Weathering the storm

Solar resilience | Hurricane-strength winds are a clear threat to solar installations in island nations, where PV is becoming an increasingly popular solution to climate change-related issues. Joseph Goodman and Frank Oudheusden, co-authors of a recent study on designing hurricane-ready solar systems, offer an insider's view of how the challenge is being met

Credit Jocelyn Augustino/FEMA

Island nations and coastal regions globally are increasingly mobilising climate change mitigation and adaptation efforts due to the local economic benefits. Distributed solar deployed in concert with complementary technologies such as batteries and/or micro-grids has growing momentum as a dual-purpose solution (mitigation and adaptation). While the case for solar as a mitigation solution is on a solid footing, the case for solar as an adaptation solution looks strong but requires field validation. Adaptation for island nations includes a need to protect electricity-dependent functions through increasingly frequent and extreme wind events including hurricanes and typhoons. For many decision makers, positive field validation will occur when PV systems resume power production promptly after an extreme wind event with little to no isolated damage.

Designing and optimising a PV power plant to be resilient to extreme wind is an emerging field. In 2018, the Rocky Mountain Institute published a report, 'Solar Under Storm' [1], which highlighted the emerging best practices for designing solar systems in hurricane-prone regions. The following article draws together some of the key lessons from the report.

One size fits all solutions rarely translate to island nations and solar is no exception

In response to temporary incentive programmes and dynamic markets, solar industry players have survived and perished on their ability to enter new markets with speed.

Hurricanes can damage or entirely destroy ground-mount solar installations without the correct design measures

Standard PV plants have been one of the tools for rapid market entry. In the design of standard plants, tensions exist between cost reduction and site flexibility. Rarely does a standard plant have extreme wind resilience as an intrinsic functionality. Yet, no aspect of PV components or systems is technically or financially incompatible with extreme wind. These bookends teach us that systematic design for extreme wind can result in resilient PV systems that provide mitigation and adaptation functions. Yet, failure to explicitly address the regional specific requirement will lead to likelihood of equipment failure when extreme wind strikes.

Extreme wind cannot be ignored

The Caribbean region has experienced a palpable increase in high-wind events over the past 20 years. Just looking at Category 5 hurricane events (Saffir-Simpson Scale >157mph 1-minute sustained wind speeds), the Atlantic region saw 22 Category 5 hurricanes between 1924 and 1998. Sixteen of those storms passed through some part of the Caribbean. Since 1998, the Atlantic region has seen 10 Category 5 hurricanes of which nine have passed through some part of the Caribbean. One of the latest of these storms, Irma (2017), holds the record for the longest sustained period at Category 5 status in the modern satellite era.

Sustained wind speeds on many of these modern storms are being measured in excess of 175-180mph and have spawned the apt discussion of creating a Category 6 on the Saffir-Simpson hurricane scale.

From a PV fleet management perspective hurricane frequency is only half the story. The increasing overall (industry) population of PV systems and their geographic distribution will make extreme wind interactions more common, if not an annual trial by wind. Designing PV plants to be resilient to tremendous wind forces poses a design challenge for the industry with great stakes at play.

Cost and value are both at stake

PV plants are subject to three cost categories in a wind damage event: 1) scrap removal and recycling (disposal); 2) reconstruction; 3) damage liability.

Removal of scrap material from a site can incur long re-start delays and transportation cost, especially on remote installations in regions with broad damage. Reconstruction after a regionally catastrophic event can incur labour premiums and supply chain delays.

While damage liability is better quantified by insurance agents they may consider the likelihood and severity of liberated modules or hardware striking surrounding infrastructure or vehicles as observed at one site by 'Solar Under Storm' authors.

While cost may be insured against, value might be the most precious asset and un-insurable. The growing market for adaptation solutions is fuelled by the confluence of rising sea levels and storm severity. In the last decade, solar has been taking market share from gas and diesel generators due to an operating cost advantage, and bolstered by the desire to eliminate generator noise and particulate emissions.

For the solar industry, growing market in high-profile regions drives investor confidence and a virtuous cycle. From our perspective, the customer's belief in PV's inherent resilience to extreme wind underpins this market share. Every PV installation that haphazardly copies a standard plant designed for low-wind applications into an extreme-wind application puts the value of a growth cycle at risk.

A starting point for the design challenge

As an industry, we can ask what features and benefits should be part of a competitive dynamic and what features should be ubiquitous. Given the overall market risk, it is our perspective that resilience to extreme wind should be ubiquitous across every installation in high wind locations. Not failing under wind aside, let's compete over: cost, speed of delivery, aesthetics, customer experience, brand and other attributes that the customer values.

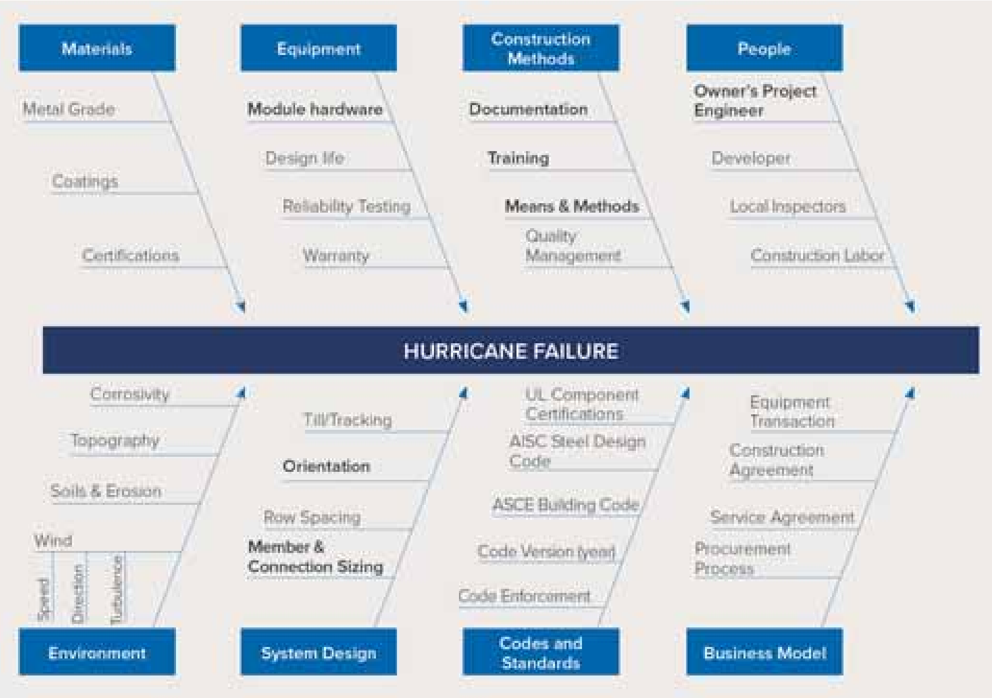
With this perspective in mind, Solar Under Storm team members from The Rocky Mountain Institute (RMI), FCX Solar, NREL (National Renewable Energy Laboratory) and Solar Island Energy set out on an ambitious reliability study. The team attempted to visit every ground-mount system in the Caribbean affected by the 2017 hurricane season. The map in Figure 1 illustrates the seven sites we visited, that included three damaged sites and four operational sites. While the human and economic impact of the 2017 storm season was utterly catastrophic, the scientific implications were also unprecedented; no other hurricane season has provided such a large sample size to learn from.

The reliability method used by the team was based on a 'failure modes & effect analysis' (FMEA). Documented field observations were fed into the FMEA process allowing the team to collaboratively analyse the underlying causes and effective mitigation actions.

Rather than having to postulate potential mitigation actions, the team drew on two proven sources of mitigation actions. First, we had over half a century of design experience across the team including deep expertise designing for wind hazards. Second, we had a population of surviving systems that taught us new tips and tricks. Collectively our confidence was greatest in the mitigation actions with a pattern of deployment across our team's experience

Credit: RMI

PV Sites visited for the 'Solar Under Storm' study. Three had been destroyed in the 2017 hurricane season, four were still operational



Credit: RMI

Root cause analysis can help identify the cause and effect of hurricane-related failures

and the population of affected surviving systems.

While we count on innovative PV plant solution providers providing equivalent or better answers over time, our published best practices attempt to set a starting point that ensures protection of system owners, electricity consumers and the solar industry.

Six best practices

Six of the highest priority best practices and the failure modes they address are presented here as a fast starting point for readers. Ultimately we hope professionals working on extreme wind projects will pick up the full report. Figure 2 shows a tool for identifying the detailed cause and effect of hurricane-related failures.

High load rating PV modules

Module frame bolthole failure was observed on multiple sites. The team found this failure mode could be mitigated with two specifications. First, specify high-load PV modules consistent with module pressures reported in the wind tunnel test (see the guidelines Appendix for instructions). Second, ensure the module connection hardware is evaluated and stamped for the site-specific wind conditions by a structural engineer.

Yet, a robust frame is not adequate alone; in lab testing conducted by the authors, laminates consistently tore out of frames under applied loads in excess of their rating. We treat laminate tear-out as a critical lurking failure mode because under-engineered modules tended to have frame failures before laminate tear-out.

Secure connection (bolt) hardware

Failed module connection hardware was another common observation across multiple sites with failures. Bolt self-loosening was the most common cause of connection failure. For most systems, dramatic improvement is possible through a combination of a hardware locking solution in combination with a carefully monitored QA/QC process. In a short time, we expect even higher levels of reliability will be achieved through pre-assembly and factory-attachment solutions.

> "We do not anticipate zero component failures in PV systems. This is neither technically nor economically justifiable. Yet,by systematically eliminating cascading failure modes a single failure can be isolated"

Failure isolation hardware

Our root-cause-analysis found that a majority of failed module connections were cascading failures. In theory a system might use a wind-proof module but we saw wind-born debris impact and liberate one module that in turn propagated a cascade of module failures.

Rather than directly failing due to wind pressure, an adjacent module failed first, allowing a shared top-clamp to rotate and liberate the adjacent modules. In the worst cases, failure cascaded across an entire row. In response to this observation, the team recommends use of failure isolation hardware that prevents an initial failure from propagating down the system. Two fail-safe options include through-bolting and single-module top clamps.

Design for lateral loads

Lateral loads in extreme wind events proved capable of failing PV racking, especially racking on the perimeter of the PV array. Lateral loads occur due to normal wind forces on electrical boxes (inverters and combiner boxes) as well as racking structural elements.

While wind tunnel studies tend to focus on normal forces (perpendicular to the module) ASCE 7 building codes and good design both require consideration of lateral loads. Structural engineers and third-party reviewers should ensure site-specific lateral load analysis includes racking and electrical elements. Site inspectors can check actual electrical box placement against engineering calculations.

We saw two simple tricks to address lateral loading.

First, the lateral structural load can be reduced by mounting inverters on freestanding posts rather than on the posts of the racking structure if the racking structure does not have adequate capacity.

Second, the lateral capacity can be increased with cross bracing on columns. Some designs even require cross bracing to be incorporated into the module rails to avoid shear load transfer through modules and cascading failure after one module liberates.

Dual foundations

Foundation overturning was observed at some sites where modules and racking remained intact. One approach to mitigating overturning is specification of

dual foundation designs. Dual foundations use structural coupling rather than bending, to resist overturning. Complementary (or alternative) mitigation measures can include use of low-tilt or dual-tilt module angles that reduce peak module pressures and overturning moments.

Single-post foundations also suffer from an engineering phenomenon known as the inverted oscillating pendulum. It's a very fancy way of saying the wind buffeting on the structure is amplified due to the natural frequency of the racking structure being below a certain point. Foundation sizes typically grow tremendously (in embedment depth) to overcome this issue. Provisions for how that's accomplished are done through industry-standard 'pluck testing' and through factors in the wind tunnel study.

Design for erosion

High-sloping terrain is common on island projects because flat terrain is less common and demands a premium. This leaves high-slope terrain for infrastructure projects such as PV plants. Hurricanes have extremely high winds but also bring extremely high volumes of rain. That rain cannot be absorbed by the earth in such large quantities in such short periods of time and often runs off to the ocean. This high-volume run-off creates erosion hazards both in access roads and around structural foundations. Our team recommends that projects engineer a water mitigation plan to slow the waters speed and spread its volume over as wide an area as possible. Mitigations such as rip-rap application, culverts and other engineered drainage systems are possible resolutions but subject-matter experts should be consulted.

Solar Under Storm is really just a starting point

In multiple lengthy debates the authors discussed how to balance the need for immediate actionable recommendations with leaving the largest potential for open-market innovation. On one hand, project owners are seeking tangible recommendations that can be incorporated into procurement specifications; on the other, some equipment suppliers may provide hurricane-resilient solutions through novel design strategies.

This tension resurfaced through public comments on the report. The best practice to use "vibration resistant hardware such as nylock nuts", for example, was a source of debate among the online community. Some practitioners prefer that the example of nylock nuts be not directly incorporated into specifications because a more cost-effective and higher reliability solution might exist.

This feedback indicates that, over time, a transition away from prescriptive specifications and development of performance-based specifications may better support continued industry innovation and advancement.

A second limitation of work is that we do not anticipate zero component failures in PV systems. This is neither technically nor economically justifiable. Airborne debris during hurricanes can come from anywhere and is very costly to engineer against. Yet, by systematically eliminating cascading failure modes a single failure can be isolated. String inverters or even module-level power electronics allow a damaged module to be isolated and go unnoticed by the electric consumer and system financiers. Meanwhile, the plant monitoring software can order up a replacement and dispatch a crew. Overall, we expect fault detection and isolation to be a cornerstone for how the solar industry rises to the resilience challenge.

The call to action

For industry professionals working in regions that experience extreme wind events, 'Solar Under Storm' must only be a starting point. The authors bet that robust collaboration will prove far more valuable than any initial set of best practices. The most exciting collaboration models include:

- 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 grade and coatings are consistent with professional engineering assumptions.
- Collaborate regionally and internationally as a community of practice that regularly shares lessons learned and best practices.

To help instantiate the recommendation to collaborate as a community of best practice, RMI has formed a PV resilience 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/PVResilency

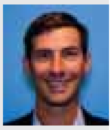
Proving the point – a 100kW early adopter

The Rocky Mountain Institute has developed a 100kW pilot project based on these recommendations on the island of Mayreau (Saint Vincent and the Grenadines) for 2019 construction. FCX Solar has consulted on the application of the 'Solar Under Storm' recommendations and RBI Solar has provided the structure to meet these guidelines. Mayreau will provide the region and its utilities with a prime example of what a resilient system design should look like today.

References

[1] Burgess, C., Goodman, J. 2018, 'Solar Under Storm', Rocky Mountain Institute, https://www.rmi.org/wp-content/uploads/2018/06/Islands_SolarUnderStorm_Report_digitalJune122018.pdf

Authors



Joseph Goodman, PhD, has 20 years of professional and educational experience in renewable energy. While on the faculty of Georgia Tech, Dr. Goodman developed advanced wind-resistant racking technology that formed the basis for Quest Renewables and his PhD dissertation. Currently at RMI, he provides technical leadership to solar and storage programmes and directly supports Amory Lovins in scaling the impact of integrative design.

Frank Oudheusden is Co-Owner of FCX Solar, along with Christopher Needham, co-author of 'Solar Under Storm'. FCX is an engineering consultancy and intellectual property development firm. FCX has led and supported cross-functional teams in the release of PV products in all major structural platforms, and qualified and completed due diligence on niche PV growth opportunities such as floating PV, bifacial module applications and 2,000/2,500V design on behalf of world-class developers. FCX Solar has over 20 years of experience in the PV industry and subject matter expertise in standard plant design, wind tunnel testing and design for manufacturing and assembly.