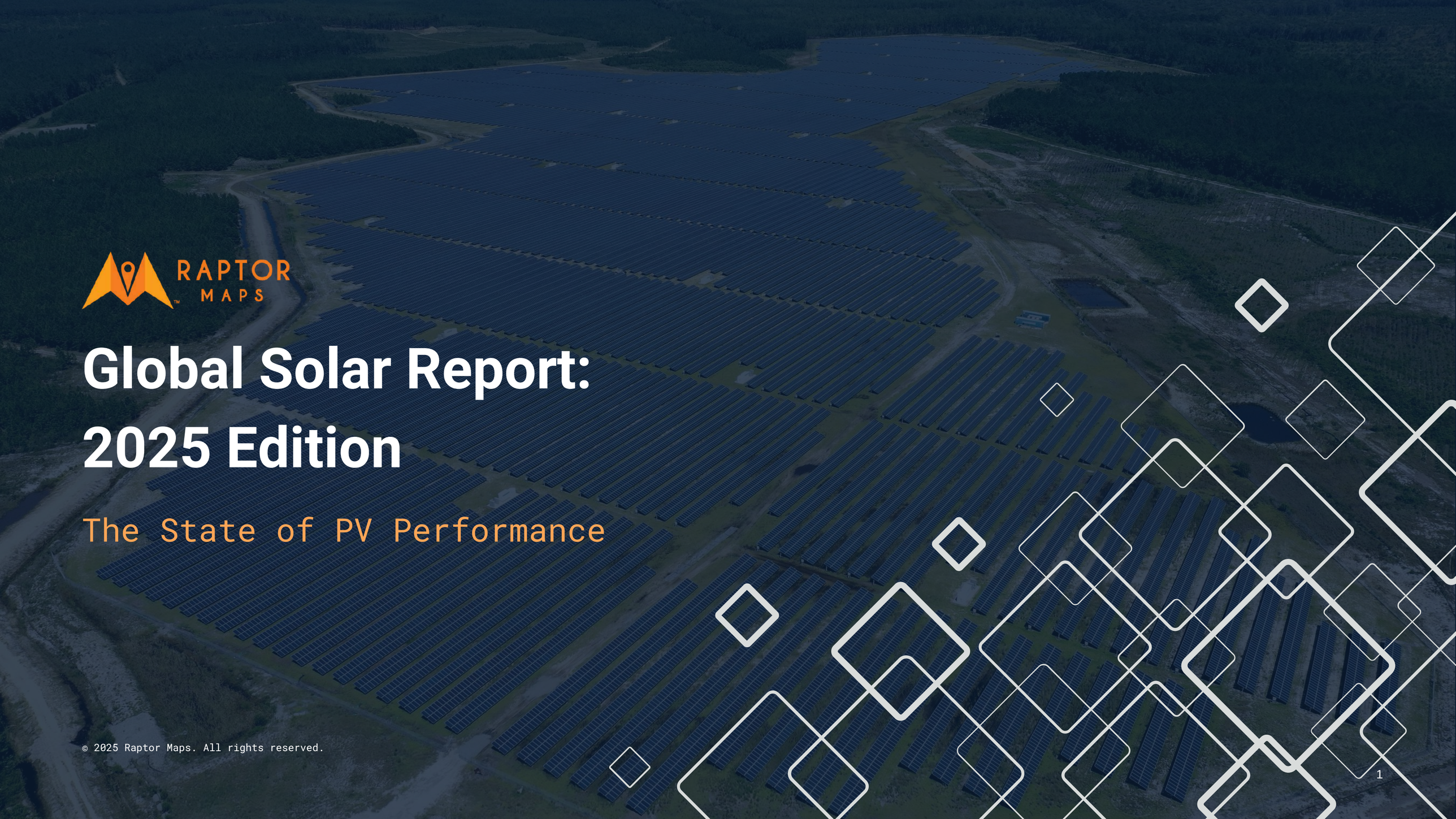


Global Solar Report: 2025 Edition

The State of PV Performance

Contents

RAPTOR MAPS

Introduction

Raptor Maps studies the performance and risk profiles of solar assets around the world in order to distill **industry trends** and to **highlight opportunities** for the rapidly growing solar industry. This report is a summary of Raptor Maps' research.

The 2025 Global Solar Report draws upon **193 GWdc** of utility-scale and commercial and industrial (C&I) solar PV analysis, with **67 GWdc of analysis in 2024 alone**. In this report, you will find:

- Asset performance metrics over the last 5 years and findings on macro-trends driving underperformance
- Common problems found and their impact on power production
- Trends in site work automation and resource deployment
- A wide range of performance benchmarks by:
  - Type of panel technology utilized
  - Capacity of installation
  - U.S. electric power markets and U.S. states

Note on Underperformance Data:
We assign underperformance (power loss) by each granular issue observed to calculate power loss. This report corrects for sites inspected multiple times in a single calendar year (an increasing trend) and significant outliers.

Executive Summary

In 2024, the solar industry demonstrated remarkable growth and resilience, **surpassing 2 terawatts (TW) in global capacity just two years after broaching 1 terawatt** [1]. The photovoltaic (PV) market has cemented its position as a robust and competitive alternative to traditional energy generation, with the International Energy Agency (IEA) projecting solar to account for 80% of renewables growth by 2030 with strong installation from some of the world's largest economies: [2][3]

- **China** is expected to account for 60% of global capacity expansion.
- The **European Union** is forecasted to 2x their installed capacity by 2030.
- **India** is expected to emerge as the fourth-largest market, growing 3.5x in capacity.
- The **United States** installed 40.5GW in 2024, bringing the total to 219 GW. The sector has solidified its role as an economic driver, with $60 billion in private investment and 280,000 jobs nationwide.

However, expansive growth in the solar industry is not without its challenges, especially as a maturing fleet reveals new and at times unexpected risk categories:

- **Equipment-driven underperformance** has tripled over the last 5 years, highlighting a continued need for efficiently deploying resources for reporting issues and corrective maintenance.
- **Increasing risk profiles**, emphasized by solar's exposure to climate change-driven risks, such as storms, floods and fires. Industry models continue to underestimate the effects of weather-related events by 300+% [4]. Asset owners have turned to creative methods to manage risk, such as preventative investment in design and maintenance to reduce costs.
- **Ongoing labor constraints**, especially as operators contend with both increasing fleet sizes and average installed capacity. In the U.S. specifically, "nearly 70% of the true cost of solar O&M comes from labor-based inflationary costs" [5].

[1][2] "Solar PV power capacity in the Net Zero Scenario, 2015-2030." IEA, www.iea.org/data-and-statistics/charts/solar-pv-power-capacity-in-the-net-zero-scenario-2015-2030.
[3] "Solar Market Insight Report Q4 2024." SEIA/Wood Mackenzie, 10 Jan. 2025, seia.org/research-resources/solar-market-insight-report-q4-2024.
[4] "Solar Risk Assessment." kwH Analytics, 2024, https://www.kwhanalytics.com/solar-risk-assessment.
[5] "The True Cost of Solar O&M Is Increasing." Origis / Wood Mackenzie, 2022. https://origisenergy.com/insights/the-true-cost-of-solar-om-is-increasing-insights/

Political headwinds, such as President Trump's tariffs and the U.S. leaving the Paris Climate Accords, could impact the growth of U.S. solar as infrastructure investors might gravitate towards lenient policies for domestic natural gas. The momentum of solar growth remains uncertain in the U.S., even as December projections still showed 43 GWdc added annually over the next five years [6].

These three industry-wide trends - rapid growth, changing energy policy landscape, and increasing financial pressure - underscore the importance of ensuring that already installed assets perform as modeled to continue delivering reliable, low-cost clean energy.

To that end, Raptor Maps has uncovered 4 main trends in this year's Report:

- While the growth in average underperformance year-over-year has slowed down, there is still significant opportunity for owners to close the gap between modeled and actual performance. In 2024, the average solar farm in our dataset **lost up to $5,720/MWdc per year from unresolved equipment issues**. Extrapolated to the whole industry, that indicates **an annualized potential revenue loss of $10.0 billion** [7] from solar underperformance.
- Owners and operators are both **increasingly adopting AI and automation to reduce truck rolls**, deploying robotics (such as remotely operated drones) to investigate specialized use cases. Among these inspections, **erosion and cracking** inspections have become most popular, **comprising 23% and 18% of non-aerial thermography inspections**, respectively.
- High priority issues accounted for 42% of total identified issues, but were **responsible for 90% of observed revenue loss**.
- Over the past 5 years, underperformance has increased across sites of all sizes, but in 2024, we observed **the widest range in performance across C&I assets**.

[6] "Solar Market Insight Report Q4 2024." SEIA/Wood Mackenzie, 10 Jan. 2025, seia.org/research-resources/solar-market-insight-report-q4-2024.
[7] Excludes residential capacity and uses global total according to IEA.

About the data

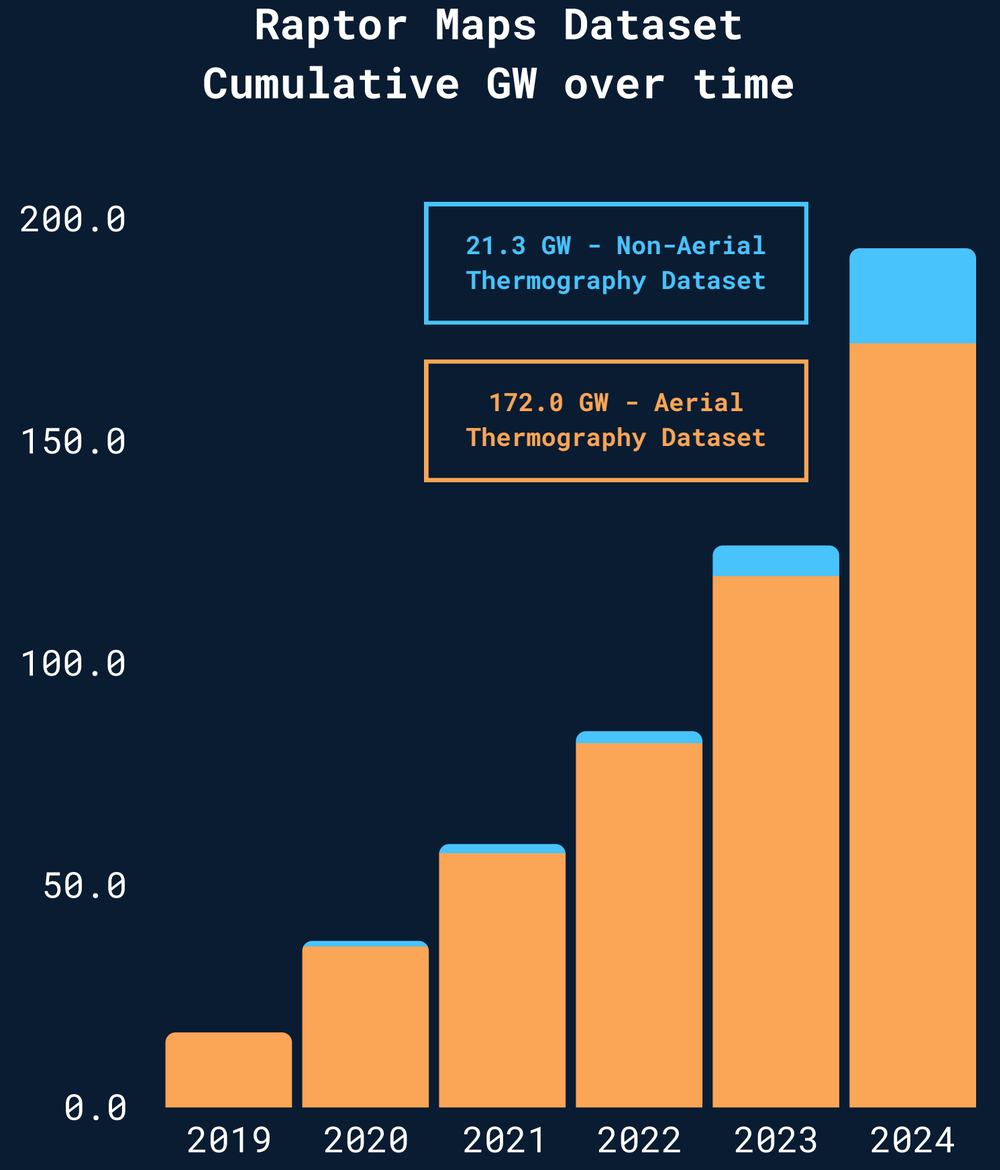
The Raptor Maps platform identifies and categorizes issues on solar assets that can cause safety, compliance, or performance issues. Our **normalized and aggregated dataset of 193 GW** contains data on issues ranging from damaged erosion BMPs to module cracking to thermographic anomalies that indicate power loss. This allows us to analyze the performance and conditions across solar assets and identify industry-wide trends.

Most of this report will focus on DC health, module cracking, and equipment-driven underperformance – a **potential $10B problem for the global solar industry**.

In 2024 alone, the Raptor Maps platform analyzed data from 67 GW of PV systems, of which 52 GW were for DC health analysis. Notably, **lost capacity from equipment anomalies has tripled (3.1x) over the last five years**, underscoring the growing challenge for solar owners and operators. The following section highlights key trends in DC health performance, using data to validate patterns that many in the industry have already sensed.

Power loss is calculated by applying a loss factor to each impacted module based on the severity of the detected issue.

This year's report applies a refined methodology to account for assets with multiple inspections within the same year, which is a rising trend that Raptor Maps has observed.



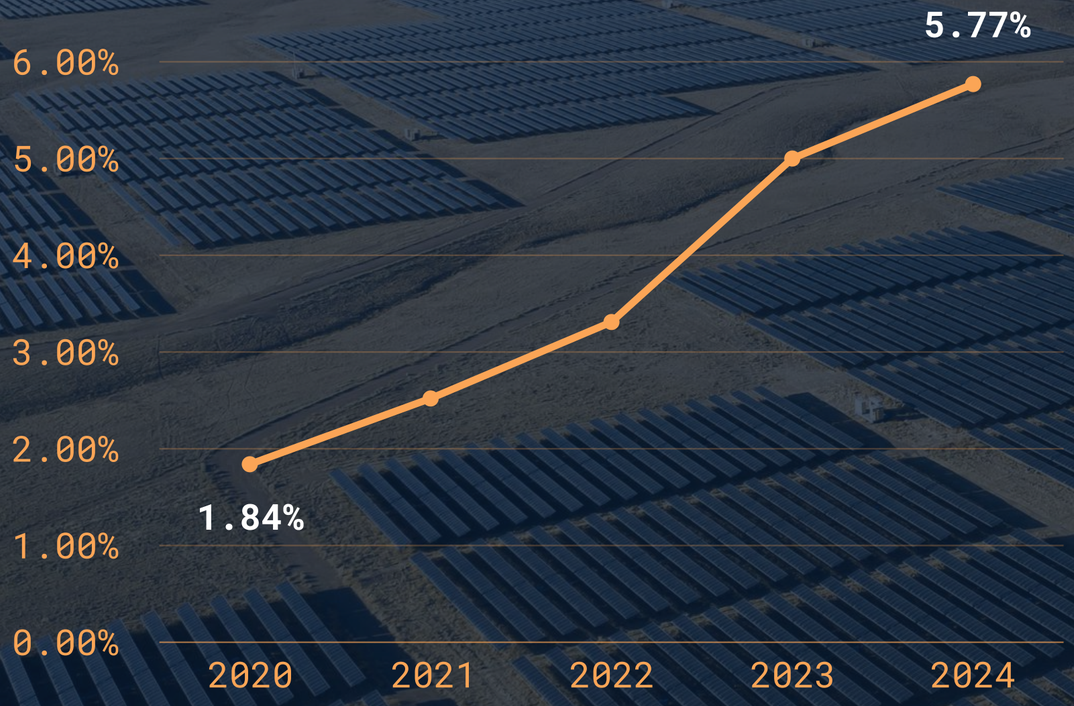
Chapter 1

SCALING CAPACITY, SHARPENING PERFORMANCE

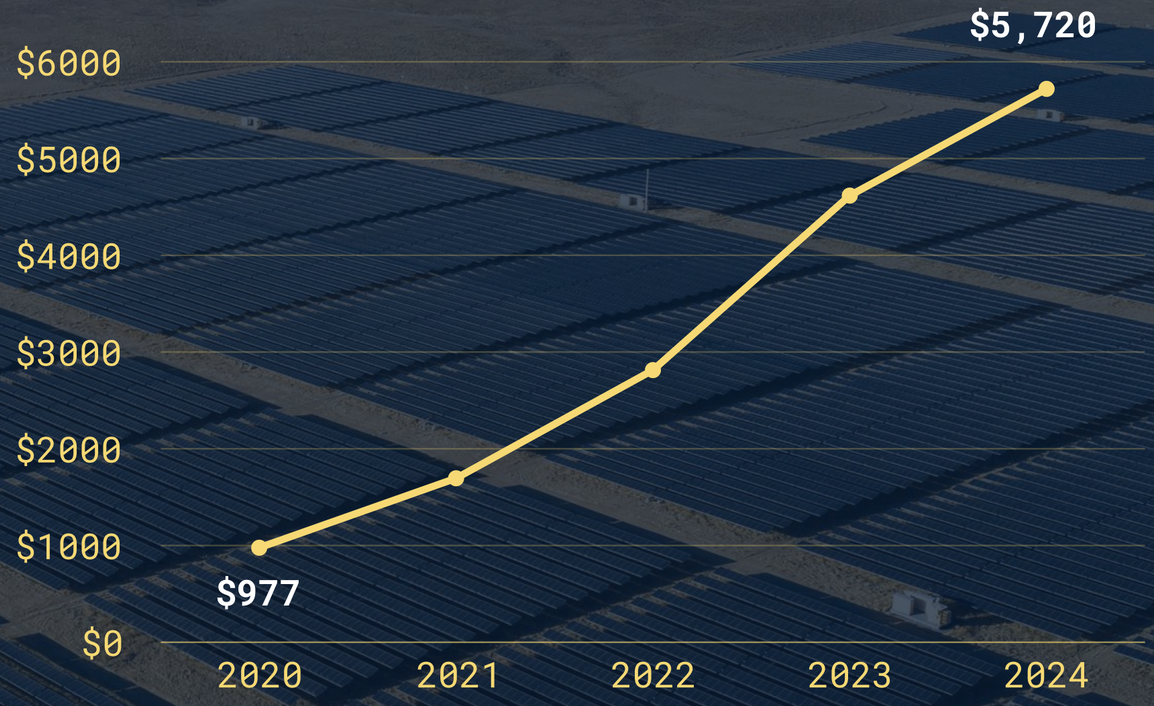
In 2024, the average solar asset experienced a potential revenue loss of **$5,720 per MWdc, per year** from equipment-driven underperformance. That represents increases of 15% from 2023 and **214% over the past 5 years**.

Underperformance Continues to Rise

Average System Power Loss
% of Total Capacity



Average System Revenue Loss Potential,
Annualized $ per MWdc



In 2024, power loss from DC health and other equipment issues (“power loss”) continued its steady climb, with solar sites experiencing 5.77% underperformance, up from 5.00% in 2023 [1]. The consistent increase in power loss is expected as owners and operators navigate the complexities of managing increasingly larger utility-scale solar sites and portfolios.

[1] Power loss calculations assume DC power capacity for annual figures.

With the industry adjusting to rising demand, it is critical for owners to take proactive steps in recovering lost revenue— the average asset experienced annualized losses of $5,720/MWdc in 2024, up from $4,617MWdc in 2023. For context, a 100MW site experiencing 5.77% underperformance from year two of operations until decommissioning would see its project IRR drop by 249 basis points (Model source: NREL, Raptor Maps analysis)

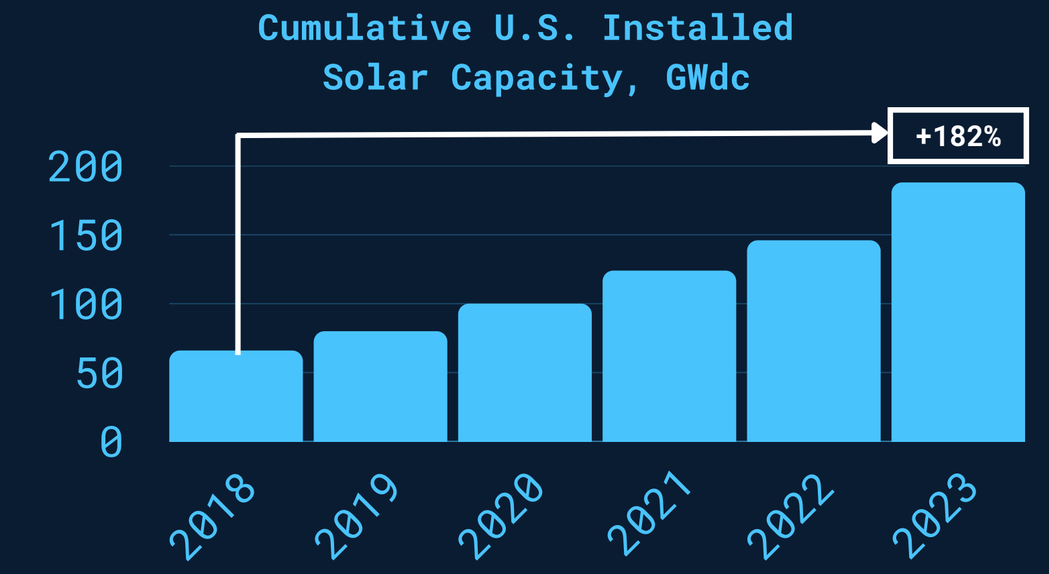
Industry Trends Underpinning Rising Underperformance

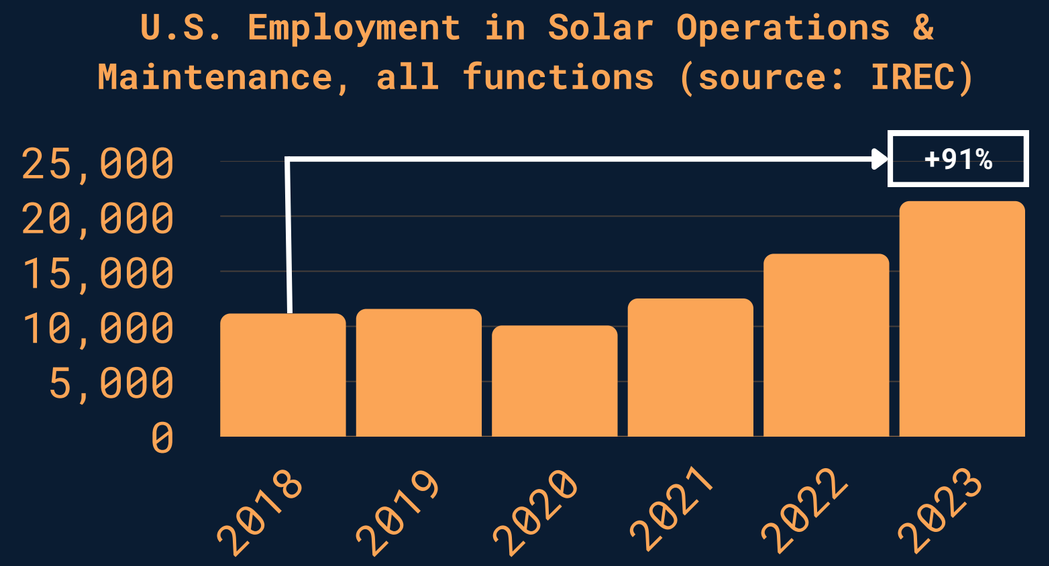
Raptor Maps' dataset provides an indicator into the overall DC health of already installed solar capacity, providing further context into the following trends in labor and manufacturing.

First, in the United States, **the growth of operational labor is failing to keep pace with the rapid expansion of solar capacity**. According to the US IREC Jobs Census and SEIA/Wood Mackenzie, solar capacity has grown by 182% over the past five years (2019-2023), while operational labor has increased by only 91% during the same period [1][2]. With **27% of operations & maintenance hiring due to churn**, the costs of hiring, onboarding, and retention exert additional pressures on budgets and time [3].

Second, **major strides in manufacturing have been made over the past decade,** as tracked by the PVEL Scorecard [4]. In fact, more than 20 new manufacturers were rated Top Performers within the scorecard. **However, PVEL has also observed a continued rise in BOM-level failures with 41% of BOMs experiencing at least one failure - up from 32% in 2023**. As the solar industry continues to mature and scale, efficiently monitoring and managing potential equipment failures will be critical.

Finally, both the magnitude and frequency of natural catastrophe events continue to grow. **In the 2010s, there were 13.1 NOAA billion-dollar weather events per year. The annual count more than doubled in 2024 with 27 billion-dollar weather events** [5]. From hail storms that cause cracking to lightning storms that can strike equipment, owners and operators continue to prioritize timely extreme weather response, increasingly relying on technology and innovative operating procedures to mitigate risk.

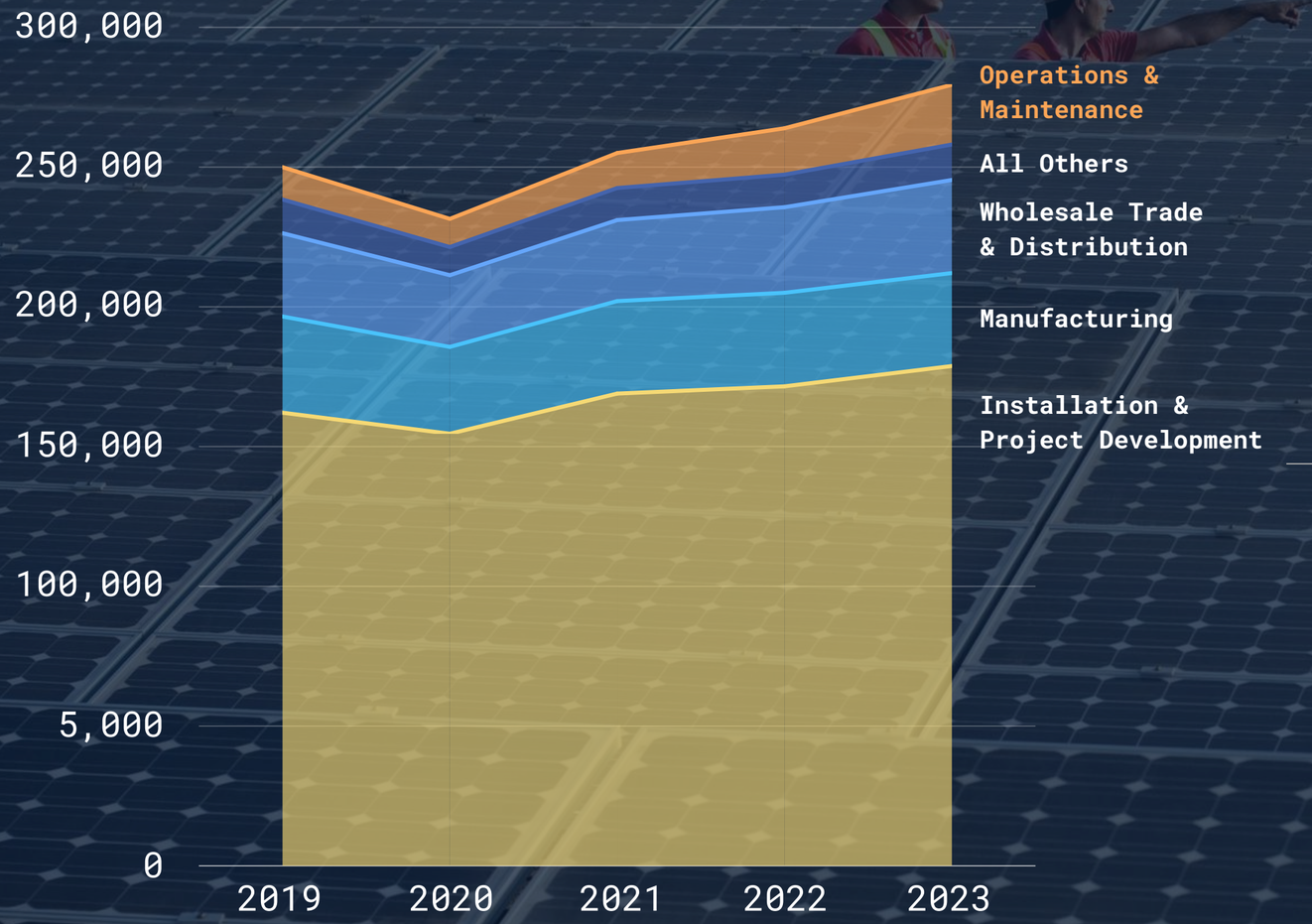




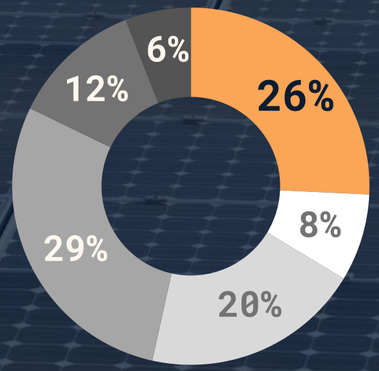
[1][3] "National Solar Jobs Census" IREC, 2024, https://irecusa.org/census-solar-job-trends/.
[2] "Solar Market Insight Report Q4 2024." SEIA/Wood Mackenzie, 10 Jan. 2025, seia.org/research-resources/solar-market-insight-report-q4-2024.
[4] "The 2024 PV Module Reliability Scorecard" Kiwa PVEL 2024, https://scorecard.pvel.com/.
[5] "U.S. Billion-Dollar Weather and Climate Disasters" NOAA National Centers for Environmental Information (NCEI), 2025. https://www.ncei.noaa.gov/access/billions/.

Spotlight: Only a Fraction of Solar Jobs for Maintenance

U.S. Solar Jobs by Sector



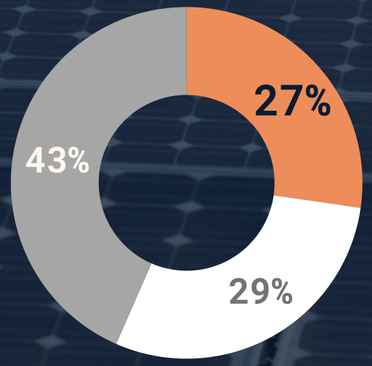
In 2023, 26% of Operations & Maintenance jobs were in the "Installation & Repair" category



Other categories:

- *Management/Professional (29%)*
- *Administrative (20%)*
- *Sales (12%)*
- *Production and Manufacturing (8%)*
- *All Other (6%)*

27% of New Hires in Operations & Maintenance were backfills due to Churn



Other categories:

- *Existing Employee Adds Solar Responsibilities (43%)*
- *New Positions (29%)*

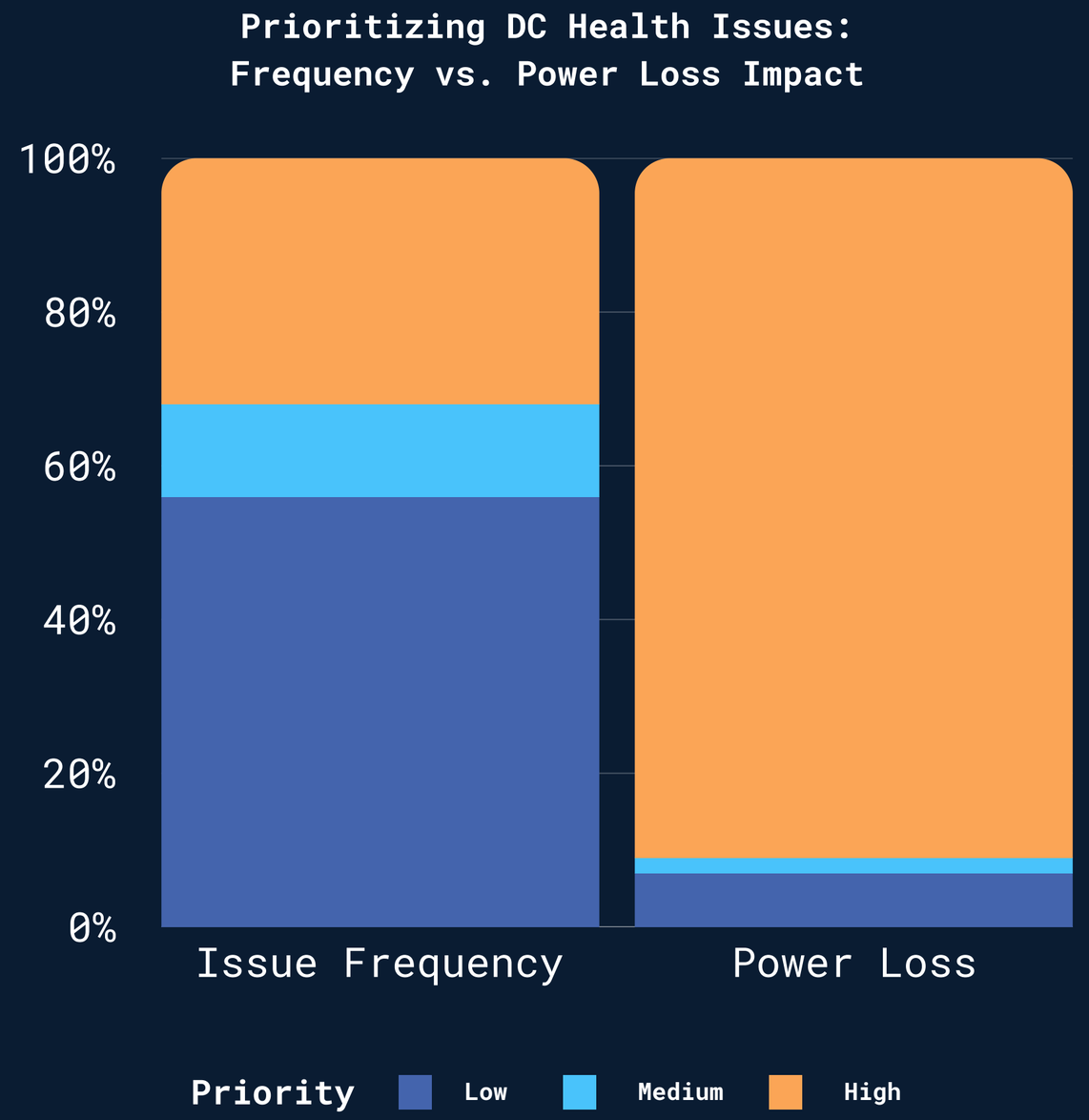
[1] "National Solar Jobs Census" IREC, 2024, https://irecusa.org/census-solar-job-trends/.

Raptor Maps Global Solar Report: 2025 Edition

In 2024, Performance Intelligence Is Bridging Power Loss Gaps

Last year, Raptor Maps identified more than 10.8 million DC health issues across 44 unique gigawatts of solar assets analyzed, or 249 issues per MWdc. As more solar is installed and a substantial portion of installed assets age, asset managers and O&M teams continue to face the difficult act of balancing between corrective and preventative maintenance of DC health issues and beyond. According to Raptor Maps' dataset, **32% of identified issues were categorized as "High Priority", accounting for 90% of the observed power loss**. 56% and 12% of identified issues were "Low Priority" and "Medium Priority", respectively. Aerial inspections allow for rapid diagnosing and geolocating of those "High Priority" issues, especially those causing SCADA alerts, providing the necessary intelligence for effective and efficient remediation.

The data emphasizes the criticality of maintaining detailed records of solar asset performance and site infrastructure conditions. While addressing immediate repairs naturally demands attention when resources are limited, the analysis reveals that nearly **70% of identified issues fall into medium or low priority categories**, making it very difficult to track, much less remediate, non-high priority issues that are at risk of escalating to larger problems - and which issues are not. This reality has led many organizations to invest in **centralized systems of record and more advanced methods of capturing data to maintain clear documentatio**n of these developing issues, including more frequent and targeted inspections.

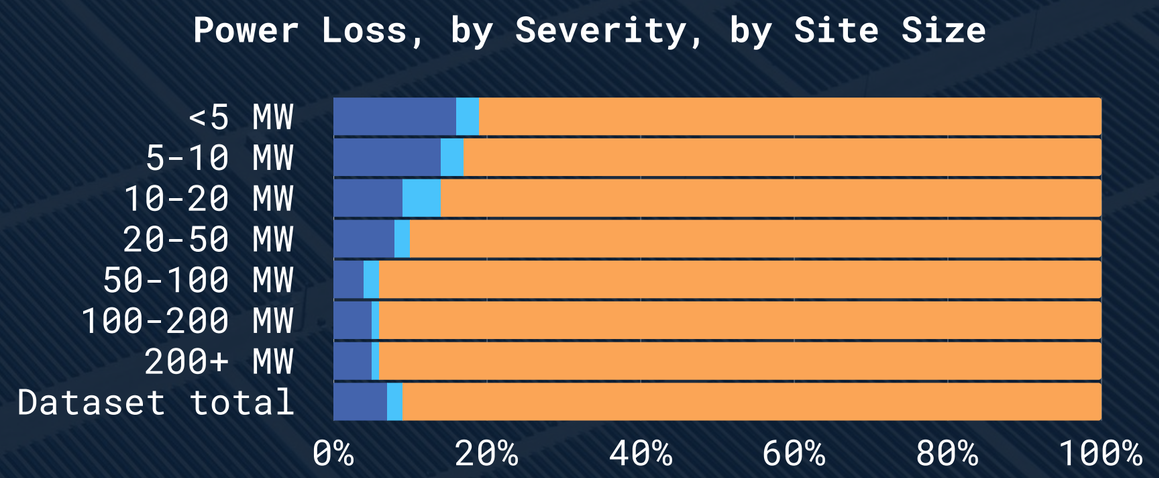


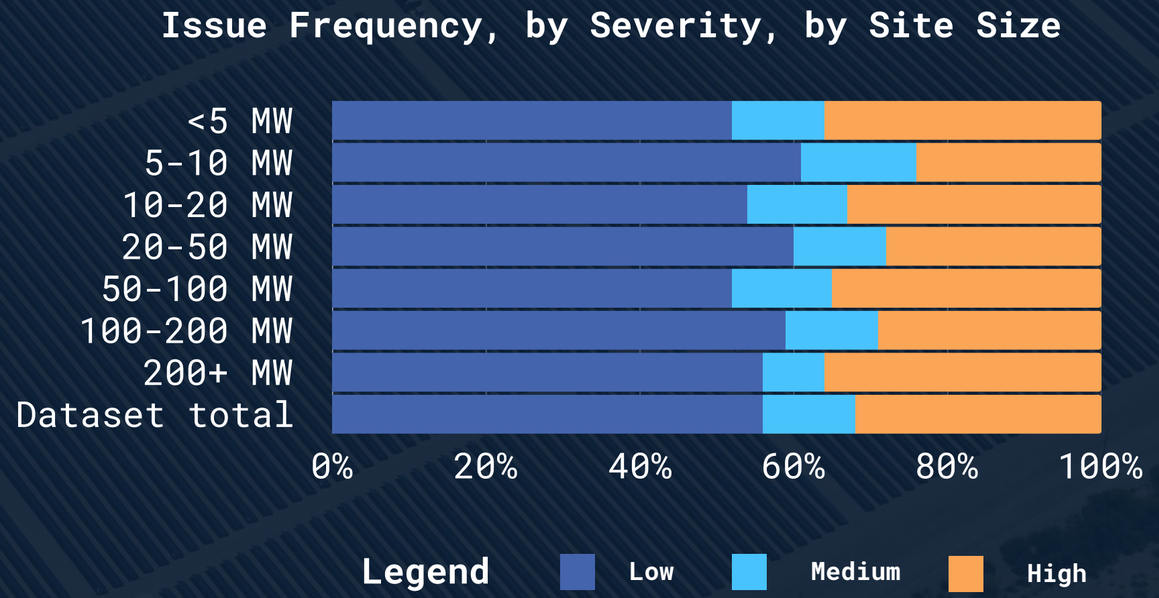
A Shift Towards Targeted, Repeated Inspections

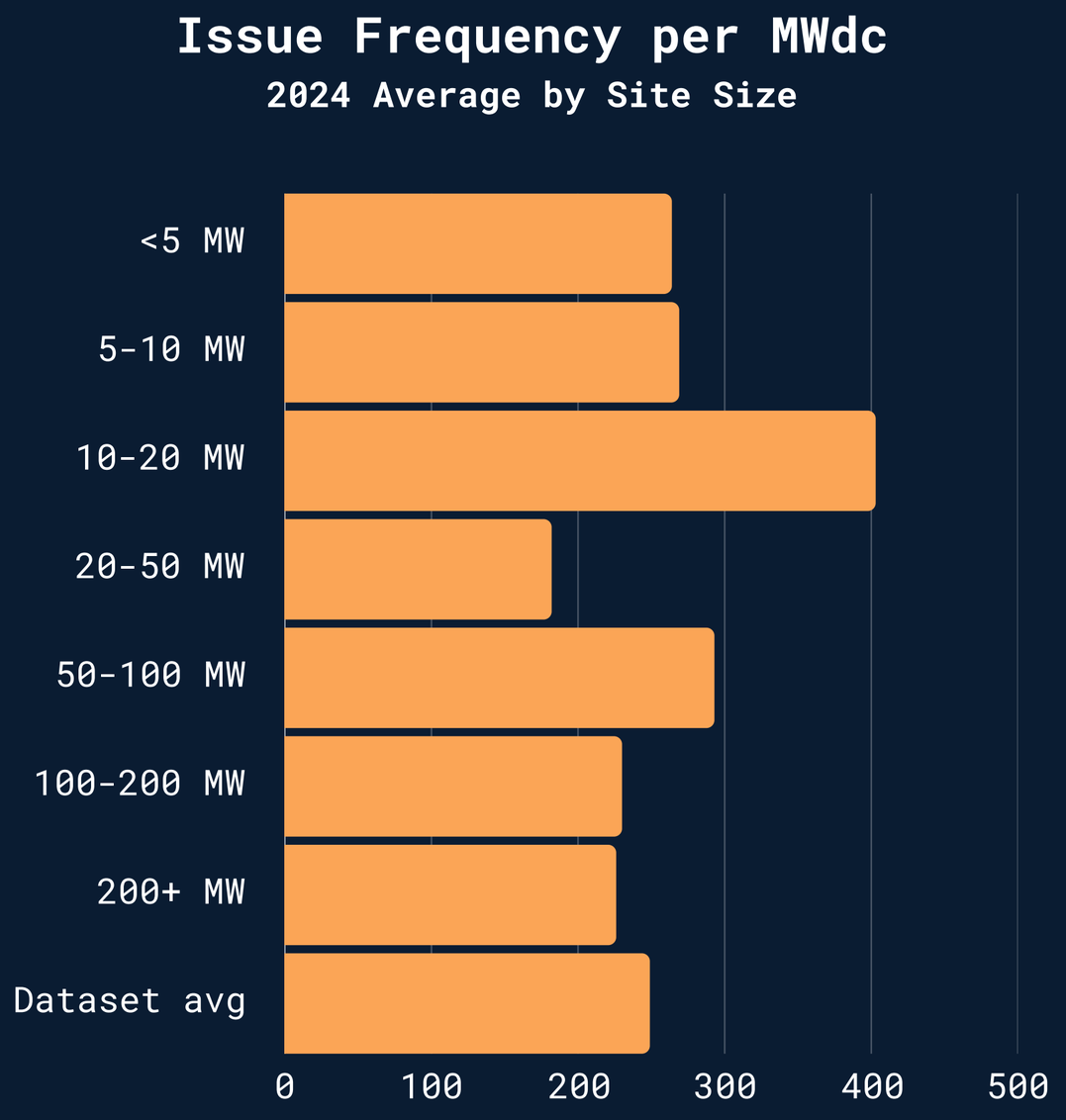
The key to employing performance intelligence is prioritizing the highest-impact issues and leveraging data to make more informed resourcing decisions. In large-scale sites between 50-200 MW, low-priority defects contribute just 0.2 kW of power loss per defect, whereas high-priority defects cause 6-8 kW of power loss per defect. However, it is important to note for C&I and smaller utility-scale farms, module-level defaults can cause 15-20% of power loss and are not insignificant when addressing site performance. Given current labor constraints and tighter O&M budgets, fixing every defect is neither practical nor cost-effective. Savvy operations teams have begun to shift towards data-informed, targeted interventions to recover power faster while minimizing windshield time.

Furthermore, industry data reflects a shift away from treating aerial inspections as isolated assessments and rather as a scalable approach towards preventative monitoring. Notably, some owners and operators have internalized this trend, inspecting the same sites 70% more in 2024 than in 2023.

With a growing volume of defects to remediate or monitor—estimated at nearly 249 defects per MW per year in 2024—operations teams are facing an overwhelming backlog of issues to manage, and increasing inspection frequency is not viable. These trends highlight the urgent need for technology solutions to efficiently identify, prioritize, and monitor issues on solar farms without mobilizing personnel. As a result, many operators are turning to new tools to support balancing between monitoring, preventative, and corrective maintenance, ensuring the most critical issues are addressed at the right time. Software-enabled sensors and on-site robotics provide frequent, autonomous, and granular diagnoses into site health. This allows teams to be deployed efficiently, in a timely manner, and only when human intervention is needed—reducing unnecessary truck rolls, automating reports, and ensuring technicians arrive prepared with clear guidance and necessary equipment, ensuring technician safety and reducing time spent on-site per task.







Different Needs for Different Fleets

Elevated power loss from equipment issues creates different challenges and opportunities for each solar industry segment. For example, commercial and industrial (C&I) sites less than 5 MWdc experienced an average of 264 identified DC health issues per MWdc, which presents significant lost revenue risk when aggregated at the fleet-level. With C&I and community solar fleets typically spread across many different locations, balancing preventative and corrective efforts can become difficult, but without those efforts, sites risk higher magnitude events such as fires or outages.

In response, some asset owners and operators have unlocked economies of scope by expanding the capabilities of their teams. For example, several of Raptor Maps' customers have trained technicians to fly drones and self-perform aerial data collection, enabling high frequency performance insights on their assets and the reallocation of technician time previously spent on manual inspections to more impactful activities.

As sites get larger, the volume of data and conditions that asset managers and O&M teams must care about increases exponentially, with many requiring some form of manual intervention. However, increasing portfolios, site sizes, and distances from population centers have made it difficult to conduct all the activities under contract. As a result, Raptor Maps has observed a rise in automation of many visual inspection activities with remotely operated robotics. For example, Raptor Maps customers leverage remotely operated drones installed on-site to conduct investigations of alerts from SCADA systems, which allow for technicians to be deployed for remediation with the right tools, supplies, and data. Furthermore, using remotely operated robotics as a first method of response reduces technician exposure to potentially hazardous or high-voltage situations, drastically increasing safety and supporting workforce retention efforts.

Automating Ground Inspections & Site Walks

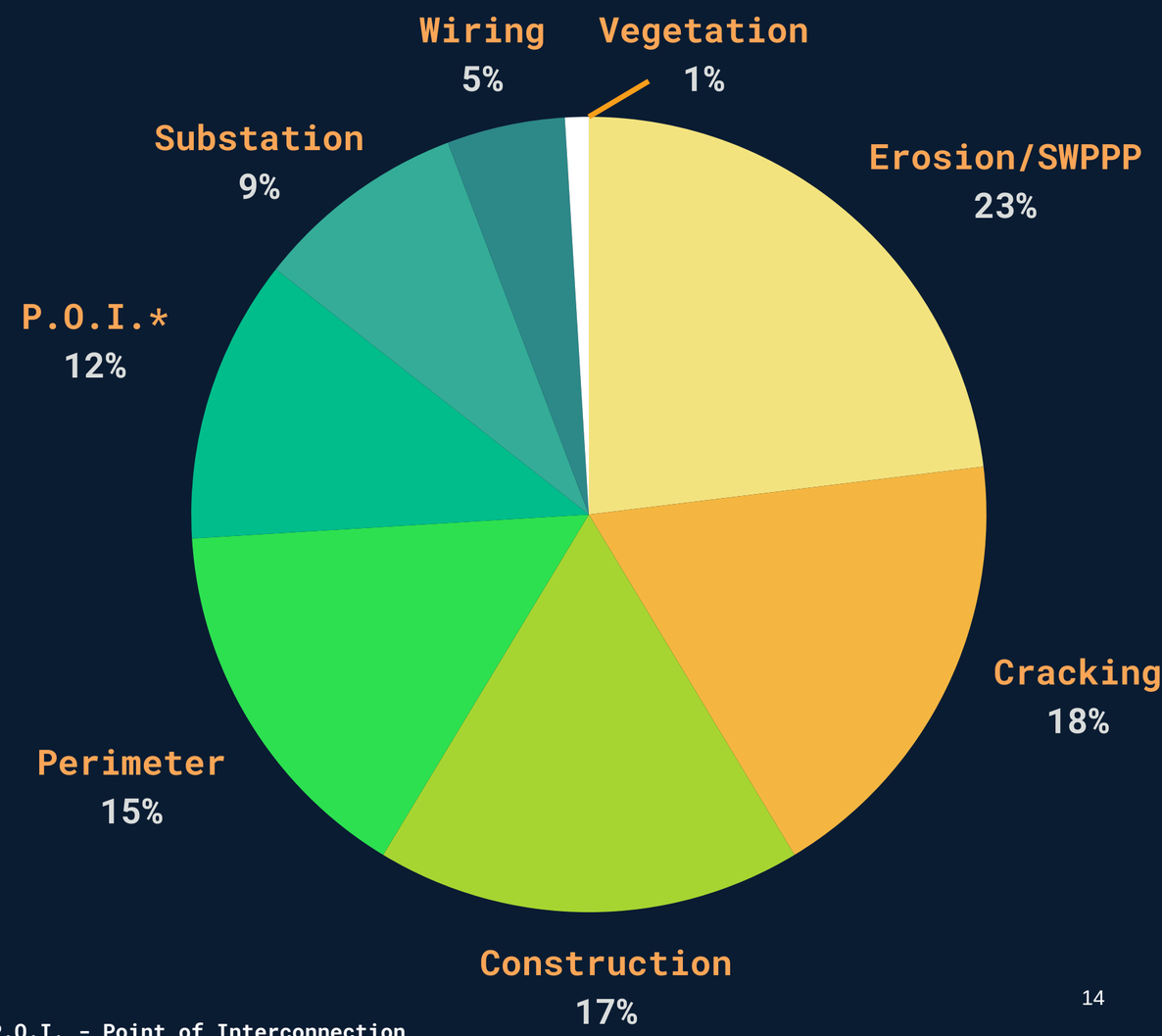
Remote operations are not the only solution to preserving technician time--customers are also widely deploying aerial inspections for non-DC health use cases. In 2024, civil works inspections were the most popular type of non-DC health inspection analyzed in the Raptor Maps platform. **Erosion/SWPPP and Perimeter Inspections** make up more than a third of all non-DC health orders. In addition, **Specialty Cracking Inspections** (e.g. for the detection of hairline cracking) have also grown popular as a way to mitigate the risk of fire and ground faults on utility-scale sites, making up 18% of non-aerial thermography inspections.

Typical ground inspections are being replaced across the entire O&M ecosystem and steadily increasing in cadence as well. Owners and operators have been increasing the rate of aerial inspections on their assets over time, with **inspections per site rising 70% from 2023 to 2024**. This includes all types of inspection types in the Raptor Maps dataset. Historically, from 2019 to 2023, owners and operators typically conducted an annual aerial inspection with an occasional mid-year check-in after a big storm or performance issues.

More recently, **the evolving needs of the asset owner have driven inspection cadences up drastically**. Technology has enabled the on-demand collection and analysis of data at-scale, allowing for more proactive management of risk while reducing when truck rolls are needed. Owners can now use aerial inspections as a preventative measure, rather than deploying reactionary inspections - especially on utility-scale sites where site risks can exacerbate and become very costly.

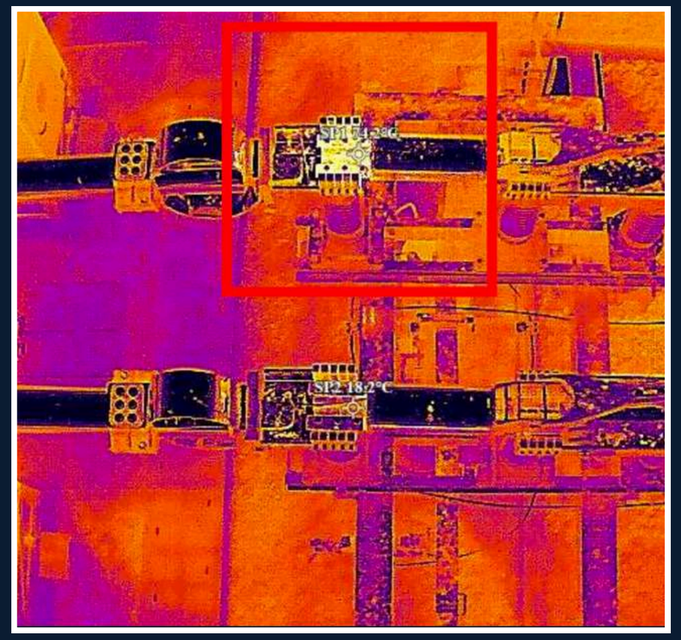
70% /yr Increase in Inspections per Site

Breakdown of 2024 Non-Aerial Thermography Inspections, by type



*P.O.I. - Point of Interconnection

Example of Risk Management Analytics from Raptor Maps



Substation P0 Thermal Signature

Vegetation Growth on CAB Line

Erosion & Water Management Issues

Chapter 2

ANATOMY OF POWER LOSS

Raptor Maps' Power Loss dataset measures lost capacity due to DC health and other equipment issues. While system-level faults continue to cause the most power loss, 2024 also saw **an increase in physical damage and module-level issues**, which present **increased fire and power loss risks** that owners need to manage across their fleet.

Raptor Maps' Power Loss Dataset

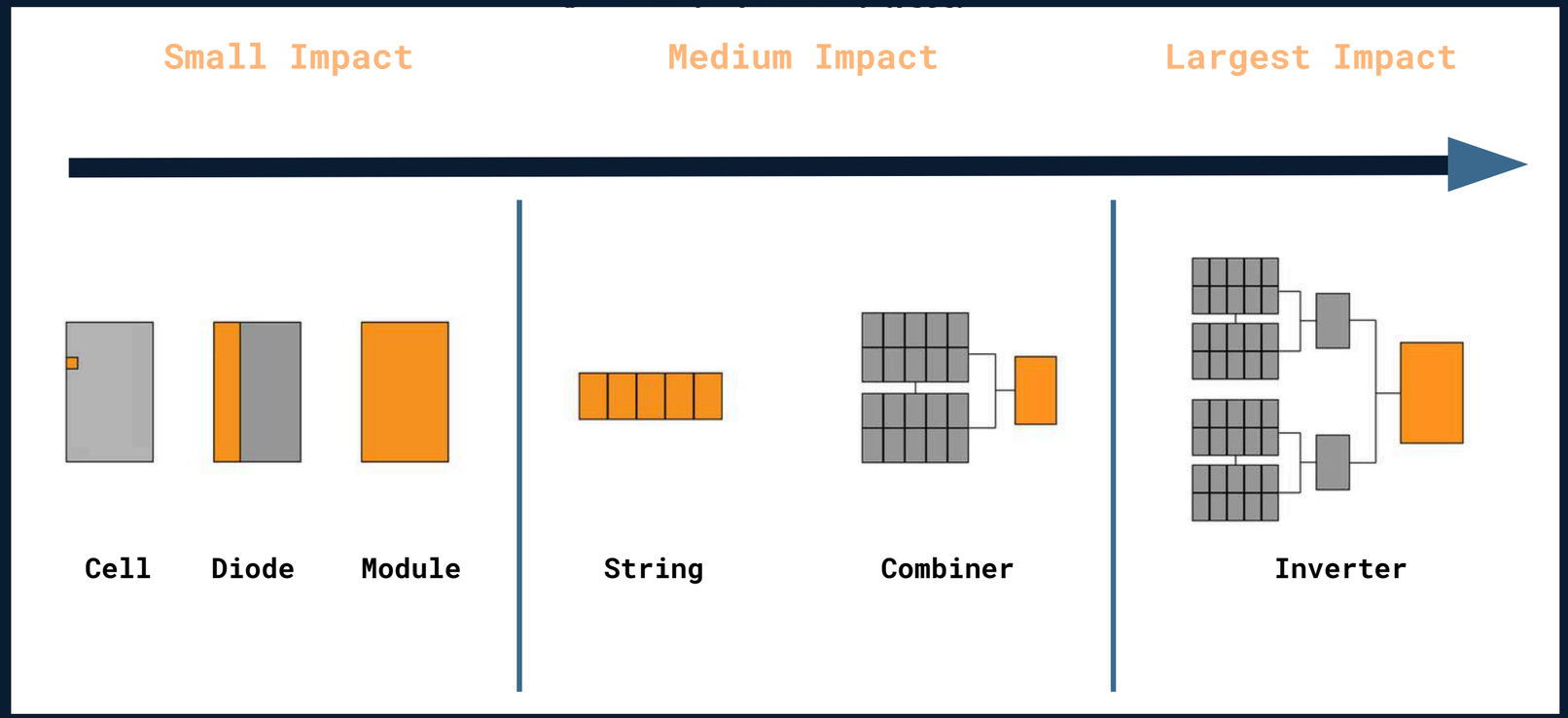
The Raptor Maps dataset contains 172 GW of DC health-driven power loss analytics and 21 GW of risk management analytics (e.g. vegetation monitoring or equipment defect detection), tagged with precise geolocations of the detected issue and an actionable categorization of what that issue is. The following section provides trends in what Raptor Maps has detected to be the leading drivers of power loss, providing owners and operators with benchmarks for their own assets.

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.

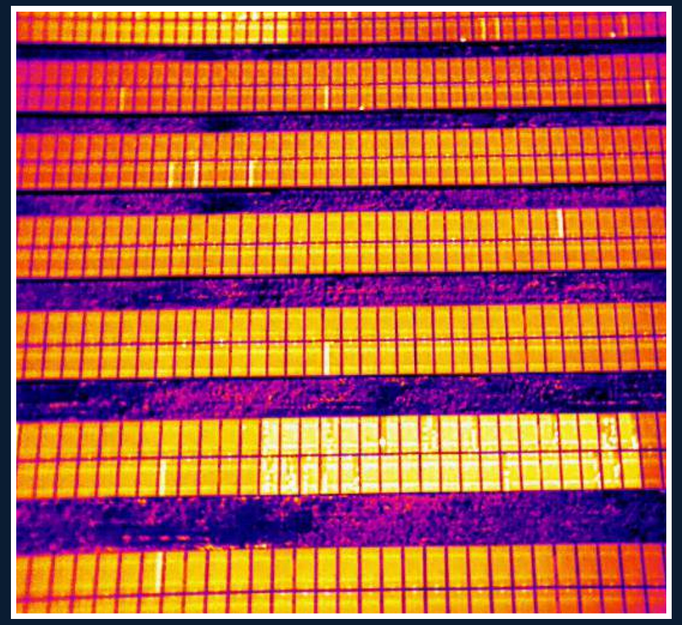
Raptor Maps analytics also utilizes temperature readings to provide further granularity into the anomaly (e.g. "Cell Medium" which classifies if the area of the cell anomaly is 10°-20°C higher than adjacent areas).

Examples of Tagged Anomalies

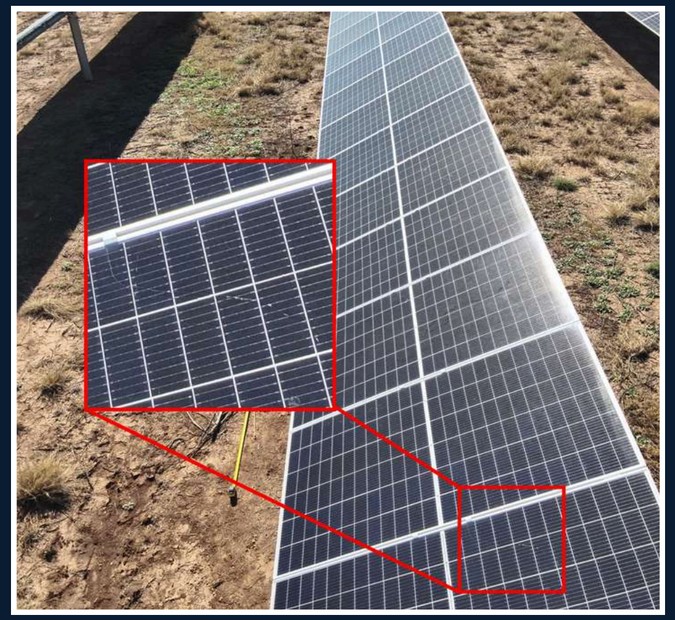
Sorted by Impact on DC Health



Example of Power Loss & Equipment Damage Analytics from Raptor Maps



String and Diode Anomalies



Hairline Cracking

Malfunctioning Trackers

Large Equipment Remains the Driver of Power Loss

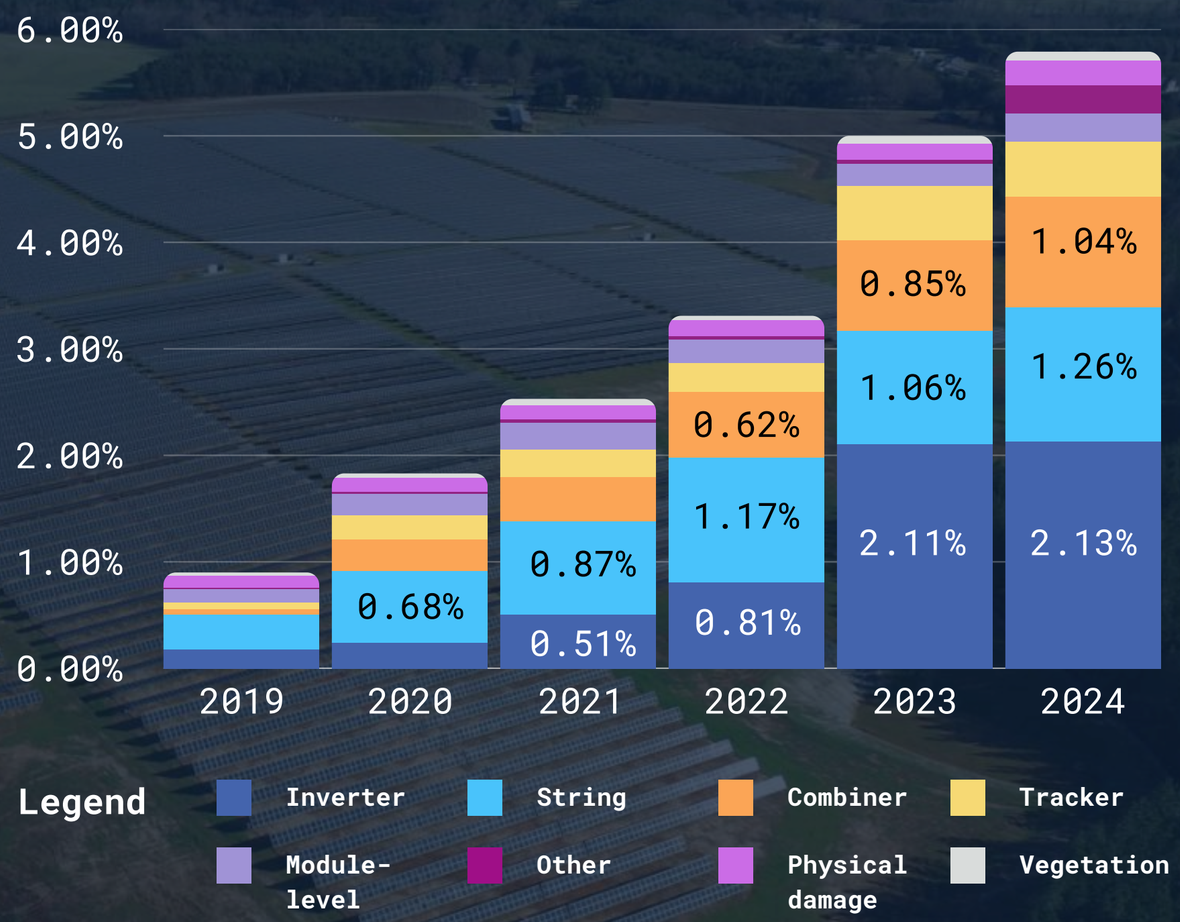
System-level faults, such as those that impact an entire string or malfunctioning trackers, continue to be the primary drivers of DC health-driven power loss within Raptor Maps' dataset. The largest fault tag - inverters - continues to be the largest driver at 37% of observed power loss in 2024. However, the average power loss observed from inverter faults has remained steady year-over-year, while **2024 saw a rise in more string (+19% since 2023) and combiner (+22%) faults compared to 2023**. Average power loss from malfunctioning or misaligned trackers, while still a larger driver, held steady year-over-year, contributing to around 10% of observed power loss in 2024. In hail-prone regions, malfunctioning trackers undermine hail damage mitigation efforts, which can cause significant damage and insurance premium increases. The high incidence of power loss from large equipment such as inverters or string-level anomalies highlight the ongoing challenge of balancing corrective maintenance across fleets, but also represent low-hanging fruit available to industry leaders when hoping to maximize performance.

Conversely, we **observed more granular module-level issues**, such as overheating junction boxes or activated diode bypasses, with an (+22%) increase from 2023. While they do not contribute to significant and immediate revenue loss, **these anomalies can degrade and pose fire risk** - highlighting another opportunity for applying advanced means of monitoring without taking resources away from higher priority corrective maintenance.

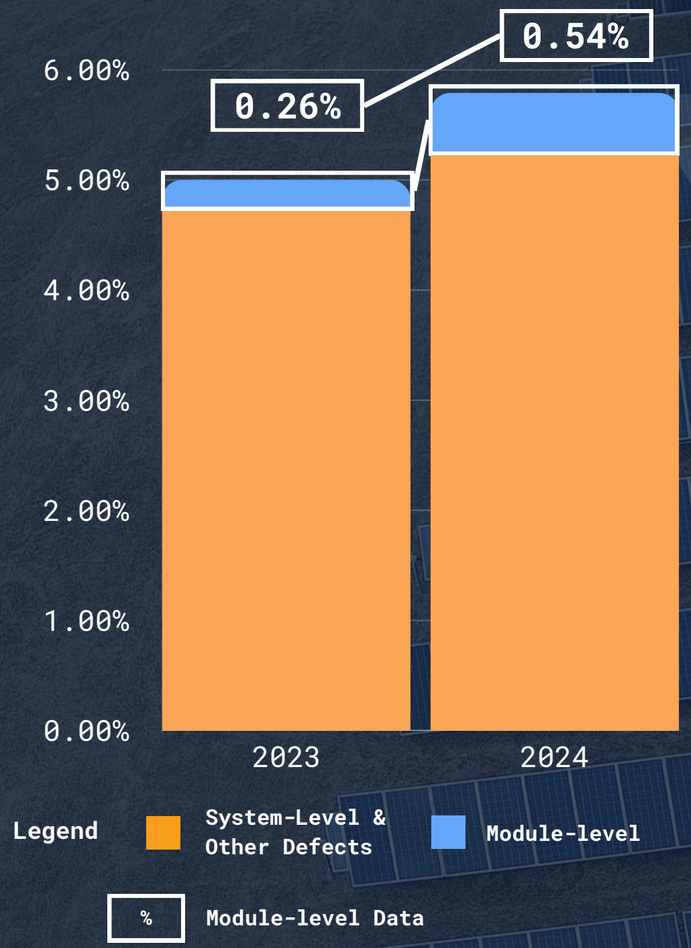
Note: All Raptor Maps inspection results include granular categorization, but several anomalies are grouped under "Module" and "Other" for the purposes of this report. All module- and submodule-level anomalies (e.g. cell defects and cracking) are grouped into "Module" in this chart. "Other" anomalies include helix faults, reverse polarity, lightning damage, amongst several other anomaly types. See definitions of Power Loss Anomalies in the Raptor Maps Knowledge Hub here.

Power Loss by Tag Category

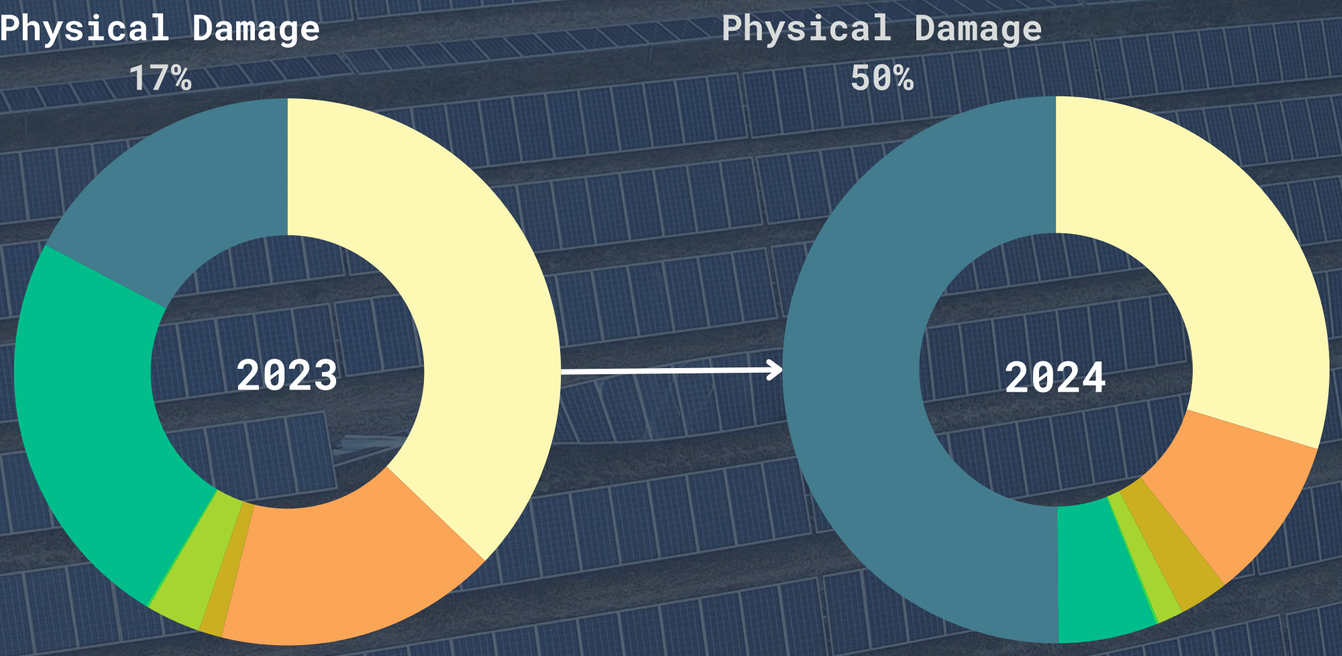
% of Total Capacity Analyzed by Year



However; The Rise in Damage has Doubled Module-level Power Loss



Module-level Power Loss by Anomaly Type and Year



Other Module-Level Defects:

- Cell (37%)
- Offline Module (24%)
- Diode (17%)
- Internal Short Circuit (3%)
- Hot Spot (1%)
- Junction Box (<1%)

Other Module-Level Defects:

- Cell (30%)
- Diode (10%)
- Offline Module (6%)
- Hot Spot (3%)
- Internal Short Circuit (2%)
- Junction Box (<1%)

Module Technology and Module Defects

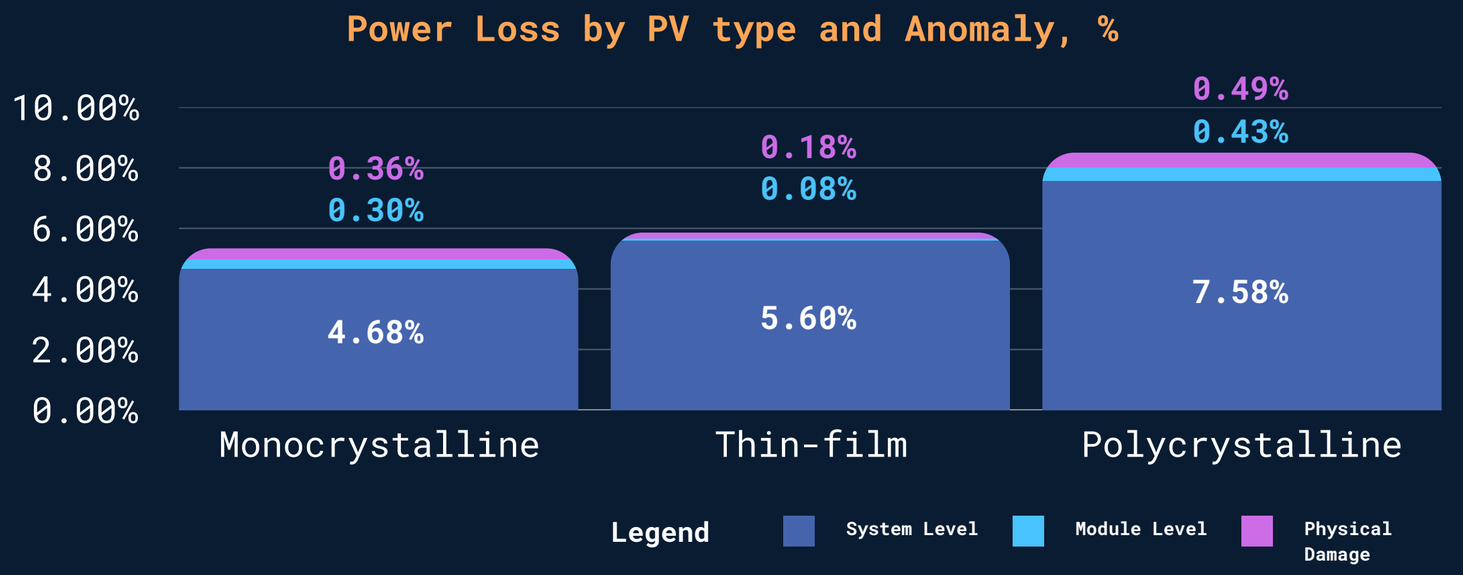
While the selection of PV modules would not necessarily impact the performance of larger equipment (such as inverters), analysis of performance across assets using different types of modules reveals that assets built with polycrystalline modules exhibited higher average power loss from equipment issues compared to assets built with monocrystalline and thin-film, while thin-film modules exhibited the least power loss from module-specific defects.

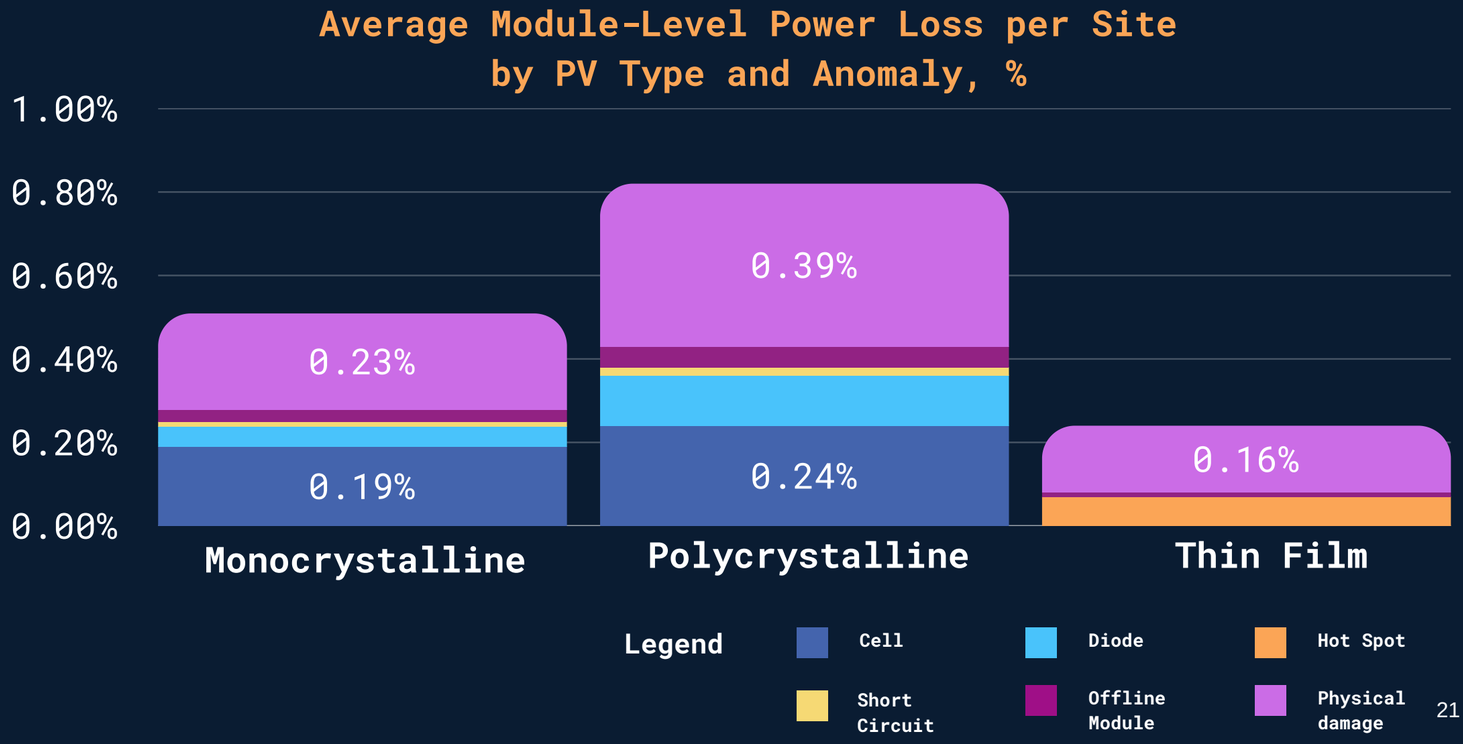
Overall, thin-film assets performed very well at the module level in the 2024 dataset, with thin-film modules exhibiting roughly a quarter of the module-level defects found in polycrystalline panels. While 70% of module-level defects identified in thin-film were due to physical damage, less physical damage was identified within thin-film modules compared to monocrystalline and polycrystalline modules in 2024. 55% and 52% of monocrystalline and polycrystalline module-level defects were attributed to damage, respectively.

It is important to note that Raptor Maps' issue identification focuses on significant thermal events that are known drivers of power loss and fire risk. As thin-film modules show more subtle temperature differentials, Raptor Maps' thin-film analytics only identifies modules with known defects that should be monitored or addressed. Raptor Maps continues to expand and refine its methodology to ensure the most critical defects are accurately identified during inspections of all types, including through partnerships with leading manufacturers [1].

This data can be susceptible to many factors year over year, but in regions susceptible to increasingly common extreme weather events, it is clear higher rates of physical damage will be observed.

[1] "Raptor Maps and First Solar Transform Detection of Glass Cracks in Thin Film Solar Panels". Raptor Maps, 2023, https://raptormaps.com/blog-posts/raptor-maps-and-first-solar-transform-detection-of-glass-cracks-in-thin-film-solar-panels-boosting-efficiency-and-safety.

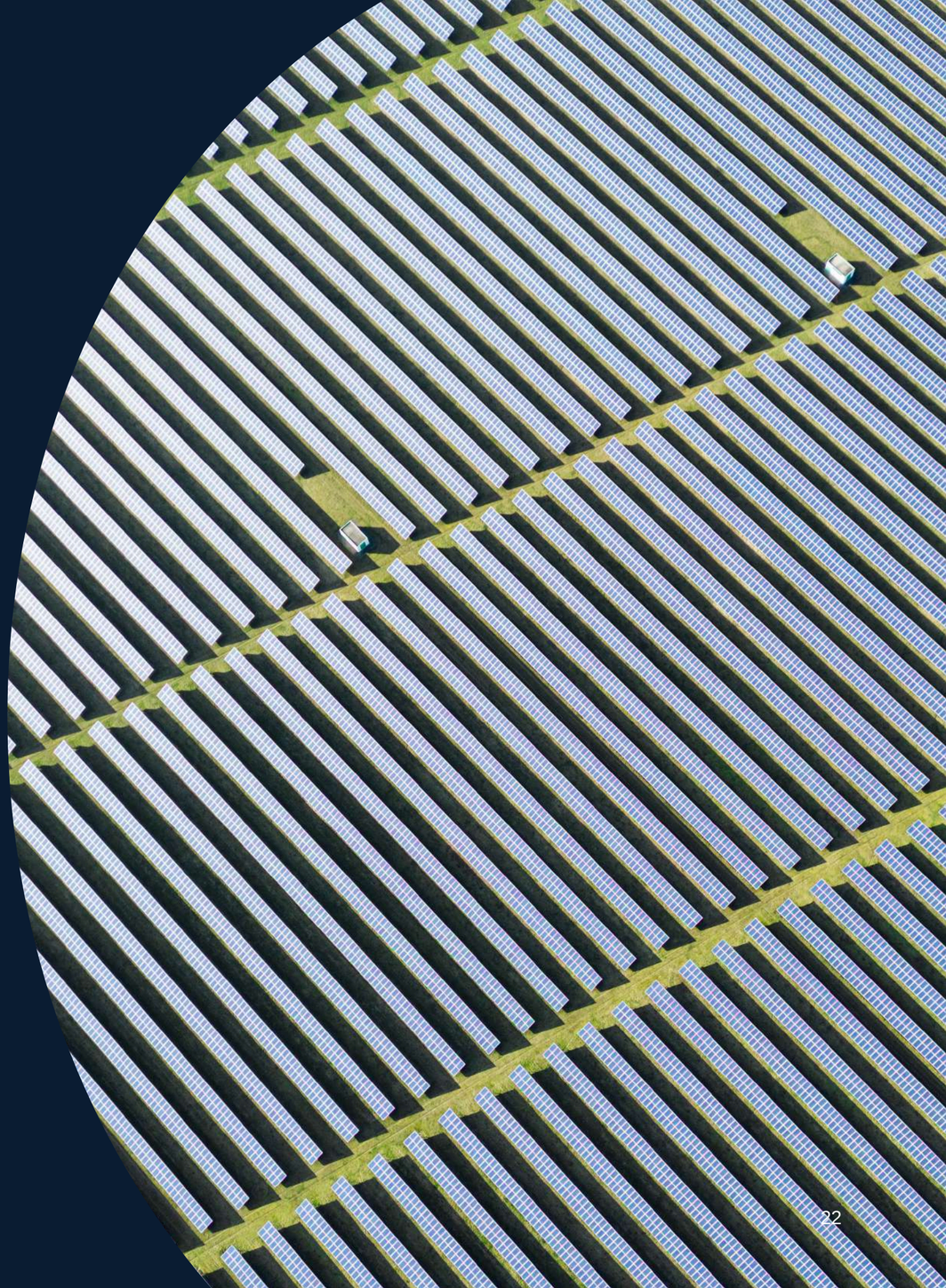




Chapter 3

BENCHMARKING DC HEALTH

While underperformance is on the rise across our dataset, some assets experienced more equipment issues than others. This section explores asset performance **benchmarks by site size, market, and geography.**



Escalating Power Loss, Regardless of Site Size

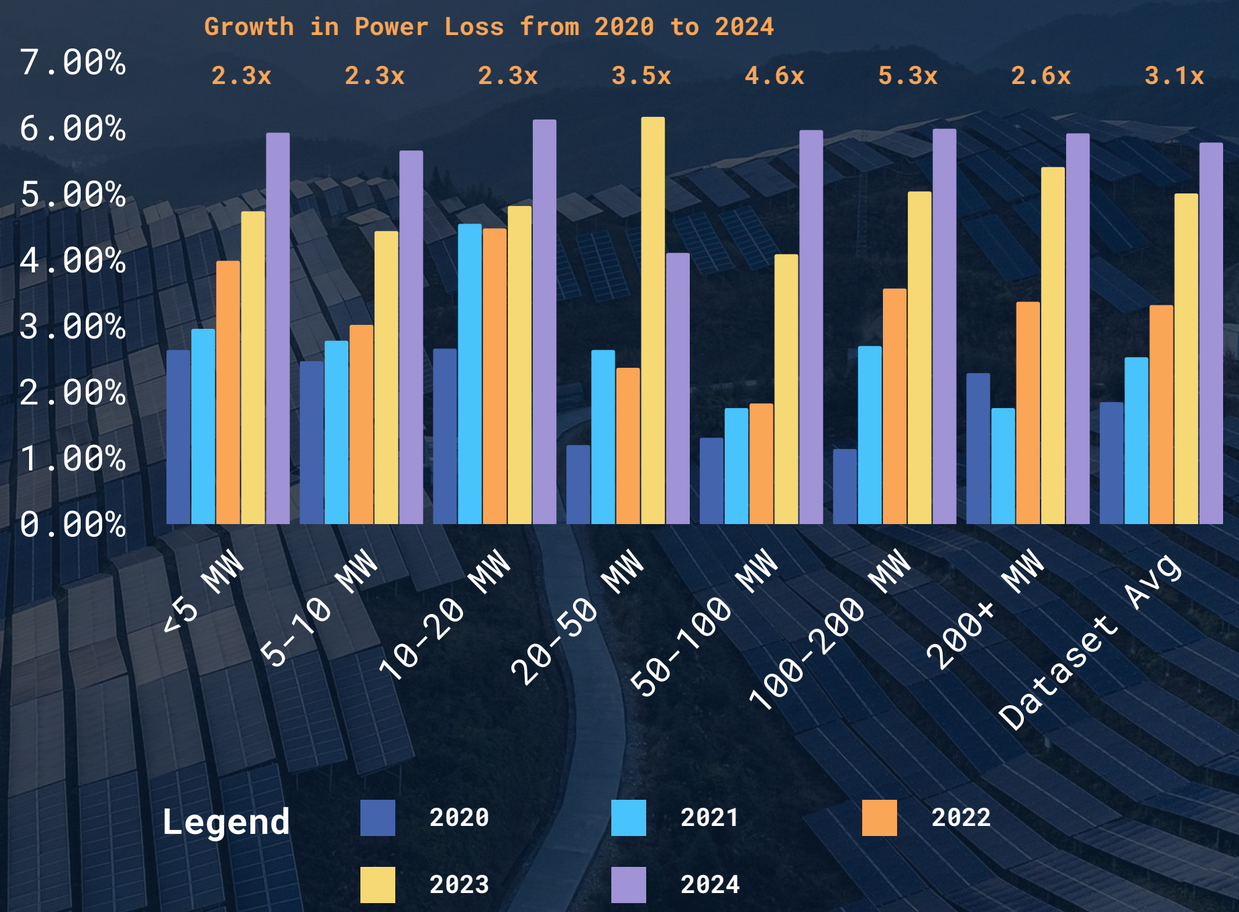
Sites of all sizes experienced significant downswings in performance from DC health and other equipment issues over the last 5 years, with only sites between 20 to 50 MWdc experiencing less underperformance on average in 2024 when compared to 2023. Underperformance has grown more rapidly on larger sites, with the average site between 100 to 200 MWdc experiencing a 5.3x increase in underperformance within the Raptor Maps dataset compared to a 2.3x increase in sites between 0 to 5 MWdc and **3.1x increase across the dataset average**.

However, 2024 data indicates less variability in underperformance across each site size category compared to prior years. With an **average annualized revenue loss potential of $5,720 per MWdc**, remediation of DC health issues are high-impact interventions that will be essential for closing the gap between modeled and actual performance.

$5,720
per MW, per year

Potential average revenue loss per site

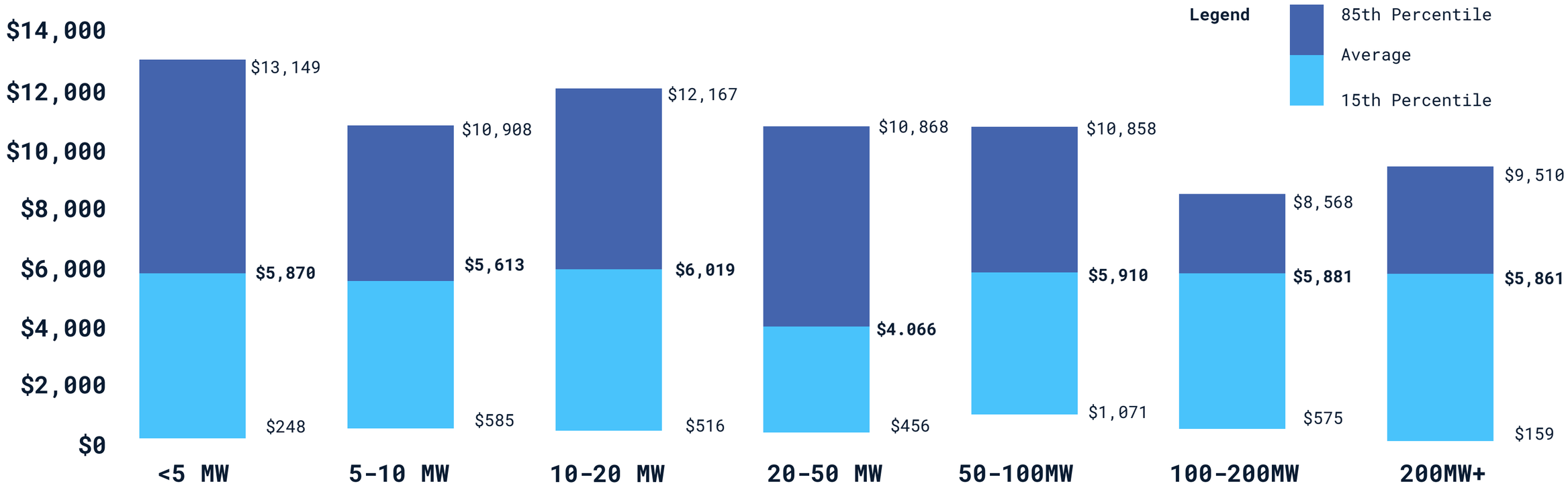
Power Loss by Site Size
(Last five years, 2020 - 2024)



Highest Variance in Performance Observed in C&I Assets

In the smallest sites (under 5 MW), the gap between the top performing 15% and the bottom performing 15% of assets was $12,901 per MW of annualized revenue loss, compared to the range of $9,351 per MW for assets larger than 200 MW. This variance in performance presents a challenge to C&I owners and operators, emphasizing the need for clear and reliable data assets to enable effective triaging and prioritization of issues. It is worth noting that the higher performing assets within the Raptor Maps dataset tend to be younger assets, reflecting a continued challenge with keeping up with corrective maintenance and warranty guarantees as fleets age.

Range of 2024 Annualized Revenue Loss per MW, by Site Size



Does Site Size Matter?

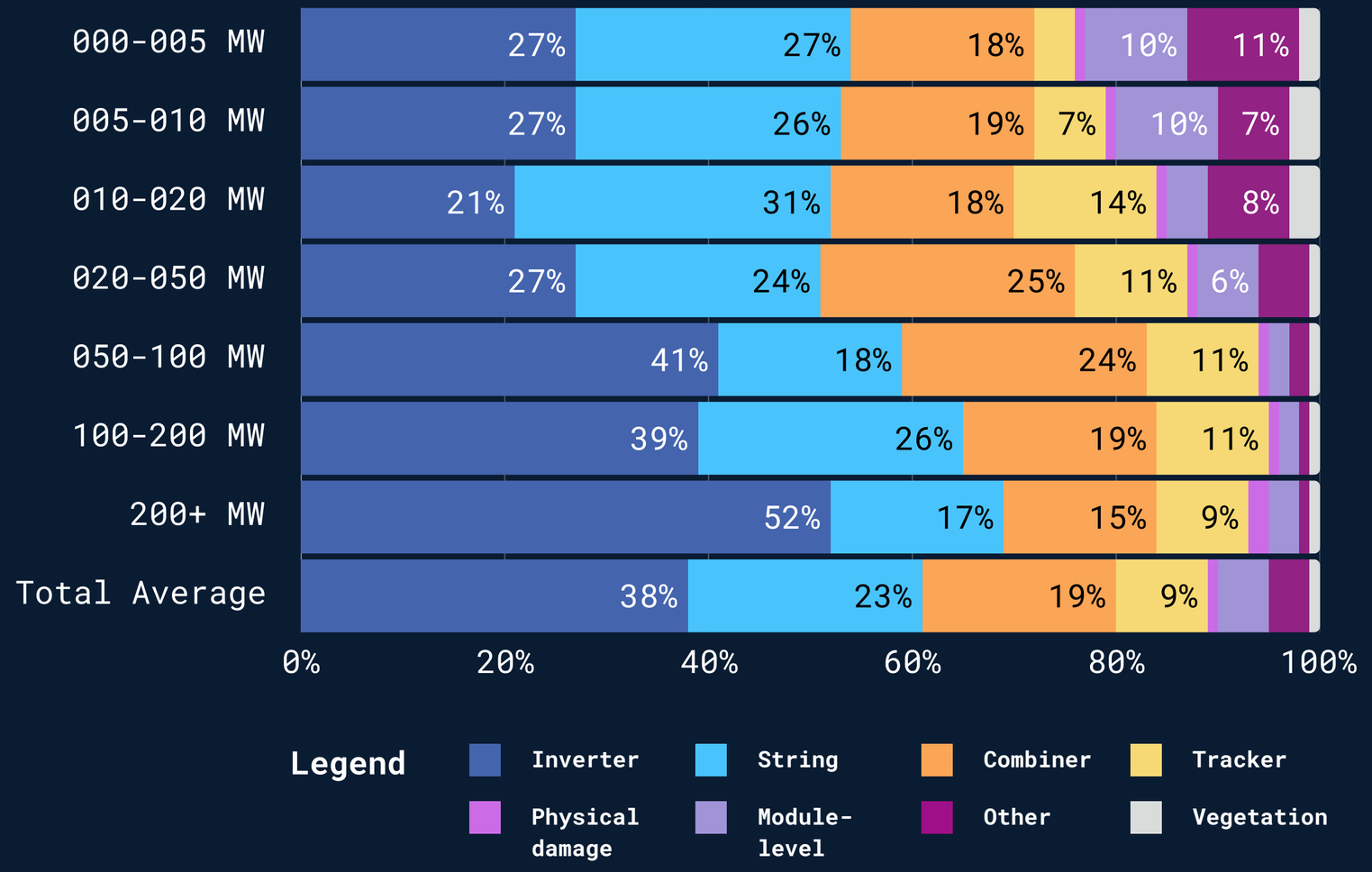
Smaller sites less than 10 MWdc had a higher percentage of power loss caused by module-level issues such as diodes and hot spots when compared to larger sites. Within the “Other” category, Raptor Maps’ analysis has found higher levels of shading and soiling in those smaller systems. As soiling is not permanent in the way an equipment defect may be and may be resolved prior to an inspection, the Raptor Maps data is not intended to fully capture the impact of soiling. However, given that this is an aggregated benchmark across thousands of sites less than 10 MWdc, C&I and community solar owners and operators should take note, especially as soiling is easiest to address earlier on.

Regardless of the capacity of the site, **high priority faults, such as inverter, string, and combiner issues, contribute to the majority of observed power loss**. This is especially true for larger sites where more than 90% of power loss were caused by inverter, string, combiner, and tracker anomalies on sites greater than 50MWdc.

**Data is adjusted for outliers.*

Power Loss by Tag Category

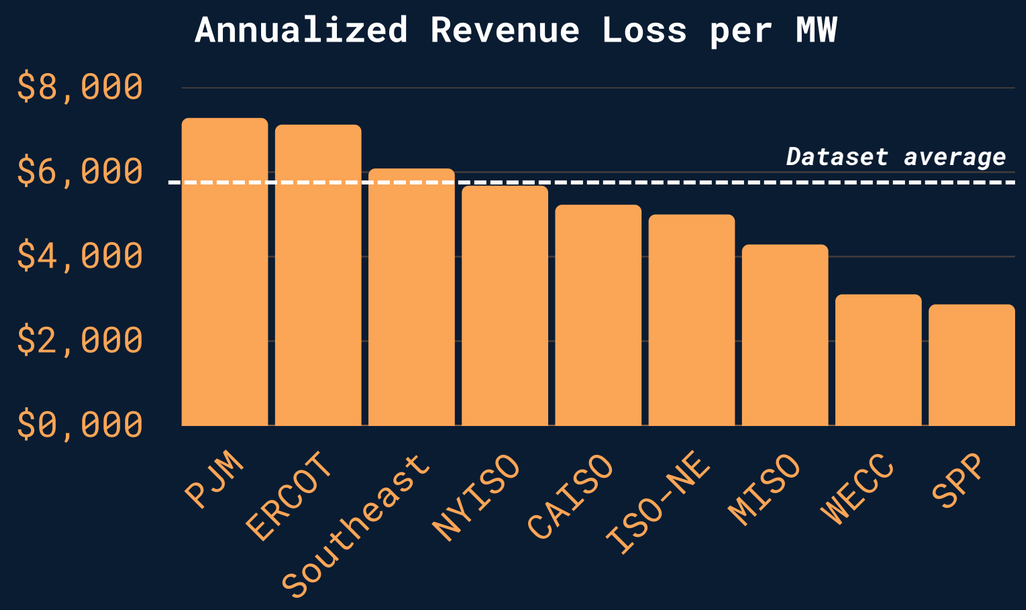
% of Observed Power Loss, by Site Size



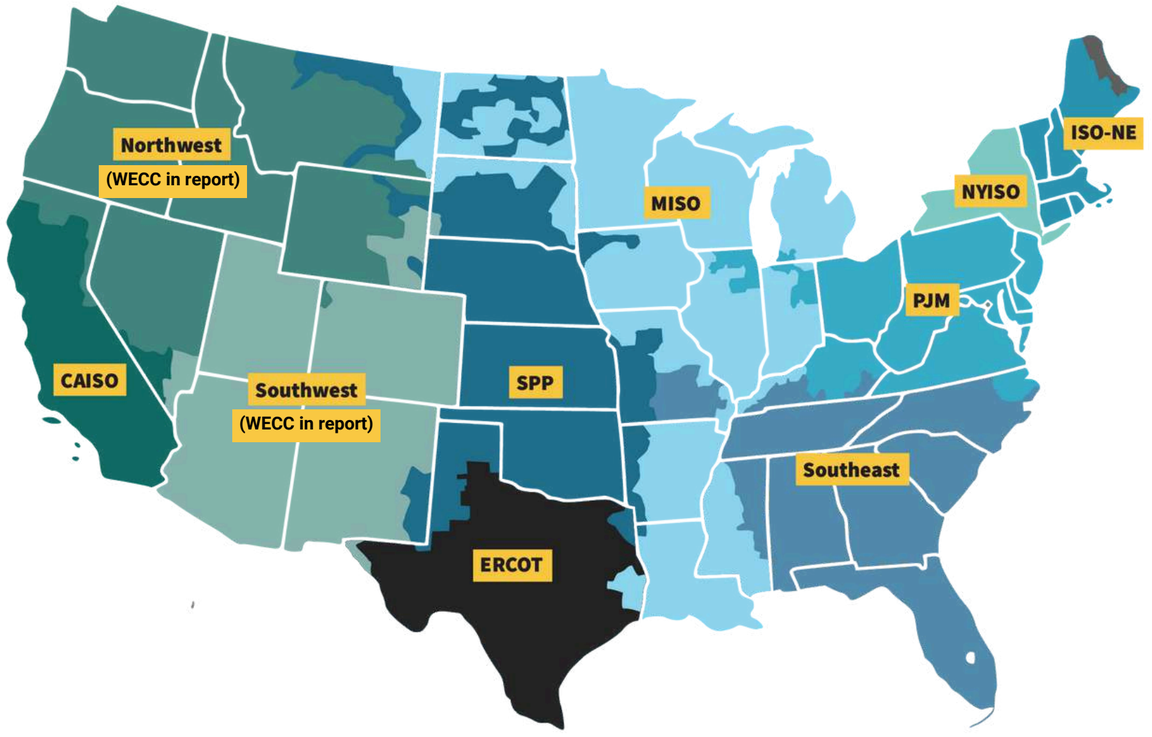
Benchmarks by U.S. Electric Power Markets

In previous years, the Global Solar Report has reported underperformance by U.S. region. This year's edition will instead report on underperformance by electric power markets and by contiguous U.S. states. For the purposes of this report, the Southwest and the Northwest markets are categorized together under WECC. The report only includes benchmarks for states and regions with sufficient data after adjusting for outliers.

In 2024, **assets in the PJM and ERCOT markets experienced the highest average power loss compared to other markets** at $7,282 per MW and $7,124 per MW respectively. The next several pages will provide more detailed analysis by market and by state.



Map of U.S. Electric Power Markets



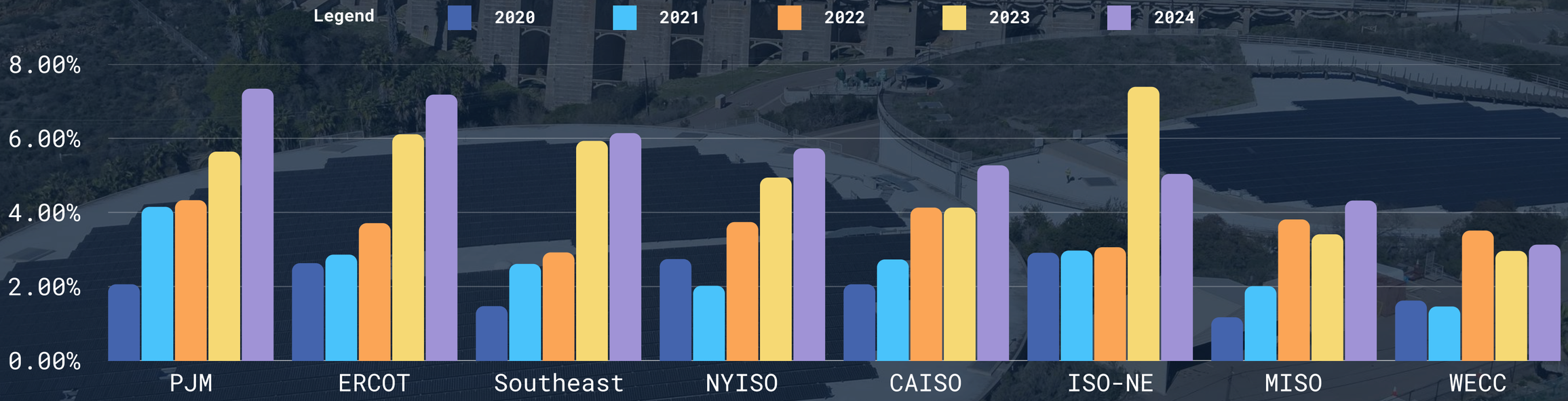
Source: Federal Energy Regulatory Commission, Electric Power Market Map.

Equipment-driven Underperformance, No Matter Where You Go

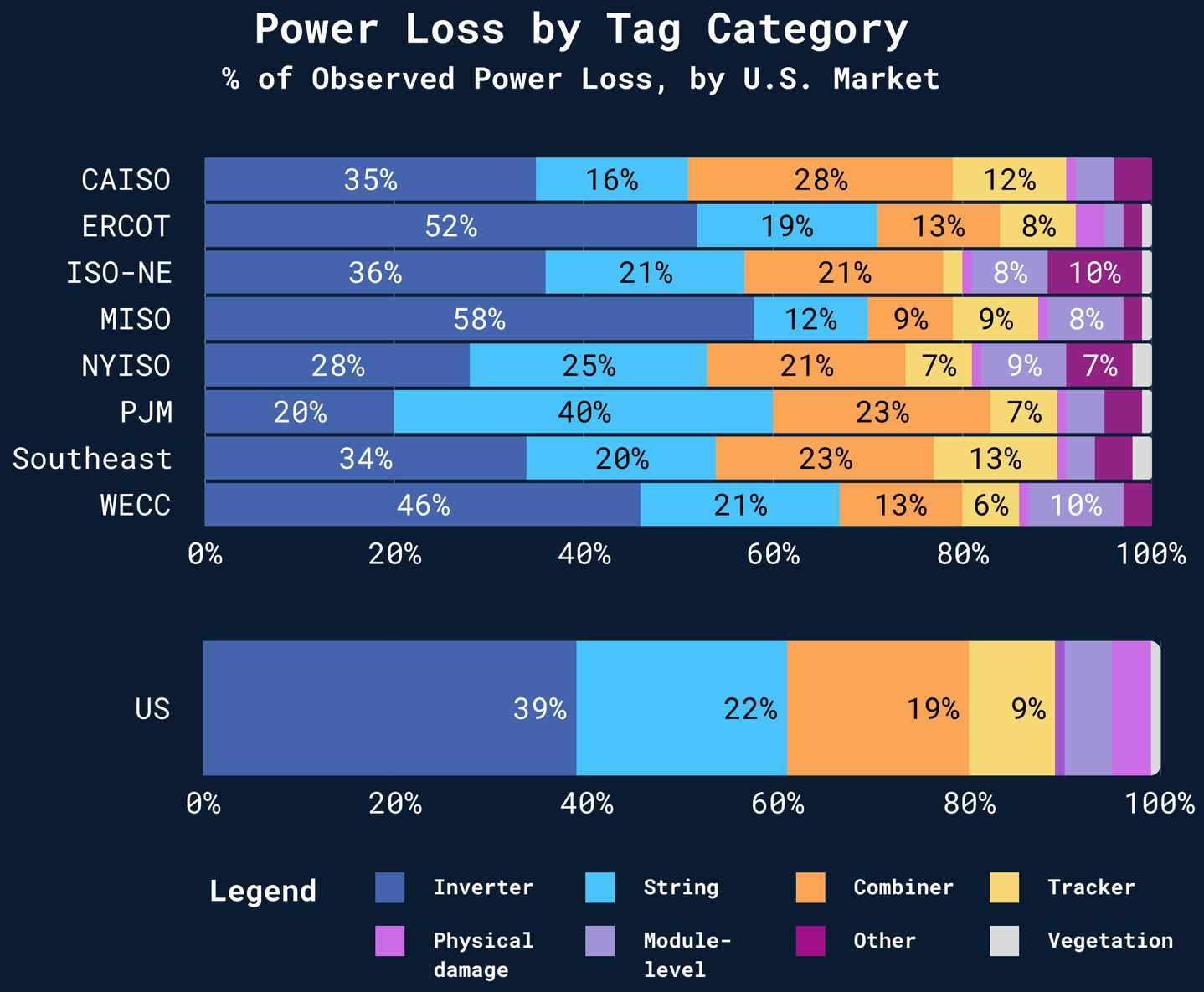
Underperformance increased over the past five years (2020 to 2024) across all U.S. electric power markets, with only ISO-NE assets experiencing a decrease in average underperformance year-over-year when compared to 2023. Underperformance has grown most rapidly in the Southeast market, whereas the ERCOT and PJM markets have consistently experienced higher power loss from DC health issues compared to the dataset average over the past several years.

Average Power Loss by U.S. Market

Last Five Years (2020 - 2024)



2024	PJM	ERCOT	Southeast	NYISO	CAISO	ISO-NE	MISO	WECC
vs 2023	+30%	+18%	+3%	+16%	+28%	-32%	+27%	+6%
vs 2020	+256%	+173%	+318%	+109%	+156%	+73%	+270%	+94%



Raptor Maps Global Solar Report: 2025 Edition

Power Loss Drivers by U.S. Market

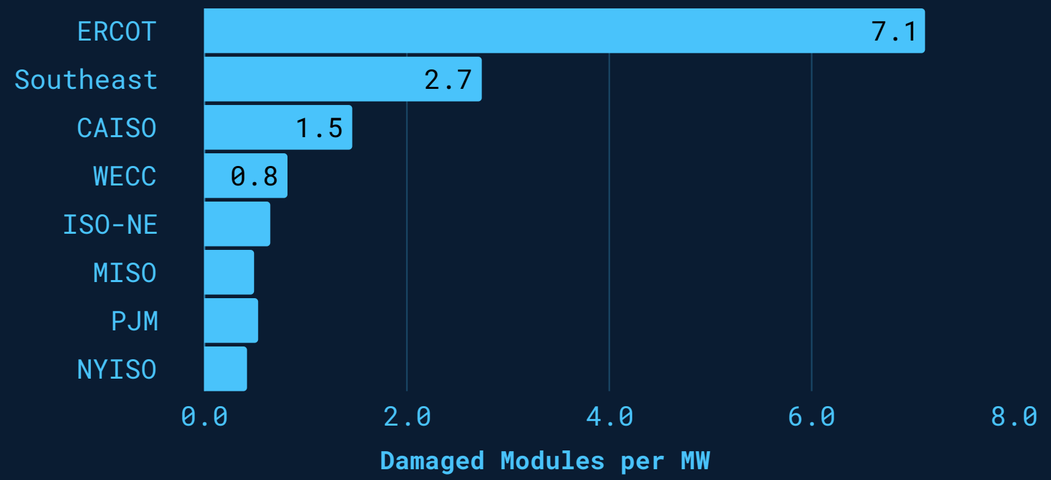
Faults like inverter and string anomalies continue to be the largest drivers of power loss across each U.S. power market, but there is **wide variance in the impact of each equipment on site power loss** across power markets. This emphasizes the importance of accurately diagnosing issues to drive efficient remediation.

For example, the average asset in the U.S. in CAISO or the Southeast experienced more power loss from tracker issues compared to other markets, whereas the average asset in markets with smaller average asset capacities, such as NYISO and ISO-NE, has higher power loss from module-level issues compared to the U.S. average.

Notably, **ERCOT exhibits higher rates of physical damage compared to other regions**, with 3% of total power loss attributed to physical damage compared to the dataset average of 1%.

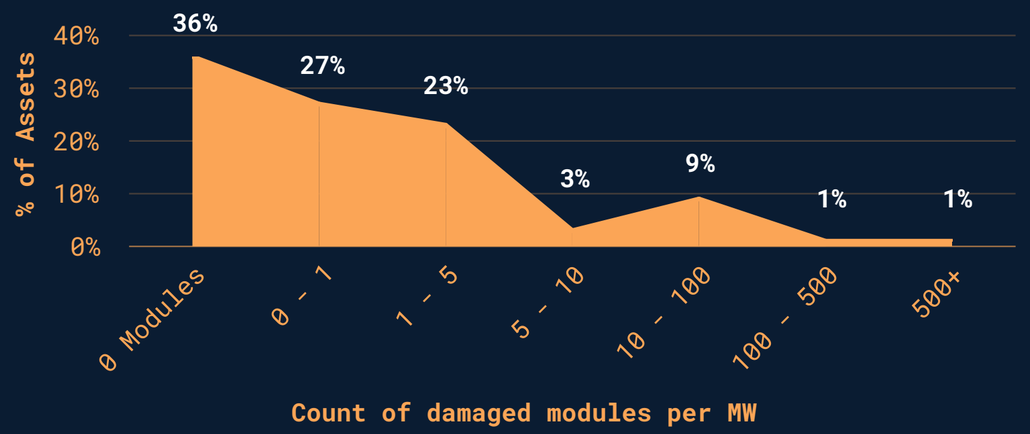
Average Frequency of Damaged Modules per MW

2024 Data, adjusted for outliers



Damaged Modules per MW, Frequency of Assets

2024, ERCOT data (includes outliers)



Approximating the Risk of Weather-driven Damage by Market

While the exact reason for module damage can vary (from installation errors to foul balls from the nearby baseball field), weather is one of the most significant drivers of module damage. Measuring the average number of damaged modules tagged per megawatt allows Raptor Maps to approximate extreme weather risk by market.

Storm-prone markets, ERCOT and the Southeast, are far more likely to experience damage to their equipment, occurring at **16x and 6.5x, respectively, the average damaged modules per MW in the market with the least physical damage per MW** (NYISO) - even after adjusting for outliers.

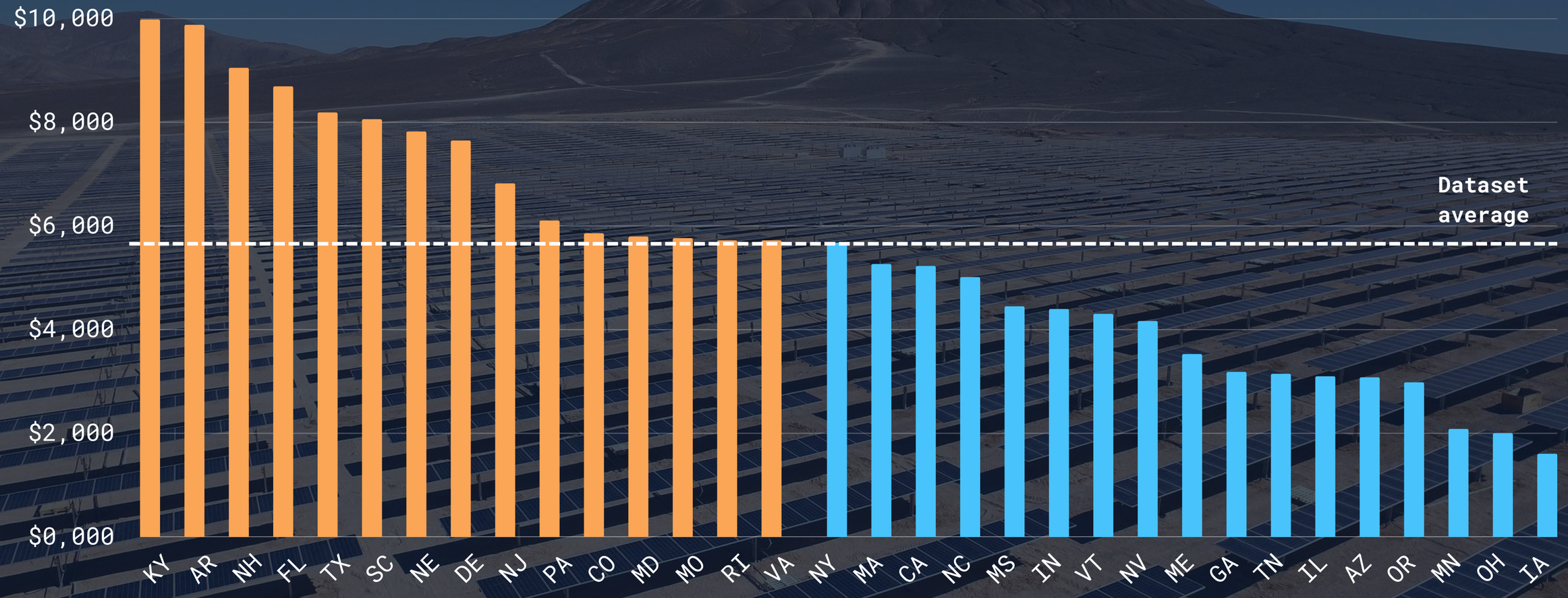
Notably, ERCOT is one of the primary solar markets where hail risk is prominent and is also exposed to tropical storms and hurricanes, reflected by a prominent focus on extreme weather risk mitigation strategy for owners and operators in ERCOT. A dive into Raptor Maps' 2024 inspection data from ERCOT reveals that extensive damage from hail and other storms is not guaranteed, but the potential magnitude of damage can be significant. Moreover, cracks can propagate over time and increase the risk of failure or fire, making frequent post-storm inspections important. Fortunately, innovation in the industry has continued to show strong results in mitigating and managing risk in hail-prone regions.

As the industry is deeply familiar with, climate change will continue to exacerbate extreme weather risk, increasing both the severity and the frequency of high-severity events. For example, a 2024 study found that the smallest hailstones are expected to decrease in frequency by an average of 25% while **the largest hailstones are expected to increase in frequency by 25% to 75%, depending on the emissions pathway** [1]. Such projections point to a need for continued evolution in managing weather risk and systematizing best practices across the fleet.

[1] Gensini, Vittorio A., et al. "Hailstone Size Dichotomy in a Warming Climate." Npj Climate and Atmospheric Science, vol. 7, no. 1, Aug. 2024, https://doi.org/10.1038/s41612-024-00728-9.

Annualized Revenue Loss per MWdc

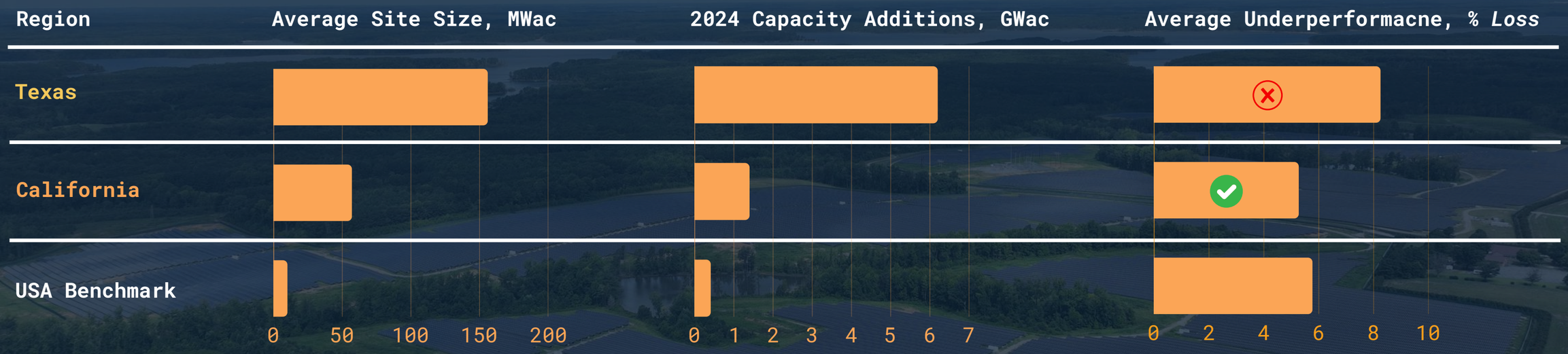
2024 Average by U.S. State



The analysis above excludes states with small volumes of data after adjusting for outliers. Even after adjusting for outliers and sample size, Raptor Maps is observing a wide variance in average underperformance across the different U.S. states, including across top solar states such as Texas and California.

Spotlight: Texas and California, Top Solar Markets

In 2024, Texas and California continued to dominate the U.S. solar market, setting benchmarks for growth and capacity. Analyzing trends in these two states through the lens of Raptor Maps' dataset provides valuable insights for stakeholders looking to understand the performance and scale of these leading regions. **As of November 2024, Texas had installed 37.7 GW of solar energy, rapidly closing the gap with California's 49.8 GW—the largest total in the nation** (SEIA, 2024).



Texas Key Stats:

- Average site size with 2025 COD is 156 MWac
- Average size size of projects under construction Is 197MWac
- Texas added 6.2GWac of C&I and utility solar capacity across 51 projects
- Texas' rate of underperformance was 8.25%, 42% above the national average

California Key Stats

- Average site size with 2025 COD is 57 MWac
- Average size size of projects under construction Is 47MWac
- California added 1.4GWac of C&I and utility solar capacity across 60 projects
- California's rate of underperformance was 5.27%, ~10% below the national average

Conclusion

With global capacity surpassing 2 terawatts (TW) just two years after reaching 1 TW, **leading players are now embracing automation, software-driven diagnostics, and robotics** to combat operational challenges and ensure long-term cost competitiveness. By integrating these technologies, industry leaders are setting the standard for the future of solar energy.

Key trends in this report:

- **Rising Power Loss:** Equipment-driven underperformance resulted in annual losses of $5,720 per MWdc in 2024, up 15% from 2023 and 214% over the past five years. Addressing these inefficiencies is crucial to increasing project returns and continuing to bolster a newly robust industry.
- **Labor Shortages and Costs:** The industry's workforce is not growing fast enough to meet the rising demand, with O&M costs increasing due to wage inflation. To counteract these pressures, top operators are leveraging performance intelligence to optimize squeezed resources and reduce manual tasks.
- **Automation and Technology Adoption:** The most successful solar asset owners are turning to aerial inspections, remotely operated robotics, and advanced analytics to pinpoint and resolve critical performance issues efficiently. High-priority defects account for 90% of revenue loss, making targeted, data-driven maintenance strategies a necessity.

About Raptor Maps

Raptor Maps' platform integrates with remotely operated robotics to automate tedious investigative work and repetitive manual tasks, enabling teams to focus on high-impact remediation while optimizing resource deployment. Rapid, on-demand analytics provide precision intelligence for asset owners and operators to reduce costs, mitigate risks, and boost project performance. As the pioneer of robotics-augmented solar operations, Raptor Maps is transforming how solar companies build, manage, and operate their assets.