Solar Under Storm Part II

Select Best Practices for Resilient Roof-Mount PV Systems with Hurricane Exposure

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ABOUT US

ABOUT ROCKY MOUNTAIN INSTITUTE

Rocky Mountain Institute (RMI)—an independent nonprofit founded in 1982—transforms global energy use to create a clean, prosperous, and secure low-carbon future. It engages businesses, communities, institutions, and entrepreneurs to accelerate the adoption of market-based solutions that cost-effectively shift from fossil fuels to efficiency and renewables. RMI has offices in Basalt and Boulder, Colorado; New York City; the San Francisco Bay Area; Washington, D.C.; and Beijing.

ABOUT THE CLINTON FOUNDATION

The Clinton Foundation convenes businesses, governments, NGOs, and individuals to improve global health and wellness, increase opportunity for girls and women, reduce childhood obesity, create economic opportunity and growth, and help communities address the effects of climate change. The Clinton Climate Initiative (CCI) collaborates with governments and partner organizations to increase the resilience of communities facing climate change while reducing greenhouse gas emissions.

ABOUT FCX SOLAR

FCX Solar is an engineering consultancy and intellectual property development company focused on the PV industry. It was founded in 2016 by Frank Oudheusden and Chris Needham, who together have a combined 25+ years in the PV industry. FCX Solar provides solar power developers and racking manufacturers with a wide range of engineering services. FCX Solar has developed several products in the solar structure space and has a passion for solving unique issues for its clients and partnerships.

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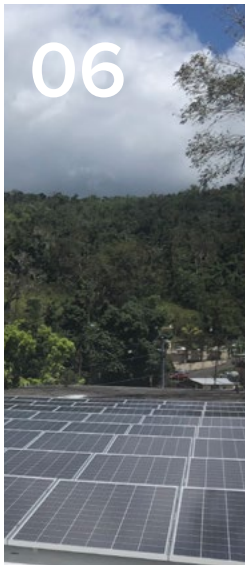
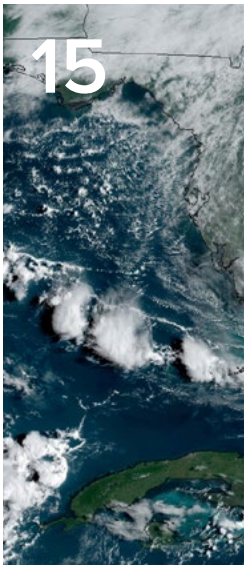
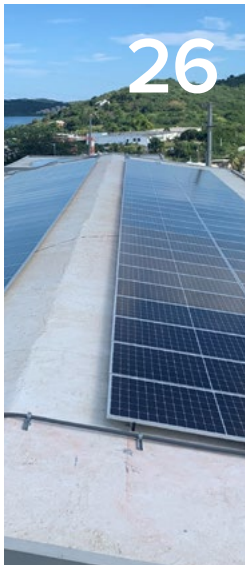






PREFACE

***Solar Under Storm Part II* is a response to the overwhelming reception of the original report, which provided best practices for ground-mount solar photovoltaic (PV) projects. It is also a response to stakeholder requests for a rooftop-focused report for the growing commercial and residential solar industry in the Caribbean and other vulnerable geographies with exposure to high-wind events.**

High wind speeds increase risk factors for solar projects tremendously, but many solar installation companies inadvertently overlook or incorrectly apply low-wind speed designs (borrowed from Europe or the United States) for projects in high-wind zones like the Caribbean. These low-wind mistakes become catastrophic in high-wind events.

Image courtesy of Rocky Mountain Institute

PREFACE

Solar PV failure reporting is needed because some failures are highly visible while others are not, either because they are infrequent in occurrence or because they are privately dealt with and not publicly published. Showcasing a wide range of failures has multiple benefits:

- It provides proof to designers, installers, and customers that solar PV system resilience matters
- Ramifications for product and project design, vendor selection, installation, and maintenance become real because they are tangibly connected to real-world failures
- It helps solar professionals learn from past mistakes, which is critical as repeating mistakes damages the reputation and credibility of the solar industry

Like the first version, this report provides an opportunity to address resilience for both a general and technical audience. The report disseminates technical information to non-technical readers and creates a more informed solar professional, regulator, government official, utility, and customer. A well-informed customer base will systematically strengthen the PV industry by requiring vendors to incorporate resilience guidelines into their projects. In an industry that has experienced drastic cost reductions year after year, in the "race-to-the-bottom" aspect of project and product design, it is critical for customers to understand best practices and not accept low-cost shortcuts that could jeopardize project life or energy production. Supplying the customer with a minimum set of guidelines raises the bar, and those guidelines can only be improved through innovation and definitive testing, which in turn creates a stronger industry.

The purpose of this document is to respond to the growing needs of the solar industry and combine field observations, photographic evidence, and expert analysis to provide actionable recommendations aimed at increasing the resilience of current and future rooftop PV systems. This report will touch upon flat-roof and pitched-roof PV power systems containing flat-mounted, tilt-mounted, fully ballasted, and hybrid ballasted/penetrating systems. It excludes canopy PV systems and ground-mounted systems (both fixed and tracking) as the recommendations for rooftop projects are specific to their application. Canopy and tracking systems may be addressed in future versions of the report if interest persists. Ground-mounted systems were addressed in the original *Solar Under Storm* report, which is still available from Rocky Mountain Institute (RMI).[1]

This report is organized into five sections:

1. Introduction
2. Root cause identification methodology and findings
3. Failure mode and effects analysis (FMEA)
4. Technical discussion
5. Conclusion

The intended audience for Sections 2, 3, 4, and the Appendix is engineering professionals responsible for PV system design, PV system specifications, and/or PV system construction oversight and approval. Sections 1 and 5 are intended for a more general audience of customers, governments, utilities, regulators, developers, and PV system installers who are interested in improving PV system survivability to intense wind-loading events.

Solar Under Storm Part II was developed with direct feedback from solar companies in the Caribbean that learned lessons in solar project resilience firsthand during and after Hurricanes Irma, Maria, and Dorian. Continuous feedback from the solar installer community is vital to the success for solar PV resilience. Thus, RMI and the Clinton Foundation's **Clinton Climate Initiative** will host workshops and other opportunity for on-going communication on this topic—notably through the forum of the Clinton Global Initiative (CGI) Action Network on Post-Disaster Recovery.[2]

EXECUTIVE SUMMARY

Image courtesy of FortisTCI, Turks and Caicos

EXECUTIVE SUMMARY

The 2017 hurricane season was one of the most active in history.[3] Hurricanes Harvey, Irma, and Maria caused widespread destruction throughout the Caribbean. In 2019, Hurricane Dorian decimated the northern Bahamas bringing historic winds, rainfall, and unprecedented destruction to the electricity system and other critical infrastructure.[4] In addition to the emotional toll these severe storms had on people in the region, the disruption of critical infrastructure left many communities without such basic services as electricity for prolonged periods of time. Over the past decades, electricity in the Caribbean has been primarily generated centrally by fuel oil or diesel-fired engines and distributed across the island by overhead lines. However, in recent years, electricity has been supplemented by solar photovoltaics (PV) on homes, businesses, industries, government facilities, and now, as a growing part of utility generation. In fact, over half of Caribbean electric utilities already own or operate solar PV as part of their generation mix. Over 571 MW of solar are installed across rooftops, parking canopies, and large tracts of land.[5] Solar PV is the most rapidly growing source of power for many Caribbean islands.[6]

Despite the record sustained wind speeds of over 180 miles per hour, many rooftop solar PV systems in Puerto Rico, British Virgin Islands, the US Virgin Islands, The Bahamas, and Dominica survived and continued producing power. In contrast, other systems in the region suffered major damage or complete failure with airborne solar modules, broken equipment, and twisted metal racking.

Generating energy with solar PV is a cost-effective and reliable solution for power generation in the Caribbean. Incorporation of the best available engineering, design, delivery, and operational practices can increase the reliability and survival rates from extreme wind loading. Given the variability in wind speed, wind direction, wind duration, topography, design, and construction, along with limited data, there is not an overarching statistical conclusion to explain survivorship versus failure. Instead, this guide combines photographs from immediately after storms along with expert analysis to deliver actionable recommendations for increasing resilience with rooftop solar PV installations.

SUMMARY OF FINDINGS

Expert structural engineers reviewed over 500 photos from over 25 systems across five islands which were taken by solar professionals and system owners immediately after the 2017 and 2019 hurricanes. The same structural experts from the first *Solar Under Storm* report evaluated these photographs to uncover several root causes of partial or full rooftop PV system failures.

RECOMMENDATIONS

The key output of this paper is a list of recommendations for building more resilient rooftop solar PV systems. The recommendations are organized into two categories: 1) specifications and 2) collaboration.

1. Specifications

The following specifications list is intended as a resource for anyone who can influence project design.

- If top-down clamps are required, use clamps that hold modules individually or independently. Alternately, specify through-bolting of modules.
- Specify bolt hardware that is vibration-resistant and appropriate for the environment and workforce.
- Do not use self-tapping screws for structural connections.
- Specify a project QA/QC process including items like bolt torqueing, ballast placement, and mechanical attachment quality.
- Pitched-roof systems should only have modules installed within the envelope of the roof structure (no overhanging modules over the roof edges) and should

EXHIBIT 1

Similarities of Systems

Similarities of Failed Systems	Similarities of Surviving Systems
Top-down or T-clamp cascading failure of module retention	Appropriate use/reliance on ballast and mechanical attachments
Lack of vibration-resistant connections	Sufficient structural connection strength
Corner of the array overturned due to incorrect design for wind	Through-bolted module retention or four top-down clips per module
Insufficient structural connection strength	Structural calculations on record
Roof attachment connection failure	Owner's engineer with QA/QC program
System struck by debris/impact damage, especially from liberated (dislodged) modules	Vibration-resistant module bolted connections
Failure of the structural integrity of the roof membrane	
PV module design pressure too low for environment	

be limited to installation only within wind zones one and two (see Section 4: *Technical Discussion*).

- Ballasted-only systems are not recommended due to the high risk of cascading failure modes. All systems should have positive mechanical attachments to the building structure that meet the minimum mechanical attachment recommendation (see Appendix B).
- Require structural engineering be performed in accordance with **ASCE 7** and site conditions, with sealed calculations for wind forces, reactions, and attachment design.
- Confirm with racking vendor and project engineer that actual site conditions comply with their base condition assumptions from wind-tunnel testing.
- Confirm with the project engineer that design best practices are met relating to worst-case joist loading, base velocity pressure, rigidity assessment, area averaging, and minimum mechanical attachment scheme (see Appendices B and C).
- Require roof pre-inspections be performed to verify that the roof conditions are acceptable and match the assumptions in the structural design (see Appendix D).
- Specify high-load (target 5,400 Pa front load rating) PV modules, based on structural calculations; these are currently available from a number of Tier-1 module manufacturers and tend to have more robust frames.
- Specify all hardware be sized based on 25 years (or project life) of corrosion.

2. Collaboration

Collaboration recommendations identify opportunities to increase the resilience of the entire value chain and life cycle of solar PV projects. This requires longer-term multi-party consideration and action intended to level up the current solar industry standard.

- Collaborate with the installer to implement and continuously improve full QA/QC and operation and maintenance (O&M) processes throughout the life of the project.
- Collaborate with professional engineers of record on calculation best practices and intent.
- Collaborate with racking suppliers to carry out full-scale and connection tests representative of **ASCE 7 3-second design wind speeds** (Saffir Simpson Category 5). Specifically including wind tunnel testing review and rigidity assessment.
- Collaborate with roofers, roofing manufacturers, and insurance companies to maintain roof warranty and roof integrity.
- Collaborate with equipment suppliers to document material origin and certificate of grade and coating consistent with assumptions used in engineering calculations.
- Collaboration between installers and module suppliers/distributors to ensure local availability of specified modules.

1 INTRODUCTION

Image courtesy of Edward Previdi, EP Energy

INTRODUCTION

Solar photovoltaic (PV) systems have proliferated throughout the Caribbean and other island communities over the past several years. Solar is now competitive with traditional fossil fuel generation and in some cases has become the primary energy source for island power systems.[7] Rooftop solar has also demonstrated an ability to withstand major wind events despite well documented failures.

During the last three years (2017–2019), the North Atlantic region saw 11 major hurricanes (Category 3 or higher); most notably in the Caribbean were Harvey, Irma, Maria, and Dorian. The solar PV failures seen from these events were well documented by the solar industry and serve as a continuous learning platform on which the industry's resilience movement stands. The survival and failure of ground-mounted solar

EXHIBIT 2
Guiding Principles and Process

Guiding Principles

- **Collaborate across organizations and integrate local experience and expertise.**
- **Address observed failure modes and lurking failure modes** (ones that did not occur only because something else failed first).
- **Plan for advancement of hardware, reliability statistics, and expert knowledge.**
- **Provide performance-based recommendations where possible to allow for innovative solutions.**
- **Limit recommendations to only those that provide a risk-adjusted economic benefit.**
- **Ensure guidelines are executable with currently available solutions.**
- **Use a risk-conscious framework for decision-making.**

Guidelines Process

1. **Conduct failure analysis of sites impacted by the hurricane seasons from 2017 through 2019.**
2. **Engage experts responsible for managing or analyzing historical failures of solar projects.**
3. **Identify and prioritize root causes through collaborative completion of a "fishbone" tool.**
4. **Complete a failure mode and effects analysis (FMEA) for the prioritized root causes.**
5. **Synthesize recommendations from the FMEA for communication and consideration.**
6. **Seek and incorporate ongoing feedback.**

PV systems in hurricanes was documented and well received in the first *Solar Under Storm* report. Following the first publication, there were significant requests to report on the resilience of roof-mounted systems. However, given the variability in wind speed, direction, roof type, roof orientation, roof pitch, solar design, and construction, one overarching conclusion cannot be made to explain the diversity of outcomes from these major wind events. Instead, this report combines photographs from immediately after the storms with expert analysis to deliver actionable recommendations for increasing resilience among retrofit and new construction solar PV rooftop installations.

APPROACH

Our approach to increasing the ability of PV systems to withstand hurricane winds utilizes design-for-reliability principles and methods.

ORGANIZATION

This document is organized to present readers with each of the major analysis steps in order of completion. Section 2 presents the root cause identification methodology and findings, along with recommendations for using the findings and the method. Section 3 utilizes the root causes identified in an failure mode and effects analysis (FMEA). The output of this analysis includes potential mitigation actions that are evaluated by cost and impact. Section 4 synthesizes mitigation actions identified in the FMEA into a list of recommendations for ease of communication and consideration by the reader.

Image courtesy of David Kaul, SALT Energy

2 ROOT CAUSE IDENTIFICATION

Hurricane Dorian September 2019. Image courtesy of NOAA

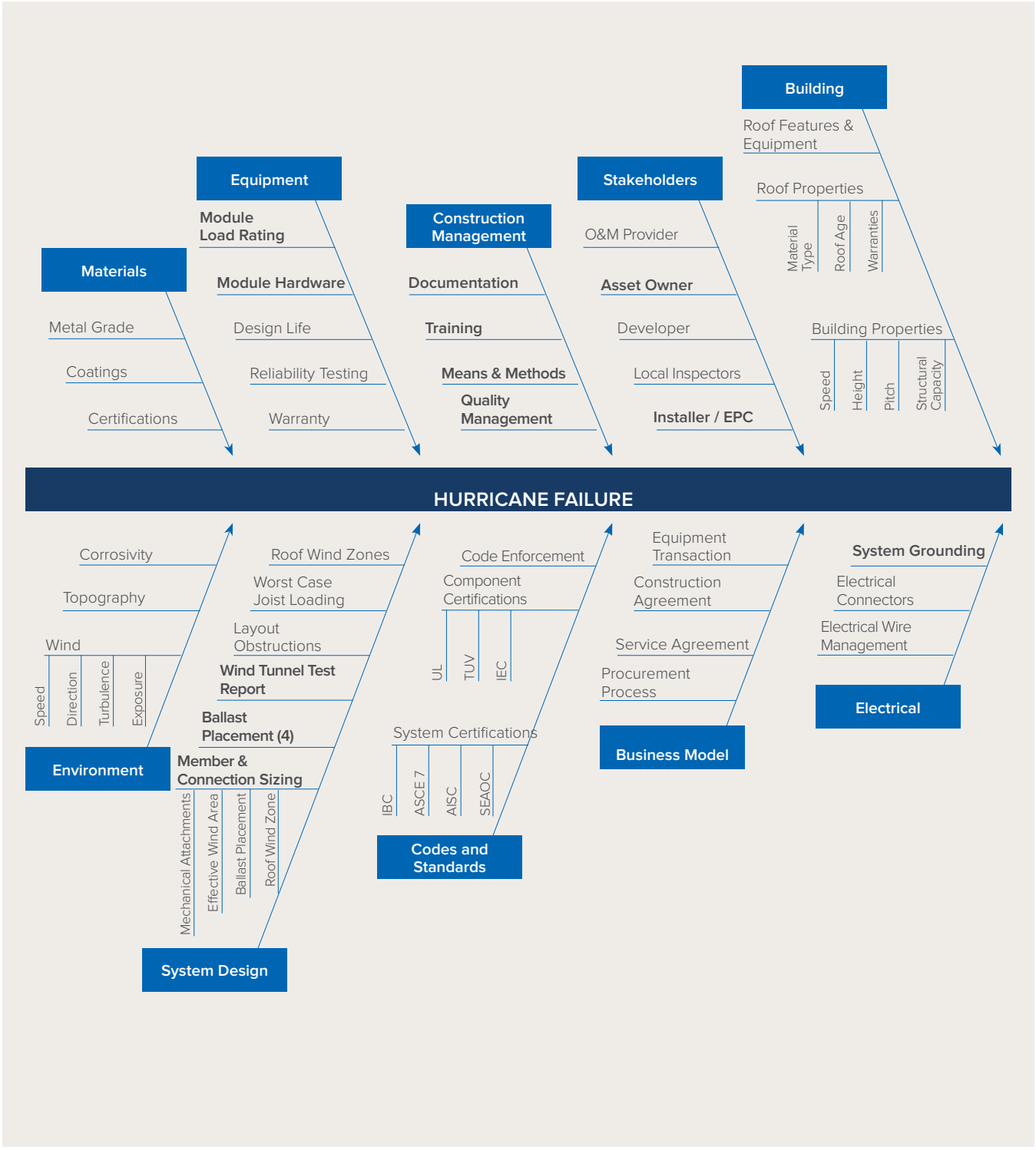
ROOT CAUSE IDENTIFICATION

The rise in hurricane intensity in the region in conjunction with the increased installed base of solar PV has provided an initial body of evidence for developing resilience guidelines for future projects. However, development of hurricane resilience guidelines based on observed failure modes alone has limitations. The observed failure modes may have served as a "mechanical fuse" relieving forces from the system. If future systems only address the observed failure modes, forces may precipitate additional failure modes. To address both observed and potential failure modes, we took a classic reliability engineering approach to design for reliability. Exhibit 3 illustrates a common reliability tool for systematic cause and effect identification called a fishbone diagram. The diagram shows the supply chain responsible for design, manufacturing, procurement, delivery, installation, and operations of a rooftop solar power plant, along with the operational use case. The most urgent causes of failure are in bold text. The current fishbone draft is limited by the data set, authors' expertise, and current technology; consequently, this analysis should be updated to incorporate new data, expertise, and technology. Future solar PV project teams are invited to utilize Exhibit 3 (and add additional categories as necessary) as a facilitation tool to explore project-specific opportunities to eliminate causes of failure in response to extreme wind or other hazards.

Image courtesy of Carlos Quiñones, CJQ Engineering

EXHIBIT 3

Fishbone diagram



3 FAILURE MODE AND EFFECTS ANALYSIS

Image courtesy of of Carlos Quiñones, CJQ Engineering

FAILURE MODE AND EFFECTS ANALYSIS

Improving the ability of PV systems to withstand hurricane winds requires not only identification of failure modes but also a cost-effective mitigation action. The failure mode and effects analysis (FMEA) framework was utilized to identify practical mitigation actions. This assessment is a culmination of two markers: expected upfront material cost to implement the mitigation actions and the impact this mitigation will have on total cost of ownership (TCO). TCO reductions are driven through a reduction in total economic damage or a reduction in the frequency of individual failure modes. Reduction in total economic damage directly improves long-term asset values by minimizing material replacements. Reduction in frequency of failures improves PV plant up-time by minimizing the time spent fixing minor issues, especially cascading issues that could lead to major, expensive failures if not immediately addressed.

Out of this data set, "top-down clip failure" was observed on 21 out of 22 projects that utilized top-down clips (96% of applicable projects).

The synthesis of the FMEA presented below is designed to teach a user the current practices and associated limitations of the most relevant failure modes and to provide a cost-effective mitigation action. The table is organized by subsystems and assemblies.

In addition to the FMEA work, we performed a statistical analysis on a limited data set (26 total rooftop projects) of available failure images. Projects included sloped pitched-roof structures (11 projects), elevated rail system flat-roof structures (11 projects), and ballasted/mechanically attached hybrid flat-roof structures (4 projects). Four major failure modes presented themselves within this data set. They are listed in order of decreasing occurrence:

1. Top-down clip failure (all projects)
2. Debris/impact failure (all projects)
3. Corner overturn failure (ballasted/mechanically attached hybrid flat roof)
4. Racking connection failure (all projects)

Debris/impact failure was largely a secondary failure mode caused by clip failures. Eighteen projects (70%) experienced debris/impact failures while only two of those projects (8%) experienced impacts from objects other than liberated modules. Mitigating the cascading failure mode by solving the "top-down clip failure" largely eliminates this failure mode as well.

Corner overturning was only present on ballasted/mechanically attached hybrid flat-roof projects. However, it was present on three of the four projects within the data set (75%). Due to the limited number of ballasted/mechanically attached hybrid projects (four), it is difficult to extrapolate these failure modes past the observed portfolio. However, the root causes in these photos are evident and are supported by the FMEA activities.

Racking connection failures speak to the compromised structural integrity of the racking system itself. It occurred on 6 out of 26 projects (23%), including the 3 projects which experienced corner overturning failures. Only on a single occasion was a racking connection failure deemed to be a primary failure mode. Mitigating the cascading failure mode by solving the "corner overturning failure" largely eliminates this failure mode as well.

EXHIBIT 4

Cost/Impact Key

	Cost ($/watt)*	Total Cost of Ownership (TCO) Impact
Low	<$0.0075	Reduces TCO Slightly
Medium	$0.0075–$0.015	Reduces TCO Moderately
High	$0.015+	Reduces TCO Greatly

**Includes material cost only as installation costs vary greatly across the applicable markets for this report. Cost increases are dependent on the baseline in which they are measured and won't be incurred by all projects in all cases. They are meant to showcase worst-case scenario increases based upon a baseline of zero mitigation for the failure mode.*

THE ADDITIONAL COST OF INCREASED RESILIENCE

Calculating the additional cost to implement the recommendations in the first ***Solar Under Storm*** report and this new rooftop version depends on the specific projects and sites/roofs. However, we estimate that in general, projects would incur an increase of approximately 5% in engineering, procurement, and construction (EPC) costs when these best practices are implemented versus the standard Category 3 or 4 rated solar PV installation. These additional costs come in the form of labor for the extra time needed to fasten modules and install more connections. There are also additional costs in material (higher-rated modules, racking supports, and fasteners) as well as minor costs for additional engineering and construction oversight.

Based on RMI's **Islands Energy Program's** recent solar PV procurement for a 250 kW standing seam roof-mounted system in the Caribbean, implementing these best resilience practices added approximately $30,000 in EPC costs to the budget versus the previous baseline.

The Clinton Climate Initiative procured a 263 kW PV system on a flat roof in Puerto Rico and it increased costs by 5.5% to achieve 175 mph rating versus 145 mph.

The additional mitigation costs for resilience are dynamic due to both the global supply chain and continuous improvements but regardless have proven to be money well spent for those exposed to hurricanes, typhoons, and other high-wind events.

EXHIBIT 5

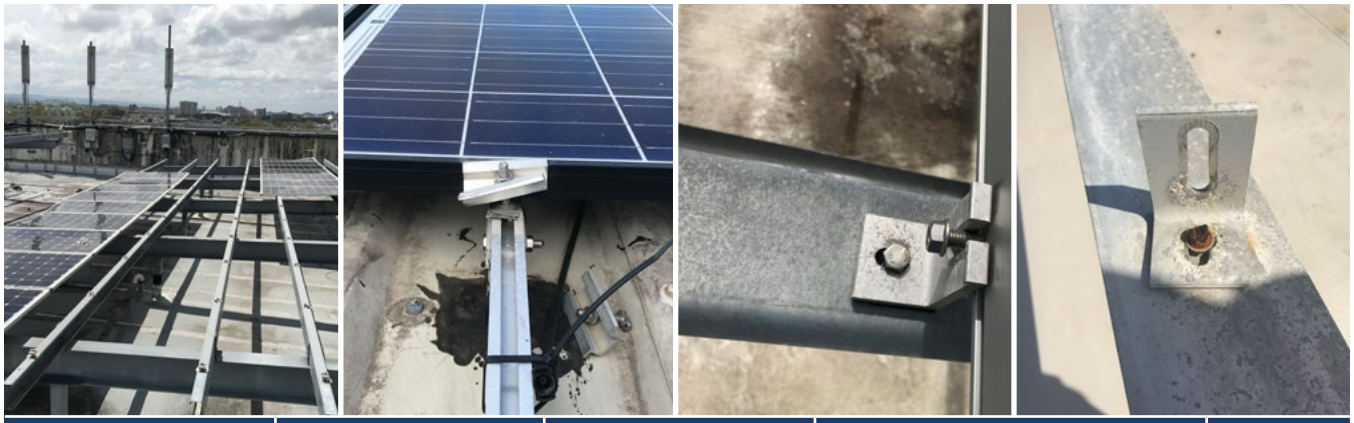
Failure Mode and Effects Analysis—Buildings

Failure Modes	Current Practice	Limitations	Potential Mitigation	Cost/TCO
Incorrectly calculated velocity pressure	ASCE 7-16	Relies on project engineer to properly capture project-specific factors.	Third party review of the ASCE 7-16 velocity pressure calculation.	Low/High
Roof structural member failure	Project engineer checks dead loading against available capacity.	Requires correct identification of governing load cases and roof capacity.	Require “worst-case joist loading” be checked in addition to “array area averaging” (see Appendix C).	Low/Med
Wind acceleration in specific wind zones	• Racking vendor specifies wind loading. • ASCE 7-16	Racking vendor analysis can be a “black box” to project engineer.	• Adopt minimum mechanical attachment specification (see Appendix B). • Must be considered in wind tunnel testing for flat-roof projects. • Require installation of modules only in Zones 1 and 2 for pitched-roof systems (see Section 4: *Technical Discussion*).	Med/High

All Images courtesy of Carlos Quiñones, CJQ Engineering

EXHIBIT 6

Failure Mode and Effects Analysis—PV Racking

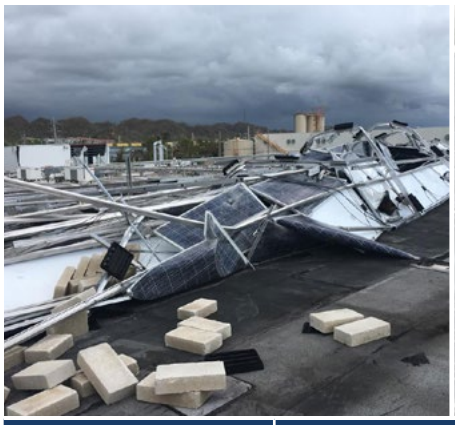


Failure Modes	Current Practice	Limitations	Potential Mitigation	Cost/TCO
Cascading failure of top-down clips	• Module top-down clips are designed to retain groups of modules with end and mid (shared) clamps. • Caribbean regional solution of a three-rail system has been popular.	Shared (middle) module top-down clips lose capacity with loss of one module and allow liberation of adjacent module.	• Use top-down clips that do not retain more than one module per clip to avoid cascading failures. • Alternately, specify module frames to be through-bolted in accordance with manufacturing specification for the design wind speed.	Low/High
Fastener self-loosening	Racking vendor selects the hardware in the design.	Wind vibrations can loosen hardware over time.	• Require vibration-resistant fasteners. • Ensure proper QA/QC during installation. • Verify tight fasteners during annual O&M activities.	Low/High
Roof to racking mechanical attachment failure	Racking vendor performs structural calculations	• Incorrect loading assumed (effective wind area) invalidates calculations. • Improper installation.	• Verify racking vendor meets recommended analysis and minimum mechanical attachment scheme (see Appendix B). • Proper installation QA/QC is critical.	Low/High
Self-tapping screw corrosion and failure	Racking vendor selects the hardware in the design.	• Subject to improper installation. • Corrosion happens over time.	• Avoid self-tapping screws for structural loading in the design.	Low/Med

All Images courtesy of Carlos Quiñones, CJQ Engineering

EXHIBIT 6 (CONTINUED)

Failure Mode and Effects Analysis—PV Racking



Failure Modes	Current Practice	Limitations	Potential Mitigation	Cost/TCO
Corner overturning failures	Racking vendor performs structural calculations	Incorrect loading assumed (effective wind area) invalidates calculations.	• Verify racking vendor meets recommended analysis and minimum mechanical attachment scheme (see Appendix B).	Med/High
Racking uplift or sliding failures	Racking vendor performs structural calculations	Incorrect loading assumed (effective wind area) invalidates calculations.	• Verify racking vendor meets recommended analysis and minimum mechanical attachment scheme (see Appendix B).	Med/High
Incorrectly calculated module-specific wind loads	Racking vendor specifies wind loading.	Racking vendor analysis can be a "black box" to project engineer.	• Adopt minimum mechanical attachment specification (see Appendix B).	Med/High
Dynamic excitation—"Walking" of the ballasted rack	Racking vendor or project engineer performs calculations.	High difficulty in designing a purely ballasted racking system around dynamic wind considerations.	• Adopt minimum mechanical attachment specification (see Appendix B). • Project engineer should review structural elements for thermal expansion considerations and seismic loading.	Med/Med
Wind deflector liberation	Specific to racking design.	• Vulnerable to installation errors. • Vulnerable to impact damage. • Vulnerable to improper design.	• Install positively retained wind deflector with vibration-resistant solution. • Proper QA/QC at installation • Verification during annual O&M activities	Low/High

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EXHIBIT 7

Failure Mode and Effects Analysis—Electrical

Failure Modes	Current Practice	Limitations	Potential Mitigation	Cost/TCO
Wire pull out or terminal damage	Specification for each electrical Component (e.g., UL, NEC, TUV, etc.).	Terminal torque values unchecked in field.	Specify QA/QC procedure and documentation for terminal torques.	Low/Low
Wire sheath chafing (ground fault)	NEC or IEC conductor management and support specifications.	Wires sag and subject to gyration based on field installation.	• Evaluate racking structures for inclusion of wire management solutions. • Proper QC of field electrical work. • Specify wire management practices, including support schedule and sag tolerance. • Specify stainless-steel or heavily galvanized wire clips or PVC-coated stainless-steel cable clamps instead of plastic zip ties.	Low/Low
Rain intrusion	NEC - NEMA specification	Hurricane force wind can drive rain.	• Verify water sealing method effective at the project design wind speed.	Low/Low
Wind load on electrical components	ASCE/NEC/UL Codes	Combiner boxes, inverters, and other equipment are exposed to wind loads but rarely analyzed or properly secured.	• Have the project engineer analyze electrical components and their structural mounting to resist applicable project environmental loads.	Low/Med

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EXHIBIT 8

Failure Mode and Effects Analysis—PV Modules

Failure Modes	Current Practice	Limitations	Potential Mitigation	Cost/TCO
Frame bolt hole failure	UL1703 certification of module testing.	Module back-side (uplift force) rating may not be adequate for local loads.	• Specify engineer calculations for module connection hardware, including frame where used. • Collaborate with module manufacturers to improve supply chain. • Engineer of record for the project should request and approve engineering connection calculations.	Low/Low
Laminate impact damage	UL 1703 hail impact tests and ASCE wind prone debris.	Hurricane debris can be large compared to hail.	• Specify that site prep and clean-up shall include removal or securement of all foreign objects (debris). • Execute proper failure mode mitigations for module liberation, especially top-down clips and vibration-resistant hardware.	Low/Med

All Images courtesy of Carlos Quiñones, CJQ Engineering

4 TECHNICAL DISCUSSION

Image courtesy of Pura Energía

TECHNICAL DISCUSSION

THREE-RAIL SYSTEMS

Pitched-roof system designers in the region have often utilized a “three-rail system” as a viable solution against module liberation on pitched-roof systems. This is driven by a requirement for 5400 Pa front load rated modules. Module manufacturers that offer such a warrantied rating do so by often requiring six module fasteners instead of the existing requirement of four. The additional two fasteners require an additional rail for mounting.

Anecdotally, designers have cited benefits of a three-rail system being used to obtain a reduction in vibratory forces in the module leading to less chance of module liberation as well as providing added structural strength toward resisting extreme wind forces. Top-down clips in this application have also performed better at retaining modules during hurricanes.

Although three-rail systems do provide these benefits, they solve module liberation issues that are rooted in other failure modes. Addressing the root cause of the failure is important. For example, hardware that vibrates loose should be replaced by vibration-resistant hardware and not simply additional hardware. Top-down clips perform better because the root cause of their failure is vibratory. It is more effective to solve the root cause in a cost-efficient way than to invest in material to reduce the vibration in the system. In fact, the structural calculations on a six-fastener system show that the loss of any corner clip would result in wind pressures overstressing remaining clips. The cascading failure mode mitigation recommendation of moving away from shared top-down clips is still a valid recommendation as additional clips don’t solve the root problem.

The six-fastener requirement of module manufacturers to obtain a 5,400 Pa rating is an externalization of cost onto the projects of the Caribbean region. Material cost increases incurred by simply supplying a heavier module frame would certainly be lower than a 50% increase in project racking material and mechanical attachments. Module frame manufacturing is done via aluminum extrusion, which is a very materially efficient process, especially at high volumes.

Thus, a three-rail system represents a significant cost increase for projects in the region (50% increase in racking structure and roof attachments) while aiming to solve problems that would be better solved with appropriate fastener selection. Some of this is driven by module manufacturers requiring higher sales volumes for high-wind zone projects to invest in a dedicated 5,400 Pa rated frame. But some of it is rooted in racking manufacturers selling additional racking rather than selecting new hardware. Owners and project engineers should be selective in this regard, scrutinizing hardware selection and pushing for the most cost-efficient solutions.

Three-rail system on St John, St. John, US Virgin Islands. Image courtesy of Caribbean Solar Company

JOINT LOOSENING / TOP DOWN CLIP FAILURE ANALYSIS

Most structural failures of PV systems originate at the connections. As highlighted in several examples in the FMEA analysis above, loosening of joints is often a contributing factor to connection failure. The probability of joint loosening can be reduced by proper selection, specification, and installation of fasteners, to avoid loss of pre-load tension (clamping force). There are a few common failure modes to be considered. When selecting and specifying fasteners, bear in mind three primary concerns. Select fasteners that will maintain their pre-load tension; the fasteners must have adequate corrosion protection to survive the life of the PV system; and they must be compatible with electrical bonding and grounding concerns. As there are multiple criteria for selection of fasteners, we recommend that no substitutions be allowed in the field once fasteners are specified without express written consent for an alternative specification from the structural engineer of record.

There are at least three modes that can contribute to loss of pre-load tension and associated joint loosening. The first mode of concern is “pre-load scatter,” which refers to an unintentional variation in initial torque of fasteners. While several references will recommend that all fasteners be individually set with a torque wrench, it is more likely that large quantities of fasteners will be installed with a calibrated, torque-controlled driver. To minimize pre-load scatter, a quality assurance program could include a data-logging torque-controlled driver, such that a record of initial torque is created and maintained with operations and maintenance (O&M) personnel. A second mode of concern is embedment of lock washers in the base material. For example, a common, low-cost star washer is likely a poor choice for bonding and grounding, as repeated vibration cycles can cause additional embedment in the base metal, causing a loss of pre-load. In this case, connections can experience joint loosening without any turn of a nut. Joint loosening caused by additional embedment after initial torque can lead to further loosening after pre-load tension is reduced. A third mode of joint loosening is when transverse vibration causes joint loosening by rotation of a nut or other fastener. This mode has gained the most attention, as it is easiest to observe by visual inspection. Joint loosening caused by transverse vibration can be simulated with the Junker vibration test. Some forms of lock nuts or lock washers that have been trusted for years in multiple industries can be shown to spin off during the course of a Junker transverse vibration test, while a certain type of two-piece stepped washer performs well in the test. It is important to recognize that transverse vibration is only one mode of concern, and each installer should perform their own due diligence on final solutions for selection and specification of fasteners in high-wind installations.

During installation, if a telltale mark is added to fasteners after initial torque setting, then O&M personnel can visually observe whether the marks continue to align or if the joint has experienced rotation.

Image courtesy of Christopher Burgess, Rocky Mountain Institute

MODULES OVERHANGING THE ROOF EDGE

Installing modules over the edges of roofs is another regional practice often encountered. This maximizes the array size for the customer, offsetting greater consumption and lowering the total cost of the project (on a per-watt basis). However, these modules are almost universally missing post-hurricane. The mitigation isn't just rooted in common sense, but also in building code.

For rooftop PV systems, the proximity of the PV panels to roof edges is of primary concern. As wind flows toward a building and is obstructed by the building, it must travel around the wall corners and up over the roof. As wind travels over the roof edge, it can "detach" from the roof, resulting in a large negative (uplift) pressure near the roof edge. For large buildings with low-slope roofs, the wind pattern reattaches to the roof at some point farther downwind. As the highest uplift wind pressures occur near roof edges, the design layout should consider some setback of PV modules from roof edges.

Fire codes typically require rooftop setbacks and access pathways for rooftop operations for fire fighters. For commercial buildings with low-slope roofs, these fire setbacks are often 4 feet or 6 feet from roof edges, depending on the size of the building. For high-slope roofs, fire setbacks and access pathways are often 3 feet from ridges and gable ends but could be as little as 18 inches or not required at all, depending on configuration of the roof and requirements of a local fire service. For PV systems installed parallel to a roof, ASCE 7-16 requires a setback from all roof edges that is at least twice the height of the PV panels above the roof. For example, if a PV system is installed 5 inches above and parallel with a high-slope roof, it must be set back at least 10 inches from all roof edges. To reduce probability of failure owing to unanticipated wind uplift pressures, PV system layout should avoid any overhangs above a roof ridge and should be set back from all roof edges.

Modules Overhanging the Roof Edge. Image courtesy of Marc Lopata, Solar Island Energy

EXHIBIT 9

Wind Loads—Components and Cladding

Exhibit 9 shows a relatively lower pressure region (green - Zone 1), medium pressure regions (yellow - Zone 2), and high pressure regions (red - Zone 3).

PV array designs should stay within the envelope of the roof boundaries, but they should also universally stay away from installation in Zone 3. The wind pressure in this zone is significantly higher (~50%) than in Zone 2. This is especially true in design wind speeds of 120 mph and above, which many municipalities of the Caribbean are rated at (or soon will be upon the latest release of wind maps from ASCE) due in part to Hurricanes Irma and Maria. Any modules within the envelope of Zones 1 and 2 should have the appropriate code-provided wind pressures applied and professional engineers should check that the structural stability of the system and its connection to the roof is adequate. Modules within Zone 3 would receive such catastrophically high wind pressures that the cost of installing them appropriately for these loads would be universally untenable.

TOPOGRAPHIC "SPEED-UP" EFFECTS FOR DETERMINATION OF DESIGN WIND SPEED

Determination of the correct design wind speed is fundamental to calculating design wind pressures using ASCE 7-16. When wind speed increases with changes in topography, it can have a strong influence on design wind pressures. Forensic studies in Puerto Rico after Hurricanes Irma and Maria determined some failures were partially attributed to absence of consideration of topographic effects in determination of design wind pressures.

After Hurricanes Irma and Maria, FEMA funded a wind-speed study for the entire island of Puerto Rico, with a goal of providing a more-accurate wind speed map and an online tool for determination of design wind speed, similar to the effort for the islands of Hawaii years ago. The wind speed maps for Puerto Rico in ASCE 7-16 still show the "old" maps with only a few contours. The Applied Technology Council (ATC) tool for Puerto Rico is now online and is critically important to use. (Do not use the maps in ASCE 7-16 for Puerto Rico.) It is important to note that the ATC online tool for Puerto Rico (only) includes wind speed-up effects, so the topographic factor is already built in. For determination of design wind pressures other than for Puerto Rico, it is important to calculate the topographic factor. (This method is being revised during the development of future ASCE 7-22, so sophisticated readers might want to look at the in-progress changes.) At the time of writing this paper, a similar wind speed study is being conducted for the US Virgin Islands.

5 CONCLUSION

Image courtesy of FortisTCI, Turks and Caicos

CONCLUSION

Generating energy with solar PV is a cost-effective and reliable solution for power generation in the Caribbean. Incorporation of the best available engineering, design, delivery, and operational practices can increase the reliability and survival rates from extreme wind loading. This paper is limited in its ability to be omniscient of all failure modes and all corrective actions and cannot guarantee the efficacy of any recommended action. However, it provides a set of best practices regarding specifications of equipment and procedures along with a framework for continued collaboration.

EXHIBIT 10
Similarities of Systems

Similarities of Failed Systems	Similarities of Surviving Systems
Top-down or T-clamp cascading failure of module retention	Appropriate use/reliance on ballast and mechanical attachments
Lack of vibration-resistant connections	Sufficient structural connection strength
Corner of the array overturned due to incorrect design for wind	Through-bolted module retention or four top-down clips per module
Insufficient structural connection strength	Structural calculations on record
Roof attachment connection failure	Owner's engineer with QA/QC program
System struck by debris/impact damage, especially from liberated (dislodged) modules	Vibration-resistant module bolted connections
Failure of the structural integrity of the roof membrane	
PV module design pressure too low for environment	

RECOMMENDATIONS

The key output of this paper is a list of recommendations for building more resilient rooftop solar PV systems. The recommendations are organized into two categories: 1) specifications and 2) collaboration.

1. Specifications

The following specifications list is intended as a resource for anyone who can influence project design.

- If top-down clamps are required, use clamps that hold modules individually or independently. Alternately, specify through-bolting of modules.
- Specify bolt hardware that is vibration-resistant and appropriate for the environment and workforce.
- Do not use self-tapping screws for structural connections.
- Specify a project QA/QC process including items like bolt torqueing, ballast placement, and mechanical attachment quality.
- Pitched-roof systems should only have modules installed within the envelope of the roof structure (no overhanging modules over the roof edges) and should be limited to installation only within wind zones one and two (see Section 4: *Technical Discussion*).
- Ballasted-only systems are not recommended due to the high risk of cascading failure modes. All systems should have positive mechanical attachments to the building structure that meet the minimum mechanical attachment recommendation (see Appendix B).
- Require structural engineering be performed in accordance with **ASCE 7** and site conditions, with sealed calculations for wind forces, reactions, and attachment design.
- Confirm with racking vendor and project engineer that actual site conditions comply with their base condition assumptions from wind-tunnel testing.
- Confirm with the project engineer that design best practices are met relating to worst-case joist loading, base velocity pressure, rigidity assessment, area averaging, and minimum mechanical attachment scheme (see Appendices B and C).
- Require roof pre-inspections be performed to verify that the roof conditions are acceptable and match the assumptions in the structural design (see Appendix D).
- Specify high-load (target 5,400 Pa front load rating) PV modules, based on structural calculations; these are currently available from a number of Tier-1 module manufacturers and tend to have more robust frames.
- Specify all hardware be sized based on 25 years (or project life) of corrosion.

2. Collaboration

Collaboration recommendations identify opportunities to increase the resilience of the entire value chain and life cycle of solar PV projects. This requires longer-term multi-party consideration and action intended to level up the current solar industry standard.

- Collaborate with the installer to implement and continuously improve full QA/QC and operation and maintenance (O&M) processes throughout the life of the project.
- Collaborate with professional engineers of record on calculation best practices and intent.
- Collaborate with racking suppliers to carry out full-scale and connection tests representative of **ASCE 7 3-second design wind speeds** (Saffir Simpson Category 5). Specifically including wind tunnel testing review and rigidity assessment.
- Collaborate with roofers, roofing manufacturers, and insurance companies to maintain roof warranty and roof integrity.
- Collaborate with equipment suppliers to document material origin and certificate of grade and coating consistent with assumptions used in engineering calculations.
- Collaboration between installers and module suppliers/distributors to ensure local availability of specified modules.

Image courtesy of Fidel Neverson, Energy Solutions, Inc.

ENERGY STORAGE SYSTEMS FOR RESILIENCE

While this paper is focused solely on solar PV systems, it is worth adding that PV systems combined with a battery storage system can continue to deliver power to a home, business, or critical facility, even during a grid outage. Most grid-connected PV systems without battery storage will shut down when a grid outage is detected, to avoid back-feed to the grid and to ensure safety of the system and utility personnel. A PV system with a multi-mode inverter, transfer switch, battery storage system, and other appropriate components can be disconnected ("islanded") from the grid during a power outage. During extended power outages, this additional resilience can ensure continued critical services to the community such as communications, water treatment and pumping, medical operations, and refrigeration for food and medicine storage.

By pairing batteries with a resilient solar PV system, facilities can count on uninterrupted power even after the most severe storms. Additional discussion on the many benefits of solar coupled with battery energy storage can be found on RMI's blog post "**Critical Facilities: Where Government and Utility Services Redefine Resilience**."[8]

Image courtesy of The Solar Foundation

RECOMMENDED REFERENCES

Image courtesy of Rocky Mountain Institute

RECOMMENDED REFERENCES

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FEMA P-2054 | Mitigation Assessment Team Compendium Report
https://www.fema.gov/media-library/assets/documents/184600

ATC Wind Hazard Tool
https://hazards.atcouncil.org/#/wind

Minimum Design Loads and Associated Criteria for Buildings and Other Structures (ASCE/SEI 7-16)
https://www.asce.org/asce-7/

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Image courtesy of Caribbean Solar Company

APPENDICES

Image courtesy of Rocky Mountain Institute

APPENDIX A
DEFINITIONS

Vibration-Resistant Fastener
Fastener that does not loosen under vibration stress even when minimally torqued. (e.g., nylock, loctite, rivets, double-nut, etc.)

Worst-Case Joist Loading
Highest calculated loading on a single joist in the array. Determined by considering all dead plus environmental (wind, snow, live, etc.) loads attributed to it by the roof area it supports (typically ½ span to adjacent joists) This is also referred to as "tributary area."

Array Area Average Loading
Average dead plus environmental loading over the entire area of an array. Typically lower than worst-case joist loading.

Cascading Failure Mode
A secondary failure mode that increases geometrically in magnitude due to an aspect of the system design.

Design for Resilience
Design practices that seek to reduce progressive (cascading) failure modes. Emphasis is on containing failures to an acceptable limit, not preventing all system damage (which may be significantly more expensive).

Effective Wind Area (EWA)
Structurally appropriate area by which a particular wind coefficient is to be applied. Effective wind area must be supported by the structural capacity of each component in the system. See Appendix C for details.

Module Liberation
Loss of retention of a module in an array, due either to impact from debris, a cascading failure mode, or purely due to overstress from wind loading.

Dynamic Excitation (Walking)
System lateral displacement that can occur on systems that rely on ballasts to resist wind loading, even when global sliding checks pass. Walking is generally preventable with the appropriate use of mechanical attachments.

Pitched-Roof Racking (Rail-based)
Flush-mounted to roof slope, fully dependent on mechanical attachments to roof, typical on standing-seam metal commercial and most residential projects.

Elevated Rail System Flat-Roof Racking
Common on flat-roof commercial installations. System is commonly elevated ~24" above the roof surface and fully dependent on mechanical attachments to the roof.

Ballasted/Mechanically Attached Hybrid Flat-Roof Racking
Specific to flat-roof commercial installations and relies either fully on self-weight of system or on some combination of self-weight and specifically placed mechanical attachments to withstand wind loading. More commonly used in lower wind zone projects (<120 mph) due to excessive ballast requirements to handle high wind being in excess of many building load capacities.

Self-weight
Gravity load (dead load) of system available to resist wind loading. Must be checked for impact to building structure. Typically equally distributed except for ballasted/mechanically attached hybrid racking (see Worst-Case Joist Loading).

Mechanical Attachment
Structural connection between building structure and PV racking. Capacity is dependent on connection design and will vary depending on if attachments are made purely to roof decking or to underlying joists/rafters.

Velocity Pressure
Project-specific measurement of wind forces. Higher for high wind speed projects.

APPENDIX B

PROJECT OWNER'S HIGH-WIND DESIGN PROCESS (BALLASTED/HYBRID RACKING ON FLAT ROOF ONLY)

Project engineers often aren't privy to the logic that connects wind tunnel testing assumptions and structural calculation packages on ballasted/mechanically attached hybrid flat-roof racking projects. Design errors are often found within this connective space. The project owner's high-wind design checklist is meant to be a process by which anyone can walk through the structural calculation package and double-check that the system meets a minimum requirement for roof attachments and ballast assignment to resist high-wind scenarios. It builds the case for the minimum roof attachment scheme and should be used on projects with design wind speeds of 120–145 mph dependent on wind exposure, and certainly on any flat-roof project with a design wind speed greater than 145 mph.

Three wind loading cases that must be checked according to governing factored load cases:

1. Pure uplift
2. Uplift and Sliding
3. Overturning

DESIGNING FOR PURE UPLIFT

Racking vendors must demonstrate that structural loads can be shared among the grouping of modules for which wind loads are being determined (effective wind area [EWA]). Loads are considered shared if no more than 1" of uplift is experienced anywhere within an area without ballast.

For example, if a "3x3" (3 modules wide x 3 rows = 9 modules) area is to be considered as a maximum EWA size, the appropriate peak wind load to be applied to this EWA is evenly applied and the perimeter of this 3x3 array is fixed to the ground. Peak deflection upward (gap between roof and racking) should be less than 1" for this EWA to be considered structurally connected. This testing should be done without including any ballast or mechanical attachments (simply done with self-weight of modules plus racking). Once the uplift EWA is established, the ballast may be distributed evenly over the area considered or otherwise as determined by the racking vendor.

DESIGNING FOR UPLIFT AND SLIDING

Racking vendor needs to demonstrate that inter-module and inter-row structural elements can supply bracing to prevent siding of every size of the array being considered.

For example, if considering a maximum uplift and sliding EWA of 9x9 (81 modules), the process to check sliding resistance is as follows:

1. Check that 1x1 sliding loads can be resisted by modules adjacent and downwind.

2. Check that 2x1 sliding loads can be resisted by module adjacent and downwind.

3. 2x2, 3x1, 3x2, 3x3, 4x1, 4x2, 4x3,4x4, etc. all the way up to 9x9 are to be checked against adjacent modules and downwind module rows to ensure structural elements can resist/brace against sliding forces.

DESIGNING FOR PURE OVERTURNING

Racking vendor needs to consider module overturning for every combination of modules up to the EWA used for pure uplift checks. In the above example of a 3x3 EWA, this means overturning needs to be checked for 1x1, 2x1, 2x2, 3x1, 3x2, and 3x3. Wind loading can be assumed to apply equally to the center of each of the module(s) of the EWA being considered. Ballast can be applied along with self-load of racking plus modules as they are distributed to determine resistance to overturning.

MINIMUM SPECIFICATION FOR ROOF MECHANICAL ATTACHMENTS

Racking vendor should include a minimum number of mechanical roof attachments that satisfies the following:

1. Mechanical attachment acting on the corner module of every array.

2. No more than a three-module span along a northern row between mechanical attachments.

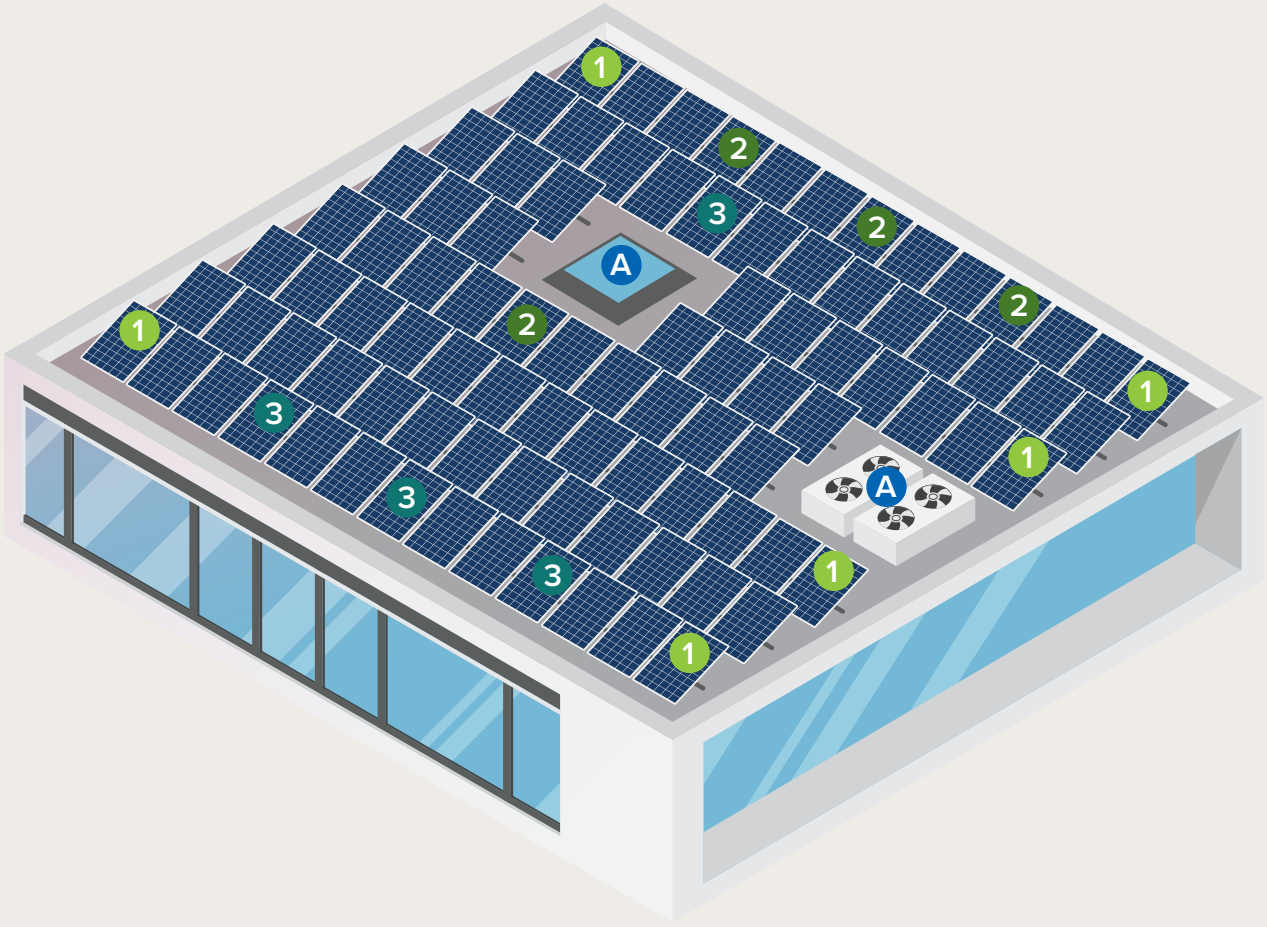
3. No more than a three-module span along a southern row between mechanical attachments.

The above requirements are a minimum and a given project may require further mechanical attachments. Adhering to the above will dramatically reduce the risk of catastrophic wind failures (overturning modules leading to cascading failure modes). It also provides significant resistance to both lift/sliding and "walking" of the system over the roof over longer periods of moderate wind and/or seismic activity.
A module is considered to be within a northern or southern row if there is no direct mechanical attachment to another row of modules on both the north and south sides of it that would prevent overturning in both directions. This means obstacles such as A/C equipment, skylights, and walkways that break up arrays can generate significant numbers of northern and southern row sections and thus may require significant numbers of new mechanical attachments.

A module is considered to be a "corner module" if located at the end of a row and if no module is attached to both northern and southern edges to prevent overturning in both directions.

EXHIBIT A1

Minimum Roof Mechanical Attachment Scheme



1 Corner Attachment

2 North Row Attachment

3 South Row Attachment

A Roof obstruction such as skylights, AC units, chimneys, etc.

APPENDIX C

PROJECT OWNER'S BUILDING STRUCTURE ANALYSIS

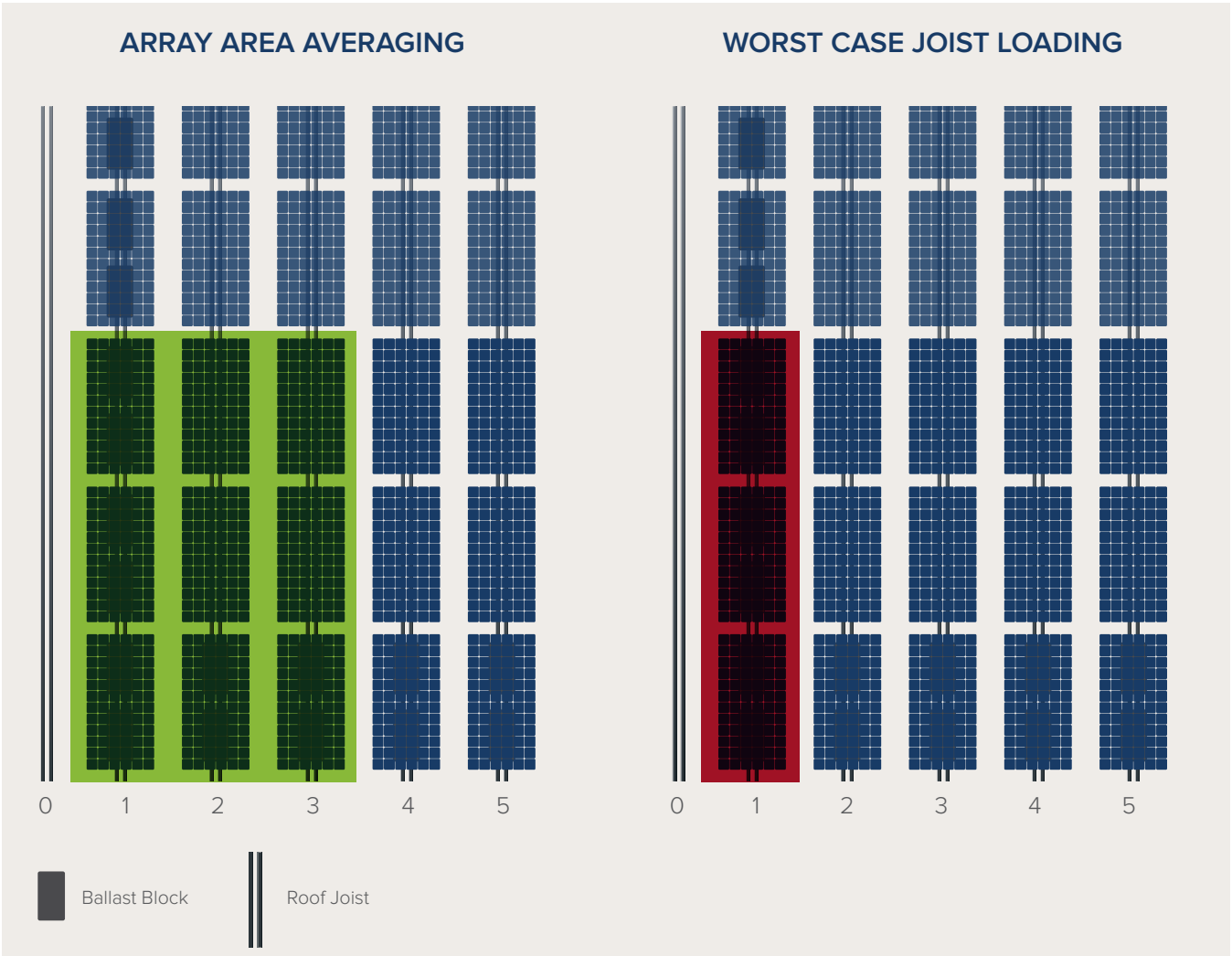
An often-misunderstood concept is the difference between array area averaging and worst-case joist loading in determining the structural capacity of a building roof system. Exhibit A2 below showcases the difference in assumptions for calculating array weight.

Array area averaging sums the self-weight of the system (including ballast) and divides it by the area it covers to get the pounds per square foot (PSF). This is incorrectly compared to the dead-load capacity of the roof structure to determine if the roof is able to hold the weight of the system.

Worst-case joist loading is a more appropriate method of calculation. It takes into account the distribution of loading from the solar array and the capacity of the weakest member of the roof structure to support that distribution. We highly recommend using this method when evaluating potential projects and roof capacity.

EXHIBIT A2

Array Area Averaging vs. Worst Case Joist Loading



APPENDIX D

PROJECT RESILIENCE CHECKLIST

Pre-Inspection of the Rooftop

- [ ] Roof type
- [ ] Roof age
- [ ] Roof condition
- [ ] Building parapet wall height
- [ ] Drain locations are marked on the planset
- [ ] Skylight locations are marked on the planset
- [ ] Equipment locations are marked on the planset
- [ ] Other obstruction locations are marked on the planset
- [ ] Nearby debris risk (nearby loose items on rooftop, overhanging trees, etc.)

Project Wind Load Inputs

- [ ] Building height assumptions are accurate
- [ ] Project risk category, topographic factor, and exposure category are accurate
- [ ] Project wind speed is accurate
- [ ] Building joist locations and sizes are accurate

Mechanical Fasteners

- [ ] Mechanical fasteners should be utilized in high-wind zones to a minimum acceptable standard (supplied within this document). No ballasted-only systems.

Discussions with the Professional Engineer of Record

- [ ] Does the project engineer have access to the building design calculations to determine capacity?
- [ ] Has the project engineer reviewed the wind tunnel testing of the racking vendor and its application to the project?
- [ ] Has the racking vendor supplied a rigidity assessment specific to their geometry that validates the effective wind areas they assume in the design? If not, the effective wind area should be assumed to be a single module (see Appendix B)
- [ ] Has the project engineer evaluated the worst-case joist loading of the building and not simple array area average loading? (See Appendix C)
- [ ] Has the project engineer verified whether the local wind pressure from the wind tunnel test and project calculations exceeds the module specification for static loading?
- [ ] Has the project engineer verified that the mechanical attachment scheme meets or exceeds the applicable minimum mechanical attachment recommendation? (See Appendix B)
- [ ] Has the project engineer verified that existing practices incorporate all “current mitigations” identified in the FMEA tables? Has the racking vendor performed and supplied their own FMEA to the project engineer?

Hardware

- [ ] Does the project use vibration-resistant hardware? Does the module mount with hardware independent of adjacent modules?

ENDNOTES

Image Courtesy of Daniel Langlois, Coulibri Ridge

ENDNOTES

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