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Toward Solar Photovoltaic Storm Resilience

Learning from Hurricane Loss and Rebuilding Better

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Disclaimer

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List of Acronyms

ASCE	American Society of Civil Engineers
BLWT	boundary level wind tunnel test
CFD	computational fluid dynamics
DOE	U.S. Department of Energy
EOR	engineer of record
ESCO	energy service company
FEMP	Federal Energy Management Program
GSA	General Services Administration
LBNL	Lawrence Berkeley National Laboratory
NREL	National Renewable Energy Laboratory
psf	pounds per square foot
RFP	request for proposal
SEAOC	Structural Engineers Association of California

Executive Summary

The General Service Administration (GSA) suffered extensive damage to its solar arrays located throughout the Caribbean from Hurricanes Irma and Maria in 2017. While the damage that occurred was unfortunate, there are excellent lessons learned that can be gained and utilized on new systems. A site on St. Croix provides a particularly high-value opportunity for lessons learned due to the innovative rebuilding process utilized by GSA managers and the in-depth analysis performed by the project engineers.

While the original St. Croix array did fail during a hurricane with high wind speeds, there were many features that contributed to and exacerbated the failure, including lack of beam stiffness, inadequate clamp and fastener use, reliance on outdated codes, and improperly selected electrical enclosures. Overall, the design and installation of the array left it vulnerable to the harsh environmental conditions it faced, including high winds, water ingress, and corrosivity, allowing the storm to inflict more damage than it otherwise could have.

The project engineers did extensive analysis prior to the rebuilding of this site. There were several findings from this analysis that are applicable to other arrays across the country. Systems must be designed to account for dynamic loading, not just static loading. This includes completing an analysis of the system resonant frequency. Structural Engineers Association of California (SEAOC) PV2-2017 provides best practices guidance for this. The engineers also built a computational fluid dynamics (CFD) model to determine loads on various parts of the array at different tilt angles and heights off the ground. A moderate array tilt (12 degrees for this specific site) was found to be a good compromise between lower tilts that left the array more susceptible to dynamic effects and a higher tilt angle that would experience more static loading.

Ultimately the design for the rebuild of the array incorporated new features aimed to increase its survivability in the face of high winds, many at the recommendation of the project engineers. These included using both front and rear support posts, locking fasteners, a 12-degree tilt angle, modules with high published load ratings, and lowering the array by 1 foot compared to standard design.

These design features do come with some upfront cost premiums. The engineers were able to reduce these through work with the racking manufacturer. Theoretically, this system should also see fewer outyear expenses as a result of the more robust design.

Interestingly, the original systems that were destroyed were all designed to code. Local wind speed data indicate that the array failed at wind speeds well below what it was designed to withstand. This implies that current building codes and installation practices may not be adequate when applied to PV systems. Compared with buildings, solar PV systems are structures that are lightly framed, have large surface areas, are assembled with small fasteners, and are arranged in rows. Wind acting on rows of racked solar modules creates power turbulence patterns that have been challenging for industry engineers to understand and design to withstand. Both severe and

routine weather events are exposing weaknesses in common design and installation practices. These weather events offer excellent opportunities to learn how to design, build, and maintain systems that are robust to storms.

Until such time when codes, standards, and industry practices mature, federal agencies seeking to place solar PV systems in locations that experience strong winds should become educated consumers as good outcomes are not guaranteed by simply following current standards. The following case study of a GSA Caribbean solar system is an excellent opportunity for agency personnel to learn more about how to build an appropriately robust system.

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1 Introduction

Each incident of storm damage to a solar photovoltaic (PV) system provides an opportunity to gain valuable lessons learned that can be used in planning new systems in regions that experience severe weather. The General Service Administration (GSA) suffered extensive damage to its solar arrays located throughout the Caribbean from Hurricanes Irma and Maria in 2017. While the damage that occurred was unfortunate, there are excellent lessons learned that can be gained and utilized on new systems. A site on St. Croix provides a particularly high-value opportunity for lessons learned due to the innovative rebuilding process utilized by GSA managers and the in-depth analysis performed by the project engineers.

This case study focuses on the rebuild of a 469 kW ground array located at the Almeric L. Christian Federal Building in Christiansted, St. Croix in the U.S. Virgin Islands. This array was destroyed by Hurricane Maria (Figure 1). The entire process of planning and subsequent rebuilding that the GSA managers undertook was highly successful. Notably, GSA managers conducting the rebuild effort obtained an independent assessment of failure modes from U.S. Department of Energy (DOE) national labs and then retained a consulting engineering firm to develop design and construction guidance for the rebuild effort. This design and construction guidance was then provided to the engineering, procurement, and constructing firm to implement while rebuilding the site.

Figure 1. Storm damage at St. Croix after Hurricane Maria (top) and after Hurricane Fiona (bottom).

Photos from Gerald Robinson, LBNL (top) and Schneider Electric (bottom).

1.1 Purpose of Case Study

In 2017, Hurricanes Irma and Maria damaged multiple solar PV systems in the U.S. Virgin Islands and Puerto Rico. Five of these arrays were government-owned arrays at GSA buildings in the Caribbean. A ground array located at the Almeric L. Christian Federal Building was assessed as a total loss from Hurricane Maria (Figure 1), meaning little if any of the components could be reused for the rebuild phase. In particular, the rebuilding process GSA undertook with its energy service company (ESCO) and engineering firm, Jacobs Engineering, provides helpful lessons learned that can be applied in planning solar PV projects in locations with severe wind and rain events. Examining failure modes and repair and rebuilding efforts on all five arrays provides important insights, however the Almeric L. Christian Federal Building site provides the strongest set of valuable lessons learned and is the focus of this case study. For more information on the other four arrays, a field report summarizing important background details and failure modes can be found in the References section (Robinson, Walker, Fu 2019). An overview of the damage to arrays for the five GSA sites is provided in Table 1.

Table 1. Summary of Losses Across GSA Owned Systems in the Caribbean from Hurricanes in 2017

Array	Location		Type	Size (kW)	Condition
1	St. Croix	Almeric L. Christian Federal Building	Ground	469	Total Loss
2	St. Thomas	Ron de Lugo Federal Building	Carport	137	~50% Loss
3	St. Thomas	Ron de Lugo Federal Building	Low Sloped Roof	139	Total Loss
4	St. Thomas	Ron de Lugo Federal Building	Standing Seam Roof	78	~50% Loss
5	Puerto Rico	Federico Degetau Federal Building	Parking Garage	125	Operational ~5% Loss

In addition to the damage caused by Hurricanes Irma and Maria, other failures occurring in more routine weather conditions have revealed the need for improved storm resilience considerations that would be useful in most regions of the United States and its territories. The recommendations offered in this case study should be discussed with a project team for applicability in any region experiencing “strong” weather such as thunderstorms, mountain front range winds and winter storms.

The main forces that destroyed the St. Croix array involved high winds, wind driven rains, and flash flooding. The manner in which this array was destroyed and rebuilt also provides valuable operations and maintenance insights on how to reinforce existing systems for storm resilience.

1.2 Background

In January 2018, the GSA contracted with Lawrence Berkeley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL) to investigate the damage to the five solar arrays (Table 1). The goals for this investigation were to:

- Investigate the root causes of structural and electrical failures caused by the hurricanes.
- Use results of the failure investigations to develop recommendations and technical specifications to guide the reconstruction of the two arrays that suffered 100% loss (St. Croix ground and the St. Thomas low sloped roof arrays).
- For the other three arrays that suffered only partial loss, apply the results of the failure investigation to develop repair and recovery scopes of work to restore the systems back to safe operating conditions.

- Develop severe wind technical specifications to be used by GSA and other federal agencies for future solar arrays that might be located in severe weather locations.

In February 2018, researchers from LBNL and NREL inspected each of the five arrays in person. The team also visited two large utility-scale ground arrays, one located on St. Croix and the second in Puerto Rico to gain a broader sense of storm damage on solar arrays locally. The lab team produced a field report that addressed GSA's objectives and is listed in the References section (Robinson, Walker, Fu 2019).

2 What Went Wrong

There were multiple core failure modes discovered from the field inspection and subsequent investigation and analysis of the St. Croix array. Total loss of the system occurred resulting from wind speeds far less severe than those used to design the system. Core failures included such issues as lack of beam stiffness and high torsional twisting (e.g., use of light-gauge unbraced beam members) and reliance on a clamping fastener of inadequate strength used to assemble large sections of the framing system, shown in Figure 2.

Figure 2. Inadequate frame stiffness and fastener strength led to failures

Photos by Gerald Robinson, LBNL

As the beam members of the racking system flexed and twisted in high winds, the clamping fasteners were levered apart. There were a few stiffening braces in the racking attached by self-tapping sheet metals screws. These screws were found corroded and so easily tore out of the braces. The failure of the clamps and screws led to a series of cascading failures as the racking assembly collapsed and modules became liberated. There were also other contributing factors to the total loss including the use of shared module clamps, reliance on older civil engineering codes, and the use of low safety factors in the design calculations, along with the large array surface area and a high tilt angle (25 degrees).

Damage to the array extended past racking assemblies and was seen in all of the electrical balance of system hardware such as conduit, inverters, switchgear, and transformers. The causes of the damage to the electrical balance of system components were numerous. The main causes can be traced to improperly specified enclosure cabinets and underground conduit that flooded and drained downhill to the inverters, switchgear, and transformers. Tropical climates require electrical equipment enclosures that are corrosion resistant that can prevent wind-blown rain from entering the interior.

2.1 Main Conclusions from Site Investigations

The main conclusions from the field report which acted as a starting point for the redesign work that followed is summarized below.

- Most of the five systems examined appeared to be code compliant and designed to applicable structural codes (e.g., American Society of Civil Engineers (ASCE) Standard – ASCE/SEI 7-10 [ASCE 2022]), yet some experienced total loss while damage to others ranged from minimal to 50% loss. This would indicate that the code version in effect at the time these damaged systems were installed had an inadequate effect on storm survivability, indicating a potential code gap.
- Another indication that there was a code gap with ASCE 7 is that the St. Croix system failed at far less than the ASCE design wind speeds of 145 mph. Best estimates for the maximum wind speed the site experienced during the hurricane was 104 mph. However, other arrays located where the highest wind speeds were recorded during Hurricane Maria experienced little damage such as the large Virgin Island Water and Power Authority ground-mounted system located near the St. Croix airport.
- There were clear and observable causes underpinning the damage seen to each array that can be easily addressed in future designs and thus minimize the likelihood of total loss. Even in situations where storm damage (e.g., wind, wind-driven rain) is unavoidable, technical specifications can reduce damage.
- Based on the damage observed during this study and the wind speeds recorded, arrays should be able to be designed and maintained to operate reliably in hurricane-prone tropical regions. In general, adequately designed and constructed arrays can be expected to provide a full 25-year service life. Therefore, solar arrays can be reasonably expected to provide a source of resilient power in regions that experience severe weather. However, there are still many unknowns yet to be investigated, including survivability in the most severe Category 5 hurricanes.

3 Engineering Analysis

Following the completion of the field study, GSA hired Jacobs Engineering (Jacobs) to work with the ESCO to engineer and specify a replacement solar array for the St. Croix ground-mounted array and for St. Thomas low sloped roof-mounted arrays based on the findings of the 2018 report. GSA worked directly with the original ESCO to perform repairs on the other three arrays that suffered partial damage.

The team from GSA and Jacobs developed a set of innovative designs. Other agencies and sites can leverage and apply the approaches and lessons learned from this analysis.

3.1 Codes Analysis

An important early step in the analysis of the failed systems and identification of focus areas for the rebuild was examining existing PV codes and standards and identifying any gaps that potentially render a PV system in the hurricane-prone region vulnerable to damage. Both of the GSA systems that suffered total loss were designed to code and failed due to winds below their designed wind speeds, providing clear evidence that some above-code design measures are necessary.

ASCE 7 is the guiding structural standard for PV systems. It was developed for buildings and large structures and has been applied to PV arrays. The most recent revisions, ASCE 7-16 and 7-22, have included special considerations for solar PV. However, ASCE 7-16 (the 2016 release of ASCE 7) does not account for dynamic effects on PV arrays. Due to the lightweight nature of PV structures, they experience much different loading than the high mass and weight buildings covered in ASCE 7.

The Structural Engineers Association of California (SEAOC)'s Wind Design for Solar Arrays (SEAOC PV2-2017) is a compendium guidance document that addresses these dynamic effects. This project implemented SEAOC PV2-2017 in addition to the minimum requirements in ASCE 7-16.

Some examples of recommendations and language for how to require enhanced code specifications in projects are given in Section 5 of this report. For more technical specification language, see Technical Specifications for Solar Photovoltaic Systems.[1]

3.2 Static and Dynamic Loading

Static loading refers to mechanical loads of a constant magnitude and direction. Currently, PV modules and racking systems are designed to accommodate specific static loads with little accommodation for dynamic forces. Wind loading on solar PV structures, however, is highly dynamic. One effect of dynamic wind loading can be the development of turbulence patterns as wind flows over the arrays. The turbulence causes fluctuating forces that move the solar PV structure. This movement can, under certain circumstances, excite the natural frequency of a

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[1] https://www.energy.gov/eere/femp/technical-specifications-site-solar-photovoltaic-systems.

structure and cause resonance. This type of loading is difficult to model, test, and design for and can cause significant damage to a PV system not designed to handle these forces. Accounting for dynamic loading is yet to be well represented in current codes and is often overlooked. Dynamic forces are a likely cause for PV systems failing under wind loads, especially for failures occurring below design wind speeds. Jacobs realized the necessity of incorporating an analysis of dynamic loading to inform the design of this system.

Racking manufacturers do not always include dynamic analysis of their systems as standard procedure, as it is not typically required by codes. Jacobs specifically required the racking manufacturer to incorporate SEAOC PV 2-2017 and include dynamic loading in their calculations of loads. This best practice takeaway should be required on all projects.

3.3 Resonant Frequency Analysis

While most design codes focus on a static load analysis, there is substantial evidence of PV failures and sub-design level loads due to vortex shedding and resulting dynamic resonant loading effects. To address this in the design phase:

- Designers need to consider SEAOC PV2-2017 recommendations including the reduced natural frequency equation of the structure, which is based on the Strouhal number. The equation includes the variables of wind speed, vertical projected height, and the natural frequency of the array structure. A range is provided where dynamic resonance effects are most pronounced.
- Designers need to find the natural frequency of the array by creating an analytical model that includes array geometry and stiffness. This model can be iterated to capture the optimal geometry and stiffness to produce the desired reduced natural frequency.
- Array geometry and layout must be considered early on in the design to provide an optimal solution for the array structure as well as energy production.
- System specifications and/or request for proposals (RFPs) must require the racking vendor to provide the design engineer calculations considering the effects of vortex shedding and resulting dynamic loading for review.
- It should be noted an analytical modeling approach like this is itself expensive and may also lead to an expensive structure. Therefore, it is recommended to take advantage of wind tunnel testing as discussed in the next section.

Through the use of modeling, the Jacobs engineering team analyzed the effects of varying the tilt angle on resonant frequencies and the front and back pressures on the module. The engineers found an optimal tilt angle for this array (12 degrees) that kept the front and back pressures on the module within rated limits while also reducing the likelihood that damaging resonant frequencies would result. At lower (flatter) tilt angles, there are lower static forces on an array but there is greater potential for higher dynamic loads. With a tilt angle of 12 degrees, the potential dynamic and resonant effects are diminished, with tolerable static forces.

3.4 Wind Tunnel Tests

Wind tunnel tests are used commonly in the PV industry to provide values for design pressure coefficients. These can be viewed as more site-specific than those given in universally applicable codes and standards documents. The team found that wind tunnel tests are most reliable when based on a standard such as the FM 1-15 standard.[2]

Many racking manufacturers have already completed wind tunnel analysis for their systems which enable them to build structures with less steel than would otherwise be required by codes. This is an avenue for substantial cost savings. See Section 7, Structural Topic 3 for more information.

3.5 Collaboration With Module Manufacturer

The team also collaborated with the manufacturer of the selected PV modules to discuss different mounting and attachment methods. They discussed the design load ratings of the modules and various mounting approaches, such as having six attachment points rather than four. This allowed for a higher performance guarantee from the module manufacturer.

3.6 Computational Fluid Dynamics Modeling

To model the extreme winds that PV systems in the Caribbean experience and help design this specific system to withstand those wind loads, Jacobs used a computational fluid dynamics (CFD) model. Figure 3a depicts the CFD model of this array, which included topographical features. Figure 3b shows the actual site under re-construction.

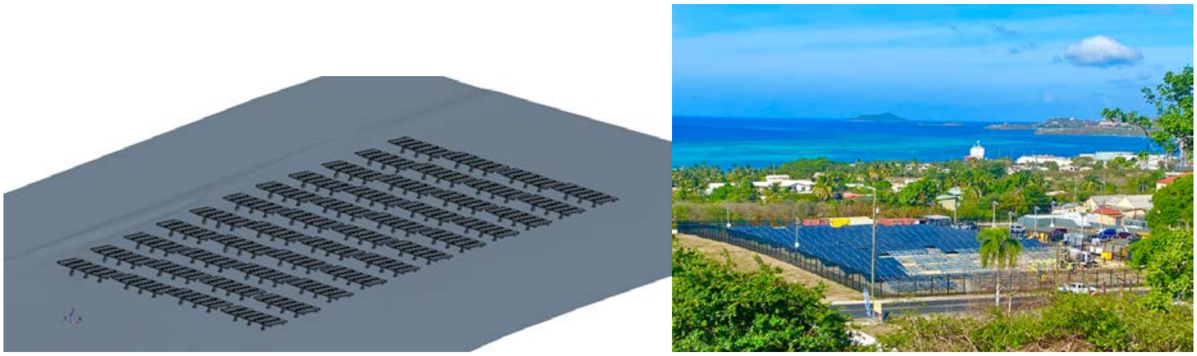

Figure 3. (a) CFD model consisting of solar arrays and ground topology, (b) actual site

Photos from Jacobs Engineering (left) and Cesar Cortes, Schneider Electric (right).

The team modeled several cases of wind loading on the array. The cases differed in wind direction, tilt angle of the modules, and height of the lower edge of the modules off the ground. To simulate hurricane strength winds, the modelers used a wind speed of 175 mph. Table 2 summarizes the different cases and gives the resulting maximum pressure from the simulations.

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[2] While FM 1-15 is specifically a rooftop PV standard, the wind tunnel sections are universally applicable to all PV arrays.

Table 2. Wind Loading Analysis Results from CFD Model

Case	Max Pressure (psf)	Force Type	Wind Direction	Panel Height	Panel Angle
1	111	Lift	Seaside	Original	5 deg
2	6	Downforce	Opposite to seaside	Original	5 deg
3	78	Lift	45 deg of seaside	Original	5 deg
4	18	Lift	90 deg of seaside	Original	5 deg
5	65	Lift	Seaside	1 ft lowered from original	5 deg
6	88	Lift	Seaside	1 ft lowered from original	12 deg

Note: Calculations are based on zero reference pressure and "seaside" is to the north of the array.[3]

This shows that the largest force anywhere on the array occurs when the wind direction is from the seaside (north) and causes a direct lift force on the underside of the panels (Case 1 compared to Cases 2-4). The heights of the panels for these first four cases vary from 4 ft to 6 ft from the ground corresponding to the topology. Lowering the panels 1 foot closer to the ground decreases the maximum static uplift pressure by 41% for this array from 111 psf to 65 psf (or from 5300 Pa to 3100 Pa, Case 5 compared to Case 1). Changing the tilt angle from 5 to 12 degrees increases this pressure from 65 psf to 88 psf (3100 Pa to 4200 Pa), or 35% (Case 6 compared to Case 5). For reference, solar panels typically publish load pressure ratings of 2400 Pa, with some modules publishing static load ratings as high as 6000 Pa for the front and 5400 for the rear side. This lift force would affect the rear side of the modules.

Figure 4 shows more detailed pressure results from the simulations for Cases 1, 5, and 6. This figure shows pressures on panels across each of the four table rows (top to bottom in Figure 4) and each of the 11 vertical sets (left to right in Figure 4). Case 1 represents the worst-case loading, Case 5 showed the lowest loads due to decreased height off the ground, and Case 6 has slightly higher loads than Case 5 due to a higher tilt angle.

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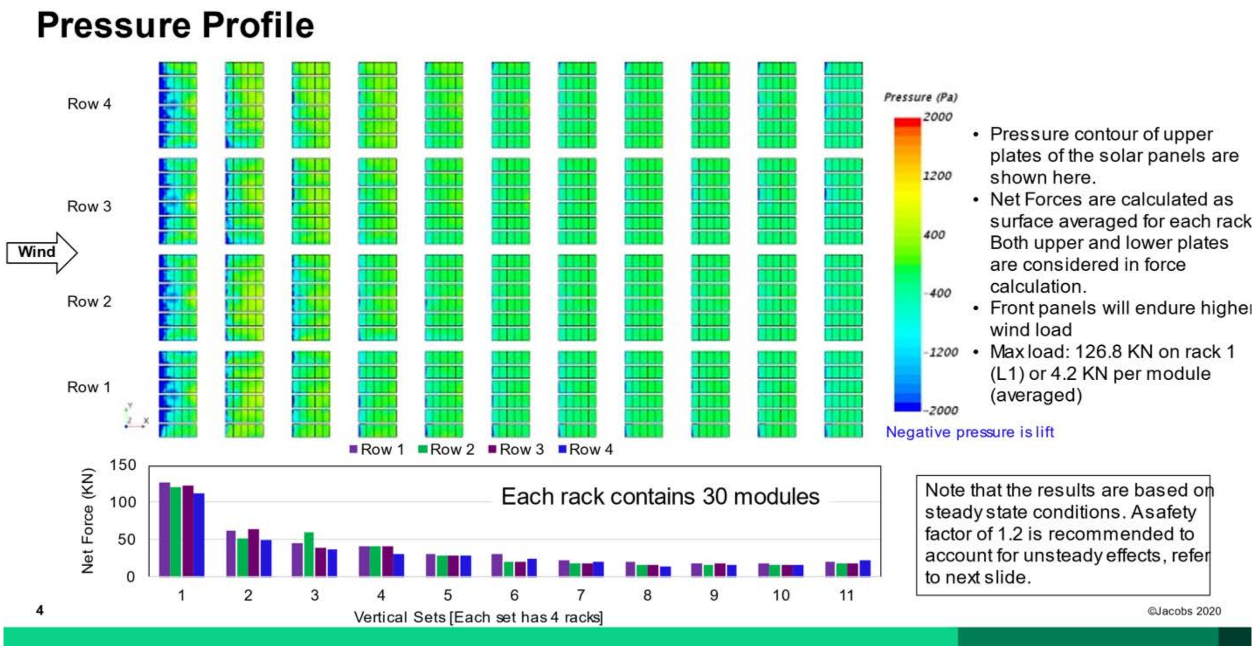
[3] Zero reference pressure sets the modeling gauge to zero and does not account for altitude or weather phenomena.



Pressure Profile

- Pressure contour of upper plates of the solar panels are shown here.
- Net Forces are calculated as surface averaged for each rack Both upper and lower plates are considered in force calculation.
- Front panels will endure highe wind load
- Max load: 126.8 KN on rack 1 (L1) or 4.2 KN per module (averaged)

Negative pressure is lift

Each rack contains 30 modules

Note that the results are based o steady state conditions. A safety factor of 1.2 is recommended to account for unsteady effects, refe to next slide.

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Figure 4. Modeled net pressure distribution resulting from 175 mph winds, on each set. Left to right: There are 11 vertical sets, and each vertical set has 4 rows/racks. (Note: Pressure difference between the upper and lower surface is reported as net pressure.)

Image from Jacobs Engineering.

The loads are demonstrably highest on the first vertical set of panels the wind came in contact with. The downstream sets had no more than about half of that load. For example, at the modeled 175 mph wind speed, only the first vertical set in Case 1 comes close to 100 psf (5000 Pa). Most of the array would experience loads around 30 psf (1400 Pa), even at 175 mph winds. This finding supports the recommendation to design the perimeter panels to be able to withstand much higher pressure. This means that the equivalent uniform design load can be lower but should be higher on perimeter areas.

The team also performed a CFD analysis in which the inlet wind speed changed over time to investigate vortex shedding and how that might influence downstream panels. Vortex shedding is an oscillating flow generated when air passes over these solar modules. This could cause resonance if the frequency from the shedding matches the resonance frequency of the structure.

Note: We understand that this level of CFD analysis is difficult to rationalize in a low profit-margin, competitive bid environment that lacks reliable open-source models. We hope that the work done for this array can be leveraged and the takeaways can be applied to other projects. For sites with substantially different characteristics, another approach would be to require similar CFD modeling from all bidders. This would have an impact on total project design costs but would create an equitable bidding environment. This requirement would be ideal, but perhaps not practical for all projects, in which case incorporating lessons learned from this case study will still benefit systems facing similar risks.

4 Implemented Designs

The extensive engineering analysis performed by Jacobs, with the ESCO and GSA, led to specifications for the rebuild of a solar PV array at the St. Croix ground site. A major takeaway was to focus on the most critical aspects of the array and on designing those to higher load ratings and risk categories, rather than incurring the more significant costs of designing every component of array to hurricane strength winds. Furthermore, there are many relatively inexpensive measures that can significantly strengthen an array.

4.1 Support Structure

One key aspect of this design was designing a stiff support structure, which would be more robust in the face of both static and dynamic loads. The system employs two posts (front and back) and the span (left-right distance) between posts is shorter than is typical for most systems (Figure 5). This increased the resonant frequency of the resulting stiffer structure, making it less likely that winds would excite the resonant frequency. It also decreased the loading that would otherwise be transferred to the fasteners as the system components deflect under wind loads. Jacobs also specified hot-dipped galvanized anti-corrosion material for the racking system.

Figure 5. A system using front and back support posts (circled)

Photo by Dennis Schroeder, NREL

4.2 Fasteners

To protect against self-loosening of bolts and nuts that can occur from wind-induced vibrations, the design team provided three fastener options to the project developer: lock bolts, wedge-lock washers, or pre-applied thread lock. Lock bolts are connections that use a special tool to permanently fix the nut to the bolt, more similar to a rivet than a traditional nut and bolt. Wedge-lock washers employ wedges around the circumference of the washer that prevent reverse rotation of the bolt and nut. Pre-applied thread lock is an adhesive compound applied to the threads of a bolt that is activated when the bolt is tightened.

These fastened connections were also designed to the highest risk category (IV), as they are a critical part of the array. Focusing on designing these fasteners to risk category IV, rather than designing the entire array to risk category IV was highly beneficial and reduced the total project cost substantially. Module attachments for this array are also independent; there are no shared clamps or clips between adjacent modules. This eliminates the possibility of a domino-type progressive failure. The team also specified vibration-resistant[4] and corrosion-resistant grades of fasteners to avoid corrosion in the salt-water environment. The final specifications required through-bolting of modules to the underlying racking where practical.

4.3 Tilt Angle

The team specified a tilt angle of 12 degrees for this site. Lower tilt angles left the array susceptible to potential natural frequency and dynamic effects that could cause damage, while higher tilt angles would result in larger static wind loads. The selected 12-degree tilt mitigated dynamic loads while maintaining manageable static loads.

The selection of 12 degrees was specific to the geometry of this project. To find a project's optimal structural tilt angle, engineering analysis and model of each array is necessary. In general, selecting a higher tilt angle will reduce dynamic effects. While 12 degrees is likely not the optimal angle for all arrays, selecting a tilt angle in the range of 10–15 degrees is likely a good mitigating approach for projects without the budget or capabilities to perform an in-depth analysis of a specific system. System designers will also have to consider the impacts of various tilt angles on power production.

4.4 Module Selection

The specifications also included modules with a 6400 Pa static front load rating and a 5000 Pa static rear load rating, representing the highest published test load ratings at the time. The only modules on the market that met these load ratings were smaller, 60 cell modules.

4.5 Additional Racking Rail

The design team consulted with the manufacturer of the selected modules about the benefits of adding an additional rail in the racking structure to allow six module mounting points rather than the traditional four. Ultimately the costs of adding an additional rail outweighed the benefits of a slightly higher performance guarantee, and the additional rail was not included in the final design.

4.6 Height off the Ground

As a result of the CFD analysis, the system height off the ground was lowered by 1 foot from the original design to decrease the wind loads. If wind loads are the main design and operational consideration, this recommendation should have a significant impact. Lowering an array also has implications for shading and vegetation management, and possibly for susceptibility to flood or storm surge damage.

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[4] Projects can specify DIN 65151 standard for vibration-resistant fasteners.

4.7 Flooding and Water Ingress Considerations

Many severe-weather-prone PV sites are also flood and storm-surge-prone. Raising electrical components such as inverters above 100- or 500- year flood levels, waterproofing electrical enclosures (including conduit entry), and being mindful of how water might flow should it enter conduit (i.e., lower elevation electrical components may be prone to water ingress flow through conduit) can all reduce the risk of substantial damage to sites.

5 Cost Implications

While the team focused on hardening the most critical components of the array, there were upfront cost premiums for these components. However, the benefits associated with these increased upfront costs include a higher probability of survivability from a wind event, decreased repair costs, lower maintenance costs, and a higher likelihood of delivering power after a severe-weather event–when it is arguably most valuable to the community. Some design specifications that incurred additional upfront costs include:

- Using hot dipped galvanized metal racking and fasteners with a 30-year anti-corrosivity requirement in the specifications.
- Selecting modules with the highest published design wind ratings available more than doubled the cost compared to cheaper modules on the market (about $1/W compared to $0.40/W). Only a portion of this additional cost is due to the load hardening; the most robust modules are also generally higher quality and higher cost for other reasons as well, such as the thicker frame material (40 mm in this case) on the selected modules.
- The vibration-resistant hardware also comes with an upfront cost premium. The costs of the three options (i.e., lock bolt, wedge-lock washer, thread lock) vary but can range from $1-4 per fastener set hardware (roughly $10-$40/kW for through-bolted systems) compared to $0.10-$0.20 for standard hardware. Through-bolts also require additional labor.
- The original structural design would have cost on the order of $6.85/W for Jacobs to design in-house. By engaging the racking manufacturer and leveraging their previously conducted wind tunnel results, they were able to reduce the amount of steel needed in the system and significantly reduce this cost.

6 Applicability to Other Arrays and Other Regions

The engineering analysis described in this report was performed for one specific array at one specific site with unique topology, however the lessons learned have broad applicability to arrays in other regions. GSA's investment in the engineering analysis has provided key insights which can now be leveraged by other agencies. As indicated throughout this report, these findings are widely applicable, including for regions outside of severe storm regions as weather damage has occurred in many regions of the country. For example, the recommended use of vibration resistant fasteners can prevent loosening during any wind event in any climate.

7 Request for Proposal/Technical Specification Language and Recommendations

Several of the lessons learned from this rebuild effort can be leveraged into valuable procurement specifications and actions agencies can take during such steps as submittal review to improve outcomes on a new construction project.

7.1 Specification Topics – Structural Engineering Requirements

7.1.1 Structural Topic 1 – Use Latest Codes and Guidance Documents

Two important codes and standards considerations:

1. States and territories adopt updated codes and standard versions at different rates, however it is very important to require use of the latest version of ASCE 7, even if it is not yet adopted for a given location.
2. Agencies should require that SEAOC PV-2 compendium guidance be used with the latest version of ASCE 7-22.

Recommended specification language to be added to solicitation and contract: The most recent version of ASCE 7 shall be used even in cases where older versions are still in effect. The latest compendium guidance documents shall be used in conjunction with the latest version of ASCE 7. Applicable compendium guidance documents shall be from 1) ASCE - Solar Structures Committee's Method of Practice document, 2) Structural Engineering Association of California[5] SEAOC PV-2, or 3) FM Global Roof Mounted Solar Photovoltaic Systems FM DS 1-15 Section 2.1.1.3 and FM 4478.[6]

7.1.2 Structural Topic 2 – Balancing Array Tilt Angles, Wind Pressures, and Resonant Frequencies

Rationale/background on recommendation: The CFD analysis modeling done by Jacobs demonstrated that it is critical for a project engineer to find the right balance between static and dynamic forces. For larger systems in high-wind climates, this iterative process should be a requirement.

Important considerations: Today, most racking systems are commercial off-the-shelf products and assembled in the field of prefabricated beams and fasteners. With the exception of shaded carports, custom designs are rare given the wide variety of off-the-shelf product options available at competitive prices. Given that, it is important that any product selected can be modified to fit site needs such as the gauge of metal, fasteners, and tilt angles.

Recommended specification language to be added to solicitation and contract: The project engineer (or product engineer) shall perform analysis to find the optimal tilt angle to prevent

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[5] https://www.seaoc.org.

[6] https://fireprotectionsupport.nl/wp-content/uploads/2021/02/FMDS0115-2021-01-Roof-mounted-Solar-Photovoltaic-Panels.pdf.

front and back pressures on modules from exceeding rated design limits while ensuring that damaging resonant frequencies are not induced in expected wind events. Wind speeds used for analysis shall represent the range of wind speeds seen at the site.

7.1.3 Structural Topic 3 – Using the Best Available Wind Pressure Data

Rationale/background on recommendation: Many commercially off-the-shelf racking systems have gone through boundary-level wind tunnel testing (BLWT) which produces wind pressure values specific to the system. Use BLWT data instead of design wind speeds as those values do not take account of project and site conditions. This wind tunnel data can then be used to confirm that the proposed racking system can withstand design wind pressures. Each racking configuration and site have unique features and the wind tunnel pressure data needs to be adjusted based on the chosen tilt angle, height of array, and topology building features for roof arrays (e.g., parapets, penthouses). Jacobs engineers have found that most often the BLWT wind pressure values are not adjusted for the proposed racking configuration and site conditions.

Recommended process to follow:

1. Choose a racking manufacturer that uses boundary-level wind tunnel testing (using FM DS 1-15 Data Sheet or ASCE 40 or equivalent international standard) that also has in-house engineering. Require that any chosen racking manufacturer become the engineer of record (EOR) for the proposed equipment.
2. EOR shall sign and seal final design drawings, post modification for site conditions, and final racking configuration.
3. The proposed racking system must be configurable to meet site conditions.
4. The manufacturer's EOR is to use wind tunnel tests pressure data that is adjusted for the following factors:
    a. Site factors
        - Building height (roof arrays)
        - Roof parapets (roof arrays)
        - Penthouses (roof arrays)
        - Topology (roof, ground, and carport)
            - Air funneled over rises or down canyons toward array
            - Open unobstructed coastal exposures

    b. Configuration of array
        - Tilt angle
        - Table dimension
        - Row, table, and module spacing
        - Height off ground

7.2 Specification Topics – Construction Phase

7.2.1 Construction Topic 1 – Adding Fastener and Torque Audit to Commissioning and Project Acceptance

Rationale/background on recommendations: Fasteners are a recognized common point of failure on many racking systems. Fastener checks and torque audits are not currently part of the common solar PV auditing standard – IEC 62446. These two items need to be added.

Recommended requirements:

1. The commissioning agent shall confirm that 100% of the as specified fasteners have been installed in the correct structural connections.
2. The commissioning agent shall torque audit at least 1% of fasteners. Should it be determined that 10% or greater of these fasteners are under or over-tightened, then the Contractor shall reinstall all fasteners.

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