 5-8% reduction in panel power over time. Peak LID degradation is generally witnessed within weeks of field exposure and has proven to be relatively insensitive to temperature. Peak LeTID degradation on the other hand, may occur over a period of years following panel deployment and can be greatly affected by temperature—progressing over a period of as many as 15 to 20 years in colder environments.

Given continued fleet monitoring and extended testing results on phenomena such as LID/LeTID resistance, Performance panels can offer a minimum warranted power output of 98.0% in their first year of operation, with a maximum annual degradation rate of 0.45% over 30 years.



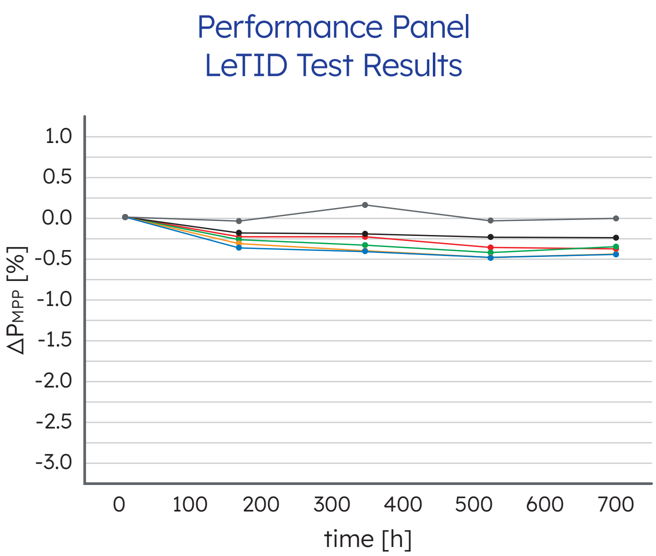


Figure 12: Fraunhofer LID and LeTID test results for Performance panels.

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Lower temperature coefficient improves yield in higher temperatures

	°C above STC	Temperature coefficient	Power loss
Performance Panels	35°C	-0.34%	-11.9%
Conventional Panels	35°C	-0.37%	-13%

The temperature of a solar panel has a direct effect on its ability to generate electricity. This has to do with the laws of thermodynamics and how heat limits the ability of electronics to produce power. As a panel heats up, power output is reduced. This relative change in the panel related to temperature increase is called its temperature coefficient. The temperature coefficient is expressed as the percentage decrease in power output for every 1-degree Celsius (°C) increase in temperature beyond 25°C. Improving the temperature coefficient of the panel will decrease the power loss experienced from higher temperatures.

Performance panels have a temperature coefficient of -0.34 %/°C, which means that for every 1°C above 25°C, Performance panels decrease in relative efficiency only by 0.34 %/°C.

This is a significant advantage for Performance panels in comparison to conventional panels that exhibit temperature coefficients in the range of 0.36% - 0.37% W/°C.

When comparing the performance of two panels in a hot climate where the operating temperature could reach 60 °C, the lower temperature coefficient of the Performance panel offers a 1.1% advantage over the conventional panel. In a 550W panel, this translates to an additional 6W of power per panel.

High-quality materials eliminate PID

Solar panels are typically connected in series, in either 1000V or 1500V strings. In many countries, electrical code requires that the panel frame must be electrically grounded within the string. This results in a potential difference (voltage) between the grounded frames and the cells in the solar panels. Low-iron soda-lime glass, the typical superstrate of solar panels, contains sodium ions. This voltage can drive mobile sodium ions towards the cells which can degrade their properties. This degradation mechanism has been correlated to the defect density in the cells' silicon nitride (SiN) anti-reflective coating. This phenomenon is commonly referred to as potential-induced degradation (PID) and can occur within days of commissioning. PID has been known to cause more than 30% power loss in the field and has been commonly labeled "performance killer number one".

TOP PERFORMER 2021 PVEL PV MODULE RELIABILITY SCORECARD

Earlier generations of the Performance panel, which feature the same technology foundation as the most recent panel generation, have been certified as a PID Top Performer in the PVEL PV Module Reliability Scorecard after being subjected to the steady-state hot (85˚C) and humid (85% RH) conditions with a negative voltage applied between the cells and the frame. Performance panels exhibited negligible power loss in these tests.

The Performance panel installation manual states that negative grounding is not required and that the modules are also compatible with transformerless inverters.

A better panel. A better warranty.

The data presented throughout this paper is intended to clearly demonstrate that Maxeon Performance panels are designed for greater reliability over time. This laser-focus on reliability underscores the bankability of the panel technology developed by Maxeon Solar Technologies. Maxeon's technology leadership has been recognised by the industry's most renowned advisors and has led to TotalEnergies, the 6th largest public oil & gas company in the world, becoming its lead investor.[10]

Each Performance panel is manufactured with the absolute confidence to deliver more energy and reliability over time. The Performance panel delivers long-term results, backed by a stronger warranty than conventional solar (figure 13). Over the course of its 30-year power warranty, the Performance panel is warranted to deliver more power than conventional panels (figure 14). As noted previously, a 25-year product and power warranty option is also available—enquire with your sales representative for more details.

In addition, Performance panels are designed to last beyond their warranty. The expected lifetime, or 'useful' life, of a solar installation is defined as the time when 1% of total panels have dropped below 70% power output. This definition is used to ensure that an installation will continue to generate useful revenue without incurring significant maintenance or large panel current mismatch. Earlier versions of Performance panels, which share the same electrical architecture of the most recent panel generation, have undergone a third-party review with Leidos. Leidos found that the use of identical encapsulant and backsheet from Maxeon Maxeon interdigitated back contact (IBC) panels in conjunction with a low-stress cell interconnection reasonably infers an expectation of a more than 35-year useful life for Performance panels.[11]

	Performance Panel Warranty	Conventional Panel Warranties[12]
Product	**12 Years**	12 Years
Power	**30 Years**	25-30 Years
Year 1	**98.0%**	97.5%
Yearly decline	**0.45%**	0.50%
Year 25	**87.2%**	85.5%
Year 30	**85.0%**	83.0%

Figure 13: Performance panel warranty coverage compared to representative standard efficiency solar manufacturers.

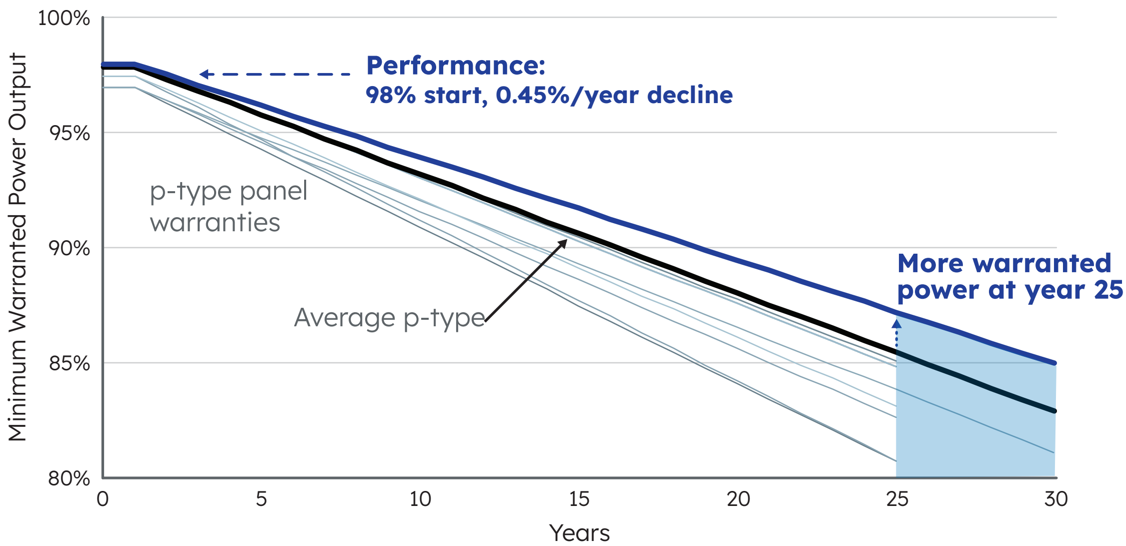

Figure 14: Performance panels offer a high-power warranty, for more bankable power every year.[13]

Looking toward the future

For over 35 years, our panels have pushed the boundaries of solar innovation—renowned for their record-setting technology, industry-leading design and engineering, and the first-rate customer experience Maxeon partners deliver every day.

As a manufacturer, Maxeon Solar Technologies is passionate about continually raising the bar on our technology. To date, more than 100 patents have already been granted to secure the inherent differentiation in the Performance panel. These safeguards not only protect the panel designs and the unique processes and equipment used to manufacture them—they provide confidence to customers as well.

Maxeon Solar Technologies has partnered with Tianjin Zhonghuan Semiconductor (TZS) to rapidly scale Performance panel manufacturing to meet a growing demand from solar power plant EPCs and developers around the globe (figure 15). TZS is a leading mono wafer provider with more than 85 GW of planned and operating mono silicon ingot and wafer capacity. Huansheng Solar (HSPV) was formed by TZS and Maxeon Solar Technologies to combine their respective strengths in wafer technology and proximity to China's strong supply chain and logistics capacity, with Silicon Valley innovation. This joint venture solidified the Performance panel's place as the leading shingled panel in terms of global deployments. In addition, it has proven both the manufacturability, as well as the strong market demand for the technology.

Maxeon Solar Technologies and TZS recently brought an additional 6 GW of capacity online at HSPV to fuel future growth in the large-scale solar power plant market. The new facilities are highly automated, utilising "Factory 4.0" intelligence to digitise and optimise the entire manufacturing value chain—from raw material loading and product assembly, through testing and packaging.

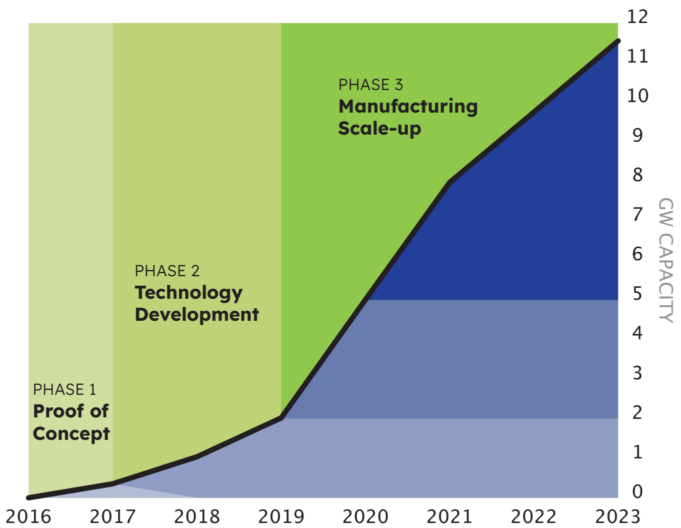

Figure 15: Taking the time to build a solid foundation centered around performance and reliability was a key factor in the scale-up of Performance panel technology.

In April of 2021, Maxeon announced an additional phased expansion of new shingled module capacity totaling 3.6 GW. Phase one will consist of Maxeon using its existing facilities in Malaysia to manufacture large-format G12 mono-PERC solar cells. Performance panel assembly will be performed at Maxeon's manufacturing facility in Mexicali, Mexico. Phase one will total an additional 1.8 GW of new Performance panel capacity with initial sales expected to begin in the first quarter of 2022. In parallel, phase two will consist of conducting a comprehensive process to select an optimal site for a U.S. based module assembly facility. Depending on site conditions and market demand, this second phase is expected to begin operation in 2023 and expand capacity up to an additional 1.8 GW.

To learn more about Performance technology, contact your local sales representative, or visit **maxeon.com**

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POWERING POSITIVE CHANGE

1 Most Efficient: Based on datasheet review of websites of top 20 manufacturers per IHS, as of June 2021. Unmatched Reliability: Jordan, et. al. Robust PV Degradation Methodology and Application. PVSC 2018
2 Based on shipments as of Q2-2021
3 SunPower Performance Series – Thermal Performance, Z. Campeau 2016
4 Dupont Global PV Reliability Field Analysis (reports issued 2016, 2018, 2019, and 2020)
5 SunPower. A Comparative Study: SunPower DC Solar Module Warranty Claim Rates vs. Conventional Panels. 2019.
6 SunPower internal bifacial field test results in Davis, CA.
7 Shifeng D, et. al. Research on hot spot risk for high-efficiency solar module. Energy Procedia, ISSN: 1876-6102, Vol: 130, Page: 77-86. 2017.
8 Kato. (2012). PV module failures observed in the field: solder bond and bypass diode failures. In Characterizing and Classifying Failures of PV Modules.
9 SunPower internal study, 2020.
10 Source: Forbes, The World's Largest Oil & Gas Companies 2021. Forbes Global 2000
11 Performance panels expected useful life of 35 years. Source: "SunPower P-Series Technology Technical Review," Leidos Independent Engineer Report. 2016.
12 Based review of manufacturer websites of IHS top 20 manufacturers as of Q3-21 for p-type panels.
13 Representative of standard efficiency solar manufacturers. Competitor warranty information provided from latest warranty documentation from various conventional panel manufacturer websites as of October September 2021.