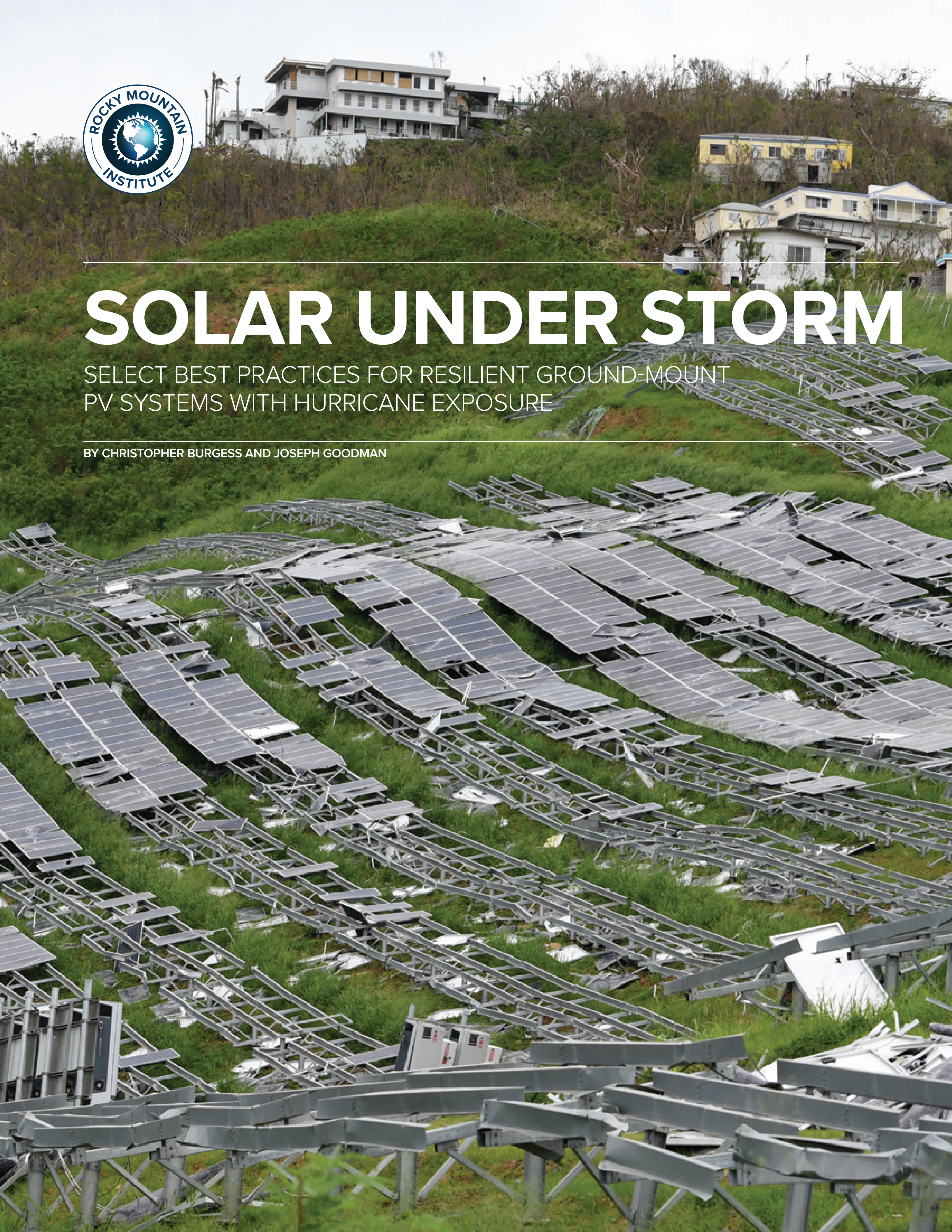
SOLAR UNDER STORM

SELECT BEST PRACTICES FOR RESILIENT GROUND-MOUNT PV SYSTEMS WITH HURRICANE EXPOSURE

BY CHRISTOPHER BURGESS AND JOSEPH GOODMAN



“Fortunately, our island was not impacted last fall by the hurricanes. However, we are planning to add a considerable amount of solar PV to our power system over the next few years and we want to know how we can ensure the survival of these new assets”

—Kendall Lee, Managing Director, Montserrat Utilities Limited

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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; Washington, D.C.; and Beijing.

ACKNOWLEDGMENTS

FCX solar

About FCX Solar

Founded in May 2016, FCX Solar is an engineering partnership between Frank Oudheusden and Christopher Needham. Together they have a combined 20+ years of solar project and project development experience ranging from residential to large-scale utility projects. FCX Solar provides solar power developers and structures manufacturers with a wide range of engineering services. FCX Solar also develops intellectual property in the solar structures space. Prior to founding FCX, Frank & Chris were Senior Staff Engineers at SunEdison, developing in-house proprietary structural products, vetting all structural products for the global supply chain, optimizing PV plant design and evaluating new technologies for M&A opportunities.

SOLARISLAND ENERGY

About Solar Island Energy

Solar Island Energy is an engineering, construction, and development services company; expert at innovative and creative solutions for solar energy, advanced technology microgrids, and energy efficiency. Solar Island has a decade of experience in the Caribbean and is dedicated to helping its clients to achieve their goals for financial performance and environmental stewardship.

CARILEC
An Association Of Electric Utilities

About Caribbean Electric Utility Services Corporation

(CARILEC) is an association of electric services, dealers, manufactures and other stakeholders operating in the electricity industry in the Caribbean region, Central and South America, and globally. The CARILEC Secretariat endeavors to improve communication among its members, providing technical information, training, capacity building, conference, and other services. The Secretariat plays a leading role in electric utility advocacy, growth, and sustainability in the Caribbean region and Central and South America.

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Hurricane Maria aftermath in Puerto Rico. People attempt to remove broken power poles that landed on top a food truck in Vega Alta, Puerto Rico

EXECUTIVE SUMMARY

The 2017 hurricane season was one of the most active in history.[1] Hurricanes Harvey, Irma, and Maria brought widespread destruction throughout the Caribbean. 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 in homes, businesses, industries, government facilities, and utilities by solar photovoltaics (PV). In fact, over half of Caribbean electric utilities already own or operate solar PV as part of their generation mix. Over 225 MW of solar is installed across rooftops, parking canopies, and large tracts of land. Solar PV is the most rapidly growing source of power for many Caribbean islands.[2]

Photo courtesy NASA Earth Observatory

Despite the record sustained wind speeds of over 180 miles per hour, many solar PV systems in the Caribbean survived. Some solar installations in the British Virgin Islands, Turks and Caicos, Puerto Rico, and St. Eustatius faced tremendous wind yet continued producing power the following day.

In contrast, some PV systems in Puerto Rico, the US Virgin Islands, and Barbuda suffered major damage or complete failure with airborne solar modules, broken equipment, and twisted metal racking.[3]

FIGURE 1

SURVIVORSHIP AND FAILURE OF GROUND-MOUNT SOLAR PV DURING HURRICANE SEASON 2017

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, we cannot give an overarching statistical conclusion to explain survivorship versus failure. Instead, this guide combines recent field observations along with expert analysis to deliver actionable recommendations for increasing resiliency among retrofit and new construction solar PV installations.

This paper is organized into four sections:

1. Introduction
2. Root cause identification methodology and findings
3. Failure mode and effects analysis (FMEA)
4. Summary of recommendations

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

Photo courtesy Stephen Mushegan, Clinton Climate Initiative

SUMMARY OF FINDINGS:

Expert structural engineering teams were deployed to the Caribbean region in the fall of 2017 to investigate root causes of solar PV system failures in the wake of Hurricanes Irma and Maria. They uncovered several root causes of partial or full system failure through observation and determined several potential failures that could have occurred if other failures did not occur first (lurking failure modes).

Some similarities of failed systems in the wake of Hurricanes Irma and Maria:

1. Top down or T clamp failure of modules
2. Undersized rack or rack not designed for wind load
3. Lack of lateral racking support (rack not properly designed for wind loading from the side)
4. Undersized bolts
5. Under torqued bolts
6. Lack of vibration-resistant connections
7. PV module design pressure to low for environment
8. Use of self-tapping screws instead of through bolting

Some common ground-mount PV attributes of surviving systems in the wake of Hurricanes Irma and Maria:

1. Dual post piers
2. Through bolting of solar modules (no top down or T clamps)
3. Lateral racking supports
4. Structural calculations on record
5. Owner's engineer of record with QA/QC program
6. Vibration-resistant module bolted connections such as Nylocs

RECOMMENDATIONS:

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

1. **Specifications:**
    - Specify high-load (up to 5,400 Pa uplift) PV modules, based on structural calculations; these are currently available from a number of Tier-1 module manufacturers.
    - Require structural engineering in accordance with ASCE 7 and site conditions, with sealed calculations for wind forces, reactions, and attachment design (ground-mount foundation).
    - Confirm with racking manufacturer that actual site conditions comply with their base condition assumptions from wind-tunnel testing.
    - Specify bolt QA/QC process: there were several instances of inadequate torqueing of bolts in the investigation—a workmanship and oversight issue.
    - Specify bolt hardware locking solution.
    - Specify through bolting of modules as opposed to top-down or T clamps, or if top clamping is required, use clamps that hold modules individually or independently.
    - Require structural engineer review of lateral loads due to racking and electrical hardware—often lateral loads are missed and recent failures have proven them to be a critical source of weakness (e.g., combiner boxes attached to end solar array posts caused increased loading and led to failure).
    - Do not recommend trackers for projects in Category 4 or higher wind zones.
    - Specify all hardware be sized based on 25 years (or project life) of corrosion.
    - Do not recommend any self-tapping screws.
    - Specify dual post fixed tilt ground mounts, which significantly reduce foundation failure risk.

2. **Collaboration:**

Collaboration recommendations identify opportunities for increased resiliency, which require multiparty consideration and action but do not represent current industry standard actions.

- Collaborate with module suppliers for implementation of static and dynamic load tests representative of Category 5 hurricane winds.
- Collaborate with racking suppliers for full scale and connection test representative of Category 5 winds.
- Collaborate with equipment suppliers to document material origin and certificate of grade and coating consistent with assumptions used in engineering calculations.

Perhaps the most opportune recommendation is for a regional and even international community of solar PV power plant stakeholders who have extreme wind exposure to regularly share lessons learned from new designs and extreme wind events. To that end, we formed a PV Resiliency working group on the online Caribbean Renewable Energy Community (CAREC), which is hosted by CARILEC, to connect, innovate, and collaborate. Join the working group at **http://community.carilec.org/c/PVResiliency.**

02 INTRODUCTION

Hurricane Maria aftermath in Puerto Rico. Storm-damaged neighborhood in Corozal, Puerto Rico

INTRODUCTION

Recently, solar energy has demonstrated increased technical and economic ability to support island communities' energy transitions. Moreover, solar energy has demonstrated an ability to withstand major hurricane events despite a portion of the installed base experiencing catastrophic damage. There are examples throughout the recent hurricane tracks of Harvey, Irma, and Maria of both survival and failure of ground-mounted solar PV systems. Given the variability in wind speed, wind direction, topography, design, and construction, along with limited data, one overarching conclusion cannot be made to explain the diversity of outcomes.

The purpose of this document is to combine recent field observations along with expert analysis to provide actionable recommendations aimed at increasing the resiliency of retrofit and new construction solar PV installations. More specifically, this paper provides guidance applicable to ground-mount and canopy PV power plants with a fixed tilt or a dual tilt (E-W) configuration. Rooftop systems and tracking systems experience unique aerodynamic phenomena that are not within the scope of this paper but will be addressed in future versions in response to interest.

The US Federal Emergency Management Agency (FEMA) recently released an advisory regarding rooftop PV in the US Virgin Islands that is available **online.**[4] The advisory is a summary of recommended practices for attachment design, installation, and maintenance of rooftop solar PV panels to increase the wind resistance of panels. This guidance was informed by lessons learned after Hurricanes Irma and Maria in 2017 and is primarily intended for architects, engineers, and contractors.

APPROACH

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

Guiding principles of this work include:

1. Collaborate across organizations and expertise.
2. Address observed failure modes and lurking failure modes (ones that did not occur only because something else failed first).
3. Plan for advancement of hardware, reliability statistics, and expert knowledge.
4. Provide performance-based recommendations where possible to allow for innovative solutions.
5. Limit recommendations to only those that provide a risk-adjusted economic benefit.

In order to realize these guiding principles, we conducted a five-step process:

1. Conduct failure analysis of sites impacted by the 2017 hurricane season.
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 effects analysis (FMEA) for the prioritized root causes.
5. Synthesize recommendations from the FMEA for communication and consideration.

Photo courtesy Owen Buggy Photography

Necker Island, British Virgin Islands, took a direct hit from Hurricane Irma on September 7, 2017. This 800 kW ground-mount solar PV system survived and powered on the next morning.

The key output of this paper is a list of recommendations for building more resilient solar PV power plants. The recommendations are organized into two categories: 1) specifications, and 2) collaboration. To the extent possible, the specifications are performance- based to allow for individual project teams to provide the most cost-effective and resilient solution. Collaboration recommendations identify opportunities for increased resiliency, which require multiparty consideration and action but do not represent industry standard actions.

Perhaps the most opportune recommendation is for a regional and even international community of solar PV power plant stakeholders who have extreme wind exposure to regularly share lessons learned from new designs and extreme wind events. To that end, we formed a PV Resiliency working group on the online Caribbean Renewable Energy Community (CAREC), which is hosted by CARILEC, to connect, innovate, and collaborate. The working group can be found at **community.carilec.org/pv-resiliency**.

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 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.

03 ROOT CAUSE IDENTIFICATION: FINDINGS AND RECOMMENDED PROJECT USE

Photo by Kenneth Wilsey - Feb 13, 2018 Guaynabo, Puerto Rico

ROOT CAUSE IDENTIFICATION:
FINDINGS AND RECOMMENDED PROJECT USE

The recent hurricane season in conjunction with the increased installed base of solar power plants has provided an initial body of evidence for developing resiliency guidelines for future projects. However, development of hurricane resiliency 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. In the event that future systems only address the observed failure modes, forces may precipitate additional failure modes. To address both observed and potential failure modes, we take a classical reliability engineering approach to design for reliability.

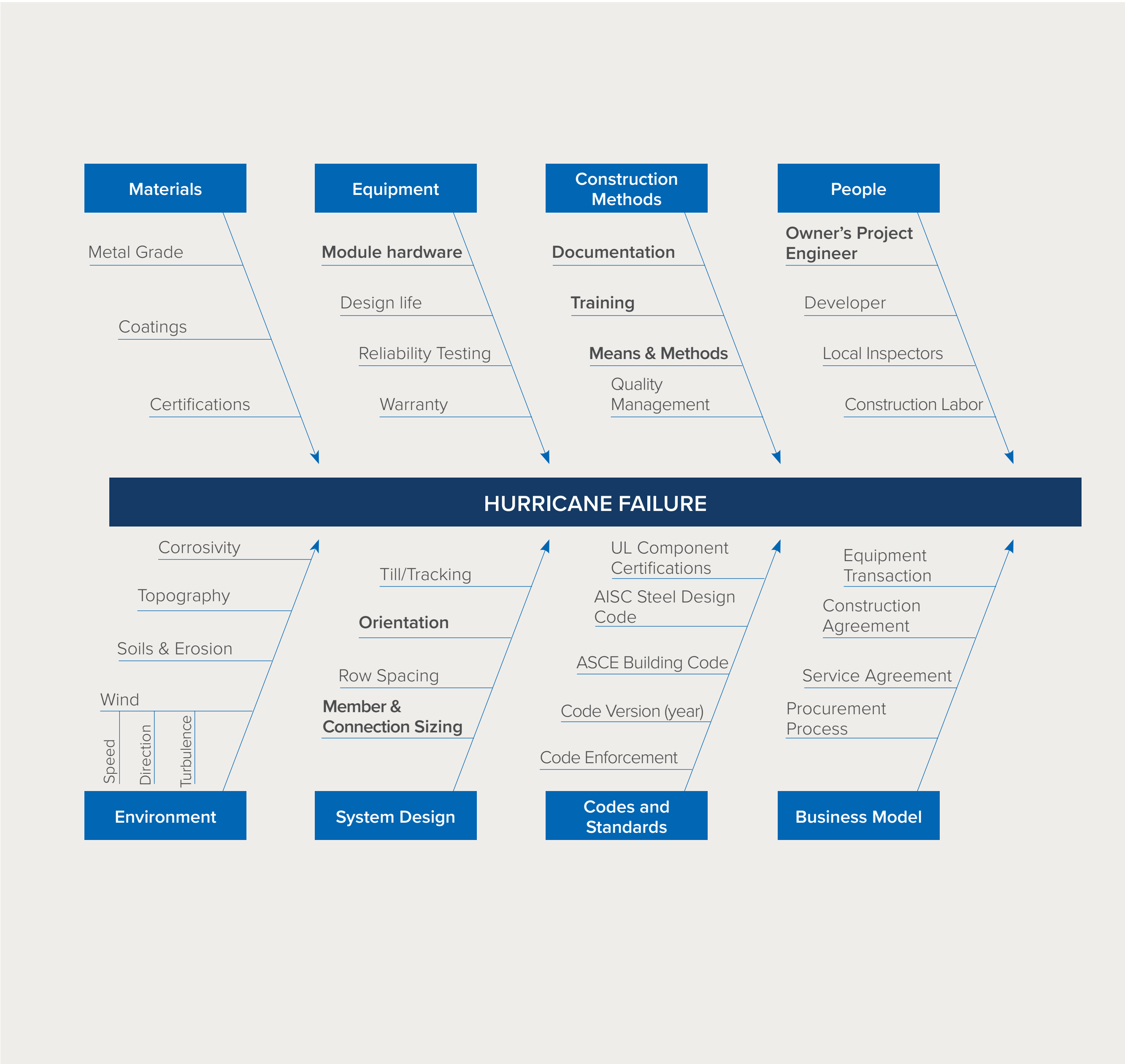
Figure 2 illustrates a common reliability tool for systematic cause and effect identification called a fishbone diagram. The diagram shows the supply chain responsible for design, manufacturing, procurement, delivery, installation, and operations of a solar power plant, along with the operational use 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 power plant project teams are invited to utilize Figure 2 as a facilitation tool to explore project-specific opportunities to eliminate causes of failure in response to extreme wind or other hazards.** During a project delivery process, the project team may explore the categories provided along with additional categories to identify causes of failure and potential mitigations. Project teams that complete the root cause analysis are invited to annotate Figure 2 and share their findings with the broader community.

Continuing the Conversation, Community of Practice
Project teams that complete a root cause analysis are invited to create their own fishbone diagram for sharing with the Caribbean Community of Practice—the CARILEC Renewable Energy Community, (CAREC). RMI will compile your findings annually with those of other participating project teams. Participating teams will be invited to an exclusive webinar for sharing best practices across teams. To join CAREC, go to **community.carilec.org.**

FIGURE 2

FISHBONE DIAGRAM FOR ROOT CAUSE ANALYSIS IDENTIFICATION



04 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Photo by Kenneth Wilsey for FEMA - Humacao, Puerto Rico, Jan. 25, 2018

FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

Improving the ability of PV systems to withstand hurricane winds requires not only identification of failure modes but also a cost-effective mitigation action. We utilized the FMEA framework to identify practical mitigation actions. Moreover, we aspired to provide actions that have a net positive impact on cost when considering the cost and benefit in a risk-adjusted financial analysis.

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

TABLE 1

PV MODULE FRAME AND LAMINATE

#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
1a	Laminate tear-out (module glass dislodged from frame)	UL 1703 static load (global PV module testing standard)	Local pressure may exceed module rated pressure	Review racking system/full structural system wind tunnel test report for local wind pressure and compare against module front and back rated pressure. Refer to example in Appendix A. Racking suppliers furnish these wind tunnel test reports upon request. Results of the test will determine the proper rating for modules (which will differ across the design of the array).	Low/Medium
1b	Frame bolt hole failure	Engineering connection calculations	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/High
1c	Laminate impact damage	UL 1703 hail impact tests and ASCE wind-prone debris. Some severe hail-damaged modules are available	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).	Low/High

Photo courtesy FCX Solar

TABLE 2

PV MODULE CONNECTION HARDWARE


#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
2a	Bolt self-loosening	Partial torque check and proper documentation of the torque checks	Self-loosening common due to washer-clamping surface translation during vibration	Specify bolt locking solution appropriate for the environment and workforce. (Nyloc nuts have been anecdotally reported to provide mitigation even when not torqued properly.)	Low/High
2b	Connection hardware failure (fracture, rupture, tear out, shear)	SE hand calculations are typical	Hand calculations not always updated with site-specific wind load and topography	Specify SE site-specific review of module attachment hardware per AISC or equivalent.	Low/High
2c	Cascading failure of T clamps	Module T clamps designed for symmetric boundary conditions	Module T clamps rotate with loss of one module and allow liberation of second module	Specify module frames to be through bolted in accordance with manufacturing specification for the design wind speed. If necessary, use top clamps that do not allow cascading failure.	Low/High

Photos courtesy FCX Solar

TABLE 3

STRUCTURAL RACKING MEMBER


#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
3a	Member global failure (plastic deflection, buckling, torsion)	Steel code (AISC or equivalent) check with software package (RISA 3D or equiv.) and updated according to site-specific ASCE 7 loads	ASCE 7 prioritizes normal loads due to buildings focus. Lateral loads on eBoS commonly omitted	1. Utilize owner's project engineer to review calculation package. 2. Specify racking design for the wind speed recommended by ASCE 7-16. 3. Specify SE review of lateral loads due to racking and eBoS hardware. 4. Specify racking with documentation of full scale load test. 5. Specify any tracker included in the project shall be designed for worst case wind exposure, no stow position for extreme wind allowed.	1. Low/Medium 2. Med/High 3. Low/High 4. Low/Medium 5. Medium (Tracking only)
3b	Dynamic excitation	Building code requires dynamic load amplification for structures with resonant frequency <1 Hz>	PV arrays with inter-row spacing experience modified airflow more conducive to dynamic excitation	SE project engineer should check dynamic loading if resonant frequency is <5 Hz (Cain and Banks, 2015).	
3c	Tracker torque tube torsion	Trackers designed for wind load experienced in "stow" mode	Stow mode is not a fail safe control. Extreme wind may occur outside of stow	If tracker must be used within Category 4–5 wind zones, solicit third-party review of tracker design by firm experienced in designing for dynamic wind loading. Tracker design is quickly evolving in regard to dynamic wind response, so this will keep recommendations most up to date.	High/Medium

Left photo courtesy FCX Solar; Right photo courtesy NREL

TABLE 4

STRUCTURAL RACKING CONNECTIONS

#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
4a	Bearing bolt shear	AISC check with hand calculations typical	Hand calculations not always updated with site-specific wind loads	Specify structural engineer to complete site-specific connection review	Low/High
4b	Bolt self-loosening	Partial torque check and documentation typical	Self-loosening common due to washer-clamping surface translation during vibration	Specify bolt-locking solution appropriate for the environment and workforce.[6]	Low/High
4c	Self-tapping screw corrosion and shear failure	Steel code	Sizing does not always account for highly corrosive environment	Either specify no self-tapping screws or specify self-tapping screws to be sized based on 25 years and for expected vibrations.	Low/High

Left photo courtesy NREL; Right photo courtesy FCX Solar

TABLE 5

RACKING FOUNDATIONS

#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
5a	Foundation structural failure	ASCE 20	Requires site-specific geotechnical data	Specify complete suite of geotechnical test for foundation design.	Medium/ Medium
5b	Overturning foundation posts	Structural design preferences	Developers want to minimize foundations per site	Specify structures with dual foundation designs over single foundation designs as they better support from an overturning moment failure. Specify low tilt angles to reduce peak module pressures and overturning moments.	Medium/High
5c	Erosion	Very few	Requires water drainage control plan	On steep-slope, loose-soil projects, develop water drainage plan and install drainage methods during site construction to control water flow. Take into account topography from surrounding land that isn't site specific.	Medium/ Medium
5d	Corrosion	American Galvanizers Association Guidance	More galvanization requires more cost	For foundations: Specify testing of soil corrosion (pH, chloride, and moisture) at multiple locations and utilize for foundation design according to ASTMA123. Be familiar with causes of accelerated corrosion like pollution, humidity, and salt water proximity and review the local (300 m radius) area for caustic-causing input to the plant.	Medium/ Medium

Photo courtesy AquaSoli

TABLE 6

ELECTRICAL BALANCE OF SYSTEMS

#	FAILURE MODE(S)	CURRENT MITIGATION	LIMITATIONS	POTENTIAL MITIGATION ACTION	COST/ IMPACT
6a	Wire pull out or terminal damage	UL specification for each electrical component (e.g., UL 1703 PV modules)	Terminal torque values unchecked in field	Specify QA/QC procedure and documentation for terminal torques.	Low/Low
6b	Wire sheath chafing (ground fault)	NEC or IEC conductor management and support specifications	Wires sag and subject to gyration based on field installation	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
6c	Wire management fracture	NEC or IEC	Direct and reflected UV exposure increases risk of embitterment and fracture	Specify UV-resistant and corrosion-resistant wire management solution. Require plan set to incorporate wire management technique for review against NEC or IEC. Specification of conduit in lieu of open-air wire management may be appropriate in some locations.	Low/Low
6d	Rain intrusion into combiner boxes or inverters	NEC - NEMA specification	Hurricane wind blowing sideways can penetrate NEMA 3	Specify NEMA 4X to 6P enclosures based on engineering review. IEC equivalent is IP56 to IP67.	Medium/High

Photos courtesy FCX Solar

05 CONCLUSION

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 within a community of practice.

Specifications include:

- Specify high-load (up to 5,400 Pa uplift) PV modules, based on structural calculations; these are currently available from a number of Tier-1 module manufacturers.
- Require structural engineering in accordance with ASCE 7 and site conditions, with sealed calculations for wind forces, reactions, and attachment design (ground-mount foundation).
- Confirm with racking manufacturer that actual site conditions comply with their base condition assumptions from wind-tunnel testing.
- Specify bolt QA/QC process: there were several instances of inadequate torqueing of bolts in the investigation—a workmanship and oversight issue.
- Specify bolt hardware locking solution.
- Specify through bolting of modules as opposed to top-down or T clamps, or if top clamping is required, use clamps that hold modules individually or independently.
- Require structural engineer review of lateral loads due to racking and electrical hardware—often lateral loads are missed and recent failures have proven them to be a critical source of weakness (e.g., combiner boxes attached to end solar array posts caused increased loading and led to failure).
- Do not recommend trackers for projects in Category 4 or higher wind zones.
- Specify all hardware be sized based on 25 years (or project life) of corrosion.
- Do not recommend any self-tapping screws.
- Specify dual post fixed tilt ground mounts, which significantly reduce foundation failure risk.

Likely the most effective strategies for improving system survival rates are communicating clear market signals to suppliers and upstream equipment providers and coordinating closely among practitioners. This includes:

- Collaboration with module suppliers for implementation of static and dynamic load tests representative of Category 5 hurricane winds.
- Collaboration with racking suppliers for full scale and connection test representative of Category 5 winds.
- Collaboration with equipment suppliers to document material origin and certificate of grade and coating consistent with assumptions used in engineering calculations.

If successful, this paper will be one of the early actions that triggers more effective coordination across supply chains and the community of practice.

06 RECOMMENDED REFERENCES

Photo courtesy Stephen Mushegan, Clinton Climate Initiative

RECOMMENDED REFERENCES

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The 5 MW Estate Donor Solar Project on the island of St. Thomas.
Photo courtesy Jennifer DeCesaro

07

APPENDIX: SOLAR PV POWER PLANT WIND PRESSURE CHECKLIST FOR PROJECT OWNERS

APPENDIX: SOLAR PV POWER PLANT WIND PRESSURE CHECKLIST FOR PROJECT OWNERS

The determination of a design wind pressure is a complex science conducted by expert scientists and engineers. Solar PV power plant owners may generally confirm that wind pressures have been appropriately determined through familiarization with the process.

General process for solar PV power plant wind pressure determination:

1. **Conduct wind tunnel study on a scaled system model in a boundary-layer wind tunnel.**
   Project stakeholders may review the wind tunnel test report to confirm the scale model represents the project's proposed system layout. Deviations in row length, spacing, tilt, height, and leading-edge height should be limited to the range identified in the wind tunnel report.

Photo courtesy Stephen Mushegan, Clinton Climate Initiative

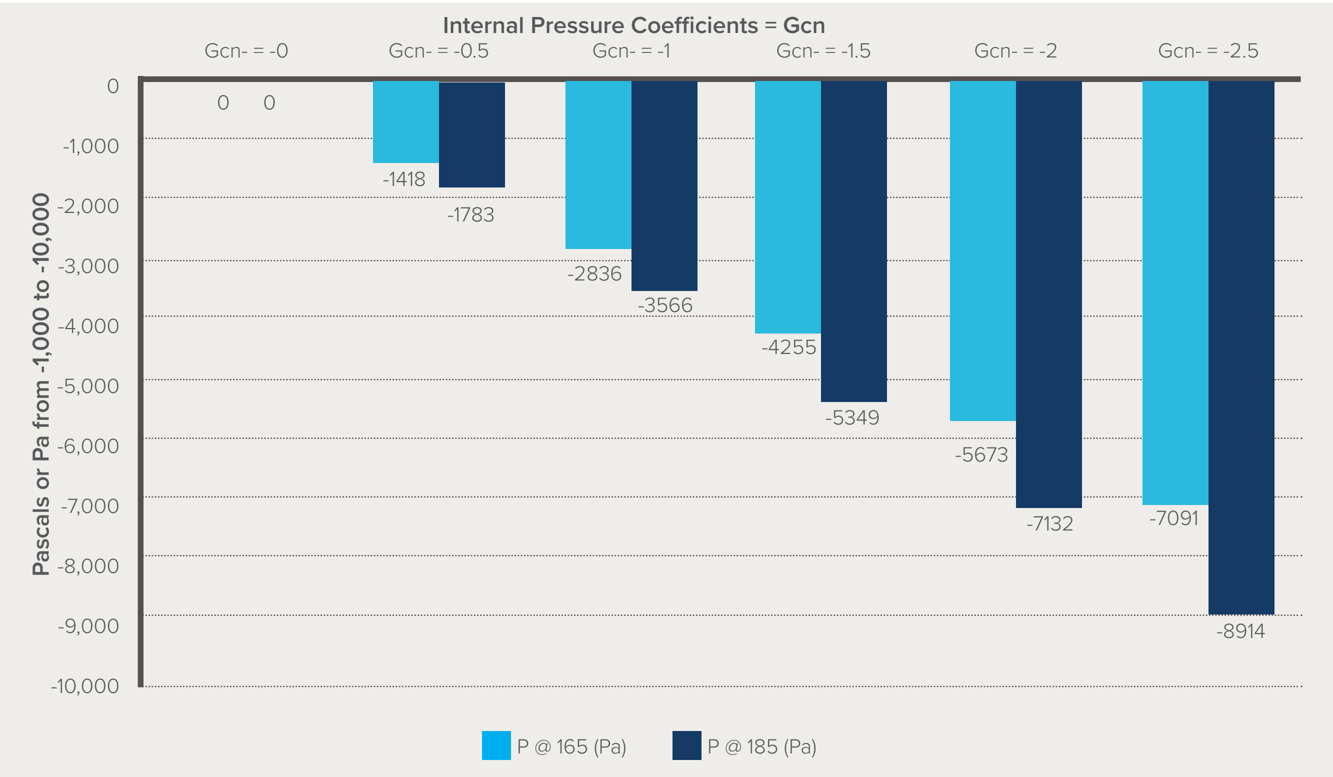
2. **Analyze pressure measurements to determine pressure coefficients for the module or structural member of interest.**
   The wind tunnel test report should contain a table of pressure coefficients for each structural member of interest corresponding to the tributary area of said member or component. A project stakeholder should be able to identify that an appropriately selected table of pressure coefficients was used for each member or component. For components that do not have a dedicated table, rounding down should provide a near approximation as long as the aspect ratio and location are also similar. If an appropriate table does not exist, the wind tunnel can most likely reprocess existing data with minimal time and resources.

3. **Determine the wind dynamic pressure by accounting for the design wind speed, local topography, system height, directionality, and importance.**
   Project stakeholders should be able to review a site-specific determination of wind dynamic pressure. The calculation should comply with the governing code and version (e.g., ASCE 7-10) and incorporate the regional design wind speed, system height, topography, and importance. Projects with any topographic features should ensure appropriate treatment of said features.

4. **Combine the pressure coefficients and dynamic pressure to calculate a wind pressure.**
   Project stakeholders should be able to review structural calculation to determine a design wind pressure for each component or member of interest. Figure 3 illustrates a set of wind pressures for design wind speeds of 165 and 185 mph for pressure coefficients from 0 to 2.5. In this example, a pressure coefficient of 0.5 corresponds to design pressures less than 2,000 Pa (Pascals, 49 Pa = 1 PSF). In contrast, a pressure coefficient of 2.5 corresponds to design pressures in excess of 7,000 Pa. Given the potential variability, **one can not assume that a high load rating module is either necessary or adequate.**

FIGURE 3

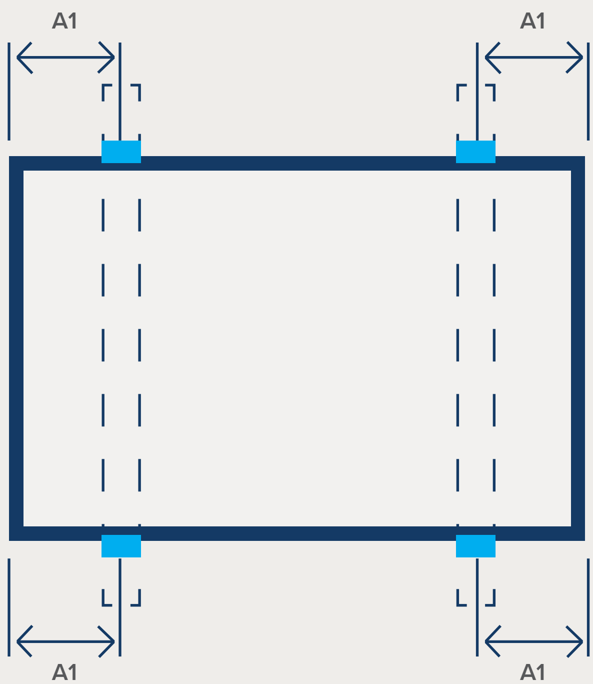
SAMPLE EXTREME WIND UPLIFT PRESSURE ON MODULE SURFACE



5. Review component and member specifications.
Project stakeholders should be able to review product specifications or engineering sets for all structural components, members, and connectors, including PV modules. Figure 4 illustrates the specification from a module that has one of the highest structural capacities known to the authors. Key information in this specification includes the range of allowable support conditions (AI) along with the specific AND unique uplift load.

FIGURE 4

PV MODULE MOUNTING SPECIFICATION



Use four clamps on the long side. Mounting rails run perpendicularly to the long side frame.

A1 range= (300–330)mm

Maximum Load:
Uplift load ≤ 4,000 Pa
Downforce load ≤ 8,100 Pa

08

ENDNOTES

ENDNOTES

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