Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar:

Findings and Recommendations for Resilient PV on Guam

James Elsworth, Otto Van Geet, Charles Kurnik, and James Salasovich

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-89629
November 2024

Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar:

Findings and Recommendations for Resilient PV on Guam

James Elsworth, Otto Van Geet, Charles Kurnik, and James Salasovich

National Renewable Energy Laboratory

Suggested Citation
Elsworth, James, Otto Van Geet, Charles Kurnik, and James Salasovich. 2024. *Solar Photovoltaic (PV) Damage Assessment After Typhoon Mawar: Findings and Recommendations for Resilient PV on Guam*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-89629. https://www.nrel.gov/docs/fy25osti/89629.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-89629
November 2024

National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Navy and U.S. Marine Corps. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free via www.OSTI.gov.

Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

NREL prints on paper that contains recycled content.

List of Acronyms

DOD	U.S. Department of Defense
GPA	Guam Power Authority
NREL	National Renewable Energy Laboratory
NWS	National Weather Service
O&M	operations and maintenance
PV	photovoltaics
SEAOC	Structural Engineers Association of California
UFC	Unified Facilities Criteria
UV	ultraviolet

Photo Credits

All photos taken by James Elsworth, Otto Van Geet, or Chuck Kurnik , National Renewable Energy Laboratory. Used with permission.

Executive Summary

A team from the National Renewable Energy Laboratory (NREL) visited Guam in August 2023 to assess failure modes of solar photovoltaic (PV) systems as a result of Category 4 Typhoon Mawar and to provide recommendations to increase the resilience of PV systems on Guam. The team visited 30 systems, all commercial and utility scale, comprised of rooftop, ground-mounted, and canopy/carport systems. The team observed systems with no apparent damage, as well as systems that were completely lost. Systems fared very well overall. The average damage to rooftop systems was 18%, with a median of 2%, meaning that few systems suffered total loss. Only 8 of the 25 rooftop systems suffered more than 5% damage. All ground-mounted systems suffered less than 0.5% damage. One carport had 16% damage. PV systems at Andersen Air Force Base suffered 5% damage on average, with a median of 0.6%. In almost all cases, damage was the result of:

- Inadequate clamping of the module frame to the mount.
- Module mounting clamps rotating out of underlying support rail (i.e., T-bolt that rotates free at less than 60° of rotation), possibly a result of inadequate clamping.
- An object hitting the panel resulting in a fracture, and in some cases leading to a cascading failure of several more panels.
- High wind loading as a result of excessive tilt angle (in Guam, greater than 5° can be a risk due to wind speed, and power production trade-offs are insignificant).

Figure ES-1. The most common failure modes, clockwise from top left: (a) Inadequate clamping of module frame to mount, leading to cascading failure. Module mounting clamps in this case rotated out of the support rail and can be seen on the roof in (b). (b) Undamaged module clamps remaining on roof surface after they rotated out of the racking and released modules. (c) Module damage from debris impact. (d) Modules that released from the mounting system. (e) System with excessive tilt angle.

Notably, the team saw no clear evidence of modules failing due to direct high wind loading; no modules were blown out of their frame or clearly failed due to overloading and not impact.

Systems that performed best exhibited the following characteristics:

- Mounted very close to the roof. On flat roofs, these systems tilt 2°–5° to allow for water drainage.
- Used clamping systems with a larger bearing surface.
- Used direct bolting of the modules to the racking or used clamping systems that use a "T"-bolt that must rotate 90° to come free from racking, rather than bolts that can rotate free with less rotation.

There were a range of failure modes, with clear root causes for each. In most cases, addressing these root causes in design and assembly would be relatively simple and would not have incurred significant additional project costs.

Systems with different features had drastically different fates, even when exposed to the same wind conditions. Some systems were totally destroyed at significantly lower wind speeds than other systems that survived unscathed; on two occasions there were side-by-side examples of this. A key finding from this trip is that **the characteristics of a system, and not the wind speed, primarily determined whether a system survived**.

Many PV systems that the assessment team visited fared well after Typhoon Mawar. There were many well-built systems and many good designs. We recommend continuing many current practices and modifying select practices as called out in this report.

The top, high-level recommendations from this trip for avoiding storm damage to solar PV systems are:

- Where possible, install ground-mounted systems low to the ground, with fixed and low tilt angles, with front and rear support posts, and cross bracing.
- Avoid high module tilt angles; aim for 5° or lower.
- Install systems as low to the ground or roof as feasible, while considering vegetation management, installation, and maintenance access.
- Through-bolt modules to the racking if feasible, using washers large enough to prevent bolt tear-out.
- If using top-clamp module attachments, use clamps with greater clamp surface area that cannot easily rotate out or pull out of the racking (see Module Attachments section for specifications).
- Tighten all system bolts to specified torque and perform a torque inspection annually.
- Use locking hardware on bolted joints to prevent loosening. Do not use split washers, even though they are commonly called "lock washers."
- Do not install PV modules in roof corner zones on roofs without parapets (see Overall System Considerations (Not Related to Specific Components) section).
- Remove objects from roof or site that could become flying debris and crack module glass.
- Systems should be permanently fixed to rooftops; they should not employ ballasts alone.

A full list of findings, recommendations, prevalence of each failure, and priority sorted by the number of systems impacted is given in Table ES-1. Additional observations and recommendations not related to specific observed failure modes caused by the typhoon are given in Table ES-2.

Table ES-1. Failures and Recommendations by System Component Observed After Typhoon Mawar on Guam, Sorted Based on Priority, as Determined by the NREL Assessment Team

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority [1]
Module clamps rotated out of racking	Through-bolt modules to racking, if feasible. If using clamps, clamps that directly bolt into rails rather than sliding into slots are preferred. If using slotted rail clamps, ensure clamps do not release from racking with less than about 90° of rotation.	Module attachments	Top clamps	3	High
Clamp loosening and releasing modules	Tighten all bolts in accordance with specifications. Ensure installers use a calibrated, digital, manual torque wrench and are trained in its use. Perform torque inspection annually. Use locking hardware on bolted connections.	Module attachments	Top clamps	1	High
Module clamps released modules	If using top clamps, either use a continuous clamping system (down the entire length of the module frame) or select top clamps that each have at least 0.4 in^2 of contact area with the module frame.	Module attachments	Top clamps	2	High
System high tilt angle/high side of racking high off roof/ground	If roof has at least 5° pitch, install flush with roof at a low height. Otherwise install PV system at around a 5° pitch, or at as low of an angle as is feasible for installation, maintenance access, and to prevent pooling water after rains.	Racking	All	3	High
Progressive failure due to shared clamp failure	Through-bolt modules to racking, if feasible. If using clamps, use clamps that hold adjacent modules individually (they do not require clamping force from one module to hold adjacent module).	Module attachments	Top clamps	7	High
Racking rails bent, damaged	Select racking elements of thicker gauges that provide both lateral and longitudinal support. Avoid systems that only support modules along one axis (laterally or longitudinally). These racking systems can impart extra loading onto the modules that exceed design limits. Cross bracing is ideal.	Racking	All	6	High
Module bolt or clamp pull out of racking	For through-bolted systems, use larger washers to increase surface area and grip length. For top clamps in slotted rails, select clamps that have adequate contact area between the clamp and rail slot (at least 0.2 in^2 per clamp recommended).	Module attachments	All	2	High

[1] Priority for inclusion in DOD project requirements in Guam and other tropical storm-prone locations. Priority was determined by the NREL site assessment team using their judgement and experience. Determination factored in prevalence of this failure observed on this trip, likelihood of this failure occurring on future systems, and potential loss should failure occur.

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority [1]
Wire management – cables on roof	Do not use wire ties for wire management. Use robust, purpose-built PV wire routing systems that are more durable and hold wires more securely than wire ties.	Wire management	All	8	High
Designed/installed by inexperienced people	Use only experienced PV designers and installers. Ensure they follow all local codes, installation manuals, and the as-built system is consistent with the approved design.	Construction	All	1	High
Adhesive failure	Ensure solar arrays are physically anchored to roof or ground.	Racking	Adhesive	1	High
Unknown quality of modules and racking – no marks on them, not traceable	Ensure components meet codes and standards and are purchased through reputable, established manufacturers and vendors, and that components have traceability back to their source.	System	All	1	High
Modules were mounted high above the ground and encountered higher wind speeds	Mount modules as close to the ground as good system design allows.	Racking	All	1	High
Damage in corner zones near roof edges – Structural Engineers Association of California (SEAOC) Zone 3	Do not install modules in SEAOC roof Zone 3.	System	All	3	Medium
Modules not attached at recommended locations on module; thus, full load rating of module not achieved	Follow solar module installation manual's guidance for location and number of module attachments.	Module attachments	All	3	Medium
Through-bolt tear-out through module frame	Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out. Select modules with predrilled holes that are not near the edge of the frame flange. Use wide-diameter washers (at least 0.688-in. outer diameter) for more clamp area and thicker washers (at least 0.125-in. thick) to lengthen the bolted attachment. Alternatively, add a metal plate between the bolt and frame to distribute the load.	Module attachments, modules	Through-bolts	1	Medium

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority [1]
Bolt tear-out in racking	Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out.	Racking attachments	All	1	Medium
Bolt slip in slotted connections in racking joints, possibly after bolt loosening	Ensure bolt is designed to provide enough clamp force to resist movement. Use locking hardware to prevent loosening. Consult a bolted joint engineer if uncertain.	Racking attachments	Ground-mounted	1	Medium
Debris impact – cracked module glass	Clear rooftop or surrounding area of objects that could become flying debris. Select modules with tempered glass at least 3.2-mm thick.	Modules	All	10	Medium
Loose nuts	Use locking hardware such as an ultraviolet (UV)-rated nylon-insert nuts.	Racking	All	3	Medium
DC surge protector damaged	Clear roof drains to avoid flooding that can damage DC surge protectors. Follow electrical enclosure recommendations in this report—NEMA 4X plus additional requirements. Consult PV service provider or local installer for repair.	Electrical	Rooftop	2	Medium
Water damage inside electrical boxes, batteries, or inverters	Specify NEMA 4X enclosures in Guam. NEMA 4X in Guam alone is not sufficient. All exterior housings must be continuously welded, NEMA 4X (or better), fully gasketed, continuously hinged (piano hinge) with three-point door closure clamps, and designed to prevent water intrusion from hose-directed water, splashing water, and wind-driven rain. Gaskets must be molded and of one continuous shape with no seams. All equipment mounted to the interior of the enclosure shall use back plates to minimize exterior cabinet penetrations. Conduit entry into electrical equipment shall be designed to prevent water intrusion. The minimum mounting height of enclosures shall be based on the 500-year flood plain and surge levels.	Electrical	All	2	Medium
Debris impact – racking damage	Clear rooftop or surrounding area of objects that could become flying debris.	Racking	All	1	Medium
Modules bent and sagging	Ensure all racking has cross members and supports both lateral and longitudinal movement of the panels. Modules and module frames should not bear loads imparted by the racking.	Racking	All	1	Medium
Module bolt tear-out on carports	Use all available module attachment points on carports systems and other systems where modules are high above the ground or roof surface.	Module attachments	Carports	1	Medium

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority [1]
Module cracked glass – no impact	Rare and unclear failure mode. No recommendation provided. Follow current practices.	Modules	All	2	Low
Roof anchors pulled up from roof structure on flat concrete roof	Rare failure mode—no additional recommendations. Follow current practices.	Racking	All	1	Low
Clamp separation	Consult a bolted joint engineer in system design. Likely a secondary failure mode in this case.	Racking attachments	Ground-mounted	1	Low
Inverter covers blown off	Secure string inverter covers with redundant, locking hardware.	Electrical	All	2	Low
Missing modules	Most likely the result of module attachment failure—see module attachment recommendations.	Module attachments, modules, racking	All	13	N/A-result of other failure modes

Table ES-2. Issues and Recommendations for Quality PV on Guam That Are Not Directly Related to Observed Typhoon Damage

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Systems poorly maintained	Engage in a third-party service contract.	System	All		High
Dynamic loading induced failures	Ensure racking system is designed for dynamic and not just static loading. Racking should be stiff enough so that wind loads do not easily excite resonant frequencies. This requires dynamic loading design not typically performed on PV systems. Guidance for dynamic design can be found in SEAOC PV 2-17.	Racking	All	[a]	High
Large modules are susceptible to higher wind loads	Use smaller panels: 60 cell, 120 half-cut cell, or equivalent is preferred and strongly recommended for rooftop. These modules are typically about 1.7 m, or 67 inches, long. Do not use "large-format" modules that are longer than approximately 2.0 m (79 in.) and rated at 500 W or higher for any PV systems on Guam.	Modules	All	0	High
PV trackers do not fare as well in high-wind locations	Do not install PV trackers on Guam.	System	All	0	High
Vegetation management	For ground-mounted systems, ensure regular vegetation management. Plant disturbed areas with low-growing grasses or other ground cover plants.	System	Ground-mounted	2	Medium
System inaccessible	Ensure all PV rooftop arrays are easily accessible, ideally via an external ladder. Relying on construction lift access is too unreliable. String inverters should not be mounted on roofs (microinverters may be mounted under panels). They should be mounted at ground/eye level. They should be shaded from direct sun exposure at all times of the year and regularly monitored for error codes (recommend monthly). If in a locked room, facility staff performing PV operations and maintenance (O&M) should have a key to access.	System	Rooftop		Medium
Corrosion	Use marine-grade stainless steel hardware in Guam.	Module attachments, racking attachments	All	3	Medium
Snail trails	Check modules for 'snail trails' defects and discoloration and file warranty claim if significant.	Modules	All	3	Medium

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Split washers not providing locking ability	Do not use split washers for locking capabilities. Although commonly called "lock washers," they do not resist vibrational loosening.	Module attachments, racking attachments	All	1	Medium
PV systems on Guam did not use any wind deflectors	Install wind deflectors on the high side of PV arrays between the roofs and panels.	System	All	0	Medium
Modules too low of a slope – water ponding or muck buildup	Ensure slope is high enough for water to shed and wash off algae and other “muck.” 4° appeared adequate based on observations from this trip, though a local installer recommended 10° due to persistent algae issues they have experienced.	Design, construction	All	2	Low
Melted PV connectors	No recommendation. One instance, unknown root cause.	Electrical	All	1	Low

[a] The impact of this cannot be conclusively determined from a post-event assessment.

Table of Contents

List of Figures

List of Tables

Introduction

In May 2023, Category 4 Typhoon Mawar struck Guam, causing major damage throughout the island. Typhoon Mawar had sustained wind speeds up to 140 mph, and a majority of the storm damage was caused by high winds, flying debris, flooding caused by torrential rains and storm surge (up to 14 feet), and the fact that the typhoon was slow moving and brought extended wind and rains, totaling 1.5–2 feet over much of Guam. The electrical power grid and potable water systems were not fully restored on the island for 4 to 6 weeks after the typhoon, and the storm caused approximately $250 million USD of damage.[2]

The National Weather Service (NWS) provided details on Typhoon Mawar, including storm categories and associated wind categories throughout the island. Figure 1 shows the wind categories throughout the island during Typhoon Mawar. These wind categories were determined from a storm impacts analysis conducted 2 weeks after the typhoon by a survey team and from images captured via drones. This was the most accurate method, as most wind sensors across the island failed. As shown, the north experienced the highest wind speeds and the lowest wind speeds were in the south, ranging from a high Category 4 typhoon in the north to a tropical storm in the south.

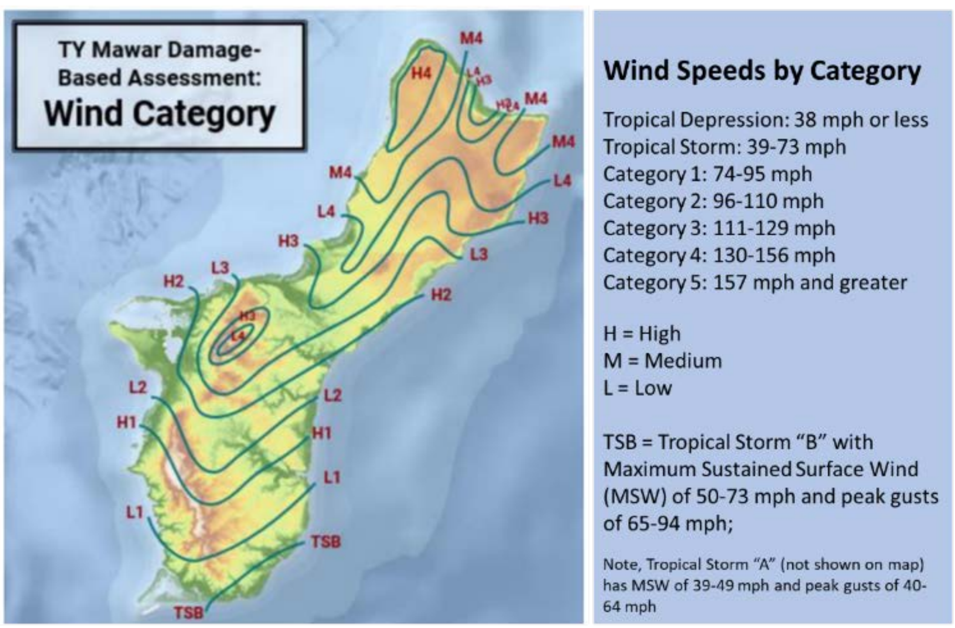


Figure 1. Typhoon Mawar wind categories on Guam.

Source: NWS

A team from the National Renewable Energy Laboratory (NREL) conducted post-storm assessments of various solar photovoltaic (PV) systems 12 weeks after Typhoon Mawar (Aug. 14–18, 2023) to identify common failure modes found in damaged or destroyed PV systems and to identify preferred design and construction practices in PV systems that experienced little to no storm damage. It was key to have the NREL team travel to Guam as soon as possible after the typhoon to collect data before the cleanup and repair process progressed, while also working

[2] "Global Catastrophe Recap First Half of 2023". Aon Benfield Analytics. September 2, 2023.

with site staff to ensure the NREL staff did not arrive too soon, which could have hindered essential recovery efforts.

NREL has core capabilities in evaluating solar PV systems from both a techno-economic and a storm-hardening perspective. The NREL team that conducted the post-storm PV assessments has done similar assessments after hurricanes Maria, Irma, Florence, Dorian, and Ian, as well as other non-named wind events. The NREL team has also collaborated closely with Joint Region Marianas to provide PV storm-hardening draft language for an update to the *Marianas Navy and Marine Corps Design and Construction Standard*s (MDACS). The NREL team leveraged this prior knowledge while conducting PV assessments on Guam.

General Background on Guam

Guam is a relatively small island of 212 mi^2, and the terrain varies from coastal beaches to densely forested mountainous regions. Guam is relatively isolated, as depicted in Figure 2. As shown, the closest major cities to Guam are Tokyo, Japan, and Manila, Philippines, both of which are approximately 1,600 miles away, and the closest major U.S. city is Honolulu, Hawaii, which is 4,000 miles away. The elevation on Guam varies from sea level to 1,334 feet above sea level, and its latitude and longitude are approximately 13.4°N and 144.8°E, respectively.

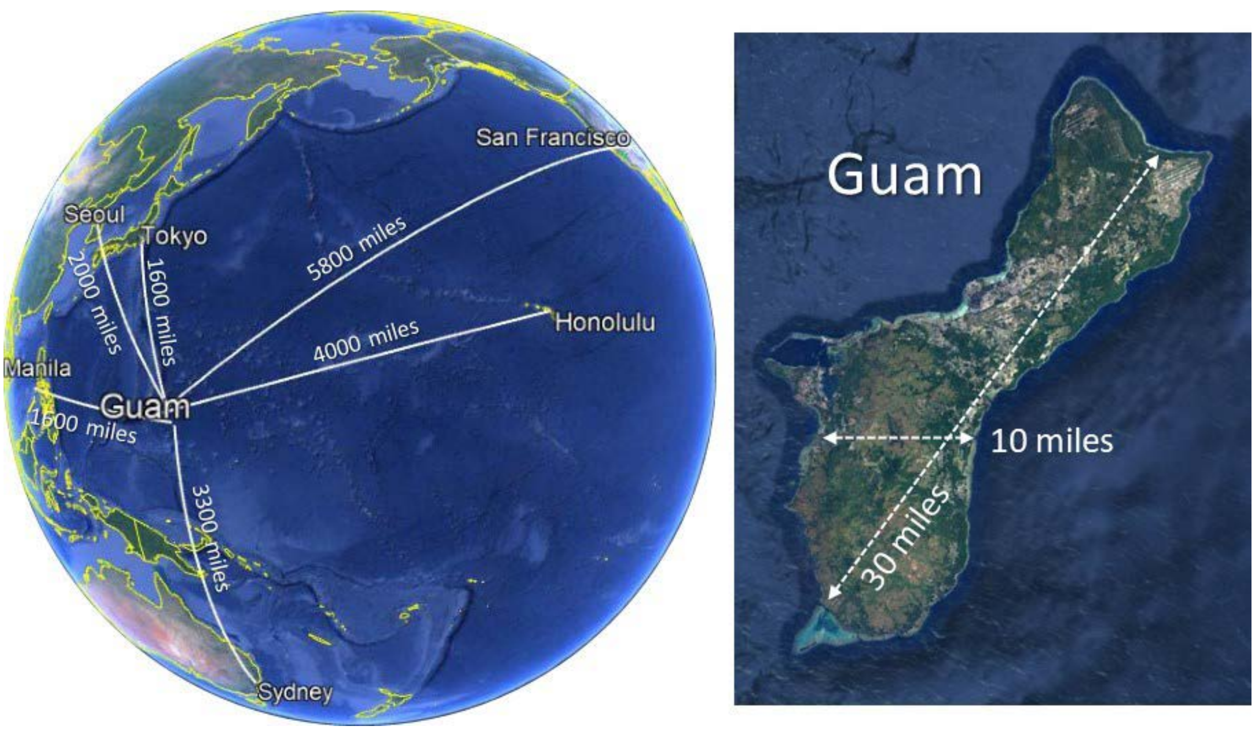


Figure 2. Relative location and size of Guam.

Source: Google Earth

Guam has a very hot and humid climate with little seasonal variation in temperature and is in the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Climate Zone 0A, which is characterized as extremely hot and humid.

Guam has a harsh seawater environment, and building materials and equipment experience high rates of corrosion. Materials selection and anti-corrosion coatings are carefully considered when designing for Guam's environment.

Tropical storms and typhoons are a regular occurrence in Guam. Some of the strongest typhoons to hit Guam include:

- Typhoon Karen, 1962, Category 5
- Typhoon Paka, 1997, Category 5
- Typhoon Yutu, 2018, Category 5
- Typhoon Pongsona, 2002, Category 4
- Typhoon Mawar, 2023, Category 4.

Guam requires more stringent construction standards because of the regular occurrence of tropical storms, typhoons, and seismic events.[3]

Overview of Energy on Guam

Guam Power Authority (GPA) is the sole electricity provider on Guam. GPA has been proactively making improvements to the electricity grid to increase its reliability and to harden the grid to make it more resilient. For example, they have converted almost all the distribution poles on the island to concrete poles. A majority of Guam's electricity currently comes from traditional generation powered by fossil fuels, but GPA is increasing the amount of renewable energy generation, which was 16% of generation in 2023, primarily from around 90 MW of solar power. Electric utility rates in Guam fluctuate between $0.35 and $0.55/kWh, which is 3–5 times the national average in the continental United States.[2,4]

The One Guam initiative, agreed upon by the government of Guam and the U.S. military branches on Guam, ensures that both entities will consider the entire island of Guam when making design decisions. On a relatively small island such as Guam, it becomes apparent that everything is connected, not only on the military installations, but also the greater community of Guam.

Future Energy Goals

GPA is targeting 50% renewable or non-greenhouse-gas-emitting power by 2030 and 100% by 2040 and is mandated to achieve these goals by 2035 and 2045, respectively. Solar PV will likely play a major role in achieving these targets. Given GPA's future energy goals and the fact that storms are increasing in intensity and frequency, ensuring that solar PV systems can withstand typhoons on Guam is essential.

---

[3] C.S. Mueller, K.M. Haller, N. Luco, M.D. Petersen, and A.D. Frankel. 2012. *Seismic Hazard Assessment for Guam and the Northern Mariana Islands*. Reston, VA: U.S. Geological Survey. Open-File Report 2012-1015. pubs.usgs.gov/of/2012/1015/.

[4] https://www.eia.gov/

PV System Components Overview and Vocabulary

This section is included to provide background on solar PV system components and vocabulary that will be used throughout the report. This is intended to provide background and a reference to those less familiar with solar PV systems and to provide clarity on what specific terms in this report refer to; certain words are used inconsistently with PV, such as "panel" and "frame." This section is broken down into system level, structural, and electrical sub-sections.

Power Generating System

Solar photovoltaic cells convert light into electricity. Cells are grouped together in PV modules. Modules are typically connected electrically in strings. One or more strings can make up a PV array. The array, plus all the other structural and electrical components make up the whole PV system.

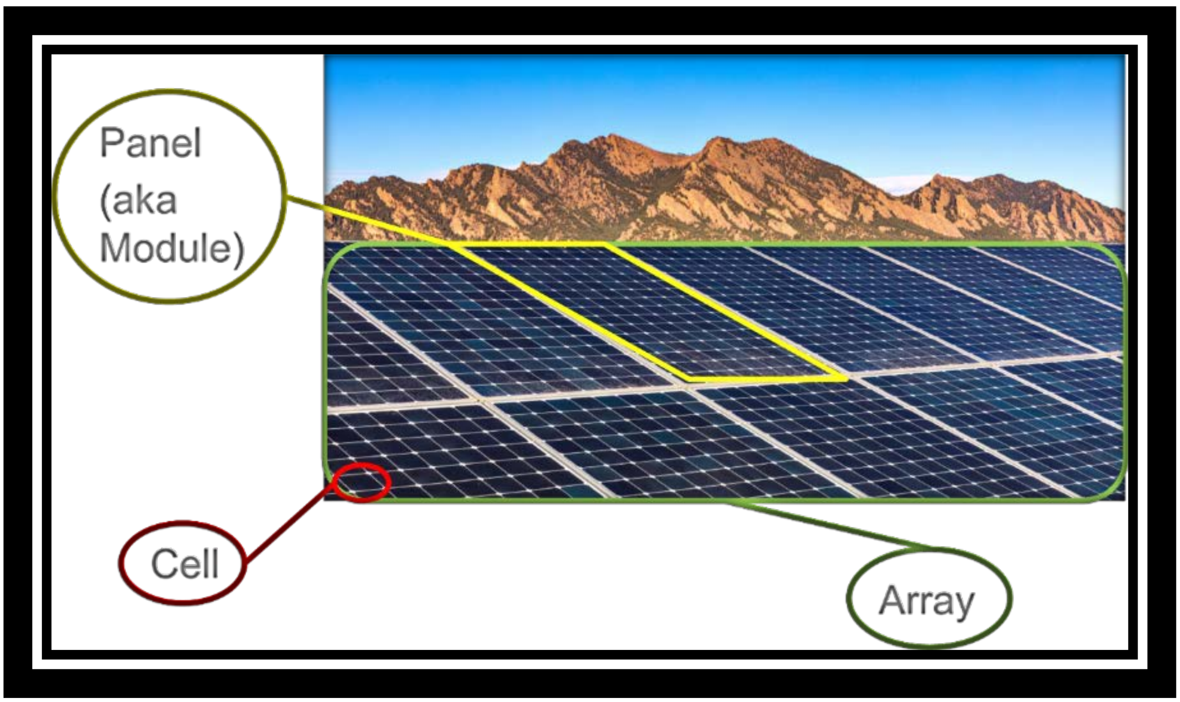


Figure 3. Components of a PV system.

Photo by Dennis Schroeder, NREL

Cell: A single semiconducting element of small size (e.g., 1 cm^2) that absorbs light or other bands of the electromagnetic spectrum and emits electricity.

Module: A unit composed of several PV cells that is the principal unit of a PV array. A PV module's size is on the order of 2 m^2, although its size is governed by convenience and application.[5] Module and panel are used interchangeably.

[5] National Renewable Energy Laboratory. 2024. "Solar Resource Glossary." Accessed April 1, 2024. www.nrel.gov/grid/solar-resource/solar-glossary.html.

Array: A set of modules used for converting solar radiation to energy.[6]

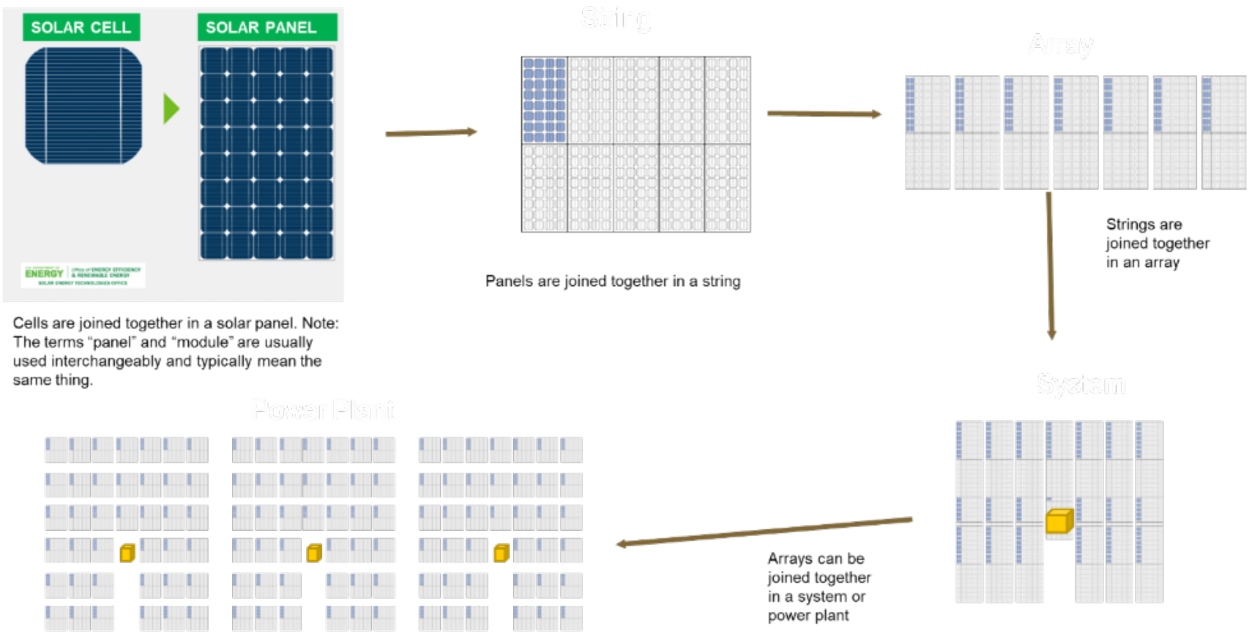


Figure 4. PV systems are modular. The smallest unit is the power-producing solar cell. Several cells (typically 60–72) make up a module. Modules are joined together to make strings. Strings can be joined to make arrays. Arrays can be combined to make power plants.

Image by Andy Walker, NREL

String: Several PV modules (typically 10–20) that are connected in series. Damage to one module or a break in this circuit will take the entire string offline.

System: The entire collection of all the strings of modules, along with all other system components, including structural supports, attachments, and electrical equipment.

Structural

The structural side of the PV system provides support for the PV modules, holding them securely at the designated tilt angle and height. These components are designed to withstand loads from wind, snow (where applicable), and seismic loads.

[6] Ibid.

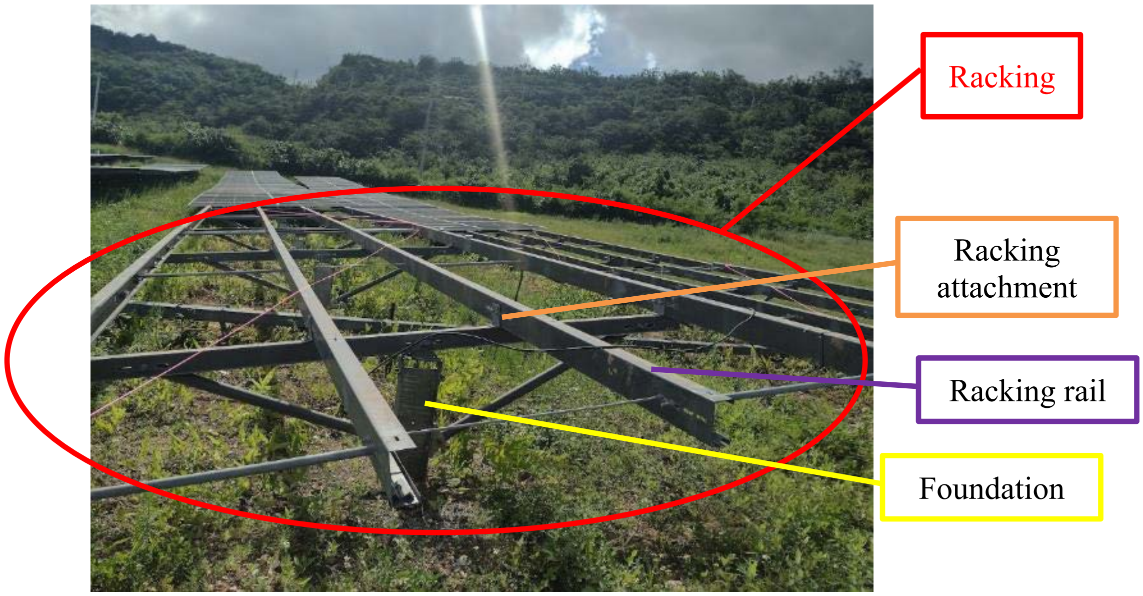


Figure 5. A PV racking system onto which modules are mounted.

Racking: The support system for the PV modules. Often consists of a cross grid of steel rails.

Racking rails: The individual metal pieces that run right-left or up-down underneath PV modules and support them. Different types and shapes of rails are commonly used, including C-rails, Z-rails, and hat channels, as well as square stock.

Racking attachment: A fastener that holds different pieces in the racking system together. These are typically some type of bolted joint.

Foundation: On ground-mounted systems, the structure embedded in the ground to which the racking is attached.

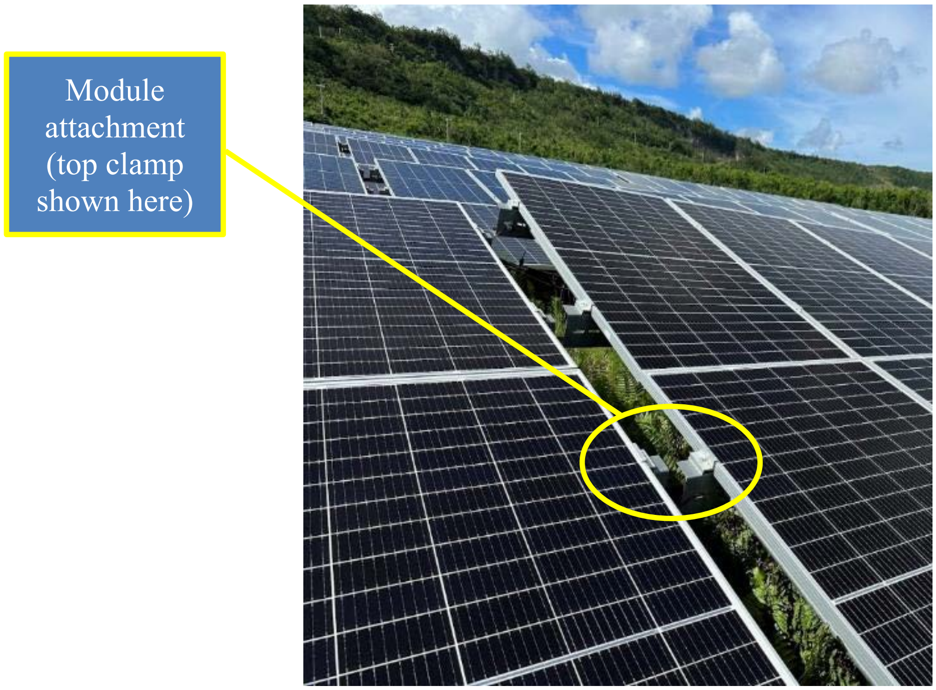


Figure 6. Example of a module attachment.

Module Attachment: A physical device that connects the PV modules to the racking, typically either a clamp or a bolt.

Module clamps/top clamps: Clamps that hold the modules down to the racking through the application of clamp force. These clamps typically hold the top metal frame of modules through a bolted connection to the racking rail.

Through bolts: Bolts that attach through a predrilled hole in the module frame and directly to the racking.

Module Frame: The metal around the edges of a PV module, typically aluminum. The frame surrounds the sides of a PV module, extends slightly over the top of the module, and has a flange lip that extends underneath the module (with a gap between the power producing components and this lip).

Roof anchor: A physical, structural connection that penetrates a roof surface to which the racking or support structure is attached.

Electrical

The electrical system carries the current produced by PV modules to whatever will use it—a building, the grid, or a battery, for example. PV modules produce direct current (DC) that has to be converted to alternating current (AC) to power most devices.

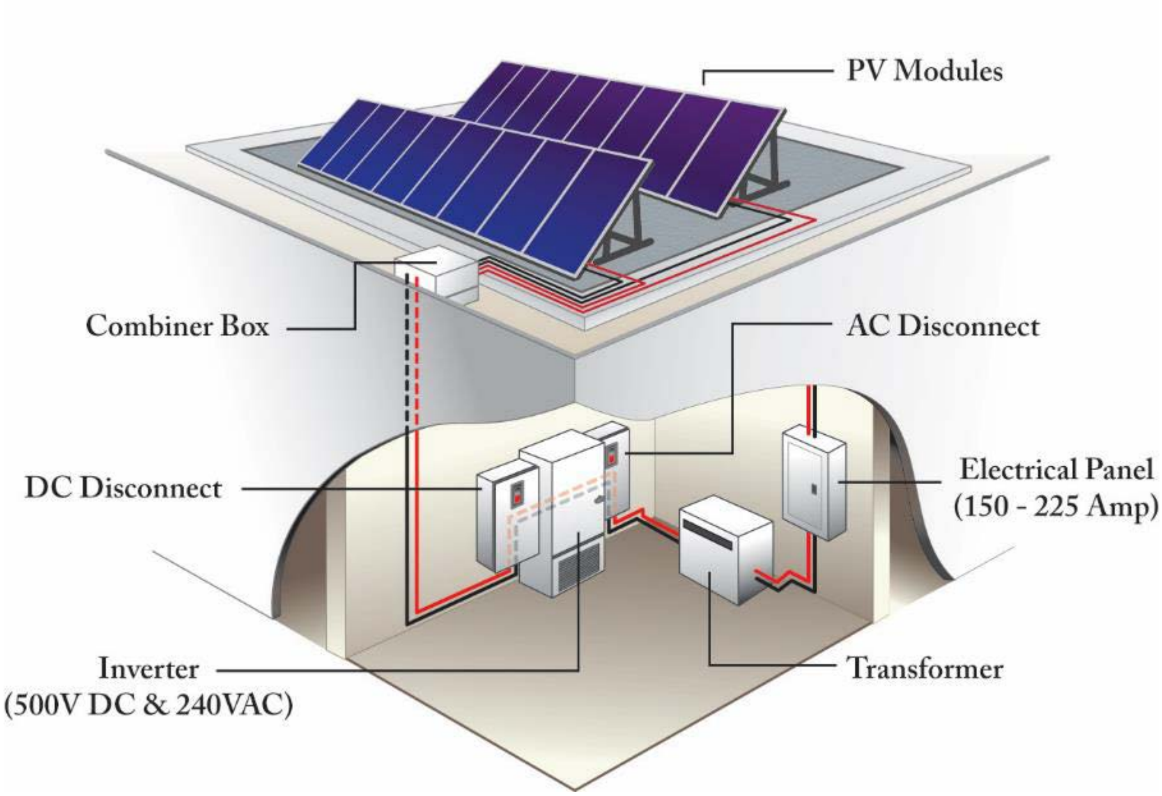


Figure 7. Electrical components of a PV system. Image by Jim Leyshon, NREL.

Inverter: A device that converts DC power to AC power. PV modules produce DC power.

Combiner Box: An electrical enclosure in which power from individual strings are combined.

PV Connector: The electrical connection between individual PV modules. Most PV modules come with PV connectors attached.

Wiring: Electricity is carried from the solar modules to and between the various electrical system components via wiring. Wiring should be routed and managed for save operation that will hold in place over the lifetime of the PV system and not leave wiring susceptible to water damage.

Summary of Findings

The assessment team visited 30 commercial-scale PV systems. Four were ground-mounted, one was a carport/canopy, and the remaining 24 were rooftop systems. They ranged in size from 15 kW to 60 MW.

There is clear evidence that PV systems can survive extreme wind and rain events such as Typhoon Mawar if they are designed and installed well. Poorly designed and installed systems fared worse. There was a wide range of damage across PV systems visited, from systems that appeared totally intact to systems that were a total loss. Systems exposed to the same conditions had different fates, showing **that the characteristics of a system, and not the wind speed, primarily determine whether a system will survive.**

Because robust design and installation should lead to high survival rates of PV systems on Guam, additional external protections to catch PV system debris are not a necessary or financially viable solution. The *Marianas Navy and Marine Corps Design and Construction Standards* (MDACS) currently recommends chain-link fences surrounding and over the top of solar installations to prevent solar panels from flying loose and damaging other property. We do not recommend fencing or other structures installed over solar arrays. The chain link can shade the panels, leading to decreased production and possible hot-spot safety issues, and constructing these enclosures will be expensive. Well-designed and installed PV systems should not release any PV modules unless they are impacted by external flying debris.

Overall Failure Rate

This trip focused on assessing the structural damage that occurred to solar PV systems from Typhoon Mawar on Guam. This damage occurred to the modules, racking, and attachments on the systems. To estimate the failure rate on each system, the team determined the percentage of missing modules or modules with broken glass. Results are summarized in Table 1.

Table 1. Average Damage Across 24 Rooftop Systems, 4 Ground-Mounted Systems, and 1 Canopy Structure.

Note: One rooftop system using an adhesive to attach flexible solar to a roof was excluded, as it was completely destroyed and the product is no longer available.

System Type	Missing or Broken Modules	Total Modules	Total Average Failure Rate	Median Failure Rate	Number of Systems
Rooftop	1,160	6,484	18%	2%	24
Ground-mount	544	305,291	0.18%	0%	4
Canopy	15	92	16%	16%	1

These high-level statistics might give the impression that rooftop systems fared far worse. While in general that is true, the damage was focused on a handful of systems that experienced total loss. Of the 24 rooftop systems observed, 17 had less than 5% damage. Ground-mounted systems have the advantage of being lower to the ground with corresponding lower wind speeds. Of the four ground-mounted systems the team visited, two were in the middle and south of Guam and did not experience as high winds as those systems in the northern part of the island. On the one canopy system, the structure itself was undamaged, but modules were blown out of their attachments and damaged by flying debris.

Using missing or broken modules to estimate percentage damage does not always give an accurate representation of total percentage of system assets that were damaged. Racking, inverters, other components, and batteries on some systems make up the remainder of the PV system, all accounting for significant costs. So, using module damage as a proxy for system damage can overestimate or underestimate damage. In the case of the canopy system (Table 1), using module damage as the metric shows 16% damage. In fact, there were 16 missing modules and no other damage. Replacing these modules and fasteners might cost $5,000 on a system with a total cost that might be $250,000, closer to 2% of system asset value. Using module damage can also underestimate total system damage. If the entire racking system needs to be replaced or if inverters were flooded, the total repair costs could be a higher percentage of system value than module damage estimates.

Wind speed does not appear to be a determining factor in how much damage systems suffered (Figure 8). Some systems experiencing gusts above 180 mph had no damage, while other systems that experienced 140 mph gusts were substantially damaged. No correlation between wind speed and damage can be made. This strongly implies that **system design and installation, rather than wind speed, determined the extent of damage.**

The design wind speed for Guam depends on the risk category (RC), which is project dependent. The American Society of Civil Engineers (ASCE) 7 RC II design wind speed is 195 mph, RC III is 210 mph, and RC IV is 220 mph. These design wind speeds have remained the same since at least the 2010 version of ASCE 7. Critical buildings and systems that are relied on for backup power should use a higher risk category. Our assumption is that all systems were designed for 195 mph. None of the systems are believed to have been exposed to gusts higher than 195 mph, and yet some of them still failed.

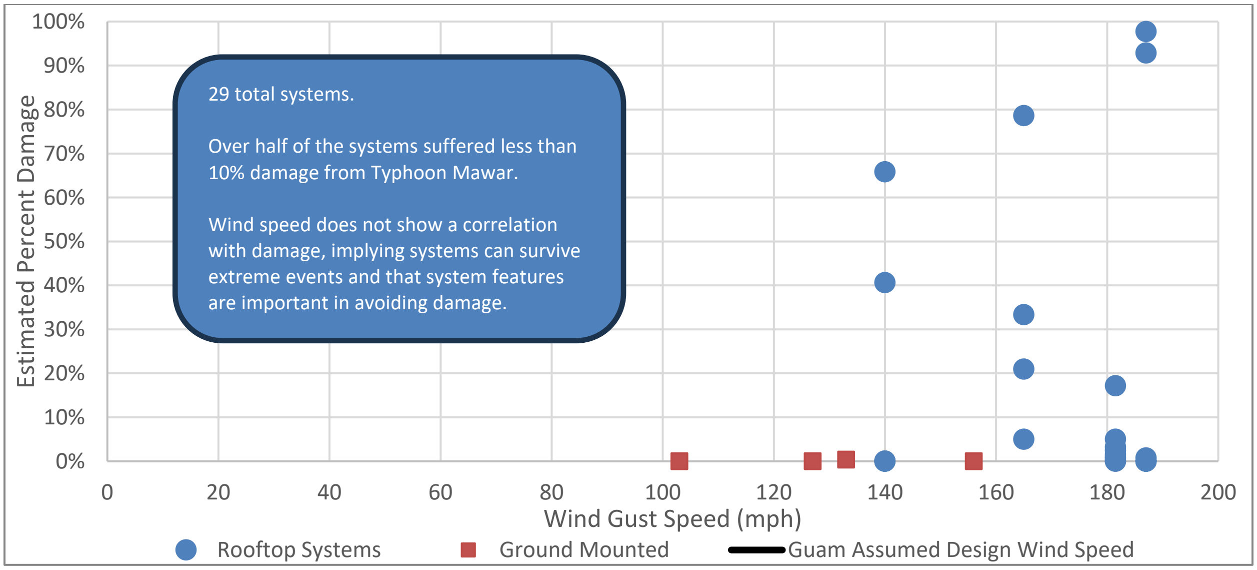


Figure 8. Wind gust speed does not appear to be a determining factor in predicting damage. Attempted curve fits showed no correlation. This implies that system design and installation ultimately determine damage, rather than the wind speed. An NWS post-typhoon analysis estimated wind gust speed. The carport system is not shown here.

The conclusion that system features, and not wind speed, determine damage is supported considering failure rates for each manufacturer of the racking support structures (Table 2). Certain manufacturers and designs fared well, while others suffered much higher damage rates.

Table 2. Failure Rate by Racking Manufacturer for Both Rooftop and Ground-Mounted PV Systems

Rooftop	Missing or Broken Modules	Total Modules	Failure Rate	Number of Sites
Pacific Solar Metgot rail	51	1731	3%	17
Unirac Pro Series T-bolt top-clamp	153	356	43%	3
Everest	7	140	5%	1
PanelClaw	0	44	<1%	1
Uni-solar adhesive	2,064	2,112	98%	1
SolaRacks	859	4,100	21%	1
Unknown manufacturer at Soccer Stadium	92	117	79%	1
Total roof (excluding adhesive)	**1,162**	**6,488**	**18%**	**25**
Ground-Mounted Systems				
Unirac through-bolt ground mount	0	85,299	<1%	2
Powerway	755	219,352	0.34%	1
Unknown east-west	0	640	<1%	1
Custom carport	15	92	16%	1
Total ground mount	**770**	**303,383**	**0.25%**	**5**

In addition to design and installation, operations & maintenance (O&M) may influence survival as well. There was significant evidence that the quality of O&M had a significant impact on power production and system availability, but the assessment team did not have enough detail on or records of O&M to make any conclusions about the impact of O&M on avoiding damage. Furthermore, O&M actions that could impact structural survival, such as regularly checking bolt torque, are not always components of an O&M plan. Even though not necessarily common, regular structural bolt torque audits are strongly recommended in high-wind regions and are one of the most cost-effective damage mitigation measures[7].

Tilt Angle of Solar Modules

Solar modules typically produce the most power when they are tilted so that the plane of the panel is perpendicular to the direct beam radiation from the sun. Annual energy production is maximized by tilting panels to a pitch equal to the latitude of the site. The latitude of Guam is about 13° north. However, annual production is relatively insensitive to deviations from this optimal tilt. Lower tilt angles, as recommended in this report, will likely result in a more robust array that is less vulnerable to damage from wind loads. The authors of this report strongly believe that this benefit far outweighs the minimal decrease in energy production that will result. On Guam, located so close to the equator, these energy losses are less than locations farther from the equator. Table 3 shows that decreasing the tilt angle only leads to slight losses in energy production; decreasing the tilt angle from 13° to 5°, for example, would lead to less than 1% lower energy production annually.

Table 3. Differences in Energy Production from PV at Various Tilt Angles on Guam.

The latitude of Guam is 13°, so this angle will yield the most production, but lower tilt angles do not lead to significant decreases in production. Furthermore, arrays with these lower tilt angles are more likely to survive extreme wind events, which could well make up for the minor decreases in energy production.

Tilt Angle (Degrees to the South)	Expected kWh/kW Annual	Percent Reduction From 10° tilt angle
13°	1,570	0%
10°	1,569	0%
5°	1,558	0.7%
2°	1,547	1.5%
−2°	1,529	2.6%

Figure 9 emphasizes this point for rooftop arrays on roof surfaces with various aspects and pitches, showing that on Guam, mounting panels facing east, west, or even north will not lead to drastic losses in annual energy production. Each concentric square in the figure represents a rooftop of a certain pitch: 10°, 20°, and 30°. Within each square, the optimal production would occur for arrays facing south. For east-, west-, and north-facing aspects, the percentages of that optimal southern-facing annual production are shown.

[7]Elsworth, James and Otto Van Geet. "Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience. June 2020. https://www.nrel.gov/docs/fy20osti/75804.pdf

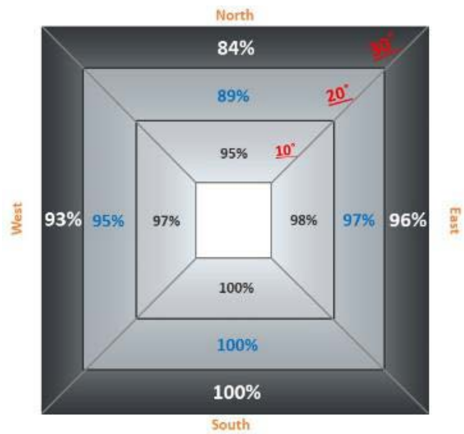


Figure 9. Illustration showing PV annual energy production on Guam for different aspects (north, south, east, and west) for different roof pitches (10°, 20°, and 30°).

Illustration by James Salasovich, NREL

Detailed Findings

Top Failure Causes and Recommendations

Failure modes and causes are described in more detail in the following sections, focused specifically on the different system components. At a high level, the most common and most devastating failure modes observed are detailed in Table 4.

Table 4. Most Common Findings and Devastating Failure Modes and Related Recommendations

Finding	Recommendation
Module clamps rotating out of the racking rail	Through-bolt modules to racking, if feasible. If using clamps, clamps that directly bolt into rails rather than sliding into slots are preferred. If using slotted rail clamps, ensure clamps do not release from racking with less than about 90° of rotation.
High tilt angles of panels or panels higher above roof surface or ground	If roof has at least 5° pitch, install flush with roof at a low height above roof racking. Otherwise, install PV system at around a 5° pitch, or at as low of an angle is feasible for installation, maintenance access, and to prevent pooling water after rains.
Broken modules from flying debris	Clear rooftop or surrounding area of objects that could become flying debris. Select modules with thicker glass (at least 3.2 mm tempered).
Bolts loosening that released modules or allowed racking movement	Tighten all bolts in accordance with specifications. Ensure installers use a calibrated, digital, manual torque wrench and are trained in its use. Perform torque inspection annually. Use locking hardware on bolted connections.
Bent and broken racking rails that were not strong enough to withstand the wind loads	Select racking elements of thicker gauges that provide both lateral and longitudinal support. Avoid systems that only support modules along one axis (laterally or longitudinally). These racking systems impact extra loading onto the modules, loads they are not designed to withstand. Cross bracing is ideal.
Panels installed near corners and edges of roofs	Do not install modules in roof Zone 3, as described Structural Engineers Association of California (SEAOC) PV 2-17 guidance document.
Module clamps with low contact areas on the modules	If using top clamps, either use a continuous clamping system (down the entire length of the module frame) or select top clamps that each have at least 0.4 in^2 of contact area with the module frame.

Modules

The clearest sign of PV system damage is missing modules or modules with broken glass. While this is damage to the modules, it is often not the result of a failure of the modules. Failed module attachments or racking can lead to missing modules, and flying debris can fracture glass, for example.

Modules failed in several ways:

1. The most common was modules that had blown off the racking.
    - A. This is not necessarily a module failure. It is likely a failure of the attachment system meant to fasten the modules to the racking. Many modules seen scattered around arrays were relatively intact, indicating the attachments failed.

Figure 10. Catastrophic failure: modules blown of racking at Guam Community College. This is most likely not a module failure, but a failure of the module attachments.

B. Some modules could have first been damaged and were able to come free of the racking because of this. If the glass is broken by flying debris, for example, the module might lose structural integrity and be able to come free of the racking. Many modules scattered around the arrays were damaged with broken glass, broken frames, and with the cells separated from other components. There is no way to tell whether this damage occurred before or after the modules came free of the racking.

Figure 11. Damaged modules that came free of racking scattered around a rooftop. It often cannot be determined if modules were damaged before or after coming free.

No recommendation: We did not observe that modules or module design were the cause of this failure.

2. Some modules were still intact in the racking system but had broken glass.

   A. In almost every case, this appeared to be the result of impact from flying debris, as there was a clear impact point on the glass from which the shatter emanated. This flying debris could well have been another PV module.

Figure 12. Module intact in racking damaged from flying debris

Recommendation: Clear rooftop or surrounding area of objects that could become flying debris. Select modules with tempered glass at least 3.2 mm thick. Priority: Medium.

   B. Out of the thousands of broken modules and hundreds of thousands of total modules seen, only two were seen with shattered glass and no obvious impact point, two were still held in bent frames (this could have been frame yielding under wind load or the result of debris impact), and one module's frame was left in the racking (damaged) with the rest of the module (cells, glass, and backsheet) missing.

Figure 13. Module damage with undetermined cause, only seen on five of the hundreds of thousands of panels seen on the trip. Top left: Cracked glass with no clear impact point; top middle: module frame bent; top right and bottom: module frame remaining in racking with the rest of the module missing.

C. Scratches and other signs of impact. Modules had scratches from flying debris. This can impair power production. There were also signs of impact on the module frames or other system components.

Figure 14. Scratch and flying debris impact damage

Table 5 provides top observed module failures and recommendations, though these are all considered lower priority compared to module attachment and racking recommendations.

Table 5. Top Observed Module Failure Modes, Recommendations, and Prevalence of Each

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Missing modules	Most likely the result of module attachment failure—see module attachment recommendations.	Module attachments, modules, racking	All	13	N/A
Debris impact – cracked module glass	Clear rooftop or surrounding area of objects that could become flying debris. Select modules with thicker glass (at least 3.2 mm tempered). Replace modules with broken glass.	Modules	All	10	Medium
Module cracked glass – no impact	Rare and uncertain failure mode. No recommendation provided. Follow current practices. Replace modules with broken glass.	Modules	All	2	Low
Top-clamp tear-out through module frame	Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out.	Module attachments, modules	Top clamps	1	Medium (through-bolted only)

Module Load Ratings

Notably, **there were no clear signs of modules failing simply due to a high wind load**. On two modules, glass was broken without a clear impact site, and two modules were seen intact on the racking with the frame bent (this could well have been from debris impact too). One module's frame was still in the racking with the rest of the module missing. In any case, out of the hundreds of thousands of panels seen on this assessment trip, about five panels on different sites were seen that possibly could have been damaged by wind loads alone, but also could have been damaged as the result of flying debris or stressed by induced racking system movement.

Typically, much of solar PV system design for wind loading is focused on module pressure load ratings and whether they will be able to withstand wind forces. These load ratings are typically given in pascals. Panels are typically tested to withstand 2,400-Pa static loads from front and rear loads, with some modules advertising loads up to 5,400 Pa. Wind loading is not static, but current codes and standards typically only require static load tests, so it is often the best proxy for module strength under wind loading. From this assessment, it appeared that the load ratings of all panels seen were adequate, and we did not see any panels that clearly failed due to being overloaded or over-flexed due to the winds. Admittedly, this would be a difficult failure mode to confirm. Panel load ratings across systems ranged from 2,400 to 7,000 Pa. So, we see panel load ratings as a secondary consideration for wind loading design, after robust module attachments, system geometry, and sturdy racking systems.

Figure 15 shows module rear test load ratings (in pascals) under standard conditions compared to percentage of damage to the modules. There is no correlation.

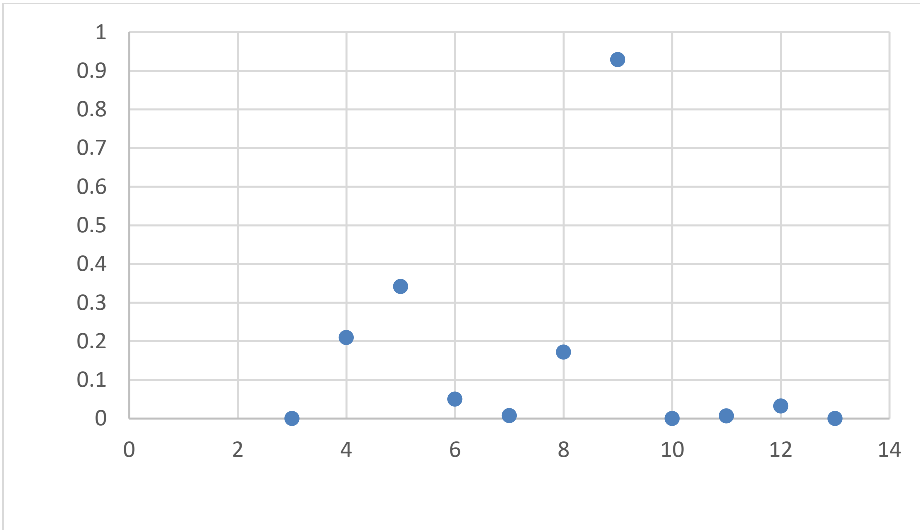


Figure 15. No correlation between module wind load (rear pressure) test ratings and damage suffered

Module Size

One installer on the island noted they only use smaller-format modules—60 cells or equivalent—in their installations to reduce the total wind load on the panels and support structure. The assessment team supports this approach.

The largest panels seen on any system were on a 2.5-MW rooftop system that suffered extensive damage (21% of modules damaged or missing, extensive racking system damage). These 72 cell panels were 2.112 m long by 1.052 m wide, totaling 2.2 m^2. These panels were larger than those seen on the 60-MW ground-mounted site. On this site, there were several other features aside from module size that contributed to this damage.

An analysis of module surface area compared to percentage damage was inconclusive, however (Figure 16).

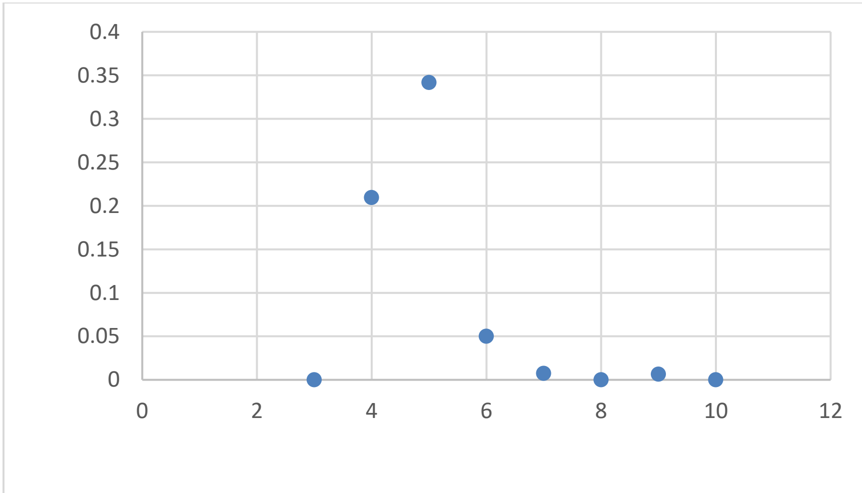


Figure 16. Module surface area showed no conclusive correlation to failure rates

Module manufacturers have recently been making larger and larger modules. These "large-format" modules also have thinner glass and thinner frames to compensate for the extra weight that comes with this larger form factor. There is no precise definition of a large-format module, but they are generally longer than 2.0 m (6 ft. 6 in.) and greater than 500-W rated DC output. We did not see any of these large-format modules in our site assessments, and strongly recommend they are not used on Guam. Figure 17 shows the typical size of various types of modules.

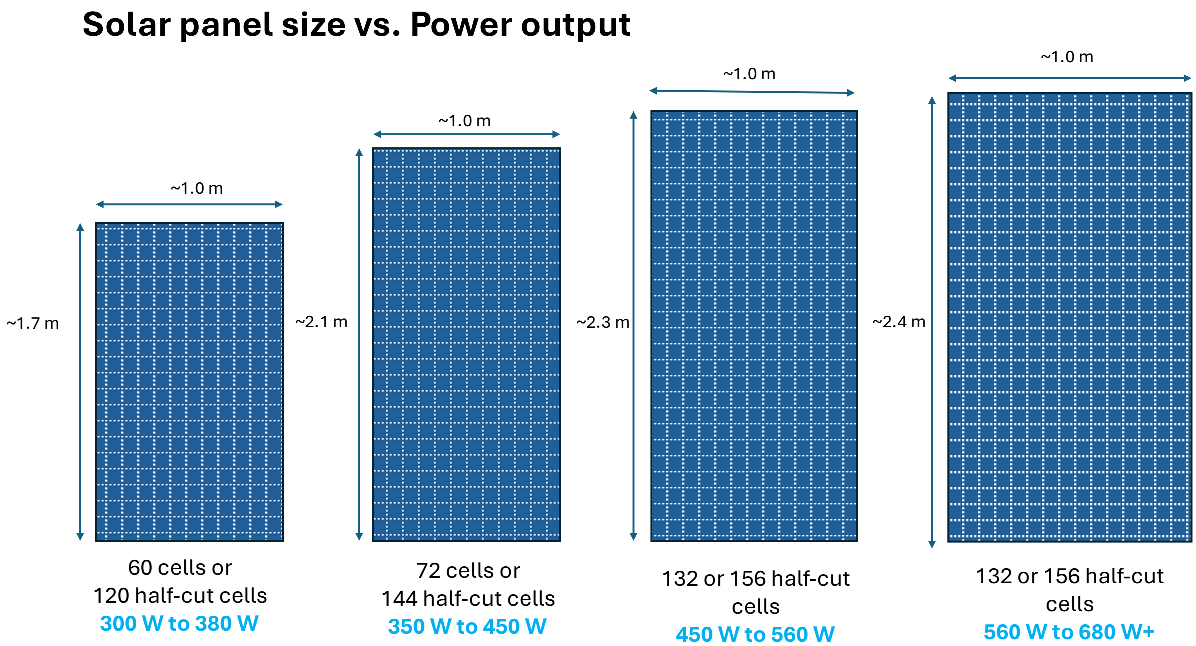


Figure 17. Various typical PV module sizes. Traditionally, rooftop PV modules were 60-cell modules and ground-mounted systems used 72-cell modules. Recently, many manufacturers have replaced 60-cell modules with 120-half-cut-cell modules and have replaced 72-cell modules with 144-half-cut-cell modules within the same module dimensions. Recently, "large-format" modules have hit the market that are longer and wider than the traditional 60- and 72-cell modules. Large-scale solar PV systems have widely adopted these large-format modules. They offer higher power density but lower robustness, especially as manufacturers have reduced glass and frame thickness to compensate for the weight increases that come with larger form factors. Large-format modules (longer than 2.0 m or higher than 500 W) should not be installed on Guam. We recommend installing 60-cell modules (or 120-half-cut-cell modules) or equivalent on rooftop systems.

Image by James Elsworth, NREL, adopted from *Solar Builder*, solarbuildermag.com/featured/benefits-and-tradeoffs-of-large-format-pv-modules/

Recommendation: Use smaller panels; 60 cell, 120 half-cut cell, or equivalent is preferred and strongly recommended for rooftop. These modules are typically about 1.7 m (5.5 feet) long. Do not use "large-format" modules that are larger than approximately 2.0 m (6 ft. 6 in.) and rated at 500 W or higher for any PV systems on Guam. Priority: High.

Glass Thickness

Traditional PV module glass is 3.2 mm or thicker. This glass is normally tempered. As manufacturers have shifted to larger modules and bifacial modules that produce power from the front and back sides and have both front and rear glass, thinner glass has become more common. These new modules typically feature 2.0-mm glass. This glass this is weaker both because it is thinner and because it is too thin to be tempered. It is "heat treated" instead, which does not result in glass as strong as tempered glass. **In hail impact tests, 3.2-mm glass performs much better than 2.0-mm glass,** and thus should be less likely to break from flying debris as well. We believe that all the modules we saw had about 3.2-mm glass, so we were not able to see a variation in storm impacts by glass thickness. However, we advise against using thinner glass.

Figure 18 demonstrates that it takes more impact energy to break PV modules with 3.2-mm glass than it does to break modules with 2.0-mm glass.

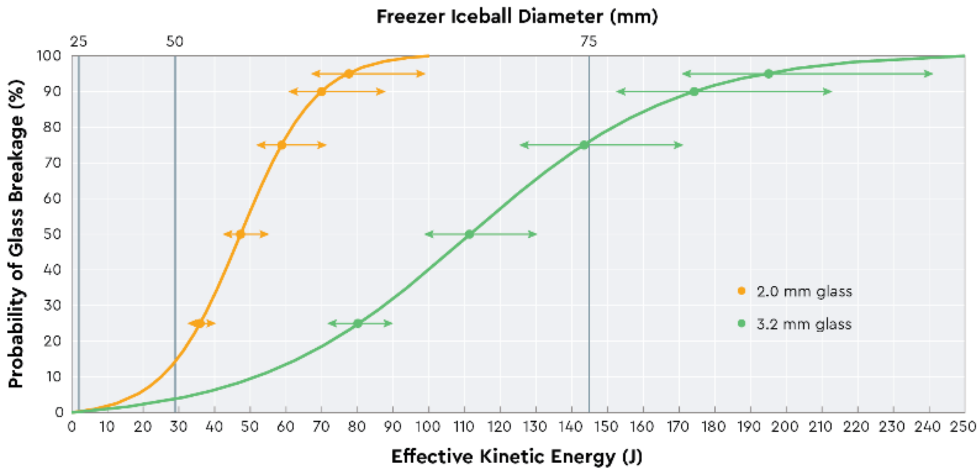


Figure 18. PV module impact testing results show that 2.0-mm glass is much more likely to break than 3.2-mm glass when impacted by objects of lower kinetic energy (lower mass and/or velocity).

Source: RETC, retc-ca.com/news/module-glass-impacts-hail-resiliency

Recommendation: Modules with thicker glass resist debris impact better; 3.2-mm glass or thicker is recommended. Bifacial modules typically use 2.0-mm glass and are not recommended. Priority: Medium.

Module Attachments

By far the most common structural failure modes seen across all of the PV systems was failure of the attachments that hold system components together, especially those that hold the PV modules to the underlying racking structure.

There are various ways of attaching modules to the underlying racking on PV systems, and the assessment team observed many different approaches on Guam. The general categories of modules attachments are:

- Top clamps: Clamps on the top and bottom of the side of the module frame that are typically tightened from above. They usually hold adjacent modules simultaneously.
- Through-bolting: The underside of module frame is bolted directly to the support structure.
- Underside module rail clamps: Seen on end rows on one rooftop system where a device clamps the underside module frame flange to the racking structure.
- Continuous clamping: A custom product used by one of the more prevalent local installers who installed a majority of PV systems at Andersen Air Force Base. This system clamps the entire length of the module on the top and bottom.

Top Clamps

Top-clamp failure was the most common and most devastating failure mode observed across these systems. Top clamps are the most common way to secure modules to PV systems, especially on rooftop arrays where access to the underside of a module frame is difficult, making through-bolting challenging. Top clamps are preferred because of their ease of installation; they typically require less time to install and are thus usually the cheapest option. There are many different types of top clamps. While the shapes of these clamps vary by manufacturer, they are typically made from aluminum extrusions with clamp force provided by tightening a stainless steel bolt between the clamp and a metal rail in the racking system. "Mid-clamps" are used in the middle of rows of PV modules and typically clamp adjacent modules at the same time, and "end clamps" are used at the end of rows of modules and clamp onto one side of the last module in a row. These clamp systems typically attach to the racking support structure with either a bolt head or nut in a slotted channel in the racking rail (Figure 19).

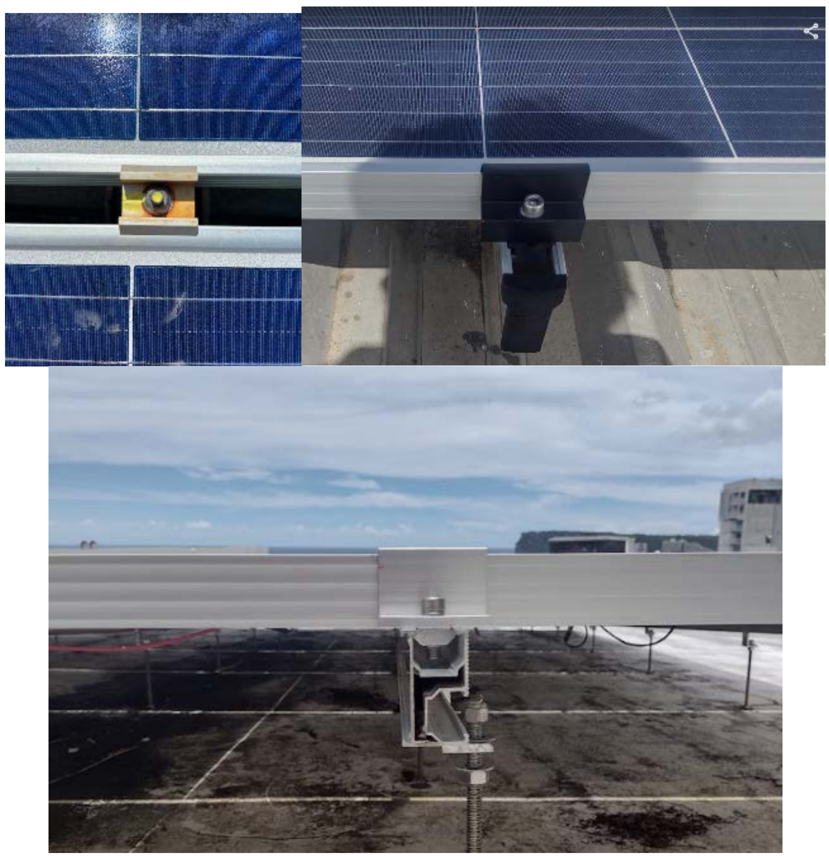


Figure 19. Various top clamps that are commonly used to attach PV modules to racking systems. Top left: A "mid-clamp" that holds adjacent modules simultaneously. Top right: An end clamp that holds the last module in a row. Bottom: The nut or bolt head of top clamps typically fits into a slot in the racking rail.

Cascading or Progressive Failure

For most top-clamp module attachments, the same clamp holds adjacent modules on the left and right side and requires clamping force on both sides to maintain clamp force (Figure 19). This is a weakness of the system, because if one module comes loose or is damaged in a way that reduces its force on the clamp, the adjacent module is no longer held securely. This module can then come free under wind loads. The same can then happen for the subsequent module. The result is that an entire row of modules can be lost because of one point of failure. This "progressive" or "cascading" failure was observed on several top-clamped systems. The impact of this is that one clamp failure can lead to a cascading failure down an entire row of panels (Figure 20). Some top-clamp systems secure modules individually. Those are recommended over shared clamps, as they are not prone to this cascading failure.

Figure 20. Cascading/progressive failure of two rows of modules that were held with top clamps. One (or a small number) of failures can lead to the loss of many neighboring modules. This is because the top clamps used require the presence of two adjacent modules to maintain adequate clamping force. If one module comes loose, the whole row is vulnerable to failure.

Recommendation: Through-bolt modules to racking if feasible. If using clamps, use clamps that hold adjacent modules individually (they do not require clamping force from one module to hold the adjacent module). Priority: High.

Variations Between Different Clamp Products

Top-clamp products on the market vary significantly in several ways:

- The amount of surface contact area between the clamp and the top of the module frame.
- The amount of rotation needed to release the clamp hardware (bolt head or nut) from the rail slot in the support structure.
- The amount of surface contact area between the clamp hardware (bolt head or nut) and the rail in the support structure.

Each of these three are places where top clamps can fail, and we saw examples of all three in Guam.

Surface Contact Area Between Clamp and Module

Top clamps differ in the amount of surface contact area between the clamp and the top of the module frame. This is significant because more surface area can provide more friction to resist movement of the panel out of the clamps under wind loads (Figure 21). Individual clamps we saw varied from 0.28 in^2 to 1.17 in^2 of contact area. There are typically four clamps per module. Surface area of all clamps ranged from 1.125 in^2 to 4.67 in^2 per module. Clamps losing grip on the module and releasing it was a primary failure mode on several systems.

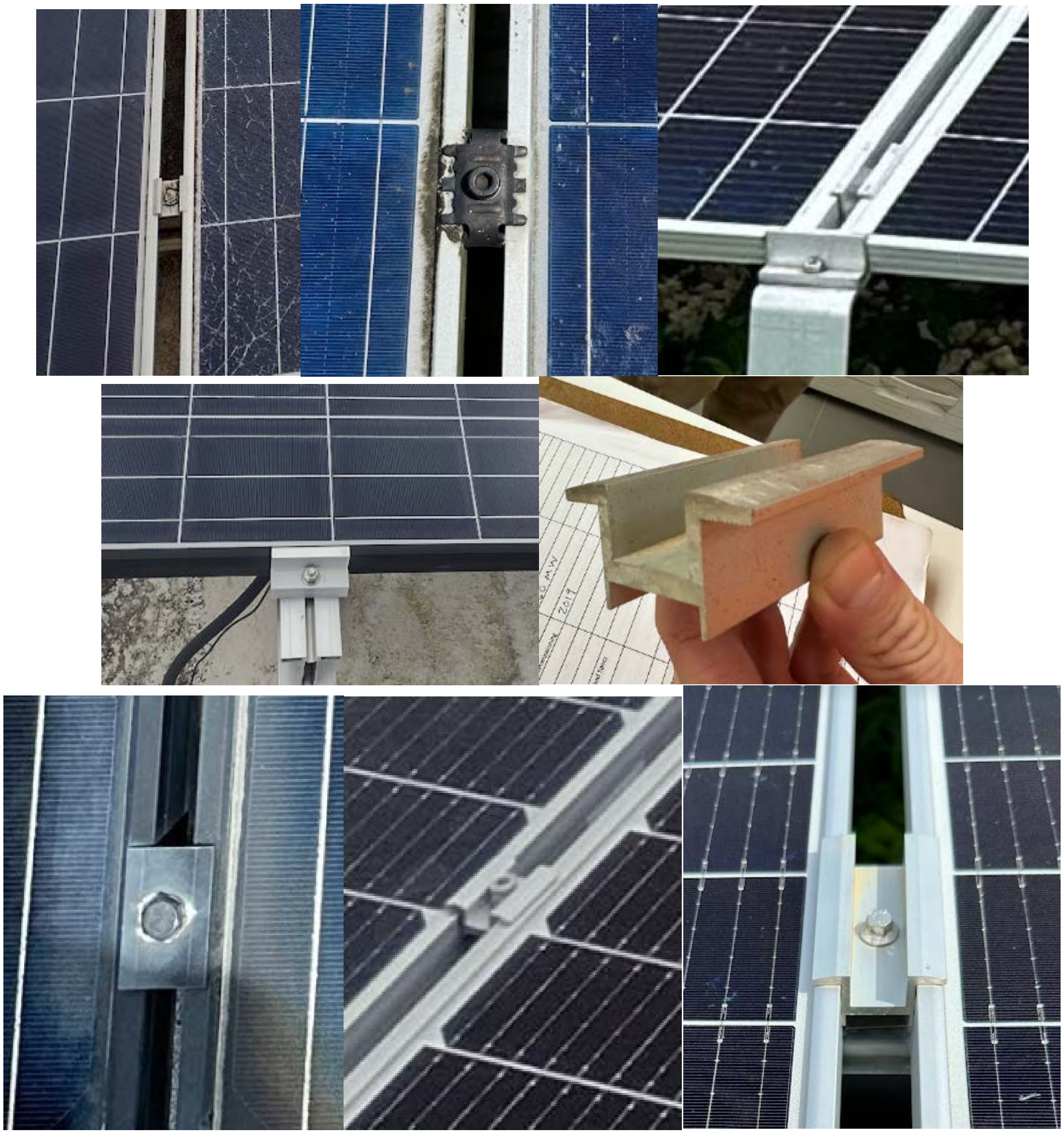


Figure 21. Top clamps come in many different shapes and sizes. Notice the varied lengths and amounts of overlap between the clamps and the module frames.

One local installer has developed their own module clamping approach that uses continuous clamping down the entire length of the module frame. This approach offers the advantage of a much greater clamp contact area with the modules (Figure 22).

Figure 22. One local racking system utilizes a continuous clamping approach down the entire length of the modules

In general, clamps with a greater surface area of contact between the clamp and the top of the module frame should hold PV modules more securely. Analyzing total clamp surface area per module generally supports this, especially for this continuous clamping mounting system.

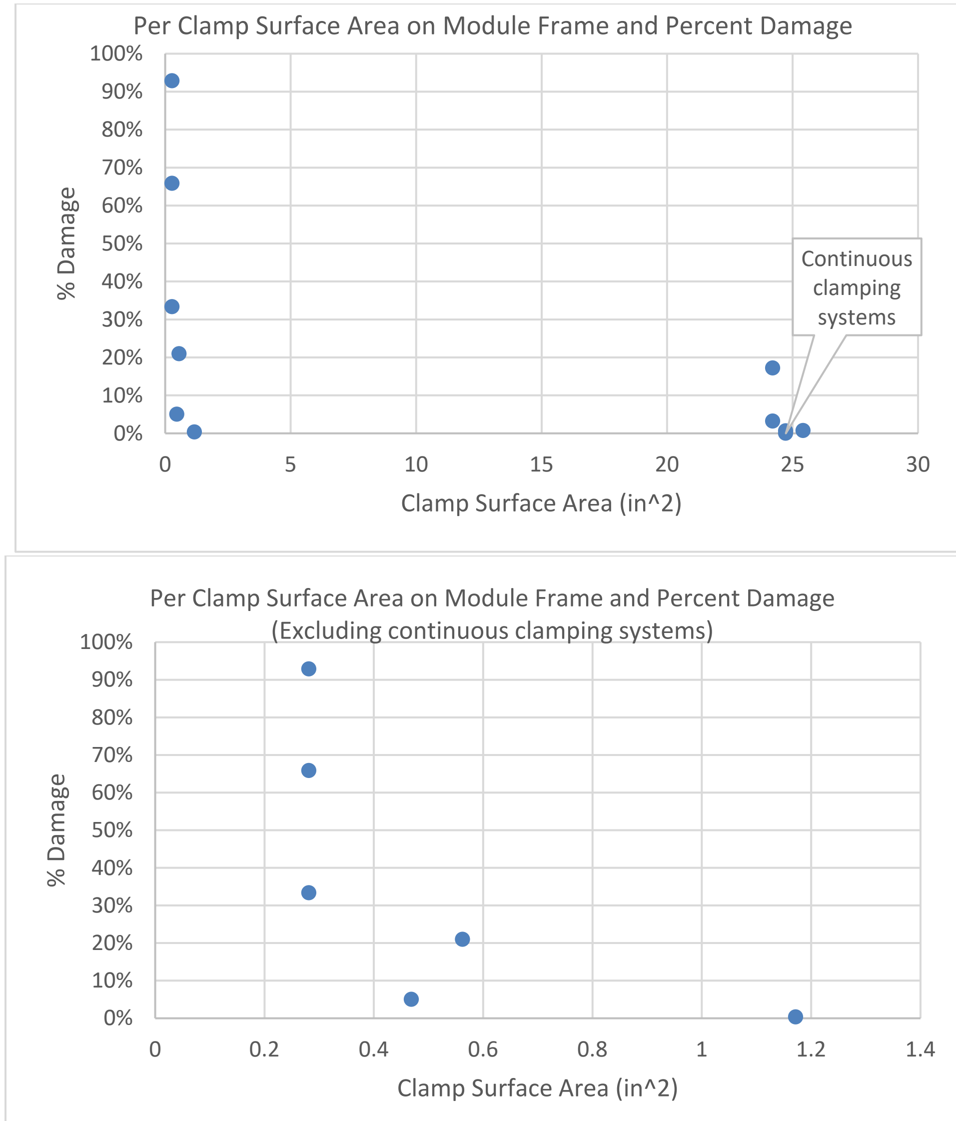


Figure 23. Clamps with more contact area with the module frames experienced less damage in general. Top: All measured top clamps including continuous clamping systems. Bottom: Excluding continuous clamping systems.

Note: The continuous clamping system with approximately 20% damage had several failure modes such as excessive flying debris which is not attributed to clamp surface area.

Recommendation: If using top clamps, either use a continuous clamping system (down the entire length of the module frame) or select top clamps that each have at least 0.4 in^2 of contact area with the module frame. Priority: High.

Rotation out of the Rail Slot

These clamps vary in how they attach to the rail underneath and how easily they can rotate and come free of the racking. There are different ways that these clamps are attached to the rail. Most commonly, either the nut or bolt head fits into a slot in the rail. It is either slid in from the end of the rail or placed into the rail from above and rotated. These types of bolts are typically called T-bolts due to the shape of the bolt head that can rotate into a rail (Figure 24).

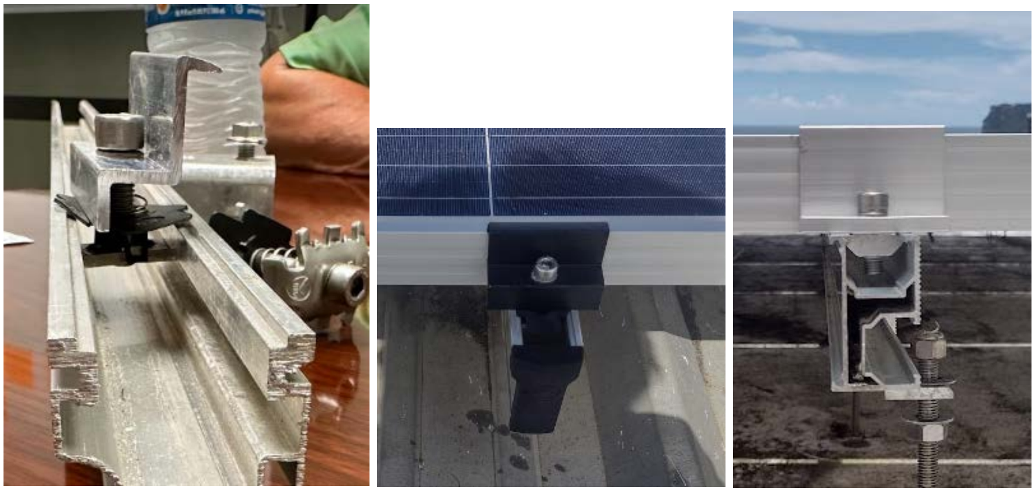


Figure 24. Top clamps typically have nuts or bolt heads that slot into racking rails. If the bolts come loose, they can rotate in the rail and easily pull out of the slot.

In particular, the Unirac Pro Series mid- and end clamps had high failure rates. We saw three systems with these clamps that all had very high failure rates—33%, 34%, and 93% of modules held with these clamps were lost or damaged. These clamps have very small contact area in the slotted rail. These clamps advertise needing 63° of rotation to install; we suspect less than that would release them. If these clamps are not adequately tightened, or if they vibrate loose during wind loads, it does not take much for them to come out of the racking, leaving modules unattached and free to blow away. The roofs of these three systems were littered with top clamps that had freed themselves from the racking. Most of these clamps looked undamaged, showing no signs of deformation or damage (Figure 25). One system even employed eight of these clamps per module. This was the system with 93% failure rate, showing that using more bad clamps does not increase likelihood of survivability.

Figure 25. Unirac Pro Series T-bolt clamps that rotated free of the racking littering a rooftop. Note that clamps do not show signs of deformation or damage, implying they came free from the racking relatively easily.

Some of these top clamps can bolt directly into a rail as well. Systems with top clamps that bolted directly into the rails were all ground-mounted systems (likely due to this being physically easier during installation), but they suffered either no damage or very little damage.

Figure 26. Top clamps through-bolted directly to racking rails are more secure because they cannot rotate out of rail slots

Recommendation: Through-bolt modules to racking if feasible. If using clamps, clamps that directly bolt into rails rather than sliding into slots are preferred. If using slotted rail clamps, ensure clamps do not release from racking with less than about 90° of rotation. Do not use Unirac Pro Series top clamps. Priority: High.

Clamp Contact Area With Rail

These clamps vary in how much contact area they have with the racking rail as well (Figure 27). Clamps with small surface contact areas between the bolt head or nut are prone to tearing or rotating out of the rail slot.

Figure 27. Some clamps have small bolt head (left) or nut (middle) contact area with the rail. These are prone to tearing out of the rail slot. Some products have significantly more contact area (right).

While we were only able to measure this contact area on five systems, those with below 0.2 in^2 of contact area per clamp suffered substantial damage (Figure 28).

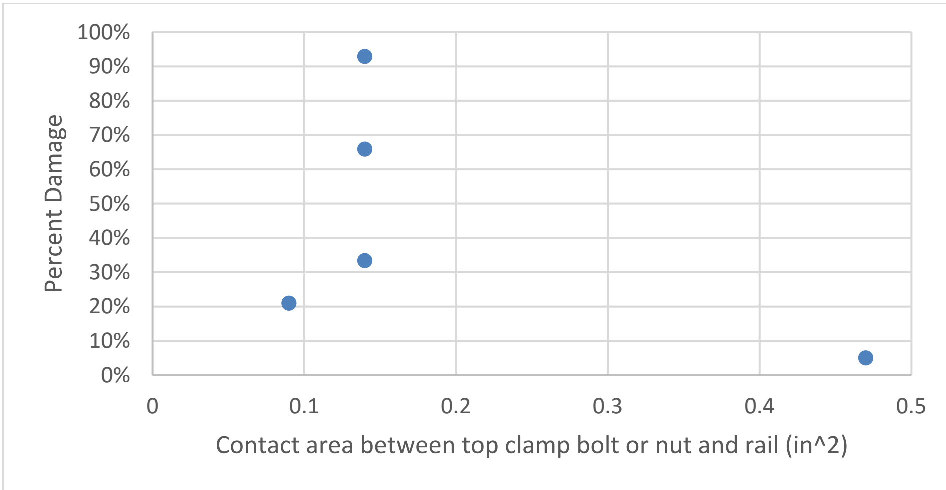


Figure 28. Per-clamp contact area with racking rail and percent damage

Recommendation: If using clamps that attach into slotted rails in the racking, select clamps that have at least 0.2 in^2 of contact area between the clamp and rail slot per clamp. Priority: High.

Materials and Strength

There are also likely variations in strength of the clamps due to materials, thickness, and manufacturing processes, but the team did not attempt to analyze that in this assessment, as other, more impactful failure modes were present. Addressing rotation out of rail slot, clamp contact area with modules, and clamp contact area with racking should be prioritized over material properties, given they meet a common PV standard such as UL2703 or employ continuous clamping.

Clamp Tear-Out of Racking Rail

At JFK High School, weak racking material and a very small contact area between the nut and the racking rail allowed the nuts on the top clamps to easily pull out of the rail. This was one of several failure modes on this system.

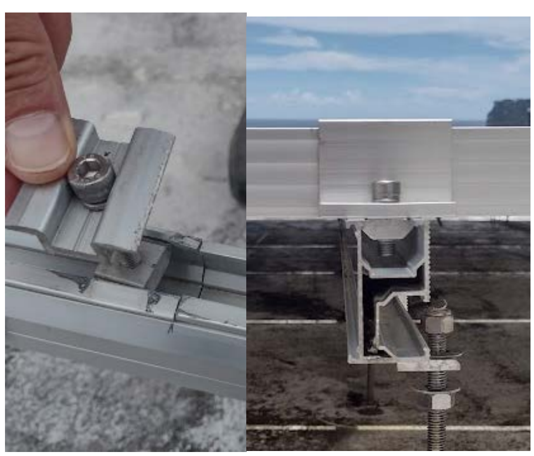


Figure 29. Weak racking material and a small amount of contact area/overlap between the rail and the clamp nut led to many clamps tearing out of the racking at JFK High School

Recommendation: For through-bolted systems, use larger washers to increase surface area and grip length. For top clamps into slotted rails, ensure adequate bolt or nut contact area with rail. Priority: High.

Clamp Loosening

At the FIFA soccer stadium, the top clamps remained in the racking rails because the slots on this system were very small. The bolts on this system needed to be slid in from the end of the rail rather than inserted from above and rotated. So, while these clamps remained in the racking, they still released the modules they were meant to hold, possibly because they loosened under wind loads.

Figure 30. At the FIFA soccer stadium, the clamps did not come free from the rail because of the narrow rail slot. Still, they loosened and released modules.

Recommendation: Torque to specifications during installation. Perform torque inspection annually. Use locking hardware on bolted connections. Priority: High.

Direct Bolting/Through-Bolts

Direct bolting, or "through-bolting," is where the module is directly bolted to a racking rail below (Figure 31). Solar modules are typically mounted in an aluminum frame. This frame has a bottom flange, below and parallel to the surface of the module. This flange is bolted to the racking. There are typically predrilled holes in the module frame for this purpose.

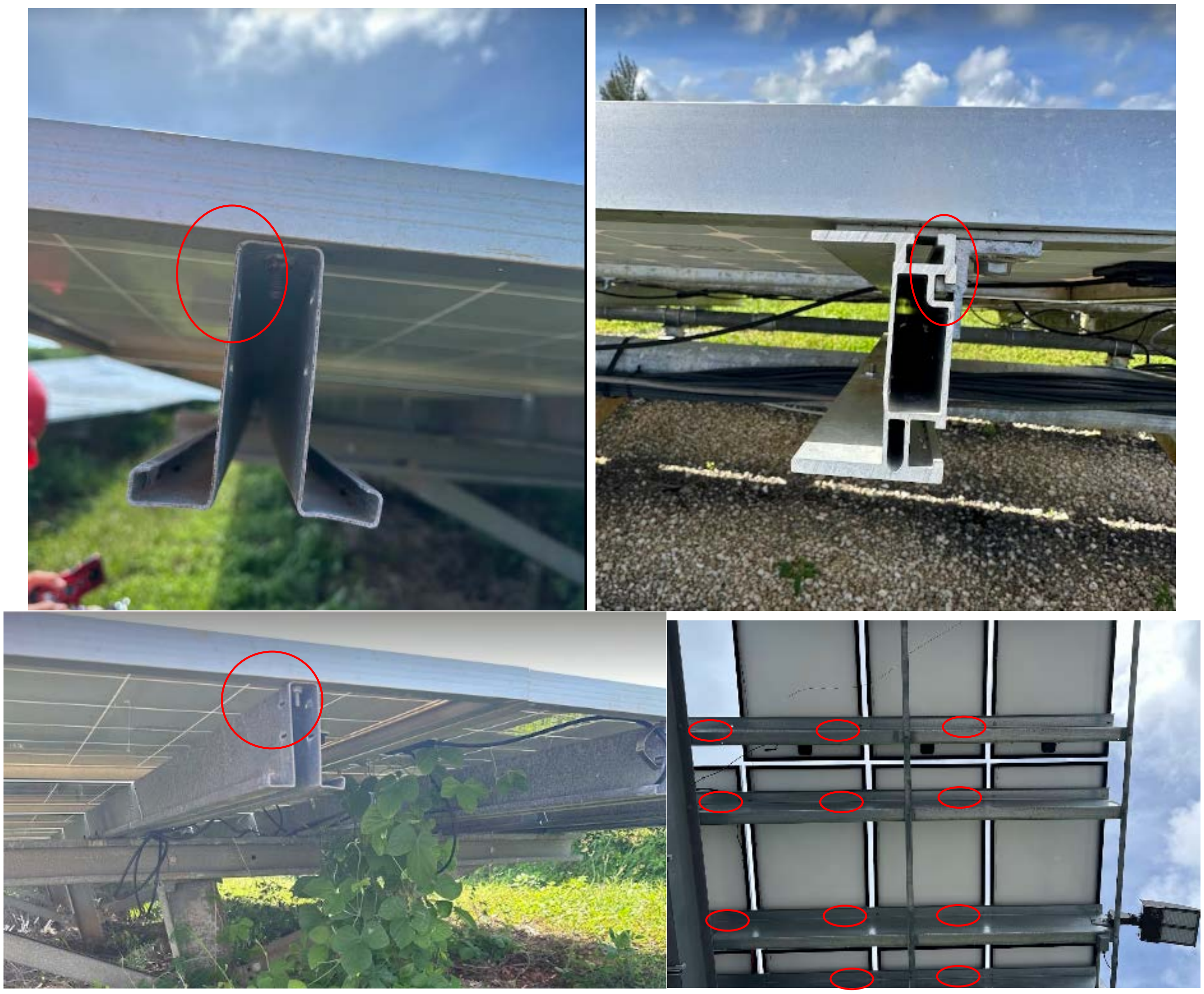


Figure 31. Various through-bolting approaches in which the bottom flange of the module's metal frame is bolted directly to the racking system underneath

Direct bolting to racking has some benefits over clamping. The bolts are not shared between modules, so if one comes loose, only one module is vulnerable; there is no chance of progressive failure. The bolts do not typically slide into slots in the rail, so they cannot simply rotate out. Through-bolting can be difficult, however, for rooftop systems where physically getting under the modules to install bolts may be impractical. There is also more labor time involved in through-bolting because there are approximately twice as many fasteners needed.

Three inspected systems employed through-bolting; all were ground-mounted systems. One of the two traditional ground-mounted systems with through-bolts experienced no structural damage, though it was located farther south on the island where wind speeds were lower during Typhoon Mawar. This system employed a combination of through-bolting and top clamping, with four through-bolts at about one-quarter and three-quarters of the way down the module, and top clamps at the center, for six attachment points total.

The other ground-mounted system fared very well (less than 1% damage). One of the failure modes was related to module attachment failure. The system used hybrid top clamps that, instead of fitting into a slot on the racking rail, were bolted directly into the rail. The bolts were attached through slots in the rail. The slots were large compared to the bolts, and some of these bolts tore out through the slotted hole (Figure 32). Larger bolts and wider-diameter washers could have prevented this.

Figure 32. Evidence of direct bolt tear-out of racking rails (left) and steel deformation from a top-clamp bolt that was close to tearing out (right)

Recommendation: Through-bolt modules to the racking if feasible. Ensure washers are thick enough to avoid bolt tear-out of the hole or slot in the racking. Priority: High.

In some cases, the bolts may have been overtightened during installation, as racking deformation was seen around bolts that were holding tension (Figure 33). This could have contributed to the clamp tear-out failures.

Figure 33. Steel deformation where a bolted joint was likely overtightened during installation

Recommendation: Tighten all bolts in accordance with specifications. Ensure installers use a calibrated, digital, manual torque wrench and are trained in its use. Priority: High.

The third through-bolted system was a solar canopy/carport system with the panels very high (about 22 feet) above the ground (Figure 34, left). This height left the panels vulnerable to higher wind loads, and several panels on this system simply blew off, tearing the module frame out at the bolt holes and leaving the bolts in the racking. On this particular module, the pre bolt holes were very close to the edge of the module frame, and the frame was made of thin aluminum. There were additional predrilled holes on the modules that could have been used for extra attachment points (Figure 34, right).

Figure 34. One carport system on Guam lost modules due to bolts tearing out of the module frames and due to flying debris. This tall structure mounted the modules about 22 feet above the ground. The modules had two potential bolt slots; only one was used. These slots were also close to the edge of the module frame where the bolts tore through (right).

Recommendation: Only mount modules as high off the ground as they need to be. Priority: High.

Recommendation: Use all available module attachment points on carports of systems where modules are high above the ground or roof surface. Priority: Medium.

Recommendation: Select modules with predrilled holes that are not near the edge of the frame flange. Use wide-diameter washers (at least 0.688-in. outer diameter) for more clamp area and thicker washers (at least 0.125-in. thick) to lengthen the bolted attachment. Priority: Medium.

Number of Module Attachments

More module attachments can provide more resistance to wind loads.

- If done well, using good hardware and installation techniques, four module attachment points were shown to be adequate in several instances.
- Additional module attachment points can help and can give the modules significantly higher wind load resistance. Six mounting points are sometimes used in areas with higher design wind loads, usually by adding two additional mounting points in the center of the module. Module installation manuals typically give load ratings for four- or six-point mounting. Six-point mounting may require the installation of an additional racking rail underneath modules, which may translate to significant additional costs. Certain projects have opted against this due to increased costs.
- Having more attachment points does not automatically guarantee increased resilience. If the attachment is poor to begin with, adding more of them will not necessarily help. One of the systems with the most damage we saw used eight module attachments clamps (as opposed to the typical four), but these clamps were vulnerable to rotating out of the

racking rail and to progressive failure, meaning more attachments did not provide much additional benefit.

- The carport in particular could have leveraged additional module mounting holes on the modules. This may have resisted wind forces enough to reduce the amount of bolts that pulled out of the module frames.

Location of Module Attachments

The location of the actual module attachments can have a significant impact on the load ratings of the modules as well:

- Module installation manuals give the optimal locations for mounting modules, either with top clamps or direct bolting to the rack. For a four-point mounting system, these are typically evenly spaced, at about one-quarter and three-quarters of the way down the module frame on the long side. Modules typically come with predrilled holes in the frame at the ideal locations through which bolts should be placed for direct bolting.
- Module installation manuals also give load ratings for various mounting configurations. Uplift strength is drastically impacted by mounting location. In the example shown in Figure 35, the uplift load rating can be as high as 4,300 Pa or as low as 1,600 Pa. Most modules are required to pass IEC 61215 static mechanical load tests of 2,400 Pa. Higher load ratings (5,400 Pa or greater) are recommended for high-wind regions like Guam.

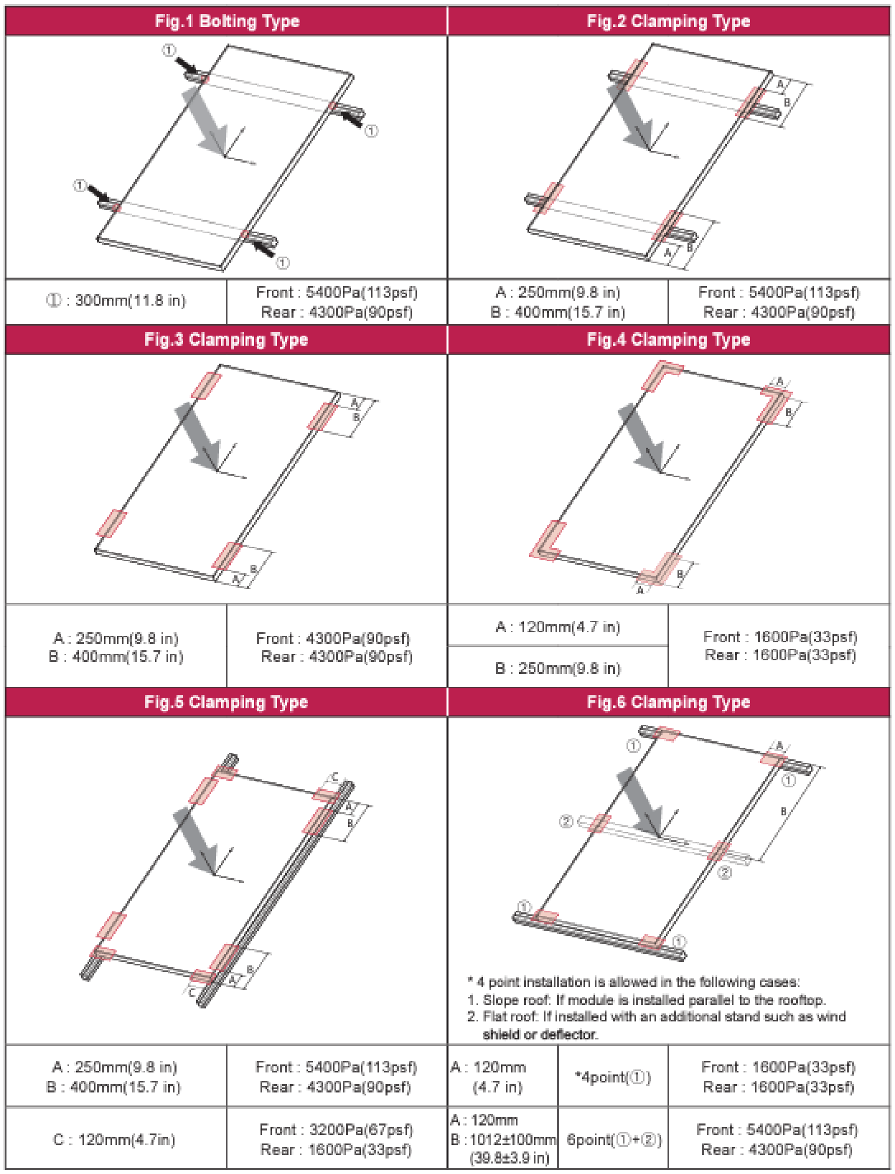


Figure 35. Excerpt from a module installation manual showing front and rear load ratings for various mounting configurations. Rear loads range from 1,600 Pa to 4,300 Pa in this example. Most modules are required to pass IEC 61215 static mechanical load tests of 2,400 Pa. Higher load ratings (5,400 Pa or greater) are recommended for high-wind regions like Guam.

- Some systems mounted modules off-center (Figure 36), leaving more of the high side of the module unsupported. This high side of the module is more likely to experience high wind loading from wind getting under the panels. These two systems experienced very high failure rates, but there were other contributing factors. These two systems used lower-quality materials and were installed by less experienced installers.

Figure 36. Clamps should be installed on modules as required in installation manuals, not off-center as shown here

Recommendation: Follow module installation manual requirements for location and types of module attachments needed to achieve desired module load ratings. Priority: Medium.

Locking Hardware

A well-designed and installed bolted joint should resist loosening under design loads. PV bolt design is a relatively immature field, however, with many inexperienced designers and installers. It may not be realistic at this point in time to expect PV bolted joints to perform the way they do in other industries (e.g., transportation, buildings, bridges). There are several factors that can lead bolts and nuts to loosen over time:

- If they are not installed to the specified torque (either too loose or too tight).
- If they are exposed to repetitive loads such as wind loads that may cause vibration in the system.
- If winds cause resonance in the system. This may be hard to determine but has been observed in PV systems. Current design standards do not directly address design for resonance.

Figure 37. Bolts on PV systems can loosen over time. Locking hardware can help resist this loosening.

There are various locking hardware solutions that can mitigate this self-loosening of bolted joints and can help module clamps hold over time. Notably, helical spring split washers (commonly referred to as "split washers" or "lock washers") are not effective against vibrational loosening. Wedge-lock washers, Belleville washers, and pre-applied threat lock can all effectively resist vibrational loosening. While nylon-insert nuts (brand name "Nyloc") do not resist vibrational loosening in lab tests, they have been used successfully on PV systems.[8]

A prevailing torque but with a nylon insert or a nut with a pre-applied nylon patch could provide an effective, inexpensive solution to loosening. Nylon in nylon-insert nuts can degrade when exposed to UV light, so they should only be used when sufficiently shaded, unless using a but that contains a special formulation of nylon that contains a UV blocker. Nuts with pre-applied nylon patches should also be immune to this UV degradation. Aside from potential UV degradation, nylon is moisture sensitive, and its properties might change over time as it is exposed to moisture, as it would be on Guam. Also, installing these nylon nuts on some racking systems could be a laborious process with a hand-held wrench, which may add significant labor time.

[8] For more information on locking hardware and comparative costs, see: J. Elsworth and O. Van Geet. 2020. *Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience*. Golden, CO: National Renewable Energy Laboratory. NREL/TO-7A40-75804. www.nrel.gov/docs/fy20osti/75804.pdf.

Figure 38. Two types of nylon nuts that can be used to resist loosening. Left is a prevailing torque nylon-insert nut. Right is a flange nut with pre-applied nylon patch.

Recommendation: Use locking mechanisms on bolt hardware such as wedge-locking washers, Belleville washers, nylon patches, ultraviolet (UV)-rated nylon-insert nuts, or thread lock. Do not use split "lock" washers. Priority: High.

Torque Audits

Bolts on PV systems can vibrate or self-loosen over time. While locking hardware is an ideal solution to resist against this, periodic torque checks of bolts—both the module attachment bolts and the racking system bolts—can help ensure that PV systems are the most able to withstand storms. There are many different methods of performing a torque audit.

Recommendation: Perform regular torque audits to ensure bolts are not loosening and stay tight. Priority: High. One torque audit method is:[9]

1. **Check 2% of the bolts on the system. If <10% fail, system passes. Otherwise proceed to Step 2.**
2. **Check 10% of the bolts on the system. If <10% fail, the system passes. Otherwise proceed to Step 3.**
3. **Check and tighten all bolts on the system. Torque stripe all bolts that meet torque specifications.**

[9] Schletter. 2017. "Mounting Systems FS System, V2."

Figure 39. Torque stripes on torqued bolts can give a visual indication if bolts have loosened over time. The bolt on the left is in line. The bolt on the right appears to have rotated loose slightly.

Table 6 gives the various module attachment failure modes observed and number of occurrences of each.

Table 6. Module Attachment Failure Modes and Number of Occurrences of Each

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Missing modules	The result of module attachment failures—see module attachment recommendations below.	Module attachments, modules, racking	All	13	N/A
Progressive failure due to shared clamp failure	Through-bolt modules to racking if feasible. If using clamps, use clamps that hold adjacent modules individually (they do not require clamping force from one module to hold adjacent module).	Module attachments	Top clamps	7	High
Module clamps rotated out of racking	Through-bolt modules to racking if feasible. If using clamps, ensure clamps do not release from racking with less than about 90° of rotation. Do not use Unirac Pro Series top clamps.	Module attachments	Top clamps	3	High
Module bolt or clamp pull out of racking	For through-bolted systems, use larger washers to increase surface area and grip length. For top clamps into slotted rails, ensure adequate bolt or nut contact area with rail.	Module attachments	All	2	Medium
Clamp loosening and releasing modules	Torque to specifications during installation. Perform torque inspection annually. Use locking hardware on bolted connections.	Module attachments	Top clamps	1	High
Through-bolt tear-out through module frame	Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out. Select modules with predrilled holes that are not near the edge of the frame flange. Use wide-	Module attachments, modules	Through-bolts	1	Medium

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
	diameter washers (at least 0.688-in. outer diameter) for more clamp area and thicker washers (at least 0.125-in. thick) to lengthen the bolted attachment. Alternatively, add a metal plate between the bolt and frame to distribute the load.				
Modules not attached at recommended locations on module, thus full load rating of module not achieved	Follow solar module installation manuals guidance for location and number of module attachments.	Module attachments	All	3	Medium
Module clamps released modules	If using top clamps, either use a continuous clamping system (down the entire length of the module frame) or select top clamps that each have at least 0.4 in^2 of contact area with the module frame.	Module attachments	Top clamps		High
Large modules are susceptible to higher wind loads	Use smaller panels: 60 cell, 120 half-cut cell, or equivalent is preferred and strongly recommended for rooftop. These modules are typically about 1.7 m (67 in.) long. Do not use "large-format" modules that are larger than approximately 2.0 m (79 in.) and rated at 500 W or higher for any PV systems on Guam.	Modules	All	0	High
Modules were mounted high above the ground and encountered higher wind speeds	Only mount modules as high off the ground as they need to be.	Racking	All	1	High
Module bolt tear-out on carports	Use all available module attachment points on carports of systems where modules are high above the ground or roof surface	Module attachments	Carports	1	Medium

Racking

Racking refers to any structural elements between the solar modules and the surface to which they are mounted—typically the ground or a rooftop. Racking systems varied significantly across systems. In general, they consist of support rails, laterally, vertically, or both, to which the module attachments connect on the top, and to which the foundations connect to on the bottom.

The best designs support the modules and protect them from forces in all directions, transmitting any loads to the ground or roof. Certain racking systems fared much better than others. This can be an indication of the qualities of the racking systems, but it could also be a result of the quality of designers and installers or the types of module attachments compatible with the racking systems. Table 7 gives a breakdown of failure rate by racking type.

Table 7. Failure Rates by Racking Type

Rooftop	Missing or Broken Modules	Total Modules	Failure Rate	Number of Sites
Pacific Solar Metgot rail	51	1,731	2.95%	17
Unirac	153	356	42.98%	3
Everest	7	140	5.00%	1
PanelClaw	0	44	0.00%	1
Uni-solar adhesive	2,064	2,112	97.73%	1
SolaRacks	859	4,100	20.95%	1
Unknown manufacturer at soccer stadium	92	117	78.63%	1
Total roof (excluding adhesive)	**1162**	**6,488**	**17.91%**	**25**
Ground Mount				
Unirac through-bolt	0	85,299	0%	2
Powerway	755	219,352	0.34%	1
Unknown east-west at Shell station	0	640	0%	1
Custom carport	15	92	16%	1
Total ground mount	**770**	**303,383**	**0.25%**	**5**

Most of the systems we saw were rooftop systems installed by one local installer, Pacific Solar. Pacific Solar has developed a custom racking design significantly different than other, typical solar PV racking systems. It fared well, with total failure rates of less than 3%, though many of the findings and recommendations on these systems are only applicable to Pacific Solar systems.

Movement in racking systems can also lead to PV system failures. These failures sometimes reveal in damage to the racking systems themselves, or sometimes lead to releasing modules or vibrating bolts loose. It is important to also consider dynamic loading and resonance of the system, rather than only static loading created by a high-wind event.

Recommendation: Ensure racking system is designed for dynamic and not just static loading. Racking should be stiff enough so that wind loads do not easily excite resonant frequencies. This requires dynamic loading design not typically performed on PV systems. Guidance for dynamic design can be found in SEAOC PV 2-17. Priority: High.

The assessment team saw different failure modes across the various racking types. Some of these may not be due to deficiencies in the racking system, such as missing modules and debris impact. Other failure modes included:

- Bent and damaged rails and other racking components. This indicates that at some point, there was too much force on the rails for them to withstand. On the systems where this occurred, the metal racking elements used thinner gauges and were less robust in general. In some cases, rails came apart at splice joints between two sections of rail.

Figure 40. Deformation of various racking components. Top left experienced higher loads due to its location near the roof corner. Top middle, top right, and bottom left used too thin gauges and low-quality components. Bottom middle and bottom right were likely the result of extreme loads and bolts that slipped in their slotted connections.

Recommendation: Select racking elements of thicker gauges that provide both lateral and longitudinal support. Try to avoid systems that only support modules along one axis (laterally or longitudinally). These racking systems impact extra loading onto the modules, loads they are not designed to withstand. Cross bracing in racking systems is ideal. Priority: High.

- Systems in which PV modules were low tilt and low to the roof surface or ground fared well. Systems with high tilt angles where the high side of the module was more exposed and allowed more wind uplift on the underside of the panels suffered much more damage (Figure 41). Some systems with high tilt angles suffered total loss. On other systems that were missing sporadic modules, these missing modules were often on the highest row of panels; modules with the most underside area were exposed to potential wind uplift forces. One system had a section with a high tilt angle and a section with a low tilt angle. The high-tilt-angle section suffered extensive damage, while the low-tilt-angle section was undamaged (Figure 42).

Figure 41. PV racking with high tilt angles allows more wind uplift forces on the undersides of the modules

Figure 42. The right section of this array had a high tilt angle (14°) and suffered extensive damage. The left portion of the array was mounted flush to the roof at a low tilt angle (4°) and suffered no damage.

Recommendation: If roof has at least 5° pitch, install PV system flush with roof at a low height above roof racking. Otherwise, install the PV system at around a 5° pitch, or at as low of an angle as feasible for installation, maintenance access, and to prevent pooling water after rains. Priority: High.

- Flying debris impact. While typically the modules take the brunt of debris impact, occasionally debris can dent or damage racking components as well. In some cases this flying debris could have been solar panels.

Figure 43. Debris impact can damage racking, which may free modules

Recommendation: Clear rooftop or surrounding area of objects that could become flying debris. Priority: Medium.

- One ground-mounted system used a minimal racking system with an "east-west" module layout. While these designs are efficient at maximizing space and sit low to the ground where wind speeds are lower, the lack of a substantial racking system puts extra loading onto the modules themselves. The modules are not rated to withstand these loads. This can lead to fatigue in the frames over time or failure in a high-wind event. Figure 44 shows the system; looking closely shows module frames sagging in the middle. While upon first glance this system was undamaged by the typhoon, it is more vulnerable to future damage, and there are undoubtedly cell cracks in the modules that will decrease production over time.

Figure 44. The lack of a substantial racking system on this "east-west" ground-mounted system puts extra loading onto the modules themselves. Modules in this array are deformed, sagging in the middle. They are vulnerable to damage in a future event and could have suffered internal damage that might diminish power production or shorten useful life.

Recommendation: Ensure all racking has cross members and supports both lateral and longitudinal movement of the panels. Do not use the panels and panel frames along the load path. Priority: Medium.

- One older system used an adhesive to attach flexible solar cells directly to the roof surface. This adhesive failed in the typhoon and almost all of the solar cells blew away, sometimes taking parts of the roofing membrane with it. This product is no longer produced, but we are including findings and recommendations of what to avoid should similar products be reintroduced to the market.

Figure 45. One system that used an adhesive to attach solar directly to the roof surface was nearly totally blown away. Although this product is no longer on the market, avoid systems like this that use adhesives or attach solar directly to the roof.

Recommendation: Ensure solar arrays are physically anchored to the roof or ground. Do not use systems that are attached with adhesives or only use ballast without physical roof anchors. Priority: High.

Table 8 shows racking failure modes and number of occurrences of each.

Table 8. Racking Failure Modes and Number of Occurrences

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Missing modules	Ensure racking system is designed for dynamic and not just static loading. Racking should be stiff enough so that wind loads do not easily excite resonant frequencies. This requires dynamic loading design not typically performed on PV systems. Guidance for dynamic design can be found in SEAOC PV 2-17.	Module attachments, modules, racking	All	13	N/A
Racking rails bent, damaged	Select racking elements of thicker gauges that provide both lateral and longitudinal support. Avoid systems that only support modules along one axis (laterally or longitudinally). These racking systems impact extra loading onto the modules, loads they are not designed to withstand. Cross bracing in racking systems is ideal.	Racking	All	6	High
System high tilt angle/high side of racking high off roof/ground	If roof has at least 5° pitch, install flush with roof at a low height above roof racking. Otherwise install PV system at around a 5° pitch, or at as low of an angle as feasible for installation, maintenance access, and to prevent pooling water after rains.	Racking	All	3	High
Debris impact – racking damage	Clear rooftop or surrounding area of objects that could become flying debris.	Racking	All	1	Medium
Roof anchors pulled up from roof structure	Rare failure mode—no additional recommendations. Follow current practices.	Racking	All	1	Low
Adhesive failure	Ensure solar arrays are physically anchored to roof or ground. Do not use systems that are attached with adhesives or only use ballast without physical roof anchors.	Racking	Adhesive	1	High
Modules bent and sagging	Ensure all racking has cross members and supports both lateral and longitudinal movement of the panels. Do not use the panels and panel frames along the load path.	Racking		1	Medium
Dynamic loading induced failures	Ensure racking system is designed for dynamic and not just static loading. Racking should be stiff enough so that wind loads do not easily excite resonant frequencies. This requires dynamic loading design not typically performed on PV systems. Guidance for dynamic design can be found in SEAOC PV 2-17.	Racking	All	[a]	High

[a] Amount of contribution to failures cannot be conclusively determined from post-event assessment.

Racking Attachments

The different components of the various racking systems also need to be held together with fasteners, typically bolts, washers, and nuts. These bolts can fail through loosening as the system vibrates over time, slip in slotted holes in the racking (perhaps due to loosening), and tear out of the slots in the rail. Other failure modes such as fatigue failure and shear fracture can happen but were not found much on this assessment trip. Almost all of the racking attachment issues we saw were on the ground-mounted system that was damaged, though this is likely because ground-mounted racking structures are typically more complicated and higher off the ground than rooftop systems.

The main failure modes observed were:

- Bolt loosening. Nuts and bolts can loosen over time when exposed to repeated vibrations. Bolts that are designed and installed correctly should not loosen, but this may require expertise. Flexibility in the racking structure allows deflection and vibration under wind loads. We observed one rooftop system with a loose rail on the front row (Figure 46) and other nuts that were finger loose on various systems. Often, PV designers and installers will try to mitigate loosening by using "locking" hardware. The most common type used is a split washer (commonly called "lock washer"), though contrary to the name, **these split washers do not provide any locking ability to resist vibrational loosening**. Other locking hardware such as wedge-lock washers, Belleville washers, and pre-applied thread locker are more effective at resisting loosening.

Figure 46. Left: Loose bolted connection between roof anchor and racking rail. Bolts were loose down the entire length of this rail, and it could move easily. Right: A loose nut on a bolted connection.

- Bolt slip. It is common to use slotted connections for bolts in PV connections that are larger than the diameter of the bolts. If the bolts are not able to hold in their position in this slotted connection, they can slip and allow the structure to move. This can result in loading on the bolts and other components that they were not designed to withstand. This slip could be the result of inadequate initial torque on the bolt, insufficient surface area between the bolt/washer and the slotted connection, or perhaps vibrational loosening of the nut and bolt over time. We observed several cases of bolt slip on the ground-mounted system that was damaged on several different racking connection locations.

Figure 47. Racking bolts that slipped in slotted connections, clearly shown by impressions left from the original position of the bolt. Bolts may have loosened due to wind-induced vibrations and then slipped.

Recommendation: Ensure bolt is designed to provide enough clamp force to resist movement. Use locking hardware to prevent loosening. Consult a bolted joint engineer if uncertain. Priority: Medium.

- Bolt tear-out. Nuts or bolt heads can pull out of the holes or slots in racking pieces if they are under enough load to deform the metal on the racking piece to the extent that the nut or bolt head can fit through. This was seen on a couple of different connections on the ground-mounted system that experienced failures.

Figure 48. Various instances of bolt tear-out or near tear-out at various places within the racking system

Recommendation: Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out. Priority: Medium.

- Clamp separation. Under loads, surfaces that are meant to be held together by a bolt may separate. This could be due to bolt loosening. Once these surfaces separate, there is not sufficient friction holding them together, and they are susceptible to movement and damage. This was seen on the ground-mounted system with damage, but this could be a secondary failure that is the result of another failure mode.

Figure 49. Clamp separation between two racking members. This could be a secondary failure as a result of other racking system failures that allowed movement in the racking system.

Recommendation: Consult a bolted joint engineer in system design; likely a secondary failure mode in this case. Priority: Low.

A summary of racking attachment failure modes and recommendations is given in Table 9.

Table 9. Racking Attachment Failure Modes, Recommendations, and Prevalence

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Split washers not providing locking ability	Do not use split washers for locking capabilities. Although commonly called "lock washers," they do not resist vibrational loosening.	Module attachments, racking attachments	All	1	Low
Bolt slip in slotted connections in racking joints, possibly after bolt loosening	Ensure bolt is designed to provide enough clamp force to resist movement. Use locking hardware to prevent loosening. Consult a bolted joint engineer if uncertain.	Racking attachments	Ground-mounted	1	Medium
Bolt tear-out in racking	Ensure bolt diameter, nut diameter, and washer diameter have been designed to provide enough surface area and grip length to resist tear-out.	Racking attachments	All	1	Medium
Clamp separation	Consult a bolted joint engineer in system design; likely a secondary failure mode in this case.	Racking attachments	Ground-mounted	1	Low

Roof Anchors and Foundations

PV systems ultimately need to be anchored to the roof or into the ground. There are many different approaches to this. Anchor and foundation failures do occur, but on the 29 systems the assessment team saw on Guam following Typhoon Mawar, these failures were insignificant. The team observed only one failure of this type: one rooftop system had a roof anchor that pulled up from the roof and damaged the roof membrane.

All rooftop systems were structurally anchored to the roof (and not ballasted). This should be a requirement; otherwise, current anchoring and foundation practices appear to be adequate.

This is in line with Unified Facilities Criteria (UFC) 3-110-03, Section 1-8.10: "PV supports must be permanently affixed stanchions that are anchored to the building structure."

Overall System Considerations (Not Related to Specific Components)

Avoid Roof Corner Zones

Wind loads on roofs are highest on the corners and second highest on the edges, especially on flat roofs without parapets. Best practice solar PV design is to avoid installing panels in these areas. In SEAOC's "Wind Design for Solar Arrays" (SEAOC PV 2-17), these roof areas are called roof Zones 3 and 2 (Figure 50).

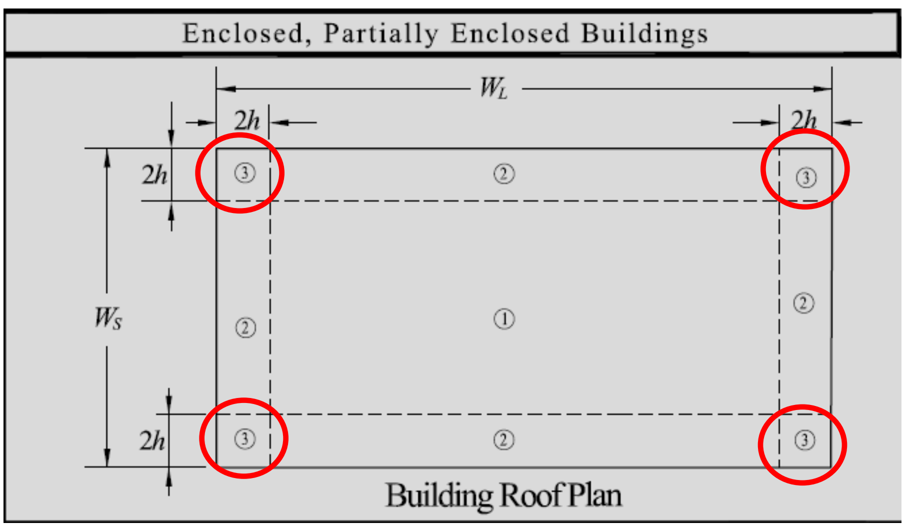


Figure 50. Roof Zones 1–3 as defined in SEAOC PV 2-17. Roof Zone 1 is the safest place to install PV, while roof Zone 3 is the riskiest due to the increased wind loading.

Systems with panels installed in these roof zones saw higher failure rates than in the center areas of the array (Figure 51).

Figure 51. Roof corner zones, especially on roofs without parapets, experience the highest wind loads and often experience the most damage (as shown here)

Recommendation: Do not install modules in SEAOC PV 2-17 roof Zone 3. Priority: Medium.

PV Trackers

PV trackers are designed to follow the sun throughout the day (single-axis trackers) and sometimes throughout the year (two-axis trackers). There are currently no PV tracker systems in Guam. Tracker systems are typically much more flexible than fixed-tilt systems and do not fare as well in high winds. They can exhibit instabilities and typically cannot be designed to design wind loads above around 150 mph. Tracker systems also typically attach to modules closer to the center of the module, leaving a longer side of the module unsecured.

Recommendation: Do not install PV trackers on Guam. Priority: High.

Wind Deflectors

The NREL team did not observe any wind deflectors on Guam PV arrays, though they are commonly used elsewhere. They are typically installed around the perimeter of an array (or on the windward side) to block the gap between the PV modules and the roof to prevent wind from getting underneath the modules and providing uplift forces. We saw notably more damage occurring on the high side of PV arrays where wind can get under the top row. Wind deflectors may help limit these failures.

Figure 52. Rooftop solar system with wind deflectors on rear side to block wind and prevent uplift forces

Recommendation: Install wind deflectors on the high side of PV arrays between the roofs and panels. Priority: Medium.

Transferrable Knowledge from a Caribbean PV Case Study

In 2017, two hurricanes hit St. Croix in the U.S. Virgin Islands within weeks of each other. While many PV systems survived, several were destroyed. One of the destroyed systems was rebuilt to a higher standard to be more resilient to future hurricanes. After extensive engineering analysis and modeling, along with collaboration with the module and racking vendors, the installed system had many hardened features, including:

- Racking system designed for dynamic loading, including a resonant frequency analysis.
- Tilt angle of 12° as a compromise between increased dynamic effects expected at lower tilt angles and higher static loads that would occur at higher angles.
- Front and rear racking support posts.
- Locking fasteners.
- Modules with high load ratings.
- Lowering the array 1 foot closer to the ground compared to the original design.

For more details on this system and the rebuild, refer to *Toward Solar Photovoltaic Storm Resilience: Learning from Hurricane Loss and Rebuilding Better* (www.energy.gov/femp/articles/toward-solar-photovoltaic-storm-resilience-learning-hurricane-loss-and-rebuilding).

Electrical Systems

The primary focus of this assessment was on the structural side of PV system damage and survivability, though there were a few notable findings related to the electrical side of the PV systems.

Wire Management

PV modules are typically connected in series to form "strings." PV modules come with wires attached on the underside, and modules are connected to each other using "PV connectors." Strings are usually connected in parallel in combiner boxes before power goes to the inverter(s). The result is a significant amount of wiring under the PV modules. This wiring is typically routed along the underside of the module frames and held in place by some type of wire management system. The most common type of wire management system is simple plastic or nylon wire ties (i.e., "zip ties"), but these are not robust and fail frequently under outdoor conditions. Even "UV-rated" wire ties are typically not adequate and are not rated for the duration of outdoor exposure that they will be exposed to in a PV system setting. When they fail, PV wiring and connectors can sag below the modules, often resting on a roof. On the roof, they are vulnerable to water damage. Wind can also blow them around, pulling on remaining wire management systems and wearing down insulative sheathings and coverings. This poses a fire and safety risk and a risk of component failure. The best wire management systems are devices that attach to module frames that are specifically designed for PV wire management. These systems are often metal, metal with rubber or silicone coverings, or made from polyvinylidene fluoride (PVFD).

The Dandan ground-mounted PV system used metal PV wire management devices and had no issues with failures, even 15 years after installation (Figure 53, top). Other, much newer, systems that used plastic or nylon wire ties were seen to have many broken ties with wires and connectors lying on the roof surface (Figure 53, middle and bottom). On some systems, we estimated 25%–50% of PV wiring had come loose and was lying on the roof surface. Overall, we saw this issue on 8 of the 16 rooftop systems for which we had roof access.

Figure 53. Various wire management approaches—some good, some bad—and failures. Top: Metal PV-specific wire management system that has held wires in place for more than 10 years. Middle: Wires and PV connectors down on the roof are a safety and fire risk due to potential water damage and insulation damage as wind drags them across the roof surface. These were likely tied under the panels with plastic or nylon wire ties that failed. Bottom left: More wires and connectors down on roof surface, likely because of failed wire ties. Notice the one plastic wire tie under the left side of the module. Bottom right: A PV connector that has come unattached, breaking the circuit and stopping power delivery from a whole string of PV modules.

We cannot determine if these wire management system failures occurred during the typhoon or existed prior to the event. In any case, these failures leave the PV systems more vulnerable to failure and fire risk in future wind events.

For more information on solar PV wire management, see "Solar Photovoltaic (PV) Cable Management - Best Practices to Support DC-String Cables Implications for New Construction Specifications and O&M," available at energy.gov (forthcoming as of April 2024).

Recommendation: Replace wire management systems with a solution more robust than wire ties. Purpose-built PV wire routing systems such as the SunBundler or others are more durable and hold wires more securely. Priority: High.

Enclosures

There are various electrical enclosures associated with PV systems: combiner boxes, junction boxes, and inverter enclosures, for example. Water ingress into electrical components is a huge concern in Guam; one of the installers we met with cited it as their biggest headache ("water finds its way everywhere!"). We saw some instances where water from the storm had damaged electrical components—either from flooding/ponding or driven rain.

One combiner box had clear evidence of water intrusion. As it was on the high side of a roof, this was likely the result of the cover blowing open during the storm (or perhaps rain driven in through inadequate seals).

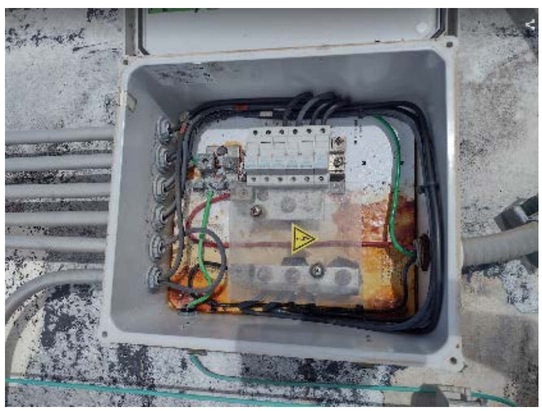


Figure 54. Combiner box damaged from water intrusion. This box was NEMA 4X rated, but still not of high enough quality.

Recommendation: Specify NEMA 4X enclosures in Guam. NEMA 4X in Guam alone is not sufficient. All exterior housings must be continuously welded, NEMA 4X (or better), fully gasketed, continuously hinged (piano hinge) with three-point door closure clamps, and designed to prevent water intrusion from hose-directed water, splashing water, and wind-driven rain. Gaskets must be molded and of one continuous shape with no seams. All equipment mounted to the interior of the enclosure shall use back plates to minimize exterior cabinet penetrations. Conduit entry into electrical equipment shall be designed to prevent water intrusion. The minimum mounting height of enclosures shall be based on the 500-year flood plain and surge levels. Priority: Medium.

DC surge protectors also suffered damage. On one system, this was the result of roof flooding caused by debris blocking roof drains. On another system with failed DC surge protectors, there was evidence of significant electrical faults and overheating and melting of PV wiring and PV connectors. In this case, the damage may not have been caused by the typhoon. Other DC surge protector failures may have occurred either during or before the storm as well.

Figure 55. Failed DC surge protection devices with signs of water ingress and burnt components

We saw an instance of an electrical pull box with a missing cover that likely blew off in the storm. This enclosure was not adequately rated for the conditions (assumed NEMA 3 rating). The missing cover could have led to water ingress into the box, through the conduit, and into the AC breaker panel and PV panel, though in this case we saw no evidence of water damage to these panels.

Figure 56. Electrical pull box with missing cover, likely blown off during the storm. The box does not appear to be rated for the conditions; it is likely a NEMA 3-rated enclosure. This leaves the system vulnerable to water ingress that could flow through the conduit into other electrical components such as inverters and AC breaker panels.

Recommendation: Clear roof drains to avoid flooding that can damage DC surge protectors. Follow electrical enclosure recommendations in this report—NEMA 4X plus additional requirements. Consult a PV service provider or local installer for repair. Priority: Medium.

Inverters

Many of the systems visited had no facility power, and thus inverters were offline. Many inverters that were online were producing error codes due to missing or damaged modules or other faults (Figure 58). Some had shade covers that were blown off (Figure 5859). Otherwise, we saw no evidence of damage to inverters, aside from several that lost shade covers in the storm winds. One of the utility-scale ground-mounted PV systems reported water intrusion into their central inverters. They had already repaired damages by the time of this assessment trip.

Figure 57. Inverter error codes. Many inverters displayed error codes and were not providing power, even before the storm.

Figure 58. Shade covers blown off inverters; low-impact and low-priority failure. Notice the faded labels on the disconnect boxes, too.

Inverters have longer lifetimes when not exposed to direct sunlight and when kept at lower operating temperatures. Ideally, they would be mounted in a climate-controlled space, but this is not always possible. Otherwise, make sure inverters are shaded and not susceptible to direct sun exposure. This is best achieved by mounting inverters inside or on the *north side* of a building. If this is not possible, inverter sun covers are also an option, but should only be used if conditioned spaces, indoor spaces, or north-side building wall mounting is not possible. *Note: All of the* *systems observed in Guam used string inverters where DC power from several modules runs into an inverter and is converted to AC power. Some PV systems also use microinverters that are mounted directly under each module. The findings and recommendations in this report do not apply to microinverters.*

Recommendation: Secure string inverter covers with redundant, locking hardware. Priority: Low.

Table 10 summarizes electrical system findings, recommendations, prevalence, and priority levels.

Table 10. Electrical System Findings and Recommendations

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
Wire management – cables on roof	Replace wire management system with solution more robust than wire ties. Purpose-built PV wire routing systems such as the SunBundler or others are more durable and hold wires more securely (see “Solar Photovoltaic (PV) Cable Management - Best Practices to Support DC-String Cables Implications for New Construction Specifications and O&M” for more information).	Wire management	All	8	High
Inverter covers blown off	Secure inverter covers with redundant, locking hardware.	Electrical	All	2	Low
DC surge protector damaged	Clear roof drains to avoid flooding that can damage DC surge protectors. Follow electrical enclosure recommendations in this report—NEMA 4X plus additional requirements. Consult PV service provider or local installer for repair.	Electrical	Rooftop	2	Medium
Water damage inside electrical boxes, batteries, or inverters	Specify NEMA 4X enclosures in Guam. NEMA 4X in Guam alone is not sufficient. All exterior housings must be continuously welded, NEMA 4X (or better), fully gasketed, continuously hinged (piano hinge) with three-point door closure clamps, and designed to prevent water intrusion from hose-directed water, splashing water, and wind-driven rain. Gaskets must be molded and of one continuous shape with no seams. All equipment mounted to the interior of the enclosure shall use back plates to minimize exterior cabinet	Electrical	All	2	Medium

Failure	Recommendation	Applicable Part of System	Applicable to	Number of Systems Impacted	Priority
	penetrations. Conduit entry into electrical equipment shall be designed to prevent water intrusion. The minimum mounting height of enclosures shall be based on the 500-year flood plain and surge levels.				
Melted PV connectors	No recommendation. One instance, unknown root cause.	Electrical	All	1	Low

Construction

PV arrays that were installed by experienced, professional PV installers notably fared better than those that were not. Two of the arrays that experienced the most damage were either self-installed or installed by inexperienced PV installers (neither were on U.S. Department of Defense [DOD] bases). Despite a perception that there is not much complexity to PV, there are many nuances (such as those discussed in this report) that an inexperienced PV installer could overlook.

Recommendation: Use only experienced PV designers and installers. Ensure they follow all local codes and installation manuals. Priority: High.

One of these arrays used unmarked PV modules and racking of unknown origin and quality (not on a DOD base). These components may not have passed PV certifications or been up to code. Project specifications should require all components to pass basic PV certifications including ASTM E1830-15, IEC 61215-1, and UL1703 for modules; UL1541 for inverters; UL2703 for racking; and UL9540 and UL 9540A for battery energy storage systems.

Recommendation: Ensure components meet codes and standards and are purchased through reputable, established manufacturers and vendors and that components have traceability back to their source. Priority: High.

Findings Unrelated to Typhoon Damage

Snail Trails and Algae

Guam is a harsh environment for infrastructure, and solar panels are no exception. There were several forms of degradation observed on modules and several factors that may have led to underproduction.

Degradation was seen in discoloration of cells on older panels. This can lead to decreased production.

Snail trails are visible silver lines across PV cells. They were present on modules at several sites, on both older and newer modules. Snail trails can be the result of moisture ingress or can reveal the location of previous microcracks. They can lead to degradation in power production of around 10%. If snail trails are present, a module manufacture warranty claim can typically be submitted for replacement panels.

Figure 59. Snail trails most likely predated the storm, though they can be caused by water ingress. These will lead to loss of production over time and may be grounds for a warranty claim.

Recommendation: Check modules for snail trails and discoloration and file a warranty claim if significant. Priority: Medium.

Algae buildup was seen on buildings throughout Guam, especially on roofs. It can build up on solar panels, especially along the lip of the frame on the lower side of modules. Regular cleaning (one local installer recommends quarterly) or treatment with algaecide can be effective in preventing this and maintaining expected solar panel production, given the algaecide is environmentally friendly. One reason for the algae buildup is the low tilt angles of the panels. With higher tilt angles, rainwater would clean the panels more effectively and less water would pool by the lower frame lip after rains. Lower tilt angles, however, are more resilient against wind events. We recommend low tilt angles of around 4°–5° as a compromise, though this might necessitate more frequent cleaning. One local installer believes 10° is necessary to eliminate this buildup.

Figure 60. Algae buildup along the frame on the lower side of PV modules. This site is experimenting with algaecide to mitigate buildup.

Recommendation: Ensure slope is high enough for water to shed and wash off algae and other "muck." Priority: Low.

In any case, modules should be inspected annually for anything that could cause degradation or decrease power production. They should be cleaned from algae or other soiling regularly. If other signs of degradation modes are found, it may be grounds for warranty claims if panels are not meeting their expected annual power production.

Vegetation Management

Vegetation management is a big concern for ground-mounted PV systems on Guam, occupying much of the site staff's time. Overgrowth can shade panels, and vines can wrap around and pull apart cables. Schedule mowing operations to keep up with the growth (Figure 61).

One vegetation management strategy could be to employ "agrivoltaics," the practice of co-locating PV on land with agricultural uses. Crops, pollinator-friendly plants, or native, low-growth vegetation could be planted underneath the PV array. The crops get the benefit of partial shading, which can increase yield and reduce water requirements. The crops likely contribute to a cooler environment under the PV system as well, which increases PV efficiency. Another agrivoltaics application that could simultaneously address vegetation overgrowth involves bringing in animals to graze on the land under PV arrays. The animals typically enjoy the shade as well, though care needs to be taken to protect certain areas of the array and choose animals that fit the site. Sheep have been the best grazers around PV systems. Goats and cows have been used as well but are more likely to eat through or damage system components.

For agrivoltaics applications, PV typically needs to be elevated higher above the ground where it will encounter higher wind loads, so there should be a cost-benefit analysis performed weighing the increased structural costs to handle this higher wind load compared to the benefits of reduced maintenance, greater land use, increased agricultural productivity, and other environmental impacts.

Figure 61. Vegetation management is a big concern on Guam. Top: An overgrown section of a utility-scale PV array. Bottom: An excellently maintained PV array at Naval Base Guam. There is a third-party service contract for this array, and it is in excellent condition, even 15 years after installation.

Recommendation: For ground-mounted systems, ensure regular vegetation management. Plant disturbed areas with low-growing grasses or other ground cover plants. Priority: Medium.

Corrosion

Guam is a very corrosive environment, surrounded by salt water, and humid with regular high winds. PV systems often employ dissimilar metals that can lead to corrosion. In general, corrosion on PV system components was low, especially when compared with other non-solar rooftop hardware and equipment such as heating, ventilating, and air-conditioning (HVAC) systems. The oldest system visited had severely rusted bolts, but no failures were observed due to corrosion. Aluminum oxide was present in places, but not at a significant enough level to be of concern.

Figure 62. Salt mist and humidity make Guam a very corrosive environment (rated C5 on the International Organization for Standardization's (ISO) corrosivity scale). This can cause signs of corrosion where dissimilar metals contact. We saw corrosion on infrastructure attachments on Guam. It was typically worse on non-PV infrastructure. We saw no failures related to corrosion.

Recommendation: Use marine-grade stainless steel hardware in Guam. Priority: Medium.

Roof Access

Several rooftop systems had difficult or no access to the array. Some would need a lift to access, others would need a key to a roof hatch. On occasion, inverters were located on these roofs or mounted high in rooms that needed ladders to access and view.

Figure 63. An example of good rooftop and PV array access from an outside ladder. Some buildings did not have easy roof access, impeding maintenance and damage assessment.

All rooftop systems need to be easily accessible. We recommend access with a minimum 10-foot ladder. Installing external ladders on building walls is the preferred access method. Systems that cannot be accessed cannot be maintained or even evaluated for damage and safety after a weather event. Many of the systems on Andersen Air Force Base were not easily accessed, so damage could not be easily assessed after the typhoon. These systems typically needed a lift for roof access. After the storm, lifts were in high demand for higher-priority recovery tasks, so were not available for PV assessment. Buildings on which PV is installed should not rely on lifts for access.

Recommendation: Ensure all PV rooftop arrays are easily accessible, ideally via an external ladder. Relying on lift access is too unreliable and costly. Priority: Medium.

Accessibility of Components

Some inverters and batteries on PV systems were difficult to access. Some required a key to access electrical rooms or rooms where roof hatches were, some inverters were mounted well above eye height and required an awkwardly placed ladder to read, and some inverters were on roofs that themselves were difficult to access. Reading inverters regularly to monitor production and look for any error codes is the most important O&M activity for PV systems. These issues make it less likely that the inverters will be read, and errors will not be found as quickly. *Note: As stated above, these recommendations and findings only apply to string inverters, not microinverters.*

Recommendation: Inverters should not be mounted on roofs. They should be mounted at ground/eye level. They should be shaded from direct sun exposure at all times of the year and regularly monitored for error codes (recommend monthly). If in a locked room, facility staff performing PV O&M should have a key to access. Priority: Medium.

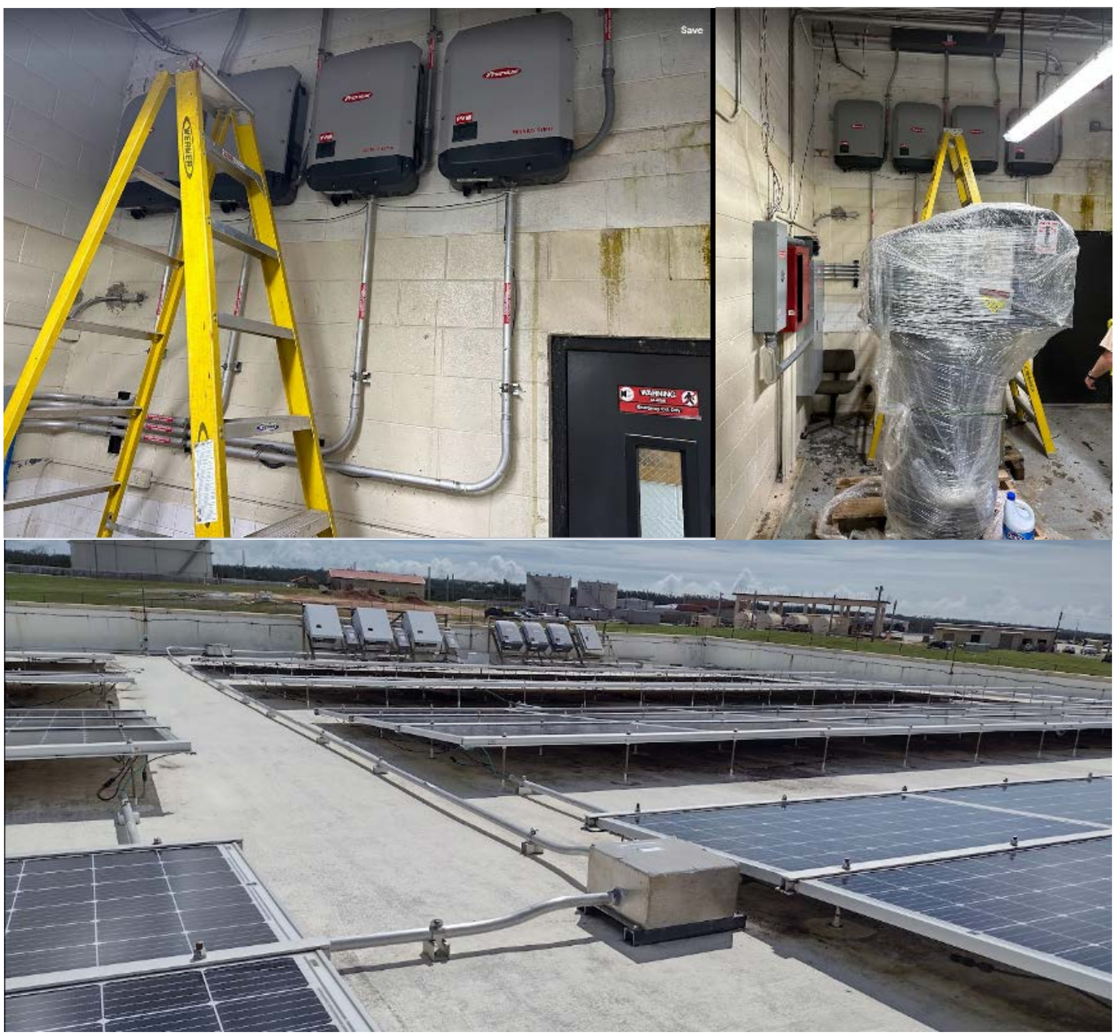


Figure 64. Inverters mounted high on walls or on roofs are difficult to access and read, which hinders maintenance and makes it more likely faults will go undetected

System Maintenance and DOD Service Contracts

Apart from typhoon impacts, the baseline state of PV systems seen on this trip varied greatly. These variations were often the result of the level of maintenance and attention the systems were given. The ground-mounted system at Naval Base Guam, installed around 15 years ago, was in excellent shape. This site utilized a third-party maintenance contract. Some other systems showed substantial signs of physical wear and degradation. Many systems at Andersen Air Force Base were either not producing or were not producing at full capacity. These systems had various faults that lead inverters to trip offline. Some of these systems had been offline since well before the typhoon. There are various reasons for this, including limited site staff availability, difficulties in diagnosing faults, difficulties in getting approvals to order replacement parts such as fuses and switches, and poor roof access. The Andersen Air Force Base systems were self-maintained.

The two large privately owned ground-mounted systems on Guam employ staff to perform maintenance, almost all of which is dedicated to vegetation management.

We strongly recommend O&M contracts with all DOD PV installations. A local experienced installer could monitor production, catch errors and underproduction early, and perform repairs with less red tape than overtasked on-site energy managers.

At Andersen Air Force Base, **many systems were offline and not producing before the typhoon.** Based on inverter readings in December 2022, only 61% of installed PV was capable of providing power before the storm. The storm reduced this percentage further, but many buildings did not have power at the time of the assessment trip to power inverters, so we do not know the percentage of PV online after the storm, but it is between 11% and 47%. Based on structural and electrical damage observed on these systems without power, we estimate 40% of PV capacity will be online when power to those buildings (all at North Ramp) is restored. This means an estimated 20% of PV capacity was lost due to the storm, but this is a very rough approximation.

There were many reasons systems were offline prior to the typhoon. We heard from site staff that ordering replacement parts, even things as small as fuses, required paperwork and approvals that take time. If possible, these items should be considered routine, regular maintenance that is budgeted for. PV O&M is also a small and low-priority portion of facility staff's jobs. It is difficult to find time for this. Also, while facilities staff are typically very adept and knowledgeable engineers or electricians, they are not specifically PV experts. Given that PV could provide resilient power to facilities after an event such as a typhoon, however, this should be given higher-priority consideration.

Advantages of Third-Party Ownership and Maintenance

Due to constraints on facility staff time, the potential for PV to provide critical power, and administrative burden of operating and maintaining PV systems at DOD facilities, a third-party service could be beneficial. Hiring a local PV installer to perform regular O&M (including performance monitoring) would ensure that PV is kept in good condition. This will yield higher power production and a longer lifetime of the asset. It is especially beneficial in a harsh environment like Guam, where soiling and algae buildup is ubiquitous on rooftops. One avenue for establishing this type of contract may be by adding O&M into a Base Operations and Support Services Contract.

We saw an excellent example of this at Naval Base Guam. A 250-kW ground-mounted system installed around 2010 was in excellent condition—clean and still producing its expected power. It also suffered no storm damage from Typhoon Mawar (see Figure 61).

Given these advantages and that so much installed PV infrastructure was effectively sitting idle on rooftops even before the storm, **we strongly recommend exploring third-party O&M of PV systems.**

Carport System Recommendations

Carport systems are susceptible to higher wind loads due to their increased height above the ground. The one carport system we saw (also referred to as a "canopy," technically termed "elevated PV structure") suffered damage only through modules pulling free of the through-bolts in their frames and from flying debris. Notably, the through-bolting system prevented any cascading failure that may have resulted from this and kept these failures isolated. Through-bolting is recommended for PV canopy systems (for all PV systems, in fact). The structure on this system was robust and well designed; foundations went 16 feet underground, and large, thick-gauge metal components were used. There were no issues with the support structure (Figure 65).

Figure 65. PV carport structure with isolated missing modules where modules tore off the bolts holding them down. The structure is also very tall (approximately 20 feet high) and thus susceptible to higher wind loads.

The structure was very tall, however, significantly taller than most PV carport systems. It is unclear why it was built so high off the ground, but this increased the wind loads on the panels. PV carports should only be built as high as they need to be for the types of vehicles that will be parked underneath.

Due to higher uplift forces on modules on PV carports, extra attention should be given to module attachments. The modules used on the one carport we visited had extra predrilled bolt slots on the frames that could have been utilized for more attachment points. Larger-diameter washers would also have provided more contact area between the bolt and the frame of the module and could have resisted bolt tear-out better. These predrilled bolt holes on the module frame on the specific module used were also close to the edge of the frame flange. When selecting between modules, select modules with predrilled holes farthest from the edge of the frame (Figure 66).

Figure 66. The predrilled bolt slots on this module were very close to the edge of the module frame lip, allowing the bolts to tear out of the frame more easily. Larger-diameter washers could help.

Post-Storm Cleanup, Repair, Replacement, and Repowering

After a potentially damaging event (e.g., wind storm, seismic event), all PV systems should be inspected as soon as feasible. This inspection should consist of visual inspection, noting missing panels and which strings they are on, and an inverter status inspection. Ideally, systems will have been disconnected before the event, given enough advance warning.

The first step in recovery should be cleaning PV sites and removing debris. We visited rooftops at Andersen Air Force Base almost 3 months after the typhoon, and there were still many panels littering the roofs. This poses a flying debris hazard. Whereas during the typhoon, there were not likely people outside who could be hit by solar panels that have flown off roofs, **loose roof debris can blow off roofs during much milder wind events that could occur while personnel are outside. This is a serious safety hazard and should be addressed immediately.**

Figure 67. Debris left on rooftop after the typhoon

Even if there is no apparent storm damage, follow standard IEC 62446-1 before powering a system back on. This involves performing grounding continuity tests, polarity inspections, combiner box tests, an insulation resistance test, and string-level testing of open-circuit voltage and short-circuit current before reconnecting. If this testing passes, monitor inverters after reconnecting to confirm production is what would be reasonably expected (given string size and current weather conditions). Should systems fail, call in a PV specialist for service.

To perform this string-level testing, use a device such as a Seaward PV150 Solar Tester.
For systems with relatively few missing panels (less than about 10%), a like-for-like replacement is viable. If the same panels are still available for purchase, replace with like panels. If panels are no longer available, the best option is to rewire and reconfigure existing system components. The result will be an array with less capacity. If the full original capacity is needed, consolidate salvageable parts of the existing array and construct a new section. This new section can likely utilize existing inverters.

For systems that suffered significant damage (more than about 20%), assess the root cause of the damage. If the root cause is structural, do not replace system like-for-like. Salvage modules that are still usable and replace the racking system with a more robust alternative, following recommendations in this report. Should damage be near total (more than about 80%), it may only be worth salvaging modules if the same module is still available on the market.

We also strongly recommend a retorqueing of structural and electrical bolted joint connections after every significant wind or seismic event to ensure components are secure and less vulnerable to damage in subsequent events.

UFC Design Guidance Concerning Solar Panels

Solar PV is addressed in several UFC documents.

UFC 3-440-01 (2015) "Facility-Scale Renewable Energy Systems" Chapter 3 is titled "Solar Photovoltaic Technical Requirements," and Appendix B-4 contains solar PV best practices. This contains requirements for life cycle cost analysis, energy security risk mitigation, selection of modules and inverters, and warranties. Section 3-3 specifies system design requirements, though some sections should be updated (one requiring tilt be within 10° of latitude, for instance).

UFC 3-540-08 (2017) covers "Utility-Scale Renewable Energy Systems." Chapter 2 discusses planning and interconnection, and Chapter 3 covers solar PV design requirements and O&M. Appendix E provides a comprehensive O&M checklist, though it is based on a 2015 publication that has since been updated. The updates could be reflected in this UFC.

Neither of these reference any requirements for PV connectors, which are the top source of failure and fires on PV systems. We recommend updating these to include requirements around PV connectors. There are also no requirements around wire management or fasteners specific to solar PV systems.

UFC 3-110-03 (2012) "Roofing" contains requirements for PV systems on roofs, including that "PV supports must be permanently affixed stanchions that are anchored to the building structure."

UFC 3-301-01 (2023) "Structural Engineering" section A-1.4 "Wind and Seismic Loads on Photovoltaic Arrays" contains the following requirements:

> *"Design provisions for rooftop-mounted photovoltaic panels and their attachments are included in ASCE 7-16 Section 13.6.12 for seismic loading and in ASCE 7-16 Chapters 29 through 31 for wind loading. Additional guidance on the design wind and seismic loads for rooftop-mounted photovoltaic arrays can be found in 'Wind Design for Solar Arrays (SEAOC PV2-2017)" and "Structural Seismic Requirements and Commentary for Rooftop Solar Photovoltaic Arrays (SEAOC PV1-2012)," prepared by the Structural Engineers Association of California Solar Photovoltaic Systems Committee. When designing support structures for photovoltaic arrays, review requirements in UFC 3-110-03 'Roofing' concerning roof mounted systems including the requirement that supports be permanently affixed to the structure, which means that ballasted systems are not permitted. 2021 IBC Section 1607.14.4 includes gravity load requirements for roof structures that provide support for photovoltaic panel systems. This section does not disallow ballasted systems. Seismic design of ballasted photovoltaic panel systems is in fact specifically permitted by 2021 IBC Section 1613.3.*

From: www.wbdg.org/FFC/DOD/UFC/ufc_3_301_01_2023_c1.pdf

We recommend updating the language in this to reference ASCE 7-22 rather than ASCE 7-22, as ASCE 7-22 has more robust solar PV wind design requirements.

GPA Forensic Analysis

GPA conducted a quasi-forensic analysis of their net-metered distributed solar PV systems after Typhoon Mawar. They reported systems that were exporting power prior to Typhoon Mawar and were not exporting power afterwards. Overall, 223 of their 2,171 registered net-metered PV systems, or 10.1%, were not exporting after the storm (and had been exporting prior to the storm). GPA was also conducting drone flyovers for visuals of system damage.

This is a significantly different way of estimating storm damage than what our assessment team did, and the 10.1% could be a significant overestimate of actual damage. For example, if one panel blows off a small residential system, the circuit will be broken, the inverter will trip offline, and no power will be delivered. GPA is effectively reporting this system as 100% damaged even though repair costs for this case would likely be less than 5%–10% of system cost. Thus, the 10.1% should be interpreted as the percentage of systems that were damaged by some amount, not the percentage of damage that systems suffered due to the storm.

Status	NEM System No Longer Exporting	Meter Not Communicating (Not Energized or Damaged)	Total NEM Systems
Count	223	75	2274
%	10.1%	3.3%	0

Status	NEM System No Longer Exporting	Meter Not Communicating (Not Energized or Damaged)	Unregistered Solar PV Systems	Registered NEM Systems	Total NEM Systems
Count	223	75	103	2171	2274
%	10.1%	3.3%	4.5%	95.5%	

Figure 68. Net energy metered (NEM) system status after Typhoon Mawar, prepared by GPA

Module Degradation and Invisible Vulnerabilities

This assessment focused on large-scale, visible damage to PV systems. Wind events also likely cause damage to PV systems that cannot be discerned in a field inspection. There are two main categories of this damage:

1. Physical damage to a system that is not immediately obvious and may not be significant enough to keep systems from producing power but would leave systems more vulnerable to damage in a future event or lead to shortened useful life. This can be in the form of deformed modules (Figure 69) or racking components (Figure 70), wear on wiring and electrical connections that have been blown about or dragged across roof surfaces, or loosening of bolted joints. Some of these (e.g., wire management, retorquing of bolts) are easily addressed. Others are more complicated.

Figure 69. Upon close inspection, modules in this array are deformed and sagging. While it did not suffer any obvious damage from the typhoon, this will likely impact production and leaves the array more vulnerable to damage from future events.

Figure 70. Racking deformation or shifting has led to some modules raised higher than others. These sections of the array are likely more exposed and racking components are more fatigued, leaving it more vulnerable to damage from future wind events.

2. Module cell-level damage and degradation. Microcracks can form in cells in PV modules. These cracks may worsen over time and reduce power production. These cracks can possibly be caused by wind events and can further propagate by subsequent wind events. This can lead to reduced production over time, and there is some research to suggest that under some circumstances they may lead to safety hazards. Many modules have

microcracks (often the result of delivery and installation). This assessment did not evaluate potential module degradation, but there is likely a significant amount of invisible damage. Electroluminescence imaging is the best way to evaluate microcracks. UV imaging is much simpler and cheaper and could show areas where microcracks are creating hot spots on modules.

Conclusions

Many solar PV systems in Guam impressively survived Typhoon Mawar. The average failure rate of rooftop systems was 18%, with a median failure rate of 2%, meaning the few systems that suffered total loss pulled up the average. Only 8 of the 25 rooftop systems suffered more than 5% damage. All ground-mounted systems suffered less than 0.5% damage, aside from a carport that lost 16% of its modules. PV systems at Andersen Air Force Base suffered 5% damage on average, with a median system failure of 0.6%. Systems that failed all had clear root causes related to system design issues and component selection. Eliminating and improving upon these issues and components would be inexpensive, but likely will require more stringent design requirements and project technical specifications.

These low failure rates and clear paths to improvement are encouraging and show that PV—both rooftop and ground-mounted—can survive typhoons and serve as a valuable, local power source on the island.

Where systems had failures, failures were the result of:

- Inadequate clamping of the module frame to the mount.
- Module mounting clamps rotating out of underlying support rail (i.e., T-bolt that rotates free at less than 60° of rotation).
- An object hitting the panel resulting in a fracture, and in some cases leading to a cascading failure of several more panels.
- Excessive tilt angle (in Guam, greater than 5° can be a risk due to wind speed, and power production trade-offs are insignificant).

A significant finding is that **the characteristics of a system, and not the wind speed, primarily determine whether a system will survive**, as systems with different features had drastically different fates, even when exposed to the same wind conditions. Quality design and installation maintenance will yield PV systems that suffer only minor damage from storms, even Category 4 typhoons.

System maintenance is also very important in getting expected production from PV arrays, quickly diagnosing and correcting faults, and identifying and fixing structural vulnerabilities, all of which will help these PV systems fulfill their potential as on-site, reliable, robust, and resilient power sources that can provide power at all times, including after the impacts of threats and hazards.

Appendix

System-Level Data and Analysis

System	Missing or Broken Modules	Modules Broken Still In Racking	Missing Modules	Total Modules	Failure Rate	Tropical Storm Category	System Size (kW)	Wind Speed	Wind Gust	Module	Module Load Rating Front (UL clamp method 4 clamps test load)	Rear	Module W	Module Length (in)	Module Area (m2)	Racking System
JFK High School	859	0	859	4100	21%	H3	2500	130	165	JA Solar JAM72S20-460/MR	5400	2400	460		2.22	SolaRacks
FIFA Soccer Stadium	92	2	89	117	79%	H3	Unkno	130	165	Yingli	Unknown	Unknow	Unknown		Unknow	Unknown
Guam Community College Unirac	79	0	41	120	66%	H2	28	111	140	Schott Solar Perform Poly 235	2400		235		1.67	Unirac
Guam Community College Pac Sol Adjacent Roof	0	0	0	36	0%	H2		111	140	Unknown	Unknown	Unknow	Unknown		Unknow	Pacific Solar Metgot Rail
GCC Lower Roof	0	0	0	60	0%	H2		111	140	Unknown	Unknown	Unknow	Unknown		Unknow	Pacific Solar Metgot Rail
GCC Other Building	0	0	0	66	0%	H2		111	140							Pacific Solar Metgot Rail
Guam Community College Curved Roof	13	0	13	32	41%	H2		111	140	Unknown	Unknown	Unknow	Unknown		Unknow	Pacific Solar Metgot Rail
Standing Seam Metal Commercial Rooftop Array	60	9	51	180	33%	H3		130	165							Unirac
Paradise Fitness	7	1	6	140	5%	L3		130	165	Astro Energy CHSM6612P-320	5400	2400	320		1.93	Everest
AAFB Building #1	3	0	3	156	5%	M4	45	143	181.5	Unknown	Unknown	Unknow	Unknown		Unknow	Pacific Solar Metgot Rail
AAFB Building #2	2	0	2	272	1%	H4	93	150	187	REC370AA	7000	4000	370	67.8	1.74	Pacific Solar Metgot Rail
AAFB Building #3	0	0	0	44	0%	H4	136	150	187							Panel Claw
AAFB Building #4	22	5	17	128	17%	M4	36	143	181.5	hyundai his-s290rg	5400	5400	290	64.57		Pacific Solar Metgot Rail
AAFB Building #5	2064	0	2064	2112	98%	H4	190	150	187	Unisolar						Adhesive
AAFB Building #6	52	0	52	56	93%	H4	15	150	187	SolarWorld Sunmodule SW240 mono	5400	3100	240	65.94		Unirac
AAFB Building #7	0	0	0	112	0%	H4	42	150	187	Unknown	Unknown	Unknow	Unknown		Unknow	Pacific Solar Metgot Rail
AAFB Building #8	0	0	0	123	0%	M4	36	143	181.5	SolarWorld Sunmodule Plus SW 300 mc	5400	3000	300	65.95	1.68	Pacific Solar Metgot Rail
AAFB Building #9	1	1	0	156	1%	M4	45	143	181.5	SolarWorld Sunmodule Plus SW 300 mc	5400	3000	300	65.95	1.68	Pacific Solar Metgot Rail
AAFB Building #10	5	1	4	204	2%	M4	60	143	181.5							Pacific Solar Metgot Rail
AAFB Building #11	1	1	0	64	2%	M4	19	143	181.5							Pacific Solar Metgot Rail
AAFB Building #12	0	0	0	48	0%	H4	16	150	187							Pacific Solar Metgot Rail
AAFB Building #13	0	0	0	50	0%	M4	15	143	181.5							Pacific Solar Metgot Rail
AAFB Building #14	1	0	0	100	1%	M4	30	143	181.5							Pacific Solar Metgot Rail
AAFB Building #15	4	1	3	124	3%	M4	36	143	181.5	hyundai his-s290rg	5400	5400	290	64.57	0	Pacific Solar Metgot Rail
AAFB Building #16	0	0	0	0	0%	H4	118	150	187							Pacific Solar Metgot Rail

Figure A-1. Data and analysis for rooftop PV systems assessed. Yellow cells are uncertain.

	System	Missing or Broken Modules	Modules Broken Still In Racking	Missing Modules	Total Modules	Failure Rate	System Size (MW)	Storm Category	Wind Speed	Wind Gust	Module	Module Load Rating	Rear	Module W	Module Length (in)	Module Area (m2)	Racking System	
Ground-Mountec	Dandan	0	0	0	83,871	0%	25.65	L1	81	103	80% Trinasolar TSM-300PD14; 20% Canad	5400	3800	300	77	1.94	Unirac Through Bolt	
	Mangilao	755	unknow	unkn	219,352	0.34%	60	H2	121	133	JA Solar JAM72S10-405/MR	5400	2400	405	80	2.01	Power Way	
	Shell	0	0	0	640	0.00%	0.26	H3	131	156	Unknown			Unknown			Unknown East-West	
	Naval Base Guam	0	0	0	1428	0.00%	0.25	L2	101	127	SolarWorld Sunmodule SW 175 mono	5400	3100	175	64	1.3	Unirac Through Bolt	
	TOTAL	755			305291	0.25%	86		####									
									####									
	System	Missing or Broken Moc			Total Modu	Failure Rate			####		Module	Module Load Rating						
Canopy	FAA Carport	15	2	13	92	16%		H3	131	156	Mission Solar MSE310SQ8T	4300	3600	310	66	1.66	Generation Renewables Custom	

Figure A-2. Data and analysis for ground-mounted PV systems assessed. Yellow cells are uncertain.

Site Assessments

The following section gives site assessments from the individual systems visited by the assessment team.

Locations of the PV systems are shown in Figure A-3.

Figure A-3. Map of Guam showing locations of systems visited

JFK High School PV Damage Assessment After Typhoon Mawar in Guam

Findings

- Overall failure rate: 859 of 4,100 modules lost (21%), total damage much higher because many all-thread rods and rails were bent (both too thin), and rails had clamps pull out.
- Much higher losses on west roofs on campus than more eastern roofs—wind out of west (ocean side). High-side edges near roof corners had most damage (Zone 3 SEAOC), high side near roof edge next most (Zone 2). No modules were lost from one section on the lower roof that was likely shielded from wind.
- Lots of bent, twisted, damaged racking. Aluminum rail seemed particularly thin. No cross bracing between racking supports. As racking moves, it puts lots of stress on module or allows modules to release. The rail system was recommended by JA Solar.
- Racking roof mounts were done with rows of threaded rods into the roof. These rods were thinner than those used by the local installer that also employs threaded rods for roof mounts, and many of them were bent. Nylon-insert nuts on top of the threaded rods generally held.
- Module attachments did not have much engagement with racking rail. Mid-clamps and end clamps were 1.5 inches long. Module installation manual specifies that mid-clamps need to be at least 2 in. in length.[10]
- No wind guards were installed to prevent direct wind above or around modules.
- Self-installed by site staff. Used local structural engineer without PV experience.

[10] www.jasolar.com/uploadfile/2022/0218/20220218094931164.pdf.

- Electrical work looked good. Wire management using thick, heavy-duty cable ties. No evidence of broken ties or disconnected wiring, though system installed less than a year ago.
- Current plan is to order replacement parts and rebuild like-for-like.

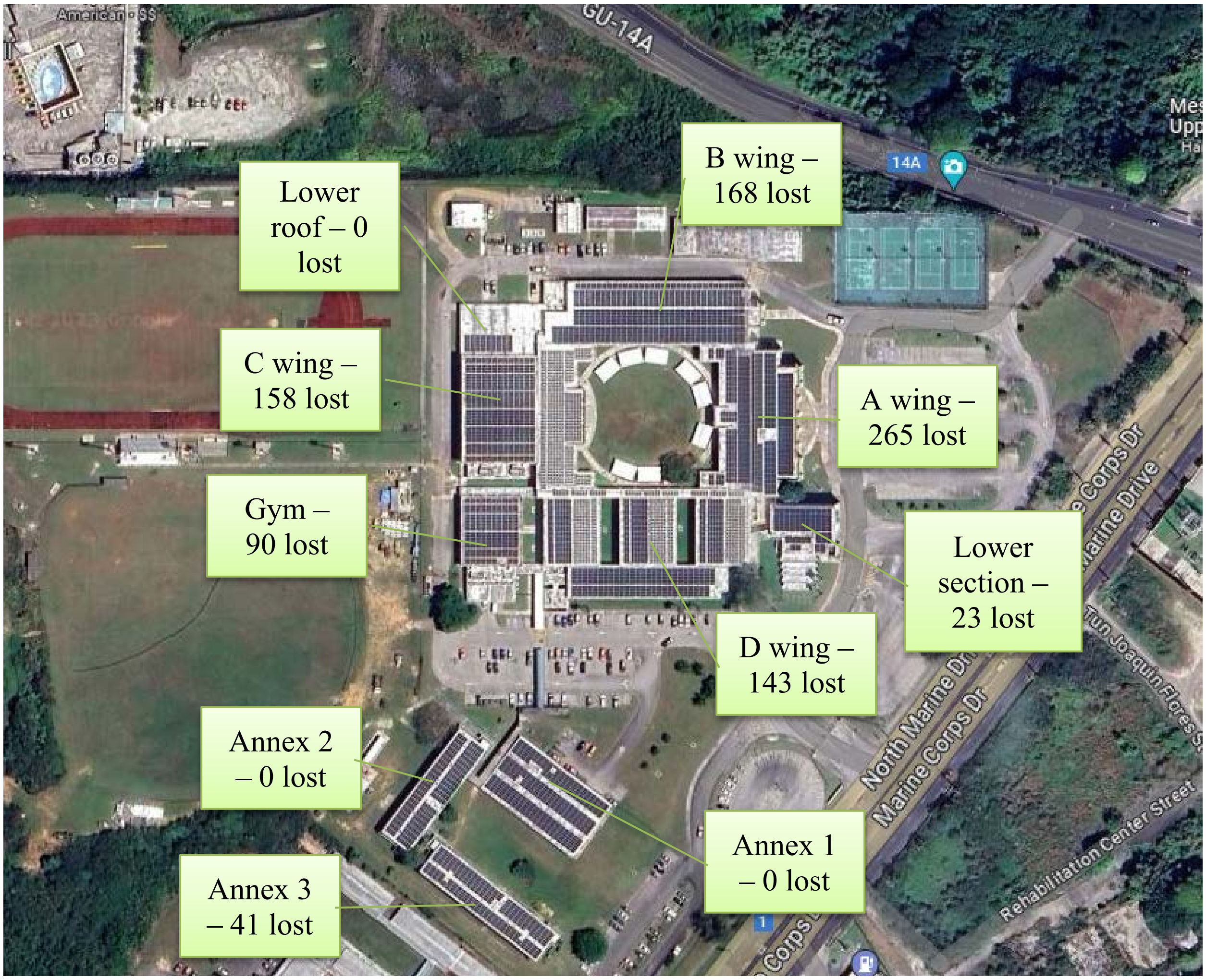


Figure A-4. Aerial view of John F. Kennedy High School, Guam. Array installed December 2022, less than half a year before Typhoon Mawar. Callout boxes show the number of modules lost from various sections of the array.

Image from Google Maps

Recommendations

- Install array flush with roof height above roof racking. Use more robust racking, torque clamps, larger and more robust clamps, and smaller modules. If elevated (sloped) above roof, use fewer modules in height so the back side is not as high above roof, cross bracing between rails/rows, more rails (three per module, i.e., six attachment points), thicker all-thread.
- Recommend using smaller-format modules for roof mount. These 465-W modules were larger than those typically used on roofs, allowing more area for wind loads to cause uplift.

- Hire contractors with proven success installing PV in storm-prone regions.
- Remove all existing racking and get professional local installers to install a new, more robust racking system.
- Salvage panels that are usable, and consolidate into the areas that saw less damage from this storm. Install smaller modules on areas that saw the most damage from this storm.

Site and System Information

- **Location:** 331 Marine Corps Dr, Tamuning, 96913, Guam; many roofs
- **System size (DC kW):** 2.5 MW reported, but also reported 4,100 modules × 465 W = 1.906 MW. Inconsistent.
- **Installation date:** Late 2022, never powered on
- **System type:** Flat roofs
- **Slope:** 5° landscape
- **Racking system:** Solar rack (China, thin aluminum)
- **Modules:** JA Solar 460W
- Mo**dule load rating:** 5,400 Pa front/2,400 Pa rear
- **Module attachments:** Top clamp to aluminum rail to roof with thin (1/4-in.) stainless steel rods drilled and epoxied into concrete roof; two rails, i.e., four attachment points/panel.
- **Roof:** Concrete sloped about 2°
- **NWS estimated windspeed:** L4; 130 mph with gusts to 165 mph
- **Failure modes (in approximate order):**

    1. End clamps came loose, cascading failure to remainder of row, many clamps still in rack.
    2. Mid-clamps came loose, cascading failure to remainder of row, many clamps still in rack.
    3. Clamps pulled out of rails (too thin rails).
    4. Rails bent (to thin rails).
    5. All-thread rods bent (to thin and to long all-thread).

FIFA Soccer Stadium PV Damage Assessment After Typhoon Mawar in Guam

Findings

- **Estimated damage:** 79%
- Northeast array on flat lower roof (15° panel tilt), almost all modules lost, many racks bent, near total loss (unknown number of modules). Approximately 13 rows of 9 modules = 117. About 25 present for a 79% failure rate.
- High-side edges near roof corners (northeast) had most damage (Zone 3 SEAOC); high side near north roof edge next most (Zone 2). These areas had twisted top rails with missing bolts.

Figure A-5. Racking destroyed near roof corner that likely experienced the highest wind loads

- On same roof, northwest array flush with roof 2° slope (roof slope) had four lost modules at roof corner (Zone 3) and edge (Zone 2).

Figure A-6. Array on northeast roof (right) suffered much more damage. Racking was higher off the roof.

- Upper roof had no access, but view from afar estimated 75% of modules missing. Same racking as northeast array on lower roof.

- Modules attached with four top clamps. Clamps largely held in their slots on the rails and were still present where modules were missing. Failure mode was loss of clamp force on modules rather than clamps pulling out of rails. Rail lip may have been thicker than on other racking designs. Clamps were installed on the lower half of the frames in general, leaving more module area on the high side exposed.

Figure A-7. Clamps largely still present in racking even after modules dislodged

Figure A-8. Module clamps appeared to have loosened. Split washers do not provide locking capability.

Figure A-9. Four module attachment clamps were offset toward the lower side of the modules. Modules not as supported against wind uplift forces from the rear/underside of the top of the modules.

- Installer blamed damage on low-quality modules they were required to use for this project.
- No nameplate or identifying branding on modules or racking.

Recommendations

- Install flush with roof at a low height above roof racking (like northwest array).
- Not recommended - IF elevated (sloped more than roof pitch). Use low slope (5° or less), more robust racking, torque clamps, and torque strip; inspect torque annually; use larger and more robust clamps.
- Ensure modules and racking are from reputable manufacturer and are labeled or stamped to show compliance with standards.

Site and System Information

- **Location:** 230 27, Dededo, 96912, Guam; lower roof, upper roof (could not access)
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Roof
- **Slope:** Northeast array = 15°, portrait; northwest array flush with roof, landscape; upper roof estimated 15°
- Northwest array 7 rows of about 16, landscape flush with roof, 2° slope
- **Racking system:** Unknown
- **Modules:** Yingli Solar, but no labels on rear of modules
- **Module load rating:** Unknown.
- **Module attachments:** Top clamp to aluminum rail to cross-braced structure to legs with angle attached to roof with (approximately 1/4-in.) stainless steel rods drilled and epoxied into concrete roof; two rails, i.e., four attachment points/panel.
- **Roof:** Concrete sloped about 2°
- **NWS estimated wind speed:** L4; 130 mph with gusts to 165 mph
- Failure modes on northeast array (in approximate order):

1. Northeast corner (Zone 1) rails bent, modules lost.
2. North edge rails bent, modules lost.
3. Once north row modules were gone, cascading failure of remaining rows. End clamps came loose, cascading failure to remainder of row, many clamps still in rack.
4. Mid-clamps came loose, cascading failure to remainder of row, many clamps still in rack.

Guam Community College PV Damage Assessment After Typhoon Mawar in Guam—Unirac Array




Findings

- **Estimated damage:** 66%
- Unirac array on lower roof (4°), most modules lost, many racks bent, near total loss (79 modules out of 120). Originally 12 rows of 10 modules; 41 remaining on rack. Many modules broken and scattered around roof. Failure rate of 66%. Rows of modules were either all present or all missing, aside from one row with one module remaining. Indicates progressive/cascading failure. Surviving rows were the three closest to one parapet on the north side of the main array section and the one row closest to the southern parapet on a smaller section.
- Solar clamps mostly came free from racking, either loosened or rotated out, and were scattered across the roof undamaged. Some clamps showed damage. Clamps slightly offset toward lower side of module—about 15% of the way up from the bottom and 20% down from the top.
- Racking rails attached to the roofs were largely still intact. First row lower rail was loose. Rails anchored to roof with L-feet about 2 feet apart. Lower and upper cross rail for modules in portrait only.
- Lots of corrosion on system hardware.
- Schott Solar 235-W panels (not manufactured since 2012) on Unirac system gives indication of age of system. Discoloration on cells of panels.

- Pacific Solar rack had zero loss on neighboring roof.
- Roof rail unsupported. Should be double bolt on roof L-feet. Allowed modules to move a lot. Joint opening on L-foot.
- Progressive failure.

Recommendations

- Install a system with proven success as replacement to Unirac system and on vacant flat roofs.
- Do not use systems with Unirac ProSeries clamps.
- Racking rails must be supported and braced for lateral movement to limit movement.

Site and System Information

- **Location:** 1 Sesame Street Mangilao, Guam 96913
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Flat roof
- **Slope:** 4°, portrait
- **Racking system:** Unirac
- **Modules:** Schott Solar
- **Module attachments:** Top clamp to aluminum rail to cross-braced structure to legs with angle attached to roof with (approximately 1/4-in.) stainless steel rods drilled and epoxied into concrete roof; two rails, i.e., four attachment points/panel.
- **From module attachment installation manual:** "The mounting clamps should be at least 1.5" long, at least 0.12" thick, and have a catch width between 0.2" and 0.3". The clamp must overlap the support rail by at least 0.4".
- **Roof:** Concrete sloped about 2°
- **NWS estimated wind speed:** L3; 111 mph with gusts to 140 mph
- Failure modes on northeast array (in approximate order):

  1. Northeast corner (Zone 1) rails bent; modules lost.
  2. North edge rails bent; modules lost.
  3. Once north row modules were gone, cascading failure of remaining rows. End clamps came loose, cascading failure to remainder of row, many clamps still in rack.
  4. Mid-clamps came loose, cascading failure to remainder of row, many clamps still in rack.

Guam Community College Solar PV Damage Assessment After Typhoon Mawar in Guam: Other systems

Findings

- **Estimated failure rate:** 7%
- Pacific Solar rack had zero loss on all other roofs except 13 of 32 on curved roof; 194 total modules across four PV systems.

Recommendations

Do not install PV on curved roofs in Guam.

Site and System Information

- **Location:** 1 Sesame Street, Mangilao, Guam 96913
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Roof
- **Slope:** Varied
- **Racking system:** Pacific Solar
- **Modules:** Varied
- **Module attachments:** Pacific Solar Metgot rail
- **Roof:** Concrete sloped about 2°
- **NWS estimated wind speed:** L3; 111 mph with gusts to 140 mph.

Metal Roof Commercial Building Rooftop PV Damage Assessment After Typhoon Mawar in Guam

Findings

- Overall failure rate about 33%
- Unirac array flush to roof (4°), many modules lost, estimated 60 of 180 total.
- Solar clamps mostly came free from racking, either loosened or rotated out, and were scattered across the roof undamaged. Some clamps showed damage.
- Racking rails attached to the roofs were all still intact and reusable. Rails anchored to roof with L-feet 1 feet apart. Lower and upper cross rail for modules in portrait only.
- Lots of corrosion on system hardware.
- Large sections of rows missing, indicating progressive/cascading failure.
- Plastic wire ties used for wire management were broken.
- Damage from flying debris, likely dislodged PV panels. Adjacent building damage from PV panels.

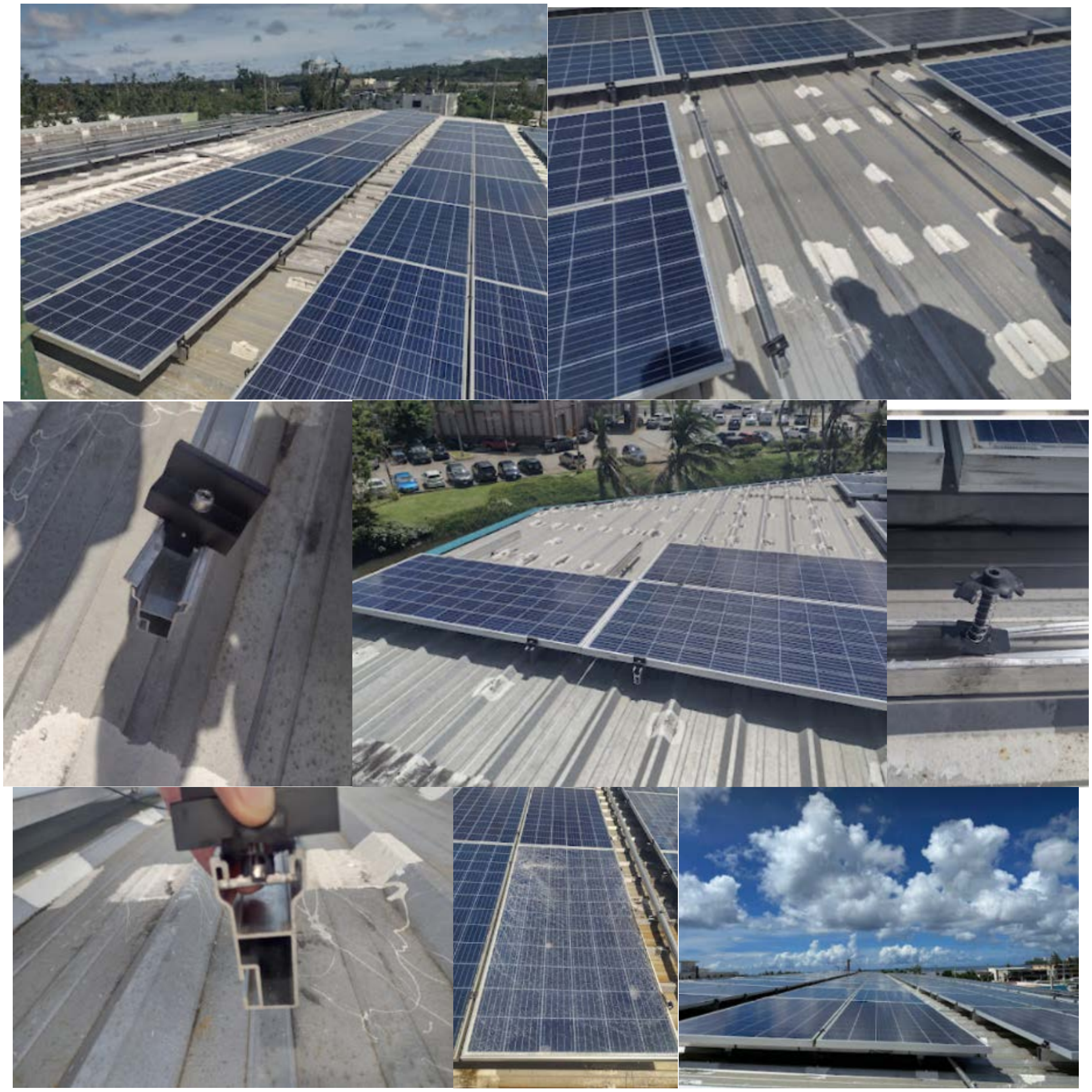
Recommendations

Install robust racking flush with roof or at a low height above roof as replacement to Unirac system.

Site and System Information

- **Location:** Dededo, Macheche
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Roof
- **Slope:** Unirac 4° (roof slope), portrait
- **Racking system:** Unirac
- **Modules:** Unknown
- **Module attachments:** Top clamp to aluminum rail with T-bolt, rail to angle on every rib (every 12 in.) attached through roof-to-roof joist with bolts; two rails, i.e., four attachment points/panel.
- **Roof:** Metal panel about 4°
- **NWS estimated wind speed:** L4; 130 mph with gusts to 165 mph
- Failure modes (in approximate order):
    1. Corner (Zone 3) and roof edge (Zone 2), wind vibrated panels and loosened end clamp and mid-clamp Unirac T-bolts in rails, modules removed in cascading failure of remaining row.
    2. Middle row roof edge (Zone 2), wind vibrated panel and loosened Unirac T-bolts in rails end clamp, edge module then removed, then mid-clamp Unirac T-bolts in rails, then modules removed in cascading failure of remaining row.

Paradise Fitness Metal Building Roof PV Damage Assessment After Typhoon Mawar in Guam



Findings

- Overall failure rate about 5%, seven modules lost on lower roof, none apparently lost on upper roof. Array installed very close to roof edge in some cases, edge (SEAOC Zone 3) modules missing in several cases.
- 4° tilt installed flush with roof.
- Used an Everest racking and module attachment system. Four mounting points but fared very well. More surface area in contact between clamp and module and significantly more surface area in contact between flat nut and racking rail. Nuts require 90° rotation and angling to remove from rack channel.

- Failure mode wherever there were missing modules was deformed metal, so some kind of metal yield.

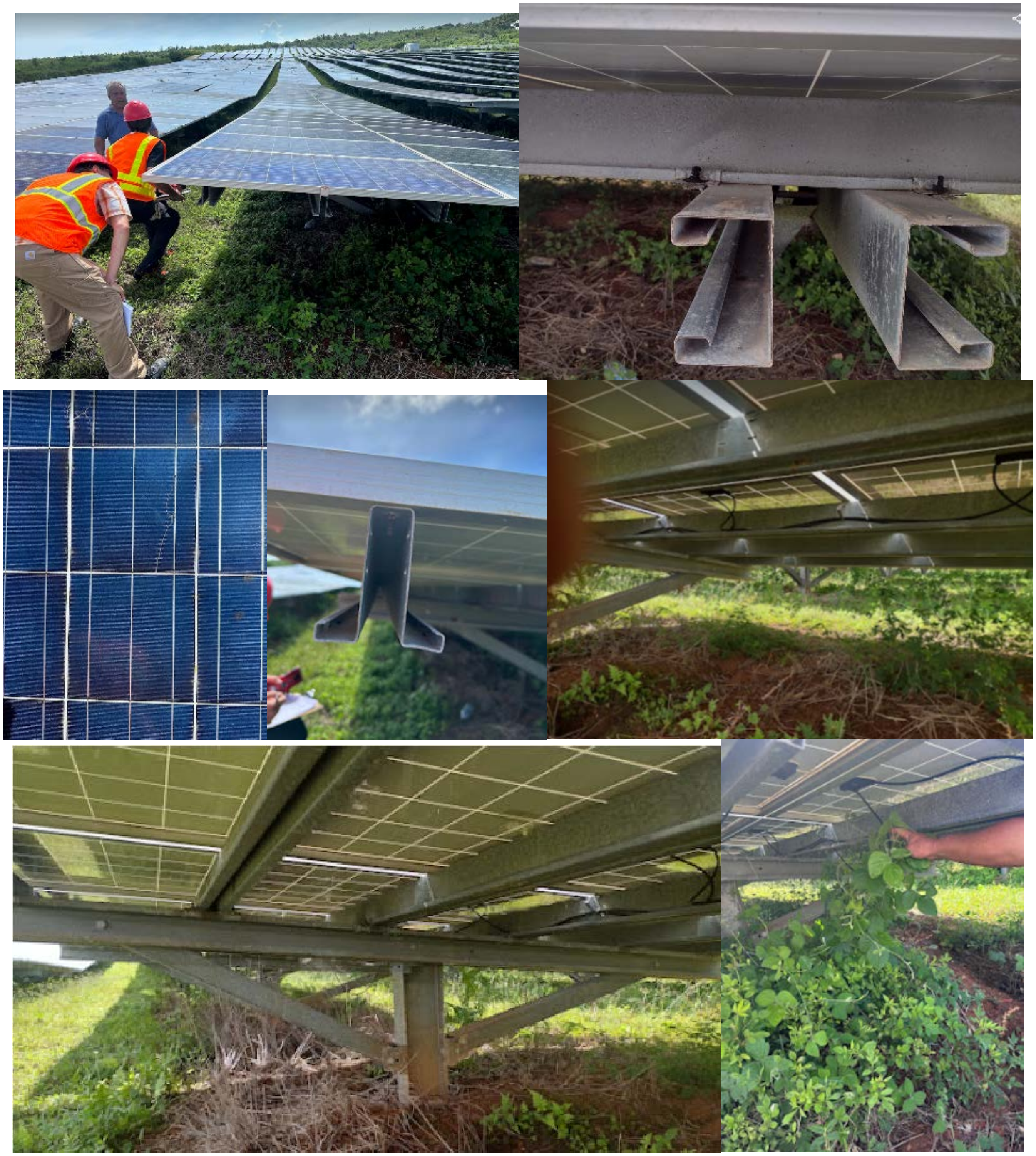
Recommendations

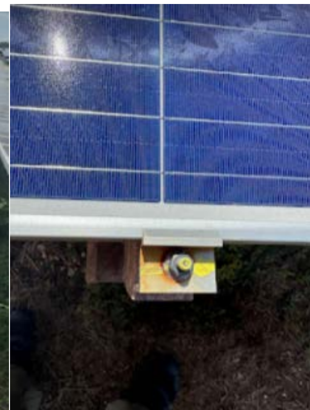
Repair roof as needed, reinstall interior panels. Corner and edge, install three rails and six attachment points per module.

Site and System Information

- **Location:** Dededo, Macheche
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Roof
- **Slope:** 4° (roof slope), landscape
- **Racking system:** Everest/K2
- **Modules:** Unknown
- **Module attachments:** Top clamp to aluminum rail with T-bolt, rail to angle (every 36 in.) attached to Pro Solar mounts through roof-to-roof joist with all-thread rods; two rails, i.e., four attachment points/panel.
- **Roof:** Metal panel about 4° slope
- **NWS estimated wind speed:** L4; 130 mph with gusts to 165 mph
- Failure modes (in approximate order):
    1. Corner (Zone 3) and roof edge (Zone 2), wind vibrated panels and loosened end clamp and mid-clamp Unirac T-bolts in rails, modules removed in corner and edge, four panels total.
    2. Middle row (Zone 1), wind vibrated panel and loosened bolts in rails end clamp, edge module then removed, then mid-clamp bolts in rails, then other modules removed, three total. Group of two modules, middle and end clamps still in rail, no rail damage.

Dandan Ground-Mount PV Damage Assessment After Typhoon Mawar in Guam





Findings

- Zero panel failures, moisture in inverters but no failures reported.
- System low to ground, low tilt angle. Six-point attachment: four through-bolts and two top clamps in middle of modules. Stiff structure. Thick racking elements. Two in portrait layout (2P), meaning each row was two panels high in portrait orientation. High side about 42 in. off ground. Low side about 25 in.
- Wind gaps in some sections of the array.

Recommendations

Improve/extend inverter air inlet and exhaust.

Site and System Information

- **Location:** Dandan (www.gem.wiki/Dandan_Solar_Farm)
- **System size (DC kW):** 36 MW_{DC}, 25 MW_{AC}
- **Installation date:** 2015
- **System type:** Ground
- **Slope:** 7°–12°, 10° average, portrait, two modules high
- **Racking system:** Unknown; 1.3 million Unirac galvanized bolts being replaced because of corrosion
- **Modules:** 300-W Trina 77 in. × 39 in. (30,000 being replaced because of poor performance (2%–3.5%/year) and snail trails, replaced with 320-W Trina Solar) 80%, 20% 315-W Canadian Solar
- **Module attachments:** Through-bolt top and bottom panel and middle top clamp to galvanized steel hat channel rails attached to galvanized C-channel with 45° support arms attached to bracket attached to single galvanized steel I-beams driven into ground; three rails, i.e., six attachment points/panel.
- **NWS estimated wind speed:** H1; 95 mph with gust to 120 mph
- **Other notes:**
    - Using algaecide to remove algae; spray on, do not need to rinse, 8% power gain.
    - Done flyover done twice per year to find hot spots.
    - Vegetation control is a huge challenge, cutting every day, 40–55 days to complete cycle. Morning glory vines creep up structure and pull wires apart. Should have installed low-growth vegetation with original construction.

FAA Carport PV Damage Assessment After Typhoon Mawar in Guam

Findings

Overall failure rate 16%, 15 of 92 modules destroyed, 13 removed with 2 in rack but destroyed by flying debris.

Recommendations

Install new modules to replace lost modules, use two bolts at each connection point (eight bolts per module) instead of one bolt.

Site and System Information

- **Location:** 3232 Hueneme Road, Barrigada, Guam 96913
- **System size (DC kW):** 28.5
- **Installation date:** April 2023, operated 1 month before storm
- **System type:** Carport
- **Slope:** About 9° (roof slope), portrait

- **Racking System:** Unknown, panels approximately 22 ft off ground low side, 24 ft high side. Unclear why so high; adds significant wind load and structural cost. 27-in. × 10.75-in.-thick I-beam on 42-in. concrete pier 14 ft deep.
- **Modules:** Mission Solar 310W
- **Module attachments:** Modules through-bolted to rails, two rails, i.e., four attachment points/panel
- **Roof:** Metal panel approximately 4° slope
- **NWS estimated wind speed:** H3; 129 mph with gusts to 164 mph
- **Failure mode:** Panel frames ripped out at bolts (47 of 52 bolts still in rails).

Shell Station PV Damage Assessment After Typhoon Mawar in Guam

Findings

- 0% panel failure.
- Racking movement clear. Likely invisible damage to modules.
- Modules loaded in the corners. Modules bent. Using module as structural element. Clamped at worst place. Yielding of module.
- Fasteners on module top clamps.

Recommendations

Do not use racking systems that have no cross supports and thus rely on the modules themselves for structural loads.

Site and System Information

- **Location:** FQXX+H4P, S Marine Corps Dr, Tamuning, 96913, Guam
- **System size (DC kW):** Unknown
- **Installation date:** Unknown
- **System type:** Ground
- **Slope:** Unknown

- **Racking system:** Unknown
- **Modules:** Unknown
- **Module attachments:** Unknown
- **NWS estimated wind speed:** 131 mph.

Grid and Base Power Storm Impacts

Utility-provided electricity from Guam Power Authority (GPA) was maintained to Andersen Air Force Base throughout the storm, delivered by underground transmission cables. On-base distribution systems failed, however, leaving portions of the base without power. Northwest Field completely lost power. Buildings with battery storage systems helped provide facilities with power after the storm. Buildings with solar PV arrays and no battery storage also lost power, as the inverters require grid power. Generators were in short supply and were not available for all buildings that needed them. Higher battery deployment can help power facilities through outages, whether caused by a storm or otherwise.