Eliminating Solar Panel Hotspot Risk with Maxeon IBC Technology

A Maxeon Solar Technologies White Paper

Contents

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 rich legacy of solar technology innovation that began with the founding of SunPower Corporation in 1985.

Maxeon Solar Technologies is Powering Positive Change™, leveraging nearly 40 years of solar energy leadership and over 1,900 patents to design innovative and sustainably made solar panels and energy solutions for residential, commercial, and power plant customers. Maxeon's integrated home energy management is a flexible ecosystem of products and services, built around the award-winning Maxeon® and SunPower® branded solar panels. With a network of more than 1,700 trusted partners and distributors, and more than one million customers worldwide, the Company is a global leader in solar.

EXECUTIVE SUMMARY

Maxeon Solar Technologies has spent nearly 40 years refining the patented cell and panel design of our proprietary Maxeon interdigitated back-contact (IBC) panel technology to maximize reliability and energy production—both critical factors in lowering the levelized cost of energy (LCOE). A longer-lasting, more durable panel translates to higher lifetime energy output.

One of the unique ways in which Maxeon IBC panels achieve their promise of industry-leading reliability is by eliminating the risk of hotspot formation. Hotspots are concentrated areas of heat energy that predominantly result from shaded or cracked solar cells. For the purposes of this paper, references to shaded cells include any changes in illumination on the panel that create a mismatch in current. These can generally come from shadows cast from neighboring structures, spot shadows on the surface of the panel, or soiling. Regardless of the source, Maxeon has worked diligently to engineer hotspot failure modes common to standard solar technologies out of our flagship panel line.

This paper provides some key insights on hotspot formation, along with a review of the primary mitigation measure used to protect standard solar panels—the bypass diode. **While bypass diodes have long been a serviceable solution for the industry, we propose that a panel such as Maxeon IBC that is engineered to stand up to shade and reduce diode reliance provides an inherently higher performing, more reliable, and safer solution for customers**. Our perspective is backed by internal field testing and a third-party literature review that examined shading and hotspot formation across various panel technologies.

- While partially shaded (half of one cell covered), Maxeon IBC panels mitigate the long-term degradation risk of panel materials by minimizing heat build-up in affected cells—staying an average of 67 °C (153 °F) cooler than the half-cell ribbon-based back contact, half-cell heterojunction (HJT) and half-cell front contact tunnel oxide passivated contact (TOPCon) panels evaluated at Maxeon's R&D test facility.

- When subjected to simulated bypass diode failure, the low reverse bias breakdown voltage of Maxeon IBC cells exhibited uniform and non-damaging behavior that continued to limit heat build-up in partially shaded cells. As a result, Maxeon IBC panels were inherently protected from the severe back sheet discoloration, bubbling, and burning that was witnessed in the ribbon-based back contact, HJT, and TOPCon panels under the same test conditions.

- Özkalay et. al. recently ran a similar series of tests on PERC half- and full-cell, HJT half-cell, and Maxeon IBC technologies. Their findings on the temperature-related effects of shadow-induced hotspots concluded that, "Based on the reverse characteristics of the IBC cell, including its diode functionality, uniform heating, and lower breakdown voltage, the IBC module exhibited a more favorable performance under partial shade compared to other module technologies."

- In addition to improved product design, the industry should revisit baseline reliability testing to further minimize hotspot risk. For example, current IEC tests for bypass diodes are designed purely for early life failure detection, not for longer-term wear out failures. Longer, higher temperature stress tests that can properly assess a panel's ability to safely withstand cell cracks and reasonable shade levels in the field would ensure safer and more reliable products for customers.

HOTSPOT SNAPSHOT

A solar panel maximizes its energy generation potential when each cell within an electrical string maintains the same current. When a cell can't match the current of its neighbors, usually due to the presence of shading or cell cracks, it begins consuming power from surrounding cells and converting it to heat—also known as operating in a state of reverse bias. As cell temperatures rise, hotspots can form in the vicinity of the obstruction. Hotspots are very concentrated areas of heat energy that can reach extreme temperatures—temperatures high enough to degrade panel materials by burning the encapsulant and back sheet, as well as damage cells and glass. When the heat build-up in shaded or cracked cells in standard solar panels is left unmitigated—or unprotected by a bypass diode—hotspots can compromise panel operation and decrease energy production, induce panel failure, and in extreme cases present a fire risk.[1] How a panel reacts to shading and cell cracks is central to determining its useful life and the amount of energy it will produce over that time.

While shading and cell cracks may seem like a minor issue, they can have major repercussions across a system—especially for standard solar panels.

All solar installations generally experience some form of shade. Shade may result from the leaves falling from a neighboring tree, bird droppings, or simply a shadow cast from a nearby structure such as a chimney or vent pipe. Regardless of the source, the result is the same—shade restricts the flow of direct sunlight to solar panels.

Cell cracks can occur from transport and installation stresses, wind and snow loads, and hail impacts to name a few. As the internal resistance generated by current travelling through damaged cells builds, cell temperatures can rapidly increase. Breaks in cell continuity can form 'dead zones' that prevent energy from leaving the affected area of the panel, lowering the current and pushing the cell into reverse bias. This failure mode is intrinsic to standard solar cells due to their architecture—a thin layer of silicon with screen-printed metal conductors and soldered metallic ribbons that lacks structural integrity. While shading is eventually removed from the panel, hotspots resulting from cell cracks essentially act as permanent shade across the panel.

BYPASS DIODES—THE LAST LINE OF DEFENSE?

Standard solar panels rely on bypass diodes to avoid the formation of damaging hotspots. As the reverse bias voltage pushes beyond the cell's reverse breakdown voltage, the dissipated power overheats the cell. This results in bypass diodes situated within the panel's junction box switching on to "bypass" the section(s) of the panel containing the affected cells. While it means an entire section of the standard panel is prevented from producing energy, the panel is protected from the irreparable damage that would result from an unmitigated hotspot.

The relationship between a solar cell's electrical properties and those of the bypass diode can result in different behavior from one panel to the next. In standard solar panels, cells exhibit a breakdown voltage that is high enough that the shading impact on one cell will bypass the entire string and thus protect the cell from damage. Some panels, however, have a reverse bias voltage that is non-uniform and damaging, and lower than the operating voltage of the diode. In these cases, bypass diodes may not switch on until shading has progressed beyond the boundaries of a single cell—meaning the bypass diode doesn't protect the panel from hotspot formation at low levels of shading (i.e. less than one cell). Maxeon IBC cells on the other hand, offer a low reverse bias breakdown voltage that is uniform and non-damaging, while remaining lower than the total voltage of the string protected by the diode. In this case, the Maxeon IBC cell does not have to rely on bypass diodes for protection from hotspots.

Looking at **Figure 1** below, **Panel Mode A** highlights standard panel operation with no shading or cracked cells. Current is forward biased throughout the panel, while each bypass diode is held in reverse bias (the diode's natural state), functioning as a 'check valve' for the flow of current.

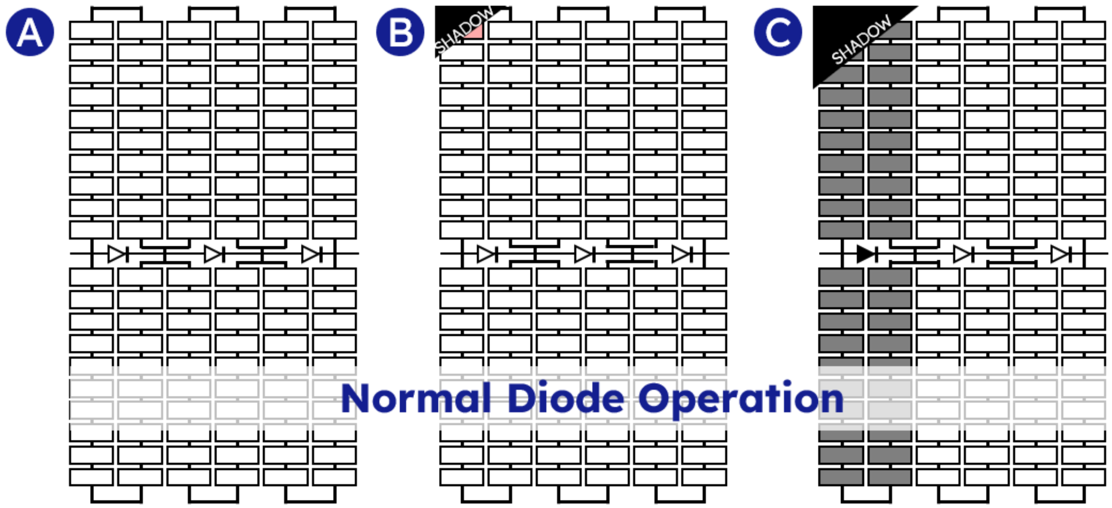

Figure 1: A standard solar panel under normal, unshaded operation (Mode A); Partial shading of cells with localized heat build-up that can degrade panel materials over time (Mode B); 33% power loss resulting from bypass diode activation as shade extends across a larger area of the panel (Mode C).

As we move to **Panel Mode B**, we can see that a shadow has begun to fall onto the surface of the panel, temporarily stopping sunlight from reaching the cell underneath. The affected cell begins converting current into heat energy—while beginning to operate in a state of reverse bias. Cell temperatures begin to rise in the shaded area due to the heat build-up. It's not uncommon for temperatures to quickly exceed 130 °C (266 °F), hot enough for the polymers used in panel construction to begin degrading. Over time, elevated cell temperatures from frequent shading can erode encapsulations and push the panel toward a state of permanent reverse bias—which will result in more severe panel damage.

And finally in **Panel Mode C**, the panel's voltage ultimately drops to a point where the bypass diode activates to alleviate any further heat generation in the panel—a transition that takes milliseconds in the field. The bypass diode is now conducting current in forward bias to create a path for the current to navigate around the impacted section of the panel. In the case of a panel with three diodes, one-third of nameplate power is lost until the obstruction is removed and the panel returns to 'normal' function.

Diodes are a cost-effective, simple solution for mitigating hotspot development, but what happens if they stop doing their job? While research on the topic is still emerging, there are indications that certain conditions can hasten diode failure in the field, many of which can be intensified by thermal stress from elevated temperatures on a roof.[2]

- Diodes can prematurely age from frequent activation because of cell cracks or varied shading events throughout the day (e.g., moving shadows, leaves, and bird droppings).
- Diode reliability can be impacted by repeated hot to cold temperature swings, or thermal cycling.

- Thermal runaway is a condition that occurs as diodes contend with heat dissipation. The effort required to dissipate the initial heat build-up can result in the generation of additional thermal energy in the diode. This dynamic creates a never-ending cycle of increased heat generation that sets the diode on a path toward failure.
- Arcing occurs when the diode's electrical leads are not properly connected during the manufacturing process, resulting in diode failure.
- Improper manufacturing controls during j-box attachment or flash testing can introduce electrostatic discharge (ESD) which enables surges of electric current to impact diode operation.
- Installation errors can also lead to diode failure when panels are improperly wired or connected in a system.
- Lightning strikes are another source of electrical surges that can render diodes inoperable.

When a diode fails, it does so in either a state of short or open circuit. **Panel Mode A** in **Figure 2** depicts a short circuit diode failure. The left-third of the panel is in a state of constant bypass even after the shade source has been removed. While the section of the panel continues to conduct current, there is no immediate reliability risk to the panel, although power is permanently reduced by one-third. This mode is easily observed through infrared scans of the array as the bypassed section of the panel will still appear with an elevated heat signature in the scan.

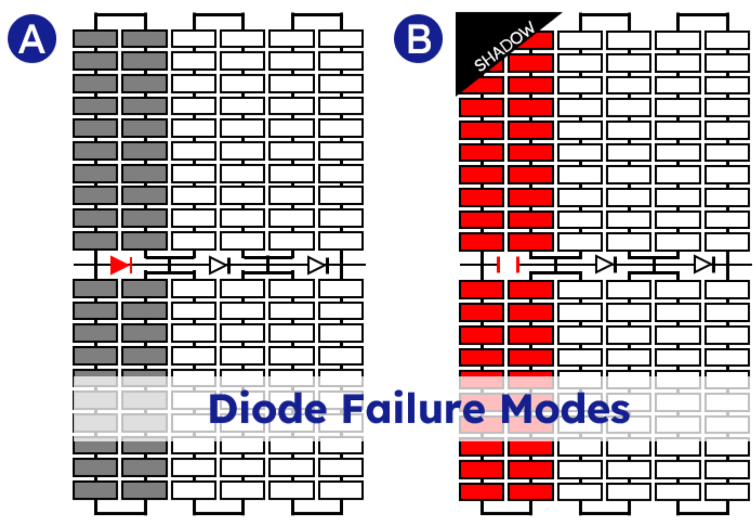

Figure 2: Bypass diodes fail in either short circuit, permanently reducing panel power with minimal reliability risk (Mode A); or open circuit, operating as if no diode exists, exposing the panel to the formation of damaging hotspots (Mode B).

Panel Mode B on the other hand depicts an open circuit diode failure. In this case, the panel operates as if no bypass diode is present. This complicates matters as, in the absence of shading, the failure mode is not observable in infrared scans of the array, giving a false sense of security that the diode is protecting against hotspots. Current will continue to move through the cells until the shade returns, at which time hotspots will begin to develop with no potential for mitigation. Extreme cell temperatures can be reached in minutes, leading to damaged back sheets, deformed electrical circuitry, frequent inverter tripping from the loss of electrical isolation, even shattered glass—essentially irreparable panel damage that drives complete panel breakdown.

MAXEON’S INTERNAL HOTSPOT AND DIODE FAILURE STUDY

As manufacturers continue to increase panel power and electrical current ratings, lengthen warranties, and exponentially scale low-cost production of unproven technologies—customers are left in a situation that doesn’t elicit confidence, especially when they expect panels to operate on the roof of their home for decades to come.

While IEC certification is inclusive of hotspot and diode testing, current test conditions are more effective in establishing a nominal level of build quality and out of the box safety, as opposed to long-term reliability. Test protocols only stress panels for a couple of hours—whereas a panel experiencing daily intervals of shade can exceed certification thresholds within days of installation.

We took a closer look at the impacts of shade and hotspots at our California R&D facility, conducting a series of field tests to monitor our flagship Maxeon IBC panel technology alongside ribbon-based back contact, heterojunction and standard TOPCon panels—with one competitive offering selected to represent each technology.

Our test protocol consisted of introducing artificial shade to the panels by covering half of one single cell on each panel. By shading only half of one cell, we introduce a current mismatch that puts the cell into reverse bias.

With the electrical connections shorted at I_{sc} to foster the flow of current and ensure individual panel testing could be conducted consistently, we first exposed the panels to sunlight to assess temperature elevation in the shaded cell. Next, we removed the corresponding bypass diode to the shaded cell, creating a quick and simple path to model diode failure and assess the impact on the shaded cell and surrounding panel materials. Note that I_{sc} is slightly higher than I_{mp} by about 5%, and this does affect the amount of power dissipated in the shaded cell. However, as noted in a recent report from Özkalay *et. al.* which will be discussed later in the paper, the IEC hotspot test requires that all cells in the module be screened to find the most hotspot-sensitive cells, and the worst-case shading condition for each of those cells, both of which would likely have led to higher temperatures than our random cell selection and half-cell shading *(Özkalay also employed random cell selection due to the time consuming nature of screening every cell in a module)*. We also performed our testing on an open rack at moderate ambient temperatures, whereas residential rooftop installations in hot and sunny climates would experience higher solar irradiance and starting temperatures than in our testing.

Multiple rounds of outdoor testing on each panel were conducted, however not all panels were tested in parallel. Given slight variations in test conditions, temperature measurements reported below have been normalized to account for differences in plane of array irradiance and ambient temperature over the course of testing. The results presented below emphasize maximum temperatures recorded while cells were partially shaded with and without the protection of the bypass diode. Focusing on the maximum temperature provides an indication of the extreme nature with which shade and hotspots tend to affect solar panel operation. An example of the outdoor test setup is visible in **Figure 3**.

Figure 3: Outdoor hotspot testing setup at Maxeon's R&D facility in California, USA.

One final note before we dive into the results, the infrared (IR) images displayed below are independently scaled for each panel test. So, while it may look like all panels are experiencing equally high concentrations of heat in the IR images, the actual scale of the infrared coloration differs greatly between panels.

Test Results: Half-cell Ribbon-based Back Contact Technology

The first panel tested represented one of the newer back contact entrants in the market. In search of higher efficiency, these panels have transitioned the conductive elements of the panel away from the front face of the cell. **Figure 4** includes the initial infrared scan of the partially shaded cell's thermal signature. From an unshaded cell temperature of 62 °C (144 °F), the cell increased to 153 °C (307 °F) under partial shade—a temperature hot enough to affect the integrity of panel materials if sustained over time. Once installed and exposed to shade on a routine basis, elevated cell operating temperatures in this range will expedite the degradation of encapsulants and back sheets, ultimately compromising panel operation. Related to the note above regarding auto-scaling of images, the infrared scans in **Figure 4** demonstrate how cell temperature is not correlated with color in these scans, or any of those that follow.

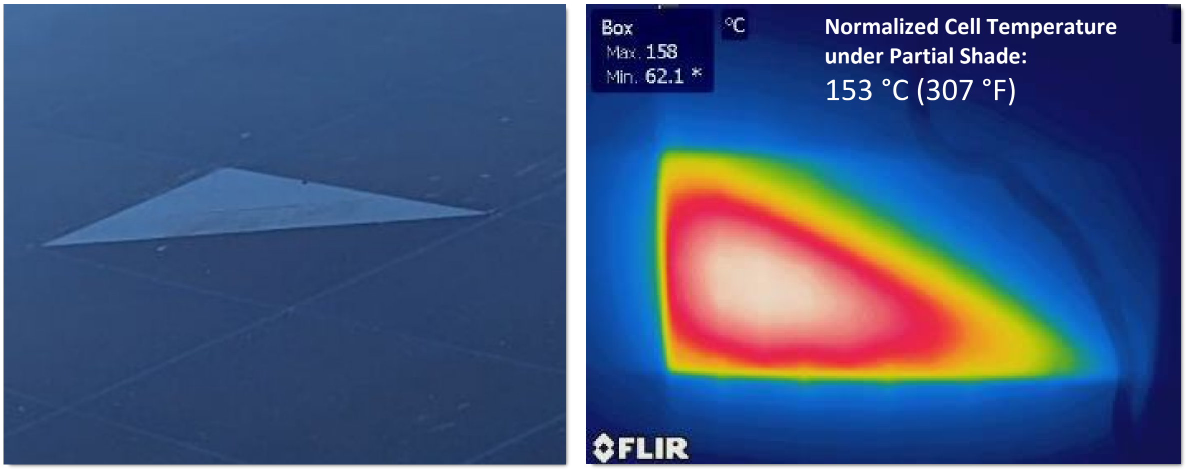

Figure 4: The shade mask applied to the front face of the half-cell ribbon-based back contact panel (left). With half of one cell shaded, the infrared image of the cell (right) shows the shading-induced hotspot reaching 153 °C (307 °F), an increase of 91 °C (163 °F) from the cell's initial unshaded temperature of 62 °C (144 °F).

Upon removing the diode, the panel developed severe back sheet burning and bubbling within 30 minutes as shown in **Figure 5**. In addition, as shown in **Figure 5 (right)**, the panel recorded a concentrated hotspot temperature of more than 550 °C (>1,022 °F), exceeding the maximum range of the infrared camera in use. These results reinforce the value of the diode as a defense mechanism against shading, as open circuit diode failure can rapidly accelerate panel failure. Additionally, the reverse bias voltage of the cell topped out at approximately 30 V—with a cell I_{sc} around 7 A, that translates to roughly 200 W of power to dissipate as heat across a very concentrated, non-uniform area within the cell.

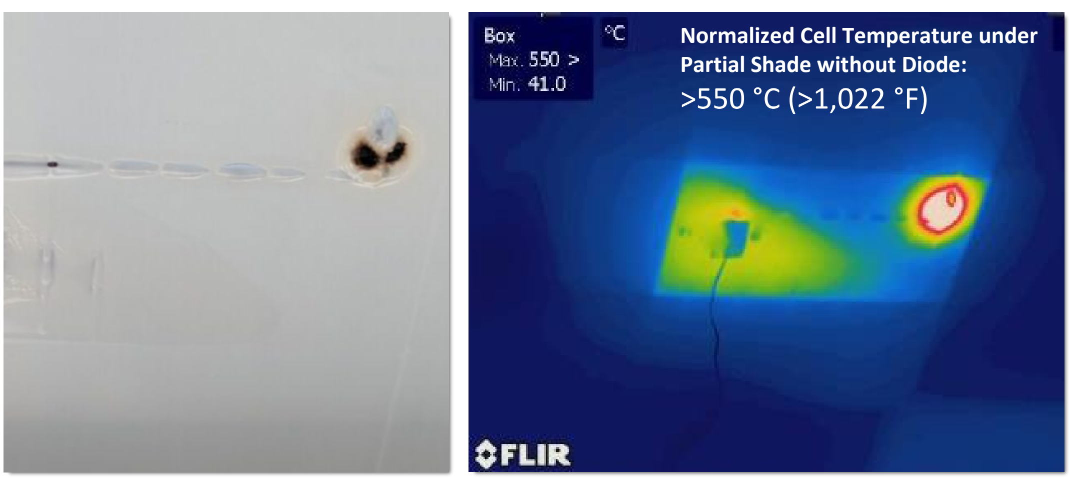

Figure 5: Visible hotspot damage (left) alongside an infrared image (right) at the maximum hotspot temperature of >550 °C (>1,022 °F) witnessed in the half-cell ribbon-based back contact panel within 30 minutes of diode removal.

As a final note, **Figure 6** highlights some additional damage that propagated to the front face of the cell due to the immense heat generated from the hotspot once the bypass diode was removed.

Figure 6: Visible hotspot damage extending to the front side of the ribbon-based back contact panel.

Test Results: Half-cell Front Contact TOPCon Technology

The next panel tested featured a half-cell front contact tunnel oxide passivated contact technology, or TOPCon. TOPCon panels are rapidly entering the market due to their increased efficiency vs. mono PERC at little added cost. The half-cell TOPCon technology didn't fare much better in the test sequence compared to the ribbon-based back contact panel. **Figure 7** highlights the infrared scan of the partially shaded cell, which increased from an unshaded temperature of 58 °C (136 °F) to 142 °C (288 °F) once partially shaded. The TOPCon panel, like the ribbon-based back contact panel, experienced enough heat build-up under shade to compromise panel operation over time. Once again, the initial tests are run with a fully functioning bypass diode.

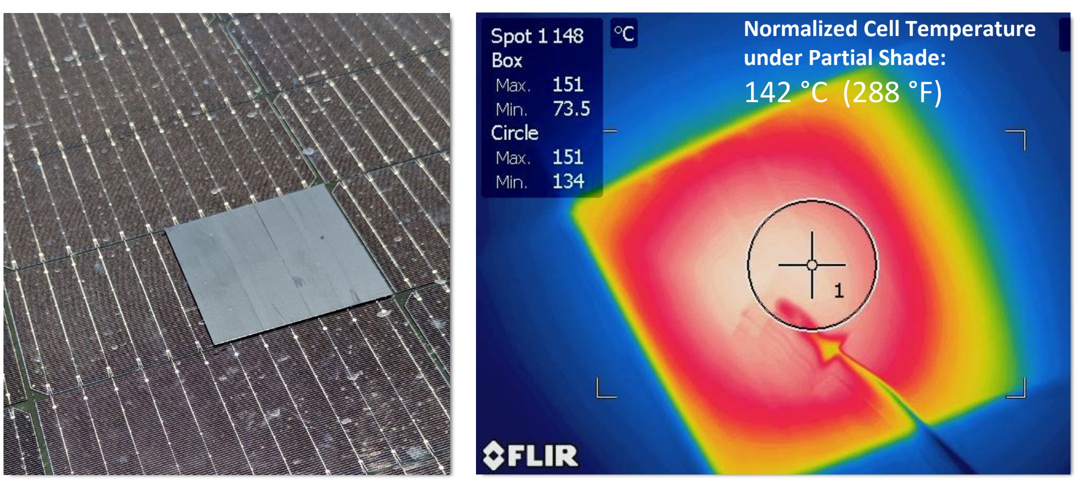

Figure 7: The shade mask applied to the front face of the TOPCon cell (left). With half of one cell shaded, the infrared image

of the cell (right) shows the shading-induced hotspot reaching 142 °C (288 °F), an increase of 84 °C (152 °F) from the cell's initial unshaded temperature of 58 °C (136 °F).

With the diode removed, **Figure 8** demonstrates that the TOPCon panel also experienced severe back sheet burning and bubbling within 30 minutes due to the extreme heat of the hotspot, generating temperatures once again in excess of 550 °C (>1,022 °F). Additionally, the reverse bias voltage of TOPCon cells will generally register higher than 30 V—with a cell I_{sc} around 6.8 A, that translates to more than 200 W of heat energy to dissipate in a very concentrated area.

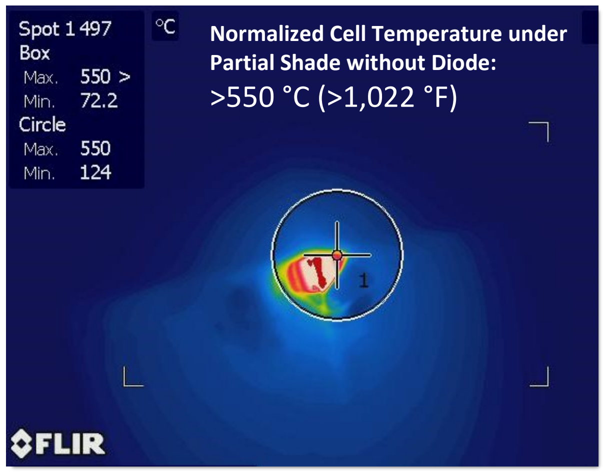

Figure 8: Visible hotspot damage (left) alongside an infrared image (right) at the maximum hotspot temperature of >550 °C (>1,022 °F) witnessed in the TOPCon panel within 30 minutes of diode removal.

Test Results: Half-cell Heterojunction (HJT) Technology

The next panel to undergo testing featured heterojunction technology, or HJT. HJT panels are another evolution in panel technology becoming somewhat more prevalent in the market in recent years. HJT offers manufacturers another path to increased efficiency over mono PERC but requires a more strategic commitment as inherent differences in equipment and materials do not present the same natural extension of existing mono PERC manufacturing offered by TOPCon. Following the same methodology as the previous panel testing, we saw similar results in shade. **Figure 9** depicts how the initial infrared scan of the partially shaded HJT cell increased from an unshaded temperature of 60 °C (140 °F) to 162 °C (324 °F) once shaded, continuing to perpetuate concerns that panel operations would be compromised over time in the field.

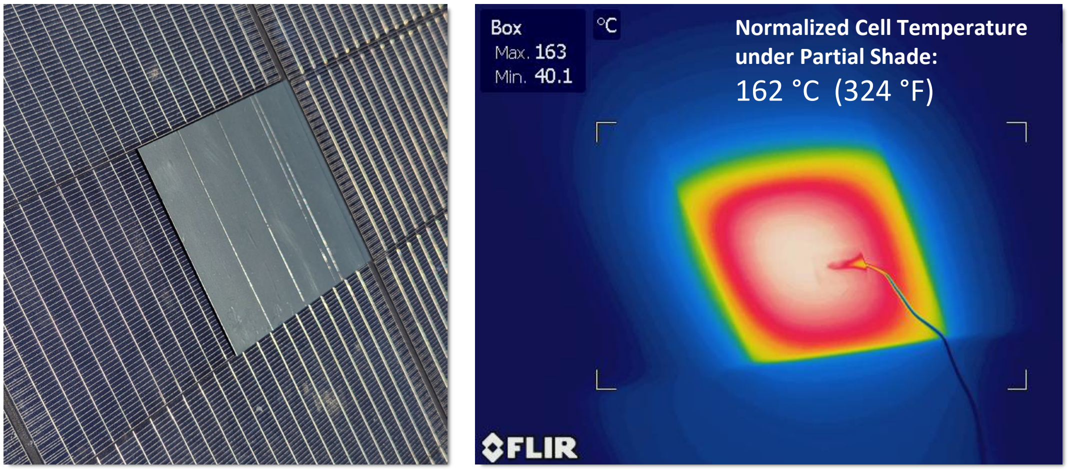

Figure 9: The shade mask applied to the front face of the HJT cell (left). With half of one cell shaded, the infrared image of the cell (right) shows the shading-induced hotspot reaching 162 °C (324 °F), an increase of 102 °C (184 °F) from the cell's initial unshaded temperature of 60 °C (140 °F).

With the diode removed, **Figure 10** shows that the HJT panel reached a maximum temperature of 305 °C (581 °F). While significantly lower than the ribbon-based back contact or TOPCon panels tested, and able to avoid the severe back sheet burning and bubbling we saw in those technologies, there was still a considerable amount of bubbling and discoloration on the back sheet within 30 minutes to indicate that panel materials would continue degrading at a rapid rate if left unattended. The reverse bias voltage of the cells topped out at 17 V—with an I_{sc} around 9 A, translating to approximately 150 W of heat energy to dissipate in a very concentrated area.

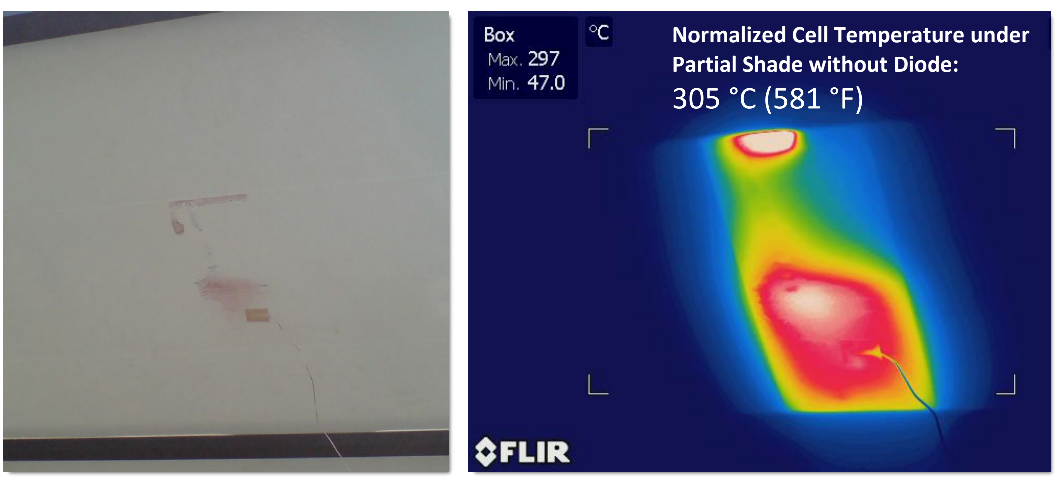

Figure 10: Visible hotspot damage (left) alongside an infrared image (right) at the maximum hotspot temperature of 305 °C (581 °F) witnessed in the HJT panel within 30 minutes of diode removal.

Test Results: Full-cell Maxeon Interdigitated Back Contact (IBC) Technology

Turning to the test results for the latest generation of Maxeon IBC technology, Maxeon 7, we find no noticeable impact to the panel resulting from the partially shaded cell. Once again, the methodology did not change in comparison to the other panels tested. The Maxeon IBC panel's unshaded cell temperature of 59 °C (138 °F) rose to 85 °C (185 °F) once shaded. This temperature rise (vs. unshaded) is 70% lower than the average temperature rise measured across the other shaded panels. By comparison, the Maxeon IBC panel stayed well within the generally accepted range of heat build-up, mitigating any concerns of long-term damage to panel materials.

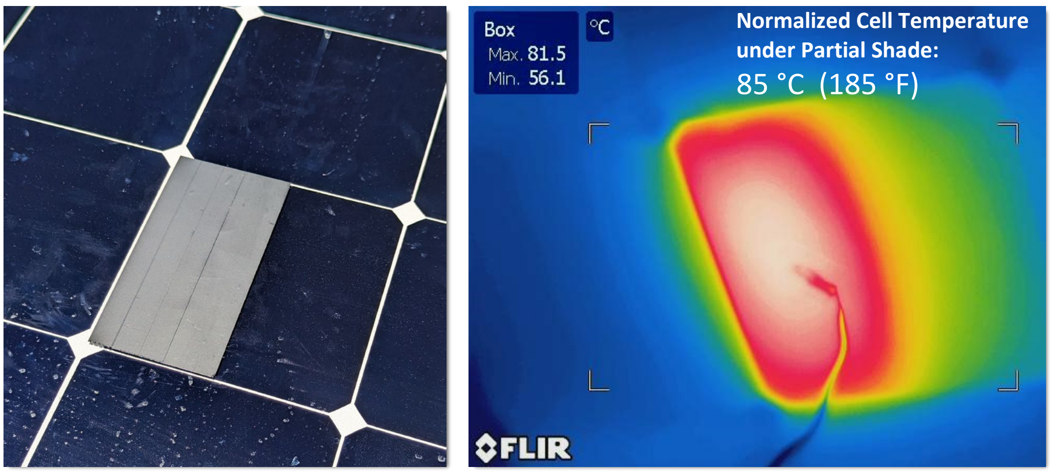

Figure 11: The shade mask applied to the front face of the Maxeon 7 IBC cell (left). With half of one cell shaded, the infrared image of the cell (right) shows the shading-induced hotspot reaching 85 °C (185 °F), an increase of 26 °C (47 °F) from the cell's initial unshaded temperature of 59 °C (138 °F).

With diodes removed, concentrated temperatures within the Maxeon 7 IBC cell depicted in **Figure 12** topped out around 78 °C (172 °F) after approximately 30 minutes. We note here that unlike the other panels, the Maxeon 7 temperature reading was slightly lower without the diode present. This can be attributed to natural variability of outdoor conditions during testing—slight variations in temperature, wind, and sunlight intensity for example, become more evident in a narrower temperature range compared to the other panel technologies. The key takeaway, however, is that the Maxeon 7 IBC panel was able to maintain a manageable cell temperature even without its diode. The reverse bias voltage of the Maxeon 7 cells comes in at approximately 2.3 V—with a cell I_{sc} around 6.6 A, that translates to only about 15 W of power to dissipate as heat in the cell, a significantly smaller figure compared to the ribbon-based back contact that was nearly 13 times higher by comparison.

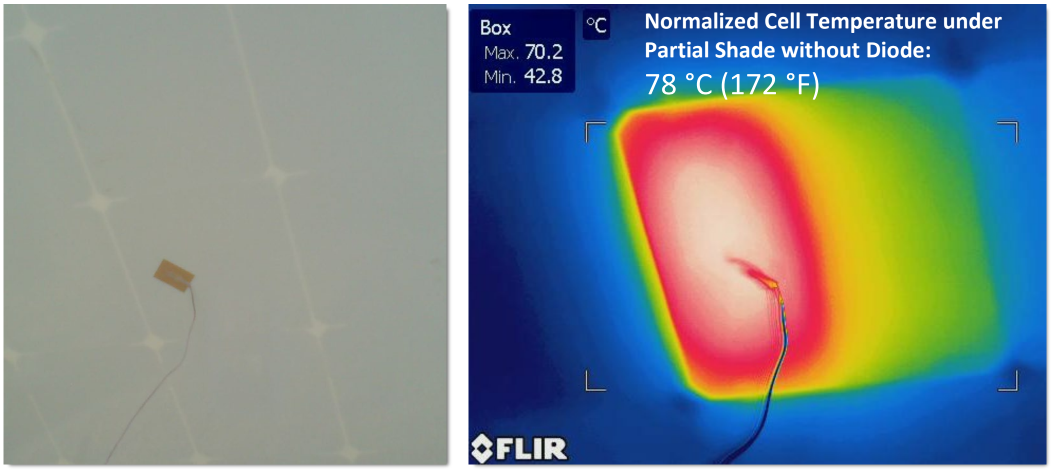

Figure 12: Contrary to all other panels tested, the Maxeon 7 IBC panel showed no visible hotspot damage (left) and maintained a safe temperature of 78 °C (172 °F) in the shaded cell upon diode removal (right).

The previous generation of Maxeon IBC panels, Maxeon 6, was also run through the test protocol. Once again, we found no noticeable effect from the shaded cell as shown in **Figure 13**. Over the same test period as the standard panel technologies, the concentrated cell temperatures of the Maxeon 6 IBC cell only reached 104 °C (219 °F) in partial shade, and 103 °C (217 °F) with the diode removed—again, well within the generally accepted range of heat build-up to avoid long-term panel damage. We do note however, that with the latest generation of Maxeon 7 IBC, we've seen improved reverse bias voltage that enables temperatures to remain even lower than our prior IBC generation (Maxeon 6).

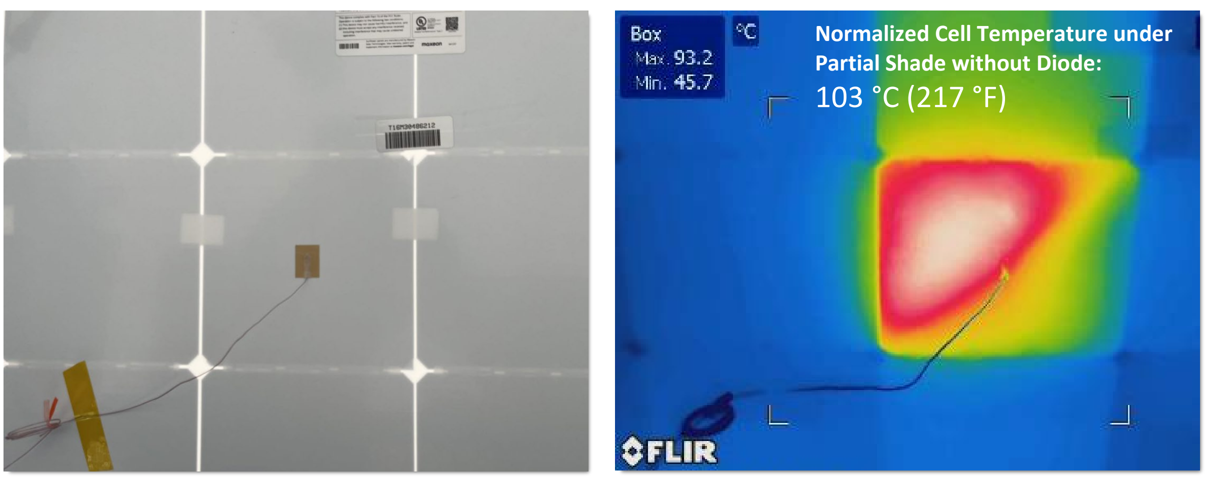

Figure 13: Prior-generation Maxeon IBC panels (Maxeon 6) also showed no visible hotspot damage (left), while maintaining a safe temperature in the shaded cell (right) upon diode removal. Additionally, the Maxeon 6 results provide evidence that changes in the Maxeon 7 cell architecture have resulted in further mitigation of heat build-up in the Maxeon IBC cell.

The results of our internal testing demonstrate that standard solar cells experiencing shade, regardless of panel technology, can reach temperatures hot enough to degrade materials over time, even with fully functioning bypass diodes. However, should the diode's operation become compromised, panels can rapidly deteriorate towards failure. If left in the field unmonitored, it would likely be days, weeks or even months before the panel was attended to—providing sufficient time for the hotspot impact to induce panel failure. A summary of test results is presented in **Table 1**.

The Maxeon IBC panel maintained a safe temperature and exhibited no visual change from the shade and resulting heat build-up. In the next section we'll take a closer look at how the Maxeon IBC panel stands up to shading and why it ultimately presents customers with an inherently safer panel.

Panel Type	Unshaded Cell Max Temp	Shaded cell, Max Temp	Shaded Cell without Diode, Max Temp	Hotspot Observations
Half-cell Ribbon-based Back Contact	62 °C (144 °F)	153 °C (307 °F)	> 550 °C (>1022 °F)	Severe bubbling, burning of back sheet and encapsulant
Half-cell Front Contact TOPCon	58 °C (136 °F)	142 °C (288 °F)	> 550 °C (>1022 °F)	Severe bubbling, burning of back sheet and encapsulant
Half-cell HJT	60 °C (140 °F)	162 °C (324 °F)	305 °C (581 °F)	Significant bubbling, discoloration of back sheet and encapsulant
Full-cell IBC. Maxeon 7	59 °C (138 °F)	85 °C (185 °F)	78 °C (172 °F)	No visible or measurable impact
Full-cell IBC. Maxeon 6*	63 °C (145 °F)	104 °C (219 °F)	103 °C (217 °F)	No visible or measurable impact

** Although not tested in this latest round of outdoor hotspot testing, Maxeon 3 (IBC) panels offer equivalent protection from damaging hotspots. Maxeon can provide additional test results for earlier generation Maxeon 3 panels upon request.*

Table 1: Summary of results from Maxeon's internal hotspot testing featuring the average temperature measured when unshaded, shaded, and shaded without diodes. Data is normalized to account for differences in plane of array (POA) irradiance and ambient temperature as panels were not all tested on the same day, at the same time.

ENGINEERING A BETTER PANEL

Maxeon Solar Technologies' design philosophy is differentiated around long-term reliability. The Maxeon IBC cell facilitates longer warranted panel life *(an industry-leading 40 years)* by designing out the basic failure modes commonly found in standard solar panels. The Maxeon IBC panel doesn't exhibit the hallmark signs of hotspot formation because it has been engineered to maximize its resilience against shade and cell cracks—offering innate hotspot protection from a patented cell architecture.[3] Additionally, the conductive metal foundation of the Maxeon IBC cell helps each cell stand up to environmental stress and keeps the cell electrically intact in the case of cell cracking.

Figure 14 (left) shows a simplified cross-section of the Maxeon IBC cell. The solid metal foundation is grown onto the silicon cell, which is then further protected through encapsulation, along with a thick front-glass layer and a resilient back sheet. On the right, the solid metal foundation brings strength and durability to the cell. Even if the silicon layer of the Maxeon IBC cell were to crack, the metal foundation would retain electrical connectivity to keep energy flowing.

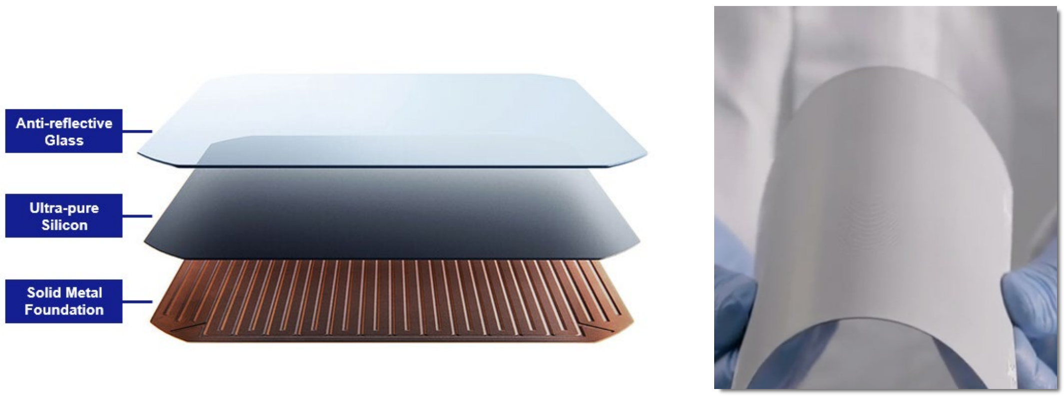

Figure 14: The advanced engineering of the Maxeon IBC cell maximizes durability and long-term performance.

Unfortunately, you can’t say the same for standard solar cells. The thin silicon layer of a standard cell is relatively fragile. It’s not uncommon to see cracks form in the silicon from transportation and installation stresses, or even from weather events such as snow, wind, or hail once the panel is installed.

In **Figure 15 (left)**, we see a ribbon-based back contact cell, like those featured in the panels that underwent our internal hotspot testing. As the cell begins to flex, it quickly shatters from increased external pressure **(right)**. In contrast to the solid metal foundation of the Maxeon IBC cell, standard cells from mono PERC, HJT, TOPCon or alternative back contact technologies are more susceptible to external stresses.

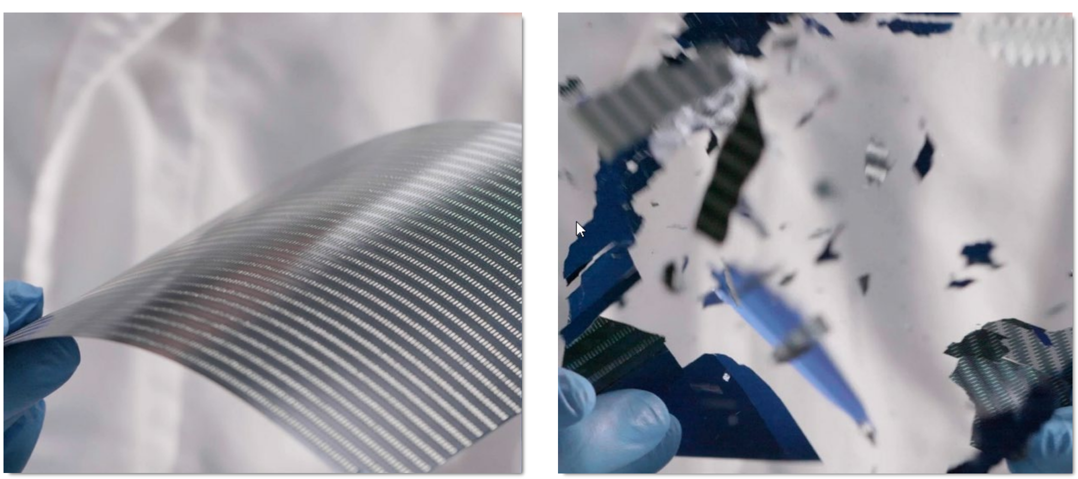

Figure 15: Standard solar cells like those found in mono PERC, HJT. TOPCon or ribbon-based back contact technologies are extremely fragile in the face of environmental stresses.

While the cell depicted in **Figure 15** isn't secured within the layered panel materials, the key takeaway centers on the brittleness of the standard solar cell. External stresses that induce cell cracks, can quickly propagate those cracks throughout the cell, creating larger dead zones that limit energy production and quicken hotspot formation.

When it comes to shade, Maxeon's IBC cell once again provides an overwhelming advantage. In a scenario where a shadow is cast on the panel, the resulting heat that begins to build in the Maxeon IBC cell can be uniformly distributed across the cell. This means Maxeon IBC cell operating temperatures don't increase to dangerous levels like we might see in the concentrated hotspot areas of standard solar cells—where it's not uncommon to see cell temperatures rise 100 °C (212 °F) or more from minor obstructions. Maxeon IBC's shade advantage results from a lower and spatially uniform breakdown voltage that enables large amounts of current to pass uniformly through shaded cells. The Maxeon IBC cell essentially acts as its own bypass diode to mitigate shade and keep energy flowing. Özkalay adds further evidence of the innate advantage Maxeon IBC panels have in maintaining significantly lower hotspot temperatures (99 °C / 210 °F) during shade tests, compared to other technologies—particularly, 179 °C (354 °F) for HJT and 152 °C (306 °F) for PERC technology.[4] The slightly higher temperatures in comparison to Maxeon's internal testing are attributable to the conditions of the testing such as climate and ambient temperature. In addition, the Özkalay study was based an earlier generation of Maxeon IBC—the latest generation of Maxeon IBC (Maxeon 7) offers even better resilience against hotspots.

And, since Maxeon IBC cells operate reliably under shade, Maxeon IBC panels are designed to use diodes to optimize energy yield. This means the diodes activate when the waste heat from the shaded cells outweighs the energy harvest from the unshaded cells. Operating without reliance on diodes ultimately means Maxeon IBC panels deliver more steady energy production, while extending the useful life of the panel. Even if a diode were to fail in a Maxeon IBC panel, cells would continue to operate naturally in reverse at safer temperatures, protecting panel components and extending the panel's operational life. Whether a customer's investment in solar is aimed at saving money, limiting grid dependence, or combatting climate change, a greater number of kWh extracted from a system means a greater contribution to the realization of the customer's energy goals.

THIRD-PARTY INSIGHTS ON HOTSPOTS AND DIODE FAILURE

Shading, bypass diodes and hotspots are consistently cited in the body of research that assesses degradation and failure modes of PV systems. This portion of the paper seeks to summarize some relevant findings to reinforce the superior engineering and reliability of Maxeon's IBC technology.

Hotspot Risk

Özkalay et. al. recently published their findings on the impacts of shadow-induced hotspots. The research carried out at the SUPSI[5] PVLab consisted of artificially shading a cell in each panel for a series of short-term indoor and long-term outdoor tests to examine the temperature-related effects of shading. The indoor tests are conducted under worst-case scenario conditions, using an opaque shade mask while placing panels into short-circuit for a maximum duration of five hours according to the IEC hotspot endurance test. By contrast, the outdoor testing aims for more real-world conditions, shading the long edge of the panel at 36% transparency while carrying out the test at the maximum power point for a duration of 13 months. The panels featured in the testing consisted of PERC half- and full-cell, HJT half-cell, and IBC full-cell technologies—the latter category being represented by the Maxeon IBC panel. **"Based on the reverse characteristics of the IBC cell, including its diode functionality, uniform heating, and lower breakdown voltage, the IBC module exhibited a more favorable performance under partial shade compared to other module technologies (i.e. PERC and HJT). Specifically, the hotspot temperature remained a maximum of 25 °C (45 °F) higher than the module temperature, and it was significantly lower than that of other module technologies, averaging 60 °C (108 °F) less."**

Figure 16 summarizes the results of the panel testing—which covered indoor and outdoor test sequences at elevated module temperatures. One key distinction to note from the internal Maxeon testing discussed above, is that this study did not extract diodes to simulate diode failure. Nonetheless, in some cases, hotspot temperatures still peaked above 150 °C (302 °F) in the HJT and PERC technologies, which was found to be hot enough to induce deterioration of surrounding materials such as the encapsulant after 13 months. It is also noted that prolonged exposure to thermal stress can accelerate diode failure. Additionally, with the continued proliferation of messaging in the market touting improved shade tolerance, the study notes these messages are often poorly defined and difficult to compare from one panel to the next. Manufacturers are generally aiming to minimize performance losses, which often comes at the expense of enhancing the reliability of the panel. As a result, the study also recommends the conditions of the IEC hotspot endurance testing be increased to more accurately reflect the temperatures that BIPV panels face once installed in the field.

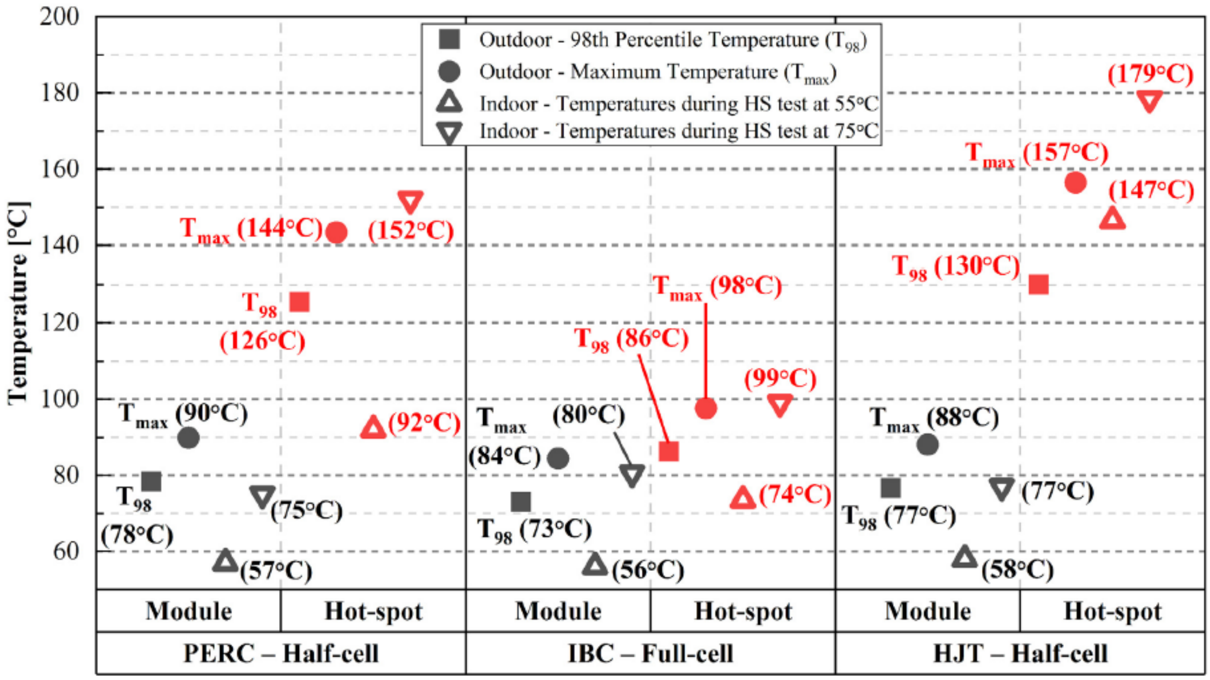

Figure 16: The 98th percentile (T98) and maximum (T_{max}) temperatures of the shaded module (black) and localized hotspots (red) from short-term indoor testing (using an opaque shade mask while placing panels into short-circuit for a maximum duration of five hours), and long-term outdoor monitoring (shading the long edge of the panel at 36% transparency while carrying out the test at the maximum power point for a duration of 13 months).

Module-level Anomalies

Raptor Maps has developed a solar management software platform that helps project owners, O&M service providers, developers and more, monitor the overall health of solar installations. From their managed asset portfolio of more than 80 GW of sites across 48 countries, Raptor Maps delivers an annual report that, "quantifies and identifies leading drivers of equipment-related revenue loss." **In the Raptor Maps global Solar Report for 2023, the company notes a trend of increased power loss due to a host of system-level and module-level anomalies, to the tune of $2.5 billion in estimated losses across the industry.**[6] Of note in **Figure 17** are some critical module-level anomalies that Raptor Maps has identified across their portfolio. These include ~4% attributed to cell-level anomalies that are defined as hotspots occurring with square geometry in one or many cells, ~3% attributed to diode anomalies which include bypass diodes actively providing a path around a faulty area of the panel, and ~0.5% attributed to anomalous hotspots found in cells.

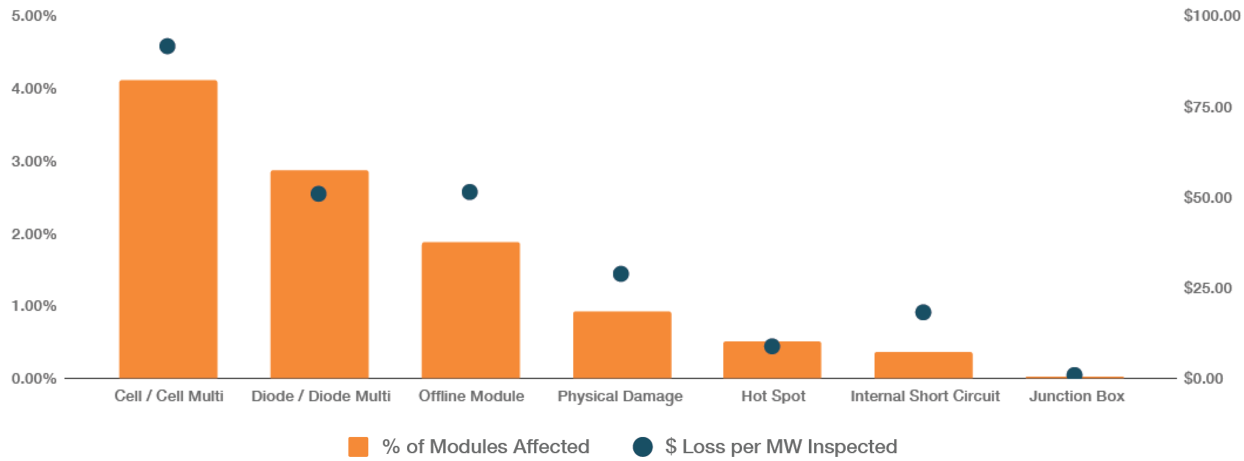

Figure 17: The frequency of module- and submodule-level anomalies detected versus revenue loss, normalized by MW inspected, from the Raptor Maps 2023 Global Solar Report.

In **Figure 18**, Raptor Maps associates the critical cell and diode anomalies identified in the first two columns of **Figure 17** with the age of the panel, noting, **"the rate of defect increases by 20-30% from Year 1 to Year 2; for cell anomalies [alone], that defect rate increases by 495% for modules older than 5 years."** This observation shows how important it is for customers to ensure they are working with trusted equipment manufacturers that can stand behind the reliability of their products.

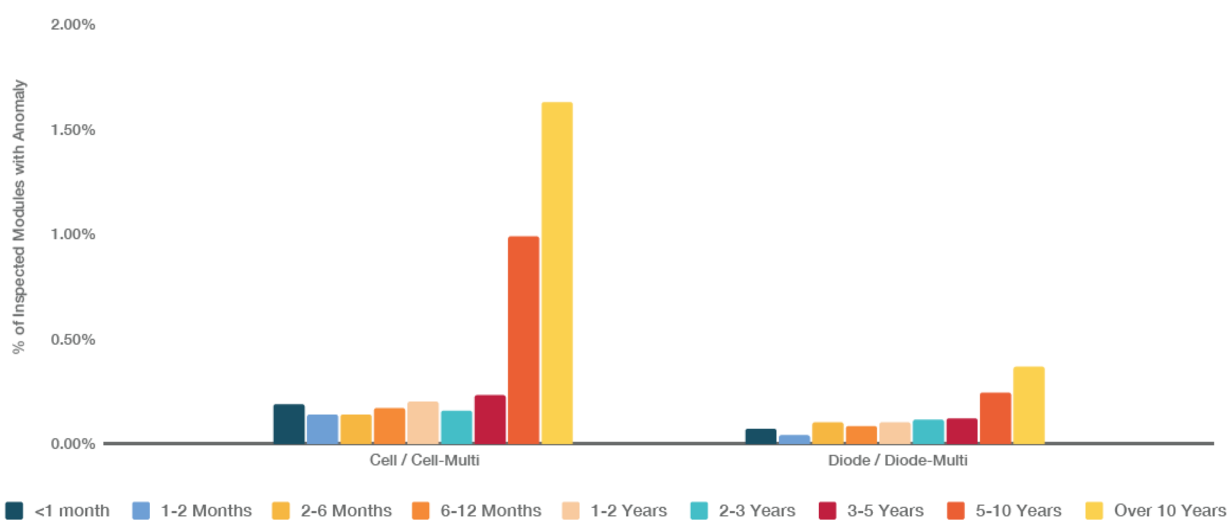

Figure 18: The frequency of cell- and diode-related anomalies detected by age of module, from the Raptor Maps 2023 Global Solar Report. For cell anomalies alone, the defect rate increases by nearly 500% for modules older than 5 years.

Diode Failure Risk

One of the earliest pieces of research on bypass diode reliability, as well as one of the most frequently referenced, was released by Kato in 2011.[7] The study assessed a total of 1,272 panels installed across a series of car parks in Japan for approximately 4 years. Upon inspection, **47% of the panels were**

determined to have defective bypass diodes, with 3% of the defective panels showing visible burn marks on sub-modules indicating a safety risk from hotspot formation (**Figure 19**). While the system suffered from poor design—most panels were exposed to partial shading from neighboring trees and streetlights, it still provides an indication of diode performance in shaded conditions.

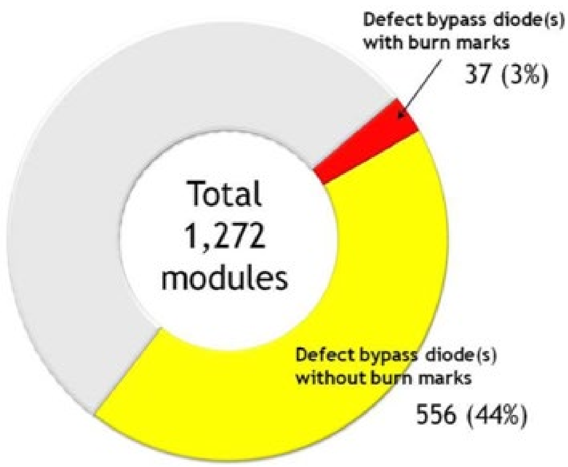

Figure 19: High rates of defective bypass diodes witnessed by Kato in 2011 during an assessment of panels installed across a series of car parks in Japan.

In 2020, Gfeller et. al. suggested the bypass diode was a weakness in today's PV systems given the increasingly larger cell surface areas and higher efficiencies forcing panels to contend with increasingly higher string currents.[8] When faced with partial shading, a danger exists that bypass diodes are more likely to overheat, thereby increasing the likelihood of damage or failure to panels. While junction boxes, potting materials and soldering techniques have evolved to improve diode performance, the diode Kato was assessing in 2011 is effectively largely the same component in use today.

A CALL FOR MORE STRINGENT TESTING, ACCOUNTABILITY

Not all solar panels are created equal. When choosing a solar panel, customers have an opportunity to maximize the performance and reliability of their system by selecting a technology designed and engineered to make a difference—a technology like Maxeon IBC panels that not only maximize lifetime energy production but can reliably stand up to real-world challenges, day-in and day-out.

Our internal testing clearly demonstrates that not all panel technologies are up to the challenge of an unmitigated hotspot. In contrast, Maxeon IBC panels represent proof that hotspot risk can be engineered out a solar panel—something that should be a priority for all manufacturers. While diodes have provided and will continue to provide a serviceable defense against hotspots, they're not immune from operational failure. As a panel technology that does not rely on diodes for hotspot mitigation, Maxeon IBC panels present an inherently safer and more reliable panel technology for customers.

We encourage the industry to work towards more stringent testing around hotspot resilience and bypass diode reliability in their R&D efforts—avoiding cost-reduction-driven decisions on material quality and component reliability, while driving improved cell and circuit design in their products.

In addition to improved product design, the industry should revisit baseline reliability testing to further minimize hotspot risk. Current IEC tests for bypass diodes are designed purely for early life failure detection, not for longer-term wear out failures—where most field failures occur. Revamped testing would center around longer, higher temperature stress tests that can properly assess a panel's ability to safely withstand cell cracks and reasonable shade levels in the field to ensure safer and more reliable products.

Panel manufacturers need to be more accountable for the reliability risks of their products—technology risk shouldn't be the customer's burden to bear. Many of today's manufacturers are sacrificing reliability as they race forward with a shortsighted strategy centered around maximizing power and efficiency. Maxeon has always maintained a balance between performance and reliability, and hence why we're the only prominent manufacturer to complement our Maxeon IBC panels with a comprehensive 40-year warranty. High efficiency panels are only valuable if they can match that performance with low degradation and long-term reliability to truly maximize the lifetime benefit for customers.

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

POWERING POSITIVE CHANGE

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