RAPTOR MAPS

Global Solar Report

2023 Edition

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Executive Summary

Stakeholders in today's solar industry have the privilege of participating in a world-changing shift toward renewable energy. And yet, as large-scale solar installations multiply, it is increasingly important that all of us ensure the industry is delivering on its promises — in terms of both power production and profitability.

A glance at many of the statistics in this report shows, however, that we are progressively losing more power and more money, with an **estimated annual revenue loss of $82 million across the 24.5GW analyzed by Raptor Maps in 2022, translating to $2.5 billion in losses for the entire solar industry**. When coupled with other learnings from the field – solar assets are chronically underperforming relative to *pro forma* assumptions[1] - there is an enormous financial impact that the industry needs to address.

These data points come as legislative and geopolitical tailwinds drive even further growth in solar. In the United States, **the passage of the Inflation Reduction Act earmarked $370 billion for renewable energy** and created unprecedented demand in the solar industry. In Europe, geopolitical and policy pressures are pushing marked progress in the shift to renewables with **the EU installing 41.4GW of solar** and the REPowerEU plan **proposing 320GW of new solar by 2025[2].**

Raptor Maps' Global Solar Report quantifies and identifies leading drivers of equipment-related revenue loss, powered by Raptor Maps' ever-growing dataset of 80GW of analyzed PV systems across 48 countries. The depth of the dataset allows us to derive unique insights into the health of solar assets globally and provide benchmarking data for Raptor Solar customers. For the first time, the 2023 edition includes benchmarks of underperformance by site size and module-level anomaly insights by PV cell type.

In this year's edition, we found:

- **Underperformance due to anomalies has nearly doubled from 1.61% in 2019 to 3.13% in 2022**, a 94% increase over the last 4 years.
- **For sites larger than 200MW**, average underperformance due to anomalies has **more than tripled since 2019**, growing from 1.10% to 4.04% in 2022.
- The resulting **annual revenue loss is estimated at $82M** for the 24.5GW of assets analyzed in 2022, translating to **an average loss of $3,350 per MW.** Extrapolating across total global installed PV capacity[3] (as of end of 2021, excluding residential) translates to a **$2.5B annual revenue loss** for the industry
- **Polycrystalline modules are more likely to show module-level and submodule-level anomalies on inspection** compared to thin film and monocrystalline modules.
- **Asset owners are increasingly looking for more granular data**, with 32% of Raptor Maps customers requesting IEC-compliant Comprehensive Inspections (see Appendix) in 2022, up from 23% in 2021.

1 kWh *2022 Solar Generation Index*: https://www.kwhanalytics.com/sgi
2 REPowerEU Plan: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en#clean-energy
3 IEA Renewable 2022 Report: https://www.iea.org/reports/renewables-2022/renewable-electricity

Anomaly-Driven Underperformance: A Continuously Growing Concern

While each solar asset is unique and the rate of anomalies varies significantly, power loss as a result of equipment anomalies has increased every year since Raptor Maps began compiling an annual report, regardless of the geography and size of a farm. **In fact, power loss has increased by 94% since 2019, resulting in an estimated $82M in annual 2022 losses (or an average of $3,350 annual loss per MW).**

This trend serves as a cautionary tale for the future, especially as the solar industry continues to scale and equipment manufacturing efforts are being ramped up domestically in the United States. Power affected by anomalies is 3.13% today, but **if anomaly-driven power loss continues at the rate we have observed, that would grow to almost 6% by 2025.** With solar assets reportedly chronically underperforming *pro forma* assumptions and rising competition driving down PPA rates, the growth in power loss would have even starker ramifications for the bankability of future projects.

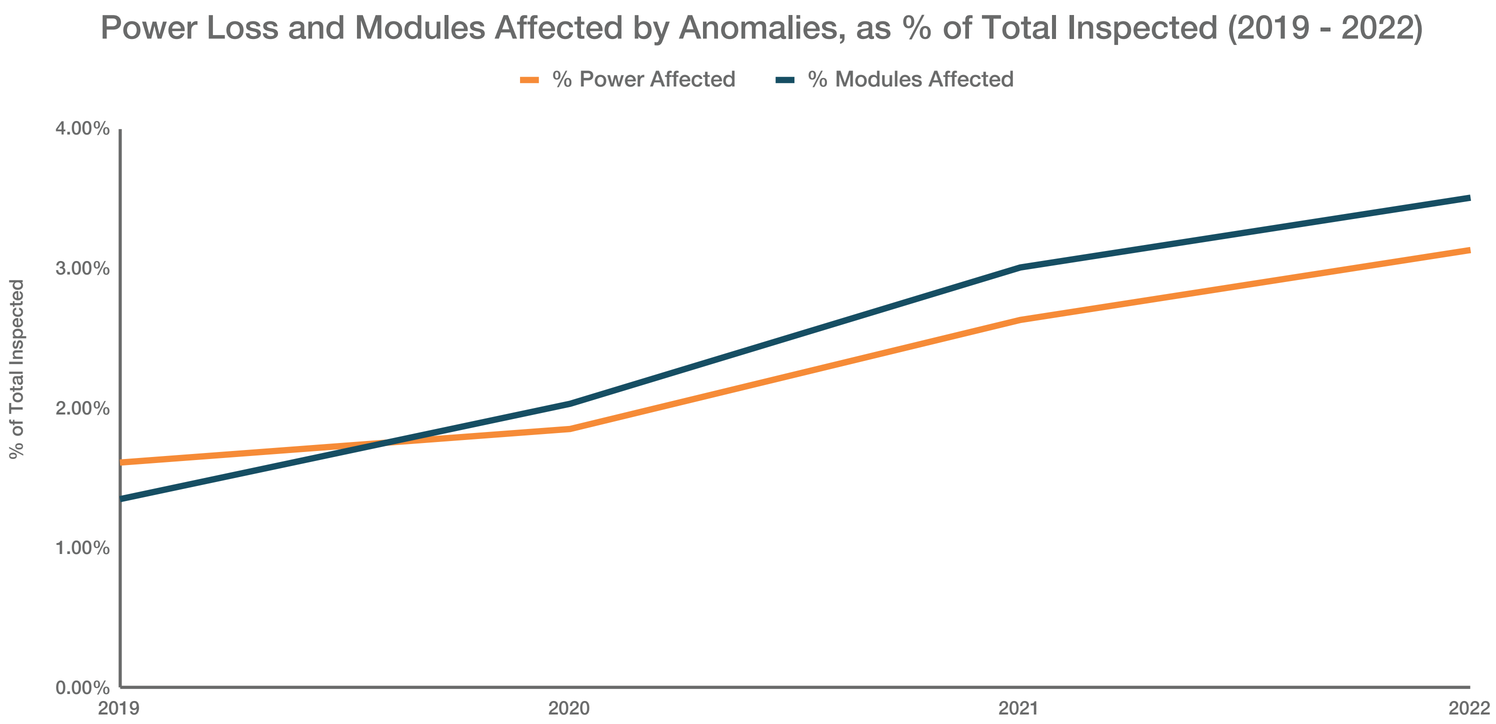


Figure 1: Power Loss and Modules Affected by Equipment Anomalies, as % of Total Inspected

The marked increase in equipment-driven power loss comes as Raptor Maps customers are looking for both more granular insights and deeper collaboration across stakeholders. Almost **one-third of all 2022 inspections were conducted at the IEC-compliant Comprehensive level** (see Appendix: Inspection Types for more detail). Such inspections can capture accurate temperature readings to calculate temperature deltas, establish a robust view of baseline performance, and provide a more thorough prioritization of remediation efforts for both revenue and safety concerns. Moreover, IEC-compliant inspection readings are necessary for more reliable PV module warranty claims, which will continue to be a hot topic as more systems come online.

The inspection results (stored as a data layer in Raptor Maps' digital twin of the solar farm) are being accessed by more users than before, with **the average number of users per solar farm increasing from 27 to 35 year-over-year.** This indicates both the increasing breadth and depth of collaboration, and **the need to ensure that access to necessary performance data is seamless and democratized.**

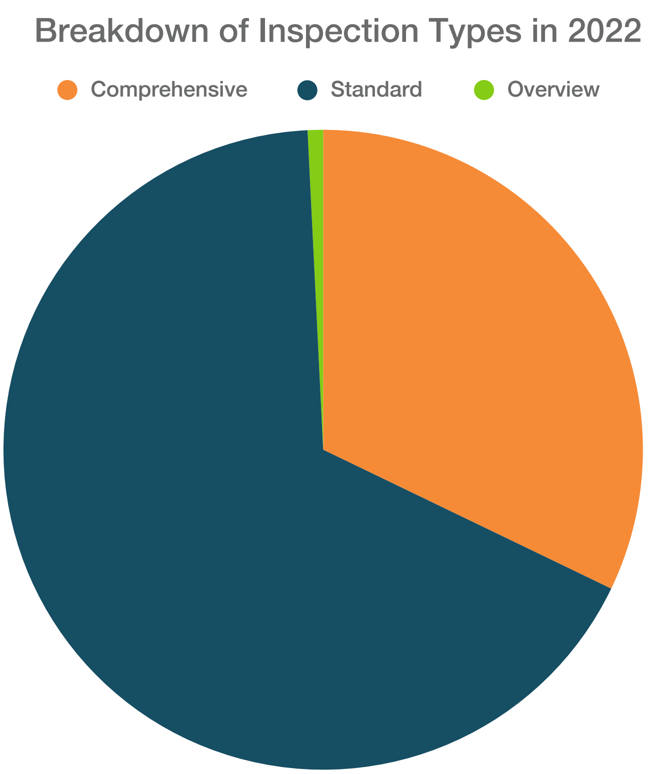


Figure 2: Breakdown of 2022 Inspections by Raptor Maps Inspection Types (See Appendix: Inspection Types for more detail)

Underperformance by U.S. Region

When homing in on the United States, the **average rate of equipment-driven underperformance was 3.45%**, compared to the global average of 3.13%.

Equipment-driven underperformance was most severe in the Pacific West. While the rate of underperformance was least severe in the Southeast, at 17% below the U.S. average, that region is most prone to anomalies driven by physical damage (such as cracking, delamination, or warped modules), **occurring at 2.5 times the rate of the rest of the country.**

The data underscores the local variability of solar installations and differing risk exposure to extreme weather events.

Average Power Loss by U.S. Region vs. U.S. National Average Power Loss

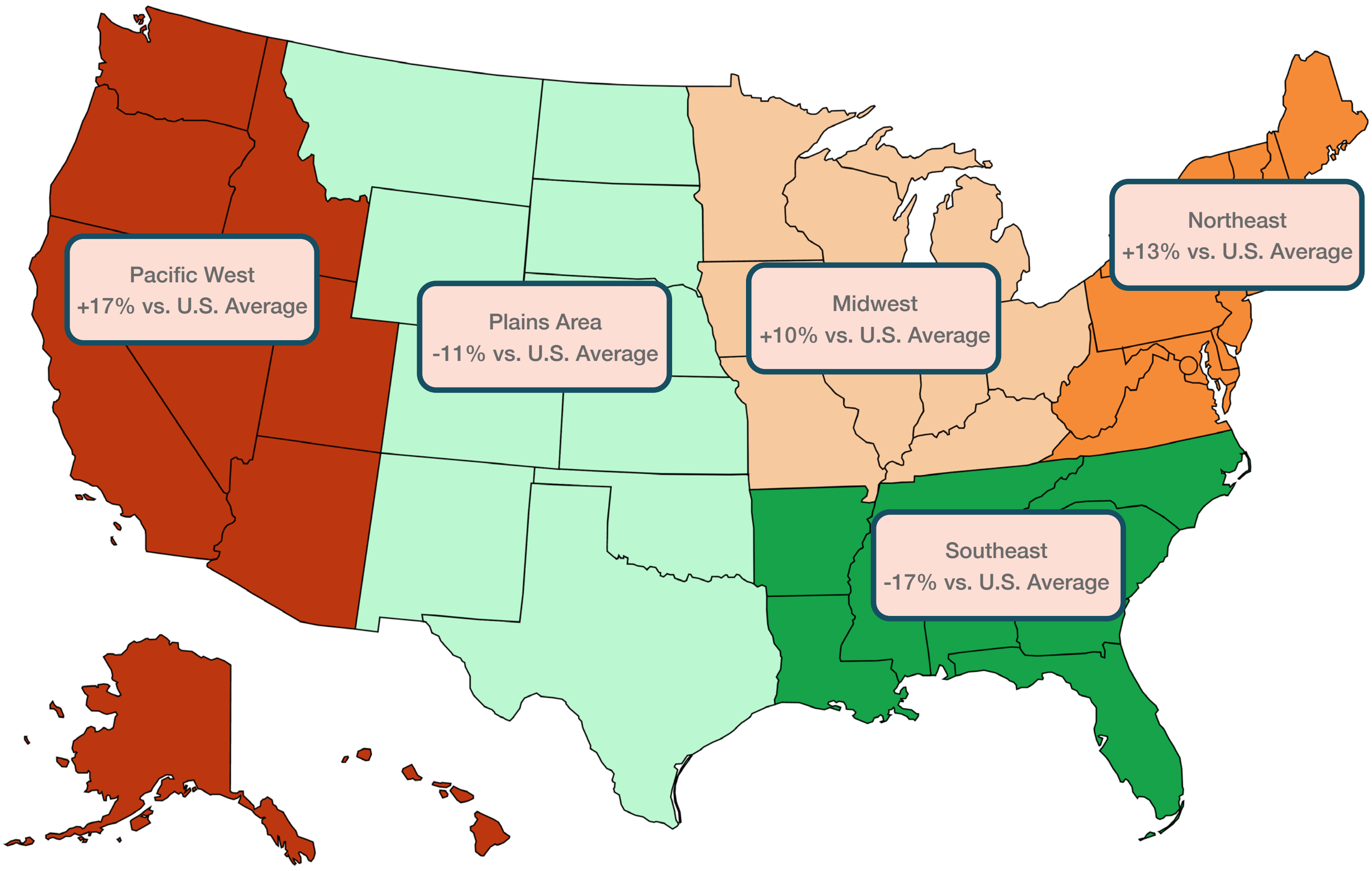


Figure 3: Equipment-driven power loss by U.S. region vs. U.S. average power loss

Underperformance by Site Size

When analyzing power loss by farm size, **smaller sites exhibited the most variability in power loss** and the highest average power loss as a percentage of their total generation capacity. This variability and power loss presents a unique challenge to C&I asset managers who must focus on how to prioritize the remediation of high-value anomalies across a vast portfolio of smaller assets. Savvy asset managers overseeing large C&I portfolios can leverage digital solutions to bridge the gap between inspection and action.

In larger site sizes, smaller ranges in power loss as a percentage of total site capacity were observed, but the largest sites tend to exhibit higher average power loss. In fact, **sites between 100MW and 200MW were 9% higher than the global average** at 3.40% average power loss, and **sites above 200MW were 29% higher** than the global average at 4.04% average power loss. These power losses bear a heavy revenue burden: **sites larger than 200MW are losing, on average, around $4,320 per MW, with some sites losing up to $12,900 per MW.**

As site sizes increase, the time and complexity of remediation efforts increase substantially, underscoring the need for sophisticated geospatial intelligence via a digital twin to pinpoint the exact locations of anomalies on sprawling sites. Such digital twins must be available both in an office setting and in the field via a mobile application in order for field technicians to quickly identify, classify, and remediate equipment anomalies.

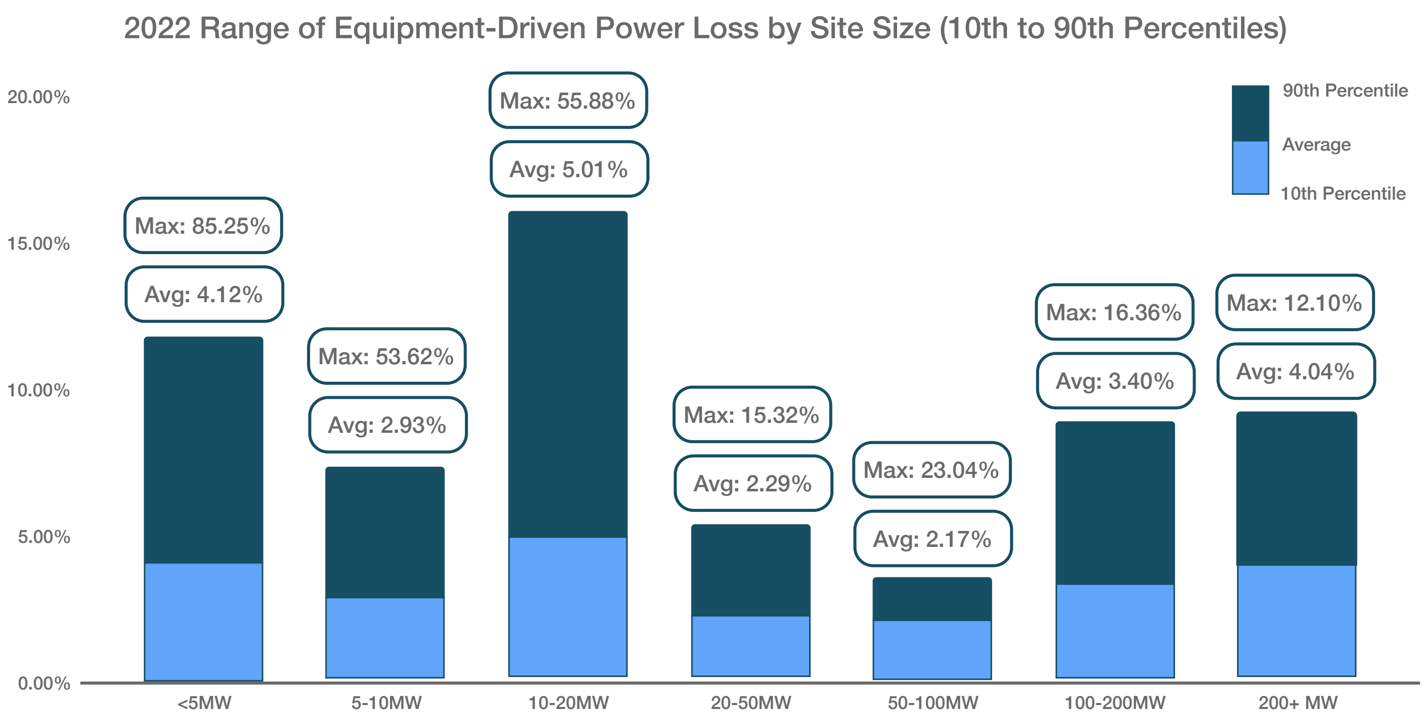


Figure 4: Power Loss by Site Size. Average, 10th and 90th Percentile Values in Chart

Moreover, as Figure 5 demonstrates, sites of all sizes have seen power loss increase significantly since 2019, with the biggest sites seeing the largest increases at **+336% for 50-100MW sites, +267% for 200+ MW sites, and +168% for 100-200MW sites**. As solar installations become larger and more complex, asset owners and managers must be armed with the right tools to robustly manage the health of their sites and quickly resolve issues that dramatically reduce financial return. A centralized and standardized system of all relevant data, such as inspections, power production, irradiance, and equipment maintenance history, is essential for the solar industry to reliably grow.

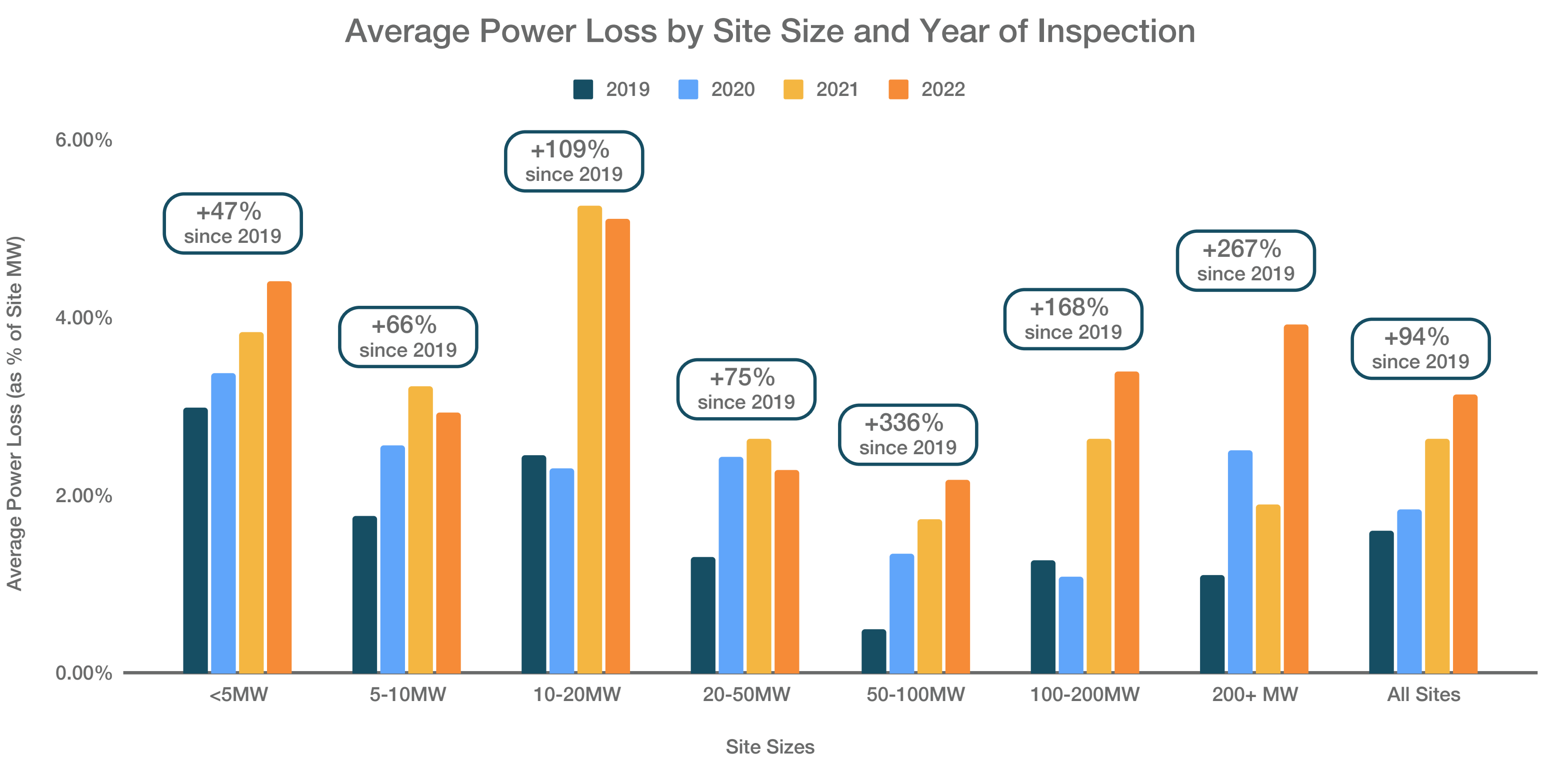


Figure 5: Average Power Loss by Site Size and Year of Inspection, with % change since 2019

Power Loss Drivers: Causes and Trends

Remediating drivers of power loss requires both a precise geolocation of the impacted module(s) and an accurate categorization of the anomaly requiring attention. All anomalies spotlighted in the Raptor Maps' Global Report are detected, classified, verified, and tied to precise geolocations on digital twins of solar farms. While the following section provides a high-level view of trends, the Raptor Solar platform also provides granular historical, comparative views of each "digitized" farm.

For the purposes of the Global Report, similar anomaly types were grouped into categories, such as the "Diode" category for both "Diode" (typically impacting 1/3 of the module) and "Diode Multi" (typically impacting 2/3 of the module) anomalies. Raptor Maps analytics also utilize temperature readings to provide further granularity into the anomaly (e.g. "Cell Medium" which classifies if the area of the cell anomaly is 10° - 20°C higher than adjacent areas).

For more information on the definitions for the anomaly categories, please reference the Appendix: Anomaly Categories section.

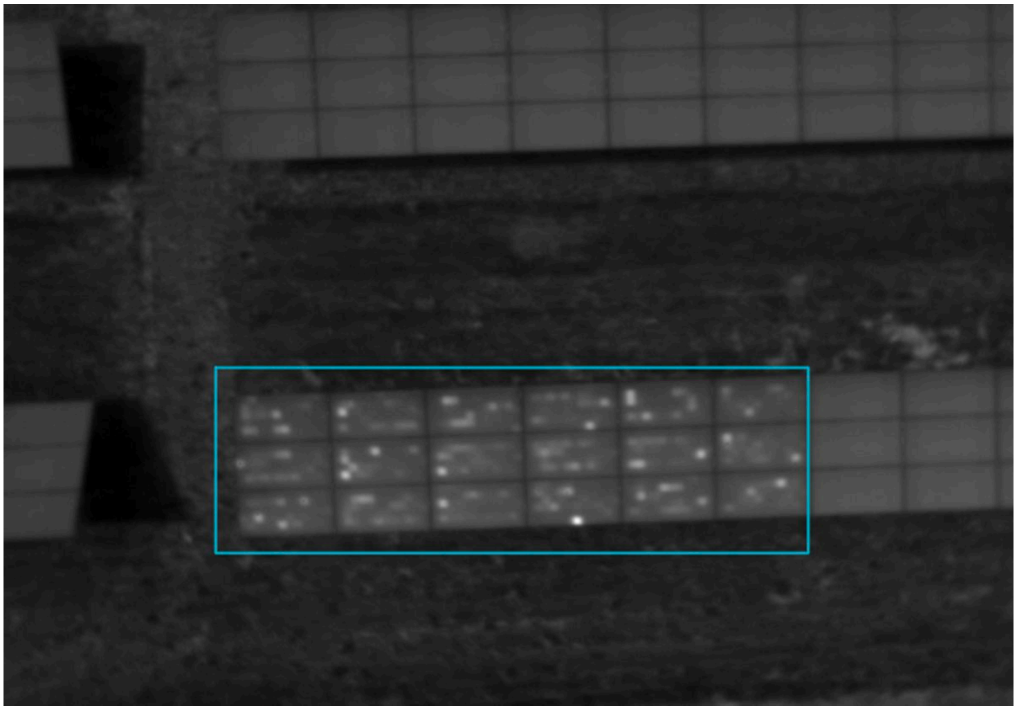


Figure 6: Example of a Reverse Polarity Anomaly Detected by Raptor Maps

Anomaly Changes Over Time

System-level anomalies continue to be the largest drivers of power loss, with string anomalies (including underperforming strings), inverter anomalies, and combiner anomalies impacting the most power as a percentage of total power inspected at 1.06%, 0.70%, and 0.67% respectively.

Figure 7 provides a year-over-year view of the growth in power impacted by each anomaly and highlights a critical point: not only has overall power loss increased consistently since 2019, but **power loss from all anomaly categories has also increased.** In fact, string anomalies have more than doubled since 2019, growing by 123%, and inverter anomalies by 61%.

Note: Figure 7 groups all module- and submodule-level anomalies into a "Module" category for the graph. "Other" includes circuit anomalies, shading, etc. All Raptor Maps reports include granular categorization, but these categories are grouped as such for the purposes of this report. Refer to Appendix: Anomaly Categories to see all anomalies detected by Raptor Maps.

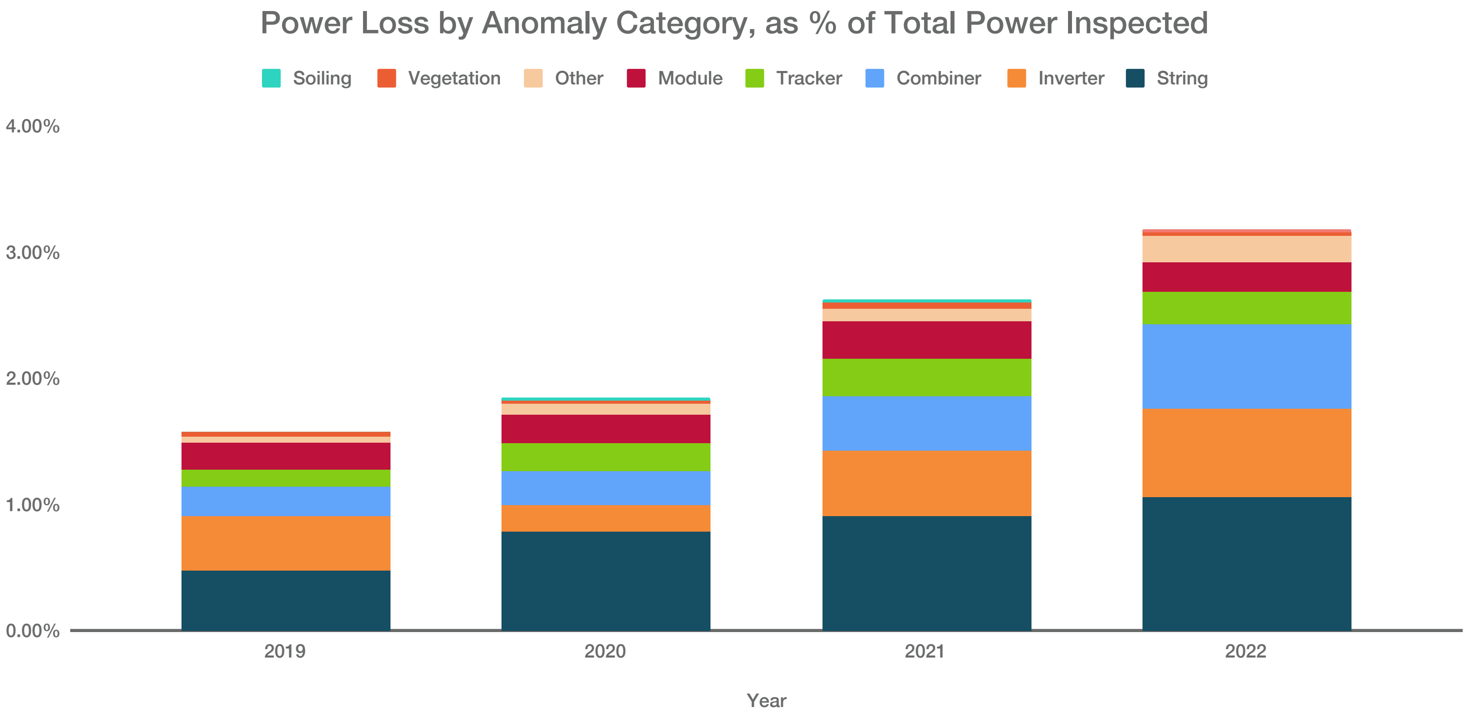


Figure 7: Power Loss by Grouped Anomaly Categories, as % of Total Power Inspected

2022 Revenue Loss by Anomaly Category

Not all anomalies are made equal, and as the rates of anomalies increase, it will be ever more important for asset owners and managers to **link equipment issues to actual revenue impact in their decision-making processes.** For example, tracker anomalies are the most common anomaly, impacting 26.86% of all anomalous modules but accounting for only 7.94% of revenue loss, whereas inverter anomalies account for 22.09% of revenue loss despite affecting 13.05% of anomalous modules.

Figures 9 and 10 on the following page provide a deeper view of this analysis, broken out by system-level and module/submodule-level anomalies and revenue impact normalized by MW inspected.

Note: "Other" includes circuit anomalies, shading, etc. All Raptor Maps reports include granular categorization, but these categories are grouped as "Other" for the purposes of this report.

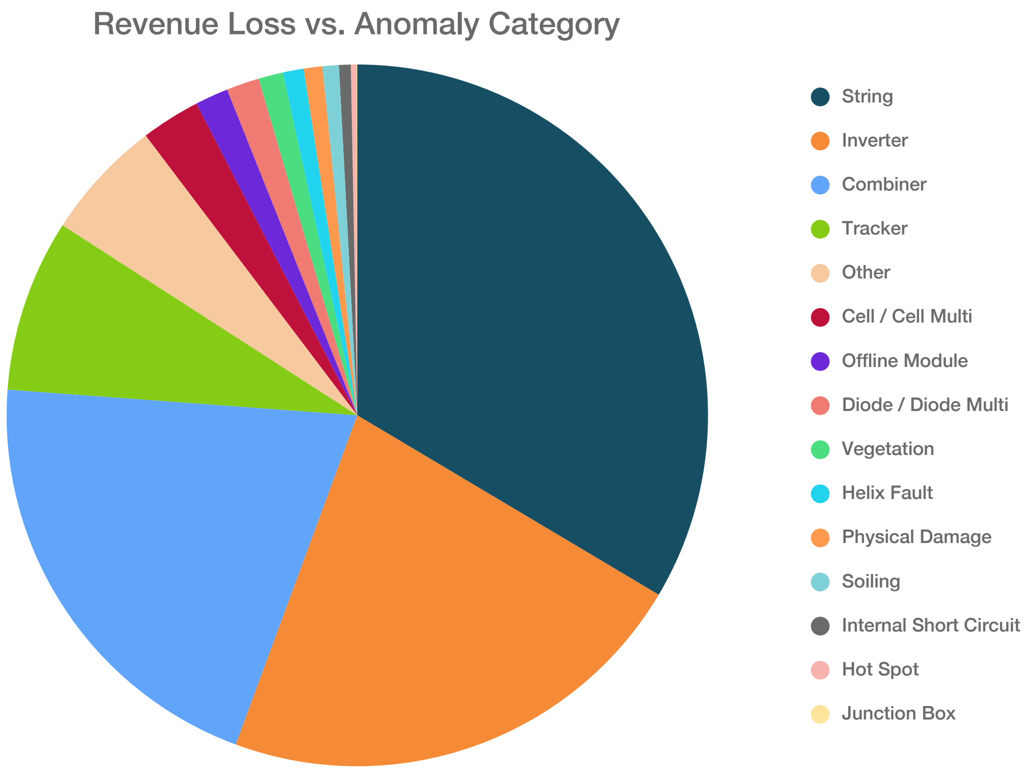


Figure 8: Breakdown of Revenue Loss by Grouped Anomaly Categories

In summary, **string, inverter, and combiner anomalies were the three main drivers of revenue loss** due to hardware issues on inspected solar assets last year. String anomalies were responsible for 34% of lost revenue, inverter anomalies caused 22% of revenue loss, and combiner anomalies resulted in 21% of revenue loss.

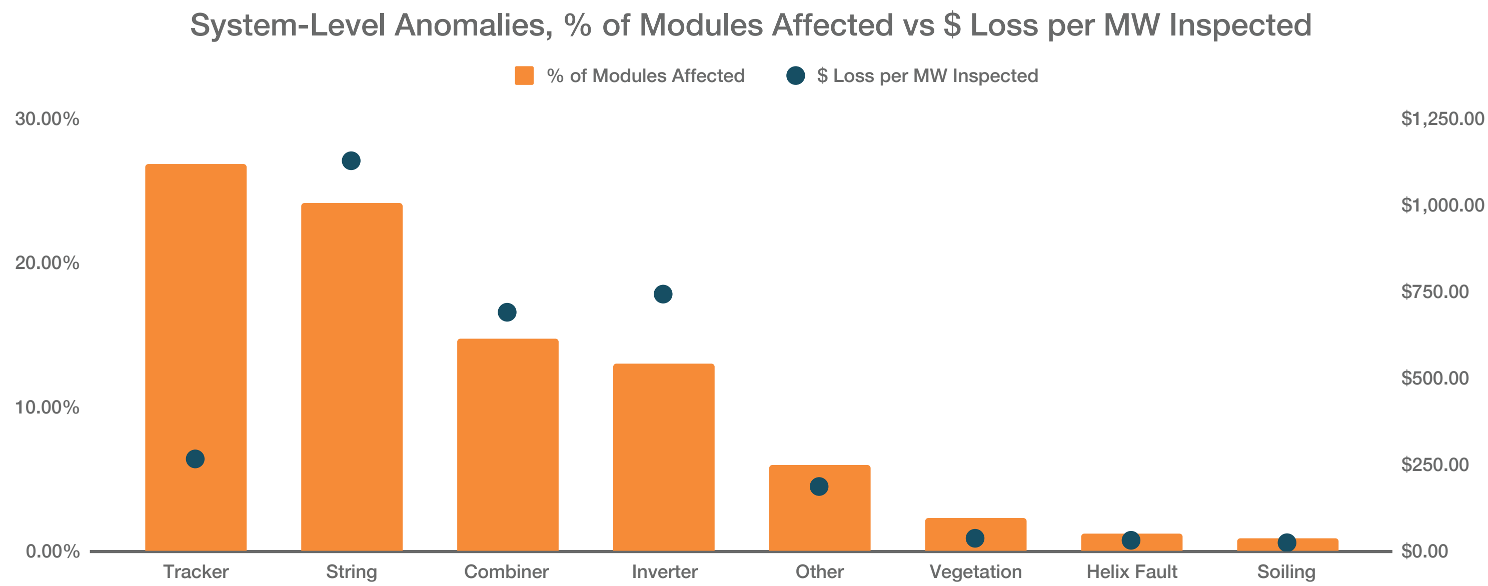


Figure 9: Frequency of System-Level Anomalies Detected vs. Revenue Loss, Normalized by MW Inspected

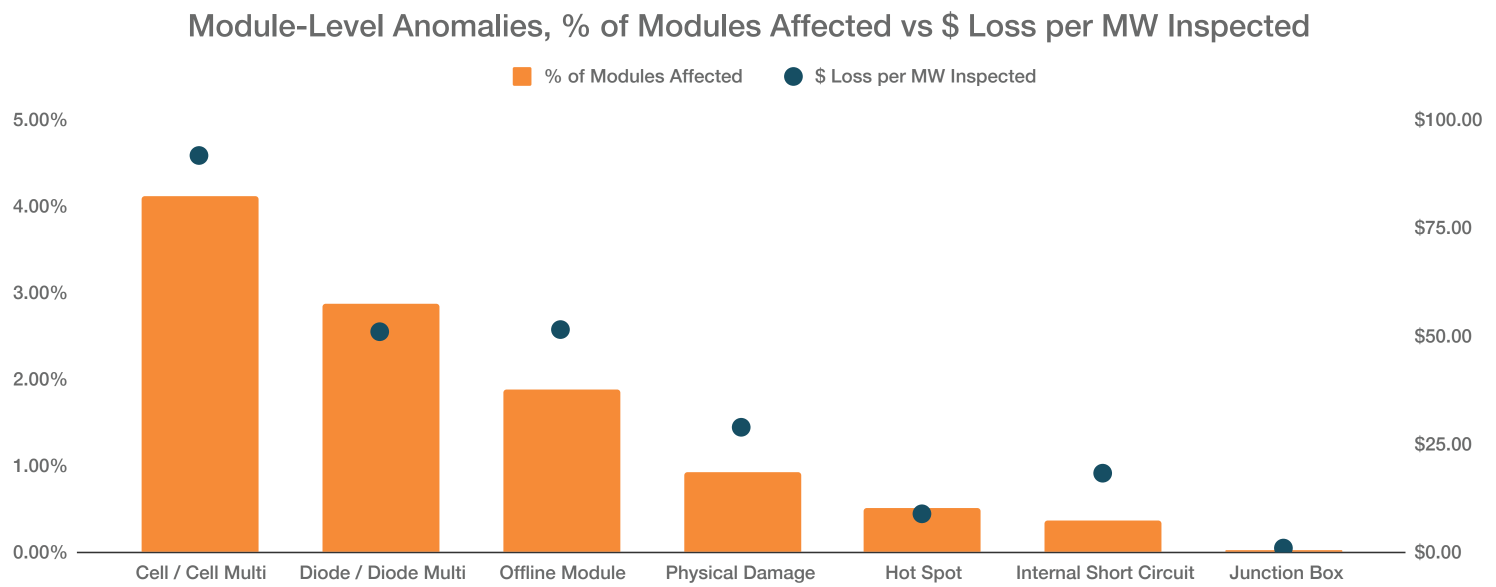


Figure 10: Frequency of Module- and Submodule-Level Anomalies Detected vs. Revenue Loss, Normalized by MW Inspected

Deep Dive on Modules

With increasing supply chain challenges, asset owners and managers must keep a close eye on module performance over time, proactively identifying maintenance and warranty claim opportunities. As this section will detail, submodule-level insights can reveal silent agents of asset degradation that can compound power loss significantly over time.

Age of Module at Time of Defect

Unsurprisingly, the module's age is highly correlated with the rate of defects present. For the two most common submodule-level defect categories, cell and diode anomalies, the rate of defect increases by 20-30% from Year 1 to Year 2; **for cell anomalies, that defect rate increases by 495% for modules older than 5 years.**

However, modules are not without issues early in their lifecycle. For modules younger than 1 year since installation, cell anomalies were most commonly detected in the first month since installation, while diode anomalies present themselves commonly in the first month but continuously increase in occurrence as the module ages. This indicates that asset owners and managers need to be particularly attuned to equipment defects when a project is new and, again, after it has been in operation for several years.

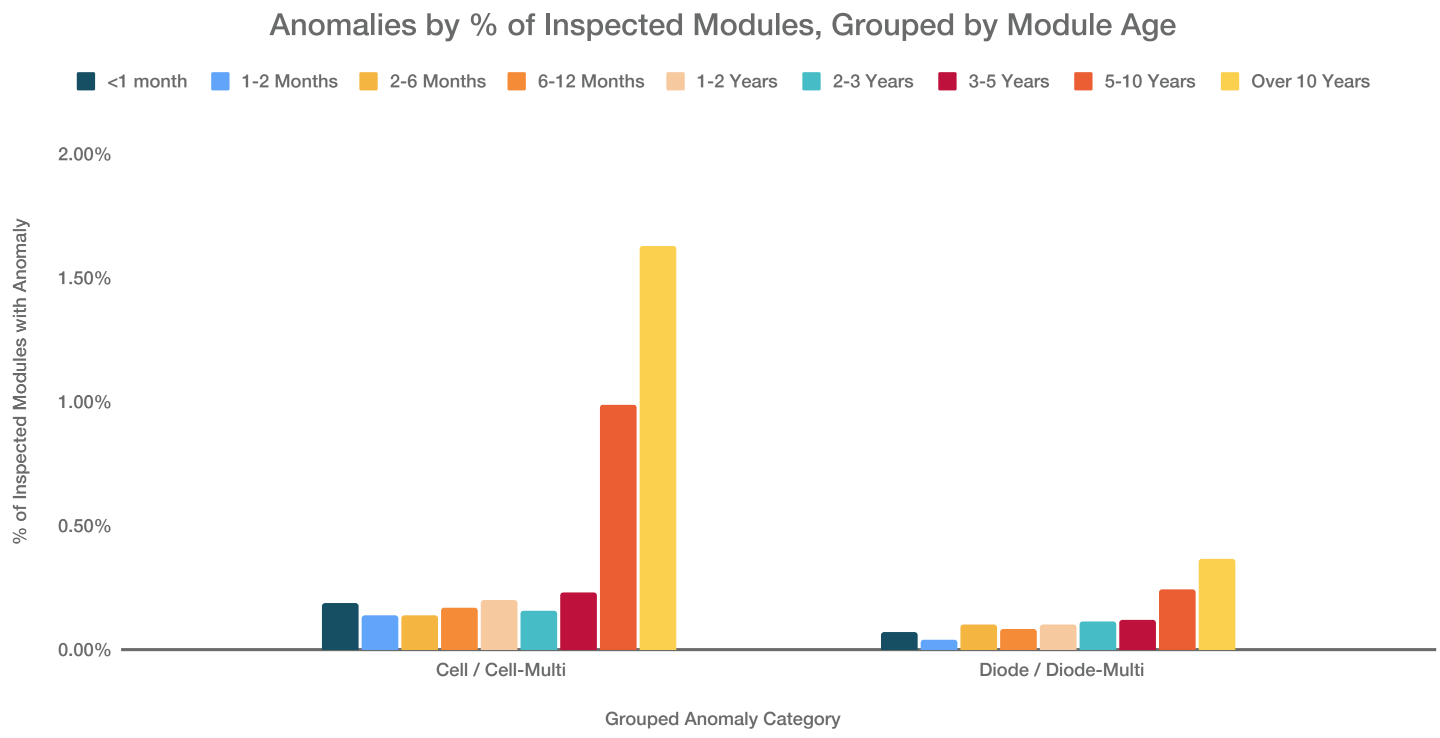


Figure 11: Frequency of Cell-related & Diode-related Anomalies Detected by Age of Module

Submodule-Level Defects by PV Technology

When analyzing submodule-level defects (i.e. excluding system-level anomalies such as inverter or combiner anomalies) by PV cell type, we found:

- On average, **inspections of monocrystalline modules have detected fewer anomalies** than thin film modules by 41% and than polycrystalline modules by 65%.
- Thin film modules are 3 times more likely than polycrystalline and 12 times more likely than monocrystalline modules to have physical damage (such as cracking, delamination, and warped modules).
- Unsurprisingly, monocrystalline and polycrystalline modules face similar defect problems, with cell and diode anomalies being the most common for both.

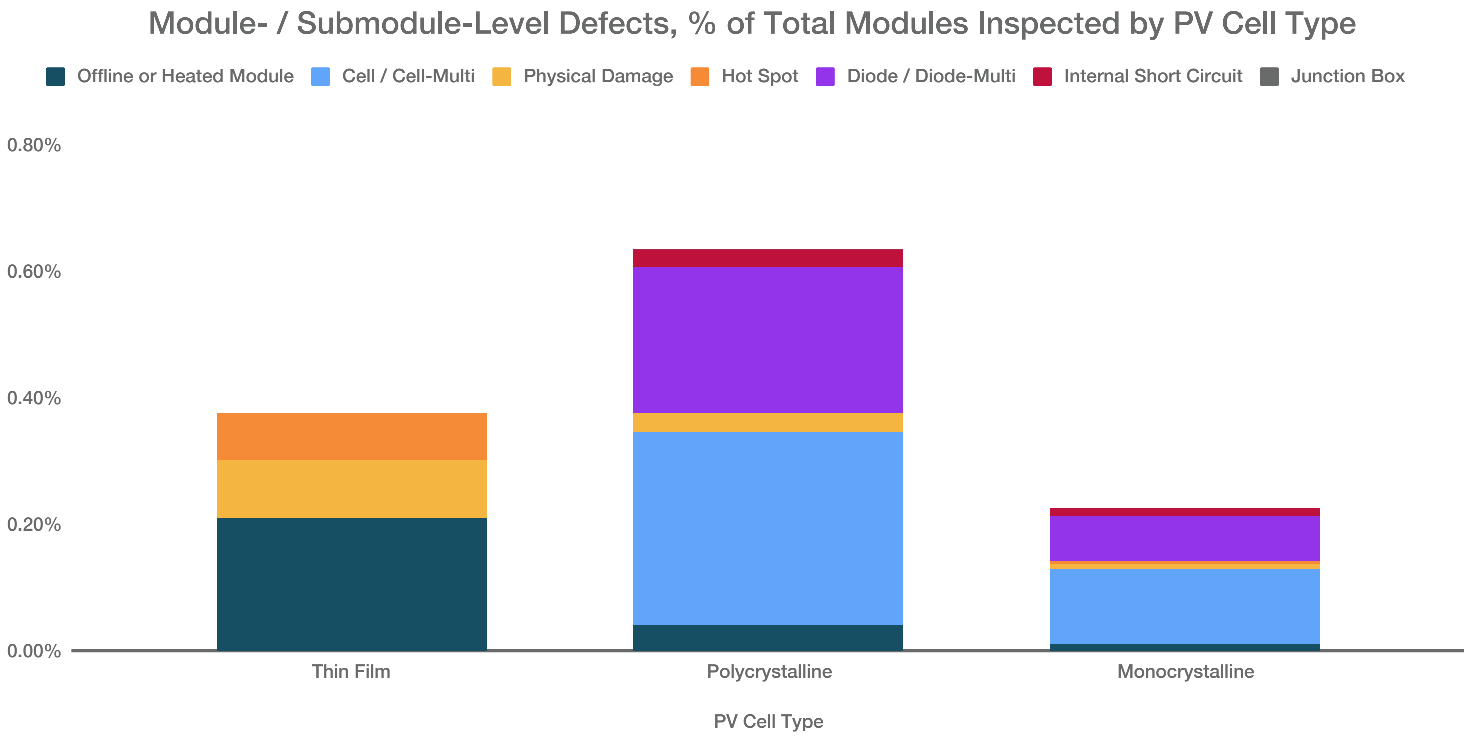


Figure 12: Frequency of Cell-related & Diode-related Anomalies Detected by Age of Module

Breakdown of Modules by OEM

While we have found that the top 10 module OEMs by analyzed MWdc capacity continue to account for the majority of PV systems year-over-year, Raptor Maps has observed **a marked increase in the number of module OEMs utilized in the 2022 dataset** compared to the previous year, growing by 74% year over year.

That being said, the top 5 most utilized module OEMs from last year's report continue to remain in the top 5 in this year's report, with Jinko representing 15% of analyzed MWdc capacity and First Solar presenting 12%.

Cell and diode anomalies were the most common module- and submodule-level anomalies among the 5 largest manufacturers of modules, and the two anomaly categories combined accounted for roughly 70% of observed defects. The physical damage (such as cracking, delamination, and warped modules) was also significant, accounting for 18% of the module- and submodule-level defects.

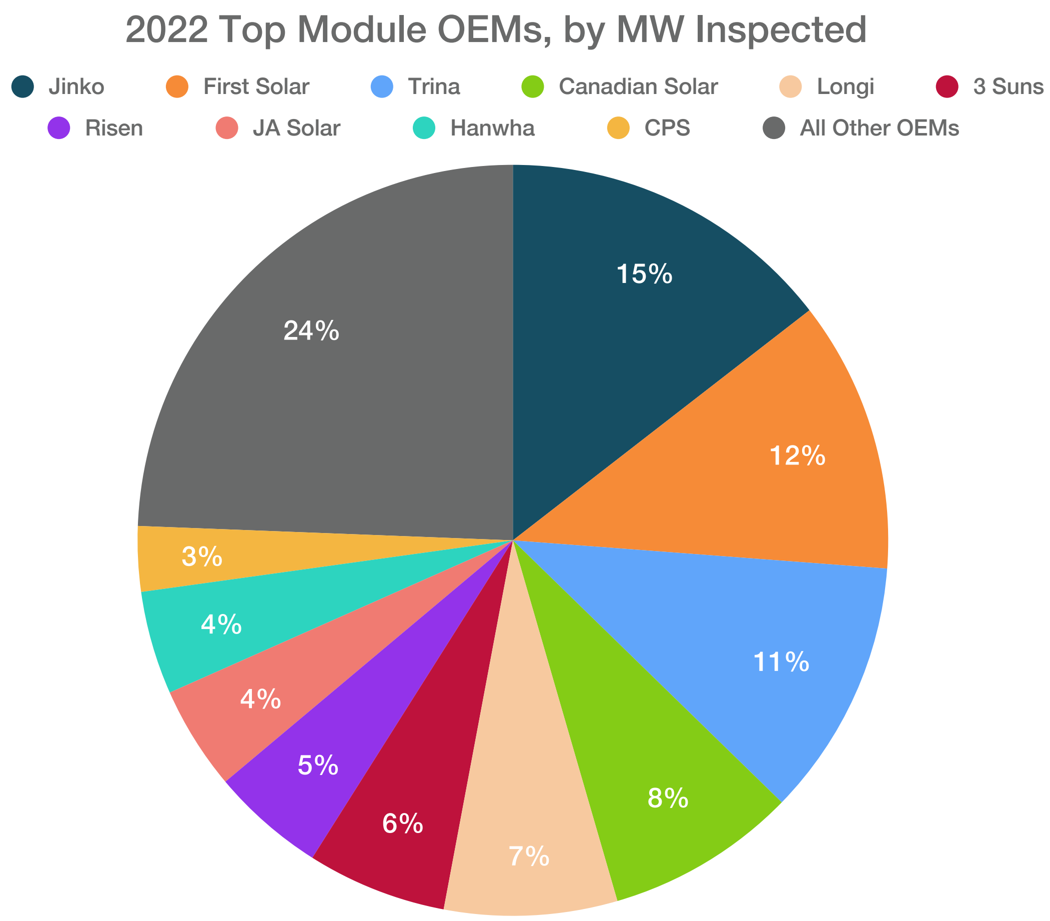


Figure 13: Module OEMs as % of MW Inspected in 2022

Appendix: Anomaly Categories

Anomaly	Description
Cell	A hot spot occurs with square geometry in a single cell.
Cell Low	This is a cell anomaly where the temperature of an anomalous area is less than 10˚C higher than adjacent areas.
Cell Medium	This is a cell anomaly where the temperature of an anomalous area is 10-20˚C higher than adjacent areas.
Cell High	This is a cell anomaly where the temperature of an anomalous area is 20˚C higher than adjacent areas.
Cell Multi	This anomaly consists of hot spots occurring with square geometry in multiple cells.
Cell Multi Low	In this type of cell multi anomaly, the temperature of an anomalous area is less than 10˚C higher than adjacent areas.
Cell Multi Medium	In this type of cell multi anomaly, the temperature of an anomalous area is 10-20˚C higher than adjacent areas.
Cell Multi High	In this type of cell multi anomaly, the temperature of an anomalous area is 20˚C higher than adjacent areas.
Circuit	A circuit anomaly is a series of adjacent offline strings. This anomaly type usually affects fewer strings than a combiner anomaly, depending on the electrical wiring and the as-built layout.
Combiner	A combiner combines many strings into a larger flow of DC (direct current). A combiner anomaly shows a fault in contiguous strings matching the combiner layout.
Cracking	This module anomaly is caused by cracking on the module surface.
Damaged	Damage anomalies result from a bent, misplaced or warped module. They may also come from a heavily cracked module that is damaged beyond the module surface.

Source: Raptor Maps Knowledge Hub

Anomaly	Description
Delamination	This module anomaly is due to compromised adhesion between glass, encapsulant or layers. The layers may be the active layers and/or the back layers. It is more common with thin-film modules.
Diode	A bypass diode provides a current path around a faulty cell or module. A diode anomaly indicates an activated bypass diode, typically 1/3 of the module.
Diode Multi	There are multiple activated bypass diodes, typically affecting ⅔ of the module.
Helix Damage	Permanent damage to panels caused as a result of a helix fault.
Helix Fault	A fault in trackers causing a helix in the racking.
Hot Spot	This shows an anomalous spot on a cell.
Hot Spot Low	A hot spot has occurred where the temperature of the anomalous area is less than 10˚C higher than adjacent areas.
Hot Spot Medium	A hot spot has occurred where the temperature of the anomalous area is 10-20˚C higher than adjacent areas.
Hot Spot High	A hot spot has occurred where the temperature of the anomalous area is 20˚C higher than adjacent areas.
Hot Spot Multi	There are multiple hot spots on a thin-film module
Hot Spot Multi Low	In this hot spot multi anomaly, the temperature of the anomalous area is less than 10˚C higher than adjacent areas.
Hot Spot Multi Medium	In this hot spot multi, the temperature of the anomalous area is 10-20˚C higher than adjacent areas.
Hot Spot Multi High	In this hot spot multi, the temperature of the anomalous area is 20˚C higher than adjacent areas.
Internal Short Circuit	Multiple cell anomalies have happened as a result of a short circuit.
Inverter	An inverter converts the DC current of many combiners into usable AC. An inverter anomaly shows a fault in contiguous strings matching the inverter layout.

Source: Raptor Maps [Knowledge Hub]

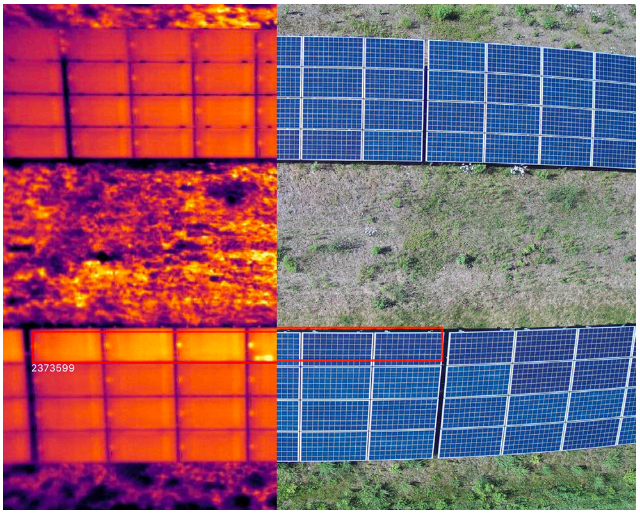
Anomaly	Description
Junction Box	A junction box is an enclosure on the module that connects the PV strings. A junction-box anomaly is a hot spot at the junction-box location on the module.
Junction Box Low	In this junction-box anomaly, the temperature of the anomalous area is less than 10˚C higher than adjacent areas.
Junction Box Medium	In this junction-box anomaly, the temperature of the anomalous area is 10-20˚C higher than adjacent areas.
Junction Box High	In this junction-box anomaly, the temperature of the anomalous area is 20˚C higher than adjacent areas.
Missing	The module is present on the as-built but missing from the PV system.
Module	The entire module is heated or offline.
Physical Obstruction	A physical obstruction or object on the surface of the module that is blocking direct sunlight or causing close proximity shading.
Reverse Polarity	A module anomaly has occurred due to incorrect wiring.
Shading	Sunlight is obstructed by vegetation.
Soiling	Dirt, dust or other debris is on the surface of the module.
Spare Module	The module is present on the as-built and marked as offline.
String	A string consists of an individual set of modules connected in series. A string anomaly shows a fault in contiguous modules matching the string layout.
Tracker	Tilt tracker position is affecting power production.
Underperforming String	A string has a delta of less than 3 degrees C when compared to an adjacent operational string. Other sub-module anomalies can also be present in underperforming strings and generally are not visible in true offline strings.
Vegetation	Modules are blocked by vegetation.

Source: Raptor Maps Knowledge Hub

Appendix: Inspection Types

Comprehensive Level Inspection

Summary: Comprehensive level aerial IR inspections are performed in compliance with IEC standards. It provides highly detailed, sub-module level granular data and allows teams to thoroughly understand the performance of each PV module. This inspection level offers absolute temperature accuracy and enables accurate sorting and prioritization of both module and string-level anomalies by temperature intensity.



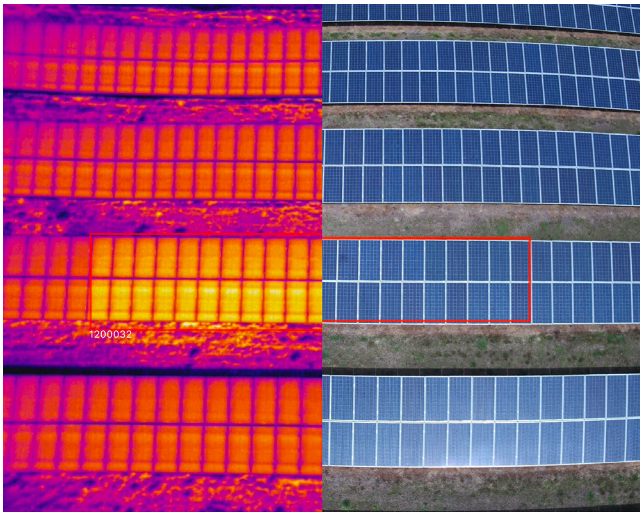
Infrared thermal imagery: 3.0 +/- 0.5 cm/px resolution

HD RGB Imagery: 1 cm/px resolution

Identifiable Anomalies Include: All anomalies identified at the Raptor Overview and Raptor Standard levels as well as data analysis in accordance with IEC TS 62446-3 Technical Specification: Photovoltaic (PV) systems. More detailed classifications of single-cell hot spot with ΔT > 10 K, heated junction box with ΔT > 4 K, and substring in short circuit with ΔT > 4 K.

Standard Level Inspection

Summary: Standard level aerial inspections balance altitude, speed, and granular site data. The level of detail in the collected data provides teams an understanding of the performance of 100% of the PV system modules.



Infrared thermal imagery: 5.5 +/- 0.5 cm/px resolution

HD RGB Imagery: 1.5-2 cm/px resolution

Identifiable Anomalies Include: All anomalies identified at the Raptor Overview level, as well as physical and visible module damage including cracked/broken modules, thin-film delamination, soiling and surface coverage of the PV module(s). Additional sub-module findings also include: diode faults, cell and multi-cell defects, and faulty junction box. Suspected PID, shading issues due to tree lines, obstructions, or adjacent rows, and damage to rows and tables.

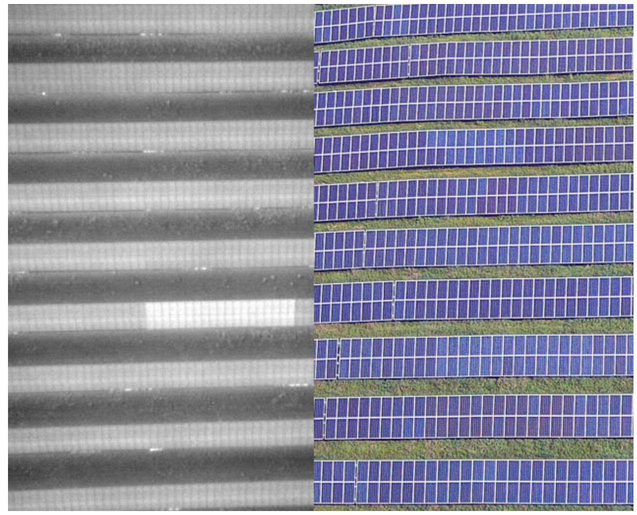
Overview Level Inspection

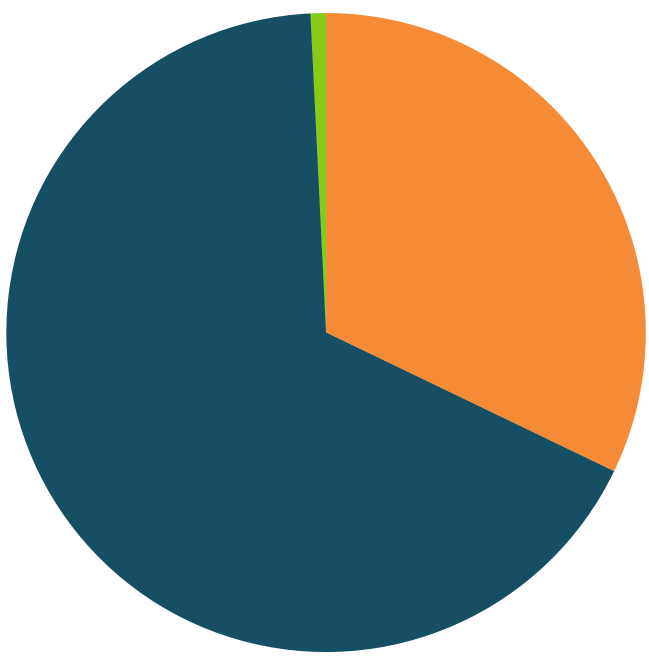
Summary: An Overview inspection is flown at the highest altitude, inspections are performed very quickly, due to a maximum flight speed of 30 MPH (48 KMH), allowing for very large sites to be inspected quickly.

Infrared thermal imagery: 15 +/- 5.0 cm/px resolution

HD RGB Imagery: 5 cm/px resolution

Identifiable Anomalies Include: Offline Inverters and Combiners, Anomalous Strings, Tracker Off Alignment or in Stow, and Module Level Faults affecting the entire module's performance.





For more information

About Raptor Maps

Raptor Maps is building the operating system for the solar industry, enabling the industry to scale and meet global climate goals. With intelligence for the entire solar industry, our solar lifecycle management platform (Raptor Solar) provides the tools and the system of record that asset owners, managers, O&M, developers, and EPCs need to build, maintain, and expand their solar plants. Raptor Solar improves asset health and power production, reduces risk, and ultimately increases the rate of return of solar assets.

Want more insights and benchmarks? Have any questions?

Reach out to mark@raptormaps.com

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