Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience

James Elsworth and Otto Van Geet

National Renewable Energy Laboratory

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List of Acronyms

ASTM	ASTM International
DCT	Dust Control Technologies
DIN	DIN Standards
DuraMAT	Durable Module Materials Consortium
FEMP	Federal Energy Management Program
ISO	International Organization for Standardization
NEMA	National Electrical Manufacturers Association
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PV	photovoltaic
PVQAT	The International Photovoltaic Quality Assurance Task Force
UL	UL LLC

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1 Introduction

Resilience can be defined as the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions through adaptable and holistic planning and technical solutions (Hotchkiss 2016). Solar photovoltaic (PV) power has many advantages as a resilient power source, including the ability to provide power after a natural disaster. While solar arrays can survive severe weather events, in some case systems are compromised and left unable to provide power (Hotchkiss 2016). For PV systems to act as resilient power providers, they must remain operational. Building a system that is more likely to survive a severe storm event can come at a higher construction cost than those built to less stringent standards.

Previous efforts have identified various system measures and practices that can increase the likelihood of a PV system surviving a severe weather event (Robinson 2018; Burgess 2018; FEMA 2018). This report provides initial estimates for the up-front cost premiums for various methods of storm hardening PV systems.

This report aims to:

- Provide an initial estimate of the additional costs of various storm hardening measures for PV systems
- Disseminate information and about strengthening PV systems and to foster greater industry communication and momentum around the topic
- Promote a greater consideration for potential lifetime PV system maintenance costs
- Encourage a greater consideration of the site environmental conditions and extreme weather events a PV system is likely to encounter over its operational lifetime
- Help developers weigh the costs of storm hardening a PV system compared to the costs of recovering, repairing, and repowering a compromised system following an extreme weather event
- Provide a resource for developers installing systems in severe weather locations, site operators, investors, codes and standards developers, among others.
- Promote the installation of more resilient PV systems
- Form the foundations of future work to more accurately estimate the costs of installing resilient PV systems.

Overall, the main steps to PV resilience are quality assurance in system design, quality control during installation, and ongoing operations and maintenance (O&M) (Lopata 2019). Systems can fail because of one, two, or all steps, or for another reason altogether—a storm of extreme force, for example. To achieve more resilient PV systems, it is paramount that PV developers and installers promote rigorous attention to quality throughout the project. This report focuses largely on specific design features that can help make PV system's more resilient, but ensuring quality construction and installation is equally important.

This report investigates 13 storm hardening measures for solar PV systems, summarized in Table 1. For more background on these measures, please reference Robinson (2018).

Table 1. Storm Hardening Measures for PV Systems and Their Added Cost

Measure	Base Case	Hardened Case	Ground Mount Premium	Roof Mount Premium
1. System Audit	No system audit	Perform a system audit	0.05 ¢/W (2%[1]) 2.5 ¢/W (100%[2])	0.05 ¢/W (2%) 2.7 ¢/W (100%)
2. Locking Fasteners	Hex bolts, flange nuts, stainless steel flat washers	Several different options explored	0.1-1.4 ¢/W	0.1-1.5 ¢/W
3. Through Bolting	Top-down clamps	Through bolts	0.6 ¢/W	0.7 ¢/W
4. Marine-Grade Steel	18-8 stainless steel	316 stainless steel	1.1 ¢/W	1.2 ¢/W
5. Module Selection	Standard modules (2400 Pa uplift)	Highest rated modules (≥ 3600 Pa uplift)	10 ¢/W	10 ¢/W
6. Three-Framed Rail System	Two-rail racking	Three-rail racking	5.2 ¢/W	5.7 ¢/W
7. Two-Pier Mounting	One driven steel pier	Dual post piers	5.9 ¢/W	N/A
8. Racking Design	Cold rolled U channel aluminum	Tubular aluminum	12 ¢/W	N/A
9. Wind-Calming Fence	Standard security fence	Wind calming fence around perimeter	6-14 ¢/W	N/A
10. Watertight Enclosures	National Electrical Manufacturers Association (NEMA) 3 rated	NEMA 4X rated	Recommendation only	
11. Elevated Pads	Electronic components not on elevated pads	Electronic components installed on elevated concrete pads	0.8-1.0 ¢/W	N/A
12. Drainage	Not well-designed drainage systems	Well designed and maintained drainage	Recommendation only. Should be a standard design component.	
13. Pre- and Post-Storm Measures	None taken	Powering down, cleaning site, fault testing, repair/replace	Recommendation only. Costs are too variable based on site and which measures are undertaken.	

[1] If 2% of the fasteners in a system are torque checked.
[2] If 100% of the fasteners in a system are torque checked.

This document summarizes early efforts to estimate the initial costs of storm hardening measures for PV systems. It is informed by feedback that the National Renewable Energy Laboratory (NREL) received from industry experts through one-on-one interviews. This work is only as reliable as the feedback received, and NREL understands that some of the cost estimates may differ from actual costs from projects around the globe. Furthermore, system costs are constantly changing, so the values in this report represent an average snapshot of the state of the industry. We also do not account for local variation in costs. The authors welcome feedback to achieve an even more accurate representation of storm hardening costs.

This report analyzes ground-mounted and roof-mounted fixed tilt solar PV systems only. It does not include tracker systems because fixed tilt systems are typically sturdier and an installation constructed to be storm hardened should be designed to be more structurally stable. However, tracker systems currently account for the majority of large-scale PV being installed, and they are being installed in storm-prone regions. Future work will aim to investigate storm-hardening for PV tracking systems.

This report only analyzes initial costs of each of the considered measures. While it will naturally cost more to design and build a more robust system, this initial cost could lead to outyear cost savings. These lifecycle cost savings could come from reduced O&M, decreased repair costs, and shorter system downtimes, among others. While difficult to quantify, there is also a value in resilience and increasing the likelihood of a PV system providing power after a severe weather event.

An intended outcome of this report is to identify the long-term benefits of installing storm hardened PV systems. While the focus is on severe weather regions, many of the design principles could increase resilience in other regions, as well. This report may spur further research into this area, the development of products and solutions specifically tailored to severe weather sites, and to greater understanding of the value of resilient PV installations, all of which could lead to more resilient PV systems worldwide.

2 Baseline Assumptions

Solar PV installations vary greatly, and design, components, location, and labor force all impact system cost. This report takes a set of assumptions for baseline systems (one ground mount, one roof mount), fully aware that PV installations vary.

2.1 Labor

Labor costs vary based on location and the quality of the labor. Published labor costs for solar also vary depending on whether the rate includes fringe benefits. Labor costs have risen steadily as well. For this report, we assume $42.44/hour as a median labor rate to represent a national average (Lopata, 2019).

2.2 Modules

Our baseline assumes 385-W modules for ground-mount systems and 320-W modules for roof-mount systems. Roof-mount modules are typically smaller, due to the added difficulty of hoisting the modules to the rooftop.

2.3 Hardware

There are many mounting and racking techniques successfully employed in the field. Our baseline representative systems are an average of the systems our team observed at several field installations, adjusted with feedback from installation professionals. The tables below outline our assumptions for ground-mount (Table 2) and roof-mount (Table 3) baseline systems.

Table 2. Ground-Mount Baseline System Assumptions

Ground-Mount System	Baseline System Assumptions
System Size	1 MW
Tilt	Fixed Tilt
Module	385 W
Rail and Racking	Two-rail mounting system Aluminum U-channel racking
Clamping/Mounting	Top down rail mounting system. Modules clamped at four points using either mid-clamps or end-clamps.
Bolts and Washers	Systemwide average of 0.0113 fastener sets per W.
Steel	18-8 stainless for all hardware components
Support	Single driven-pier support 0.32 support piles per module average

The representative ground-mount system is modeled after a 1.17-MW installation in Towaoc, Colorado. NREL received a bill of materials for this installation and visited the site during construction. We also incorporated data anonymously provided by another site operator for other PV installations.

Table 3. Roof-Mount Baseline System Assumptions

Roof-Mount System Component	Baseline System Assumptions
System Size	100 kW
Tilt	Fixed Tilt
Module	320 W
Modules per Row	10
Rails and Racking	Two-rail mounting system
Clamping/Mounting	Top-down rail mounting system. Modules clamped at four points using either mid-clamps or end-clamps.
Bolts and Washers	0.0119 fastener sets per W (for the entire system)
Steel	18-8 stainless for all hardware components

2.4 Other Considerations

There are additional considerations in developing a baseline that are not included in this report. As previously mentioned, there are many different system designs and components. Economies of scale reduce costs when measured on a per-Watt basis. Furthermore, costs will vary based on geographies and local economies.

3 Storm Hardening Measure Costs

In this analysis, we considered 13 measures for storm hardening PV systems. These measures were previously identified from site visits and conversations with industry professionals after the 2017 Hurricanes Irma and Maria in the Caribbean. A summary of those findings and recommendations is available in *Solar Photovoltaic Systems in Hurricanes and Other Severe Weather* (Robinson 2018). This analysis is not intended to be a comprehensive survey of techniques for the storm hardening of PV systems; various other methods exist, and others are yet to be identified, proven, or implemented.

3.1 Measure 1: Properly Torque Fasteners and Perform a Torque Audit

> "Fasteners that loosened and fell out under vibration—causing photovoltaic systems to disassemble in high winds—were a common equipment loss factor identified in [Federal Energy Management Program's (FEMP's)] analysis of recent storms. An easy, low-cost measure to prevent disassembly is to properly torque fasteners rated with true-locking capability (applicable standard: DIN 65151)…Consider adding [an] audit step to the system commissioning process [to ensure fasteners have been torqued properly]." (Robinson 2018)

Loose fasteners are a common failure mode of PV systems in storms or high winds. The bolts, nuts, and washers that secure system components by attaching the modules to the racking, racking components to other racking elements, and racking to roofs may loosen or fail due to poor installation, poor design specifications, vibrations caused by wind, or high shear loads (Ness 2019).

A relatively cost-effective measure to address this is simply ensuring all fasteners are properly torqued upon installation. A regular system torque check is also a good practice on existing systems and can be a good prestorm practice as well.

Some system installers currently require an in-field precommissioning spot check of a certain percentage of fasteners—typically 2%-10%. Should some fasteners fail this torque check, entire strings or rows may need be rechecked.

Unfortunately, even this imperfect approach is not standard practice. Sometimes the same initial installers are deployed for this auditing step, leading to the possibility of repeating any original mistakes. Samples may not be taken randomly throughout the array or chosen with tact. Compounding this, establishing the acceptance criteria for torque audits can be difficult, and, in many cases, this information is not available from racking or module vendors (Ness 2019).

Furthermore, there is the incentive to install systems quickly, which may leave inadequate time to check and correct quality issues. Installers may sell system ownership shortly after commissioning, so their interest in lifetime system performance may be limited as well.

One site operator cited an array in a high-wind area on which fasteners regularly loosen. This has led to biannual, entire system fastener retightening at a cost of up to $300,000 for a 5-MW system. This case illustrates the favorable economics of correctly designing fasteners or designing a hardier fastener system that does not loosen over time.

The cost of this measure is the additional labor cost from the audit. The number of bolts that need be checked depends on the number that fail the test. Thus, the cost of this measure is highly variable based on the quality of the initial installation and environmental factors the system has encountered. Performing a torque audit requires installers to use torque wrenches, for which they may need to be trained. The cost of this training is not considered here. Table 4 and Table 5 give cost calculations for performing a torque audit of 100% of the fasteners for ground-mounted and roof-mounted systems, respectively.

Table 4. Ground-Mount Cost Calculation for Measure 1: System Torque Audit

Row #	Metric	Value	Source
1	Cost (¢/bolt)	120	Site Operator Provided Data
2	Number of Module Mounting Bolts (bolts/W)	0.0113	Site Operator Provided Data
3	Number of Racking Bolts (bolts/W)	0.00945	Site Operator Provided Data
4	Cost Premium - Modules Only (¢/W)	1.4	Calculation: row 1* row 2
5	Cost Premium - Modules Only – 10% check (¢/W)	0.1	Row 4 ÷ 10
6	Cost Premium - Modules Only – 2% check (¢/W)	0.03	Row 4 ÷ 50
7	Cost Premium - Entire System (¢/W)	2.5	Calculation: row 1 * row 3 + row 4
8	Cost Premium – Entire System – 10% check (¢/W)	0.3	Row 7 ÷ 10
9	Cost Premium – Entire System – 2% check (¢/W)	0.05	Row 7 ÷ 50

Table 5. Roof Mount Cost Calculation for Measure 1: System Torque Audit

Row #	Metric	Value	Source
1	Cost (¢/bolt)	241	Site Operator Provided Data
2	Number of Module Mounting Bolts (bolts/W)	0.0119	Site Operator Provided Data
3	Cost Premium - Modules Only – 100% check (¢/W)	2.7	Site Operator Provided Data
4	Cost Premium - Modules Only – 10% check (¢/W)	0.3	Row 3 ÷ 10
5	Cost Premium - Modules Only – 2% check (¢/W)	0.05	Row 3 ÷ 50

This report only presents module fastener torque check cost estimates for roof-mounted systems due to the wide range of racking and roof attachment designs. The costs calculated above are for checking 2%, 10%, and 100% of the fasteners in a system. Typical torque audits begin with a 2% or 10% check. For a 2% to 10% check, this measure proves to be one of the least costly measures for storm hardening a PV system. Even a 100% torque check is a relatively cost-effective preventative measure that can lead to immediate system hardening as fasteners are retightened to torque specs.

For a flush-mount roof-mount system, it may be difficult to torque check many of the fasteners located under the modules because of close row spacing or inaccessible fasteners.

3.2 Measure 2: Fasteners

> "When choosing locking hardware, avoid split washers, nylon nuts, serrated-flanged nuts, and doublenutting, as these technologies are proven ineffective under Junker testing—the industry standard vibration test. Wedge-lock washers are one example of a highly effective, economical class of locking hardware." (Robinson 2018)

Well-designed fasteners should remain secure throughout their life. This is exemplified by fasteners in the automobile industry—cars and trucks undergo much more regular and strong vibrations than PV systems, with the expectation that bolts do not shake loose. This is achieved in a cost-effective manner in the automotive industry, as well (Ness 2019).

Fasteners generally loosen by one of two modes: relaxation or self-loosening. Relaxation refers to the loss of clamp load that begins to occur immediately after a joint is tightened. This occurs in all joints to varying degrees—sometimes insignificantly, sometimes significantly. To address relaxation, designers can reduce the joint-bolt stiffness, which can be achieved through longer bolts or the use of Belleville washers (see Section 3.2.3), reduce the fastener tightening speed, or retighten bolts soon after their initial tightening (Ness 2019).

Self-loosening refers to loosening caused by rotation of the nut. This is typically caused by vibrations, such as those experienced from wind on a PV system. To mitigate this, designers can use larger or stronger fasteners or use some type of fastener locking method. Three locking methods are wedge-lock washers, pre-applied threat locker, and lock bolts (all described below).

These solutions can all decrease the chances of a fastener loosening over time as it is subjected to wind, weather, other vibrations, or inadequate design or installation.

Prices of these fasteners are subject to change, due to availability, quantity ordered, vendor markup, and other factors that may influence the price an actual developer may pay.

3.2.1 Wedge-Lock Washers

One locking fastener solution is the use of wedge-lock washers. This technology essentially locks in place and resists bolted joint self-loosening when tightened (Figure 1).

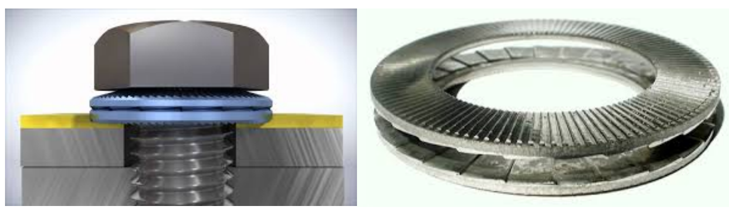

Figure 1. Wedge-lock washers

Image credit: Nord-lock

This technology has been used on concentrated solar power applications with heliostats, wind turbines, on wind deflectors for PV systems, and is in the nascent stages of use with PV system hardware.

The additional cost for this measure is the added cost of wedge-lock washers. The base case washers used here are assumed to be ⅜” galvanized zinc standard washers for a module mounts and ¾” galvanized for the racking system.

These washers certainly mitigate bolt self-loosening, as evidenced by a Junker test. The general sentiment in the industry is that it is an expensive solution that involves more complicated installation and training of installers. There are concerns over whether off-the-shelf wedge-lock washers would comply with UL2703 for “galvanic compatibility with other joint and fastener materials and also the electrical conductivity of the joint if it is defined as a grounding path” (Ness 2019; UL 2703 2015).

Table 6 and Table 7 give cost calculations for ground mount and roof mounted systems, respectively.

Table 6. Ground-Mount Cost Calculation for Measure 2.1: Wedge-Lock Washers

Row #	Metric	Value	Source
1	Labor Additional Time (s)	0	Assumed no additional time
2	Module Mounting Flat Washers 3/8" (¢/washer)	14	Site Operator Data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	Racking Flat Washers 3/4" (¢/washer)	22	
4	Wedge-lock Module Washers 3/8" (¢/washer set)	77	
5	Wedge-lock Racking Washers (¢/washer set)	186	
6	Number of Module Washers (washers/W)	0.023	Site Operator Data, SEI Solar Electric Handbook, Engineering Calculations
7	Number of Racking Washers (washers/W)	0.019	
8	Baseline Cost - Modules Only (¢/W)	0.32	Calculation: row 2 * row 6
9	Baseline Cost - Entire System (¢/W)	0.73	Calculation: row 3 * row 7 + row 8
10	Wedge-lock Washer Premium - Module Only (¢/W)	1.4	Calculation: row 4 * row 6 – row 8
11	Wedge-lock Washer Premium - Entire System (¢/W)	4.5	Calculation: row 5 * row 7 – row 9 + row 8 + row 10

Table 7. Roof-Mount Cost Calculation for Measure 2.1: Wedge-Lock Washers

Row #	Metric	Value	Source
1	Labor additional time	0	Assumed no additional time
2	Module Mounting Flat Washers 3/8" (¢/washer)	14	Site Operator Data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	Wedge-lock Module Washers 3/8” (¢/washer set)	77	
4	Number of washers (washers/W)	0.0238	Site Operator Data, SEI Solar Electric Handbook
5	Baseline Cost - Modules Only (¢/W)	0.33	Calculation: row 2 * row 4
6	Wedge-lock Washer Premium - Module Only (¢/W)	1.5	Calculation: row 3 * row 4 – row 5

This report only presents module fastener cost estimates for roof-mounted systems due to the wide range of racking and roof attachment designs.

Other Locking Systems

While our initial recommendation is to use wedge lock washers, and they do prove to be effective against vibration loosening, there are other bolted joint techniques that may also be effective when applied to PV systems.

3.2.2 Belville Washers

Belleville washers are conical shaped, spring washers that can help a bolted joint maintain tension through relaxation (Figure 2). Due their shape, they act like a spring, helping hold tension on the joint even if there is relaxation in the bolt or nut. Another advantage to Belleville washers is that they lie flat when tightened, providing a visual cue to the installer that the fastener is adequately torqued. Table 8 and Table 9 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Figure 2. Belleville washer

Image from Grainger.com

Table 8. Ground-Mount Cost Calculation for Measure 2.3: Belville Washers

Row #	Metric	Value	Source
1	Labor Additional Time (s)	0	Assumed no additional time
2	Module Mounting Flat Washers 3/8" (¢/washer)	14	Site Operator Data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	Racking Flat Washers 3/4" (¢/washer)	22	
4	Belleville Washers Module Mount 3/8” (c/washer)	38	
5	Belleville Washers - Racking 3/4” (c/washer)	190	
6	Number of Module Washers (washers/W)	0.023	GRID Alternatives 1.17 MW installation bill of materials, other installation observations, site operator provided data
7	Number of Racking Washers (washers/W)	0.038	
8	Baseline Cost - Modules Only (¢/W)	0.32	Calculation: row 2 * row 6
9	Baseline Cost - Entire System (¢/W)	1.14	Calculation: row 3 * row 7 + row 8
10	Belleville Washer Module Mount Premium (c/W)	0.54	Calculation: row 4 * row 6 – row 8
11	Belleville Washer Entire System Premium (c/W)	6.9	Calculation: row 5 * row 7 – row 9 + row 8 + row 10

Table 9. Roof-Mount Cost Calculation for Measure 2.3: Belville Washers

Row #	Metric	Value	Source
1	Labor Additional Time	0	Assumed no additional time
2	Module Mounting Flat Washers 3/8" (¢/washer)	14	Site Operator Data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	Belleville Washers Module Mount 3/8” (c/washer)	38	
4	Number of Module Washers (washers/W)	0.024	GRID Alternatives 1.17 MW installation bill of materials, other installation observations, site operator provided data
5	Baseline Cost (c/W)	0.33	Calculation: row 2 * row 4
6	Belleville Washer Premium - Modules Only (¢/W)	0.57	Calculation: row 3 * row 4 – row 5

This report only presents module fastener cost estimates for roof-mounted systems due to the wide range of racking and roof attachment designs.

3.2.3 Rivet Lock Bolts

Rivet lock bolts are a bolted system that, once bolted, uses a special rivet-like tool to compress the nut and lock the hardware in place. While this does require specialized tools and a different assembly (which might require tool acquisition and training), it secures the bolted joint in place for life. This offers significant benefits in combatting joint loosening. Should a bolt need to be removed, there is a tool that can break the bolted joints. This measure also theoretically eliminates the need for torque audit, as rivet lock bolts should never loosen. Neither the training costs or the audit cost savings are incorporated into this cost analysis. Table 10 and Table 11 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Table 10. Ground-Mount Cost Calculation for Measure 2.4: Rivet Lock Bolts

Row #	Metric	Value	Source
1	Labor Additional Time	0	Assumed no additional time
2	3/8" Module Mounting Stack (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	3/4" Stack (¢/stack)	230	
4	Lock Bolt 3/8" (¢/bolt set)	130	McMaster Carr, Grainger, Tanner Bolt, Fastenal, Bolt Depot, Zoro. October 2019
5	Lock Bolt 3/4" (¢/bolt set)	250	
6	Tool Purchase Cost ($)	592.5	Grainger.com and blindrivetsupply.com, assuming 100% markup
7	Number of Tools necessary (#/W)	0.000004	assumed 4 per MW
8	Number of Module Stacks (stacks/W)	0.0113	GRID alternatives 1.17 MW installation bill of materials, other installation observations, site operator provided data
9	Number of Racking Stacks (stacks/W)	0.00945	
10	Baseline Cost - Modules Only (¢/W)	1.10	Calculation: row 2 * row 8
11	Baseline Cost - Entire System (¢/W)	3.27	Calculation: row 3 * row 9 + row 10
12	Lock Bolts Premium - Module Only (¢/W)	0.61	Calculation: row 4 * row 8 + row 6 * 100 * row 7 – row 10
13	Lock bolts Premium - Entire System (¢/W)	1.0	Calculation: row 5 * row 9 + row 6 * 100 * row 7 – row 11 + row 10 + row 12

Table 11. Roof-Mount Cost Calculation for Measure 2.4: Rivet Lock Bolts

Row #	Metric	Value	Source
1	Labor Additional Time	0	Assumed no additional time
2	3/8" Module Mounting Stack (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3	Lock Bolt 3/8" (¢/bolt set)	130	McMaster Carr, Grainger, Tanner Bolt, Fastenal, Bolt Depot, Zoro. Oct 2019
4	Tool Purchase Cost ($)	592.5	
5	Number of Tools Necessary (#/W)	0.000004	assumed 4 per MW
6	Number of Stacks (stacks/W)	0.0119	Observations of installed systems, SEI Solar Electric Handbook
7	Baseline Cost (¢/W)	1.1	Calculation: row 2 * row 6
8	Lock Bolt Premium (¢/W)	0.63	Calculation: row 3 * row 4 + row 4 * 100 * row 5 – row 7

This report only presents module fastener cost estimates for roof-mounted systems due to the wide range of racking and roof attachment designs.

3.2.4 Pre-Applied Thread Lock

Thread lock can be applied to bolts. This product is applied to the threading with a cured solid seal between the bolt and nut. Bolts can be purchased with thread lock pre-applied or thread lock can be applied to prepurchased bolts. For a large-scale installation, bolts would be purchased with the thread lock pre-applied. The costs for this measure were estimated using purchase costs for the thread lock substance itself, based on manufacturer supplied single-use volume. Table 12 and Table 13 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Table 12. Ground-Mount Cost Calculation for Measure 2.5: Pre-Applied Thread Lock

Metric	Value	Source
Labor Additional Time	0	Assumed no additional time
3/8" Module Hex Screw (¢/bolt)	35	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
3/4" Racking Hex Screw (¢/bolt)	56	
Hex Screw with Thread Lock 3/8" (¢/bolt)	45	
Hex Screw with Thread Lock 3/4" (¢/bolt)	202	
Number of Module Bolts (bolts/W)	0.0113	GRID Alternatives 1.17 MW installation bill of materials, other installation observations, site operator provided data
Number of Racking Bolts (bolts/W)	0.00945	
Number of Module Stacks (stacks/W)	0.40	Calculation: row 2 * row 6
Number of Racking Stacks (stacks/W)	0.92	Calculation: row 3 * row 7 + row 8
Thread lock Premium - Module Only (¢/W)	0.11	Calculation: row 4 * row 6 – row 8
Thread lock Premium - Entire System (¢/W)	1.5	Calculation: row 5 * row 7 – row 9 + row 8 + row 10

Table 13. Roof-Mount Cost Calculation for Measure 2.5: Pre-Applied Thread Lock

Metric	Value	Source
Labor Additional Time	0	Assumed no additional time
3/8" Module Hex Screw (¢/bolt)	35	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
Hex Screw with Thread Lock 3/8" (¢/bolt)	45	
Number of Module Bolts (bolts/W)	0.0119	GRID Alternatives 1.17 MW installation bill of materials, other installation observations, site operator provided data
Number of Module Stacks (stacks/W)	0.42	Calculation: row 2 * row 4
Thread lock Premium - Module Only (¢/W)	0.12	Calculation: row 3 * row 4 – row 5

This report only presents module fastener cost estimates for roof-mounted systems due to the wide range of racking and roof attachment designs.

3.2.5 Bolted Joint Standards

Currently there is not an effective standard for bolted joints for PV systems; the risks of their failure are just beginning to be realized and quantified. Furthermore, codes for PV are typically linked to building codes and treated as a static system. This is not always the case, especially in severe weather, where PV systems are often subject to more dynamic loading. There does not appear to be widespread awareness in the industry for physical bolt properties and modes of loosening, such as preload relaxation—the loss of tension in a bolt after initial tightening. This is especially problematic with commonly deployed flange nuts.

The fasteners that tie PV systems together need more consideration, from development of appropriate standards to dissemination of knowledge surrounding their physics. At a minimum, bolts should comply with ASTM A193 or ASTM A593, and nuts should comply with ASTM A194 or ASTM A594 or corresponding International Organization for Standardization (ISO) standards (Ness 2019).

3.3 Measure 3: Through Bolt Modules

> "Module clamping fasteners were also a core cause of equipment loss during the 2017 hurricane season. Nearly all racking manufacturers use clamps to attach modules to sub-framing, which rely on friction to hold equipment in place. Clamping fasteners allow for fast field assembly but, as a general rule, are not adequate for photovoltaic systems in severe weather regions." (Robinson 2018)

> "Module mid-clamps are bolted to the module rails between two adjacent modules. Both module frames must be present and intact for the module mid-clamp to hold them in place. It is common that flying debris will impact the solar array and likely break the glass on some of the modules. The glass itself provides a great deal of rigid strength to PV modules. When the glass is broken, the module integrity and resistance to wind is compromised. At that point, the module frame can quickly buckle under the wind force, and the module will pull free of the module clamps. Without both modules under the mid-clamp, the mid-clamp will become loose and cannot hold the adjacent intact module. That intact adjacent module will be unsecured, resulting in its easy displacement by the wind. That will compromise the next mid-clamp in the row, and so on, leading to the loss of all the modules in that row." (Lopata, 2019)

Many PV systems are installed using top-down or T-clamps. While these offer advantages of fast installation and use of fewer system parts, they are a clear weak point of systems that have failed in severe weather. With this system, one clamp is typically shared between adjacent modules, so if one module comes free of the racking it could have a cascading effect and reduce the clamp strength holding adjacent modules, because these top-down clamps need modules on either side to be effective. T-clamps can also more easily pull out of the racking channel into which they are inserted, which has been another common failure mode for PV systems.

Through bolting, the practice of bolting modules directly to the underlying racking, is becoming a more common practice for commercial sized ground mount systems (O'Hara 2019). It offers advantages of increased clamp strength and clamping each module to the racking, rather than to an adjacent module. It does come with a cost premium, mostly through increased labor time—it requires about twice as many fasteners and each fastener takes longer to install.

Table 14 and Table 15 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Table 14. Ground-Mount Cost Calculation for Measure 3: Through Bolting

Metric	Value	Source
Top down T-Clamp Set Cost (¢/clamp)	176	SolarisShop.com, GoGreenSolar.com, EcoDirect.Com, SolarWholesale.com
Number (clamps/module)	2.1	SEI solar electric handbook. Assume rows of 10+ modules
W/Module	385	Market trends
Top Down Materials Cost (¢/W)	0.96	Calculation
Through Bolt Stack Cost (Bolt, Flange Nut, 2 Washers) (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
Through Bolt Stacks/Module	4	Standard installation, GRID Alternatives 1.17 MW installation specs
Through Bolt Materials Cost (¢/W)	1.01	Calculation
Materials Premium (¢/W)	0.05	Calculation
Labor Rate ($/hr)	42.44	Site operator provided data, NREL Solar Benchmark
Labor Time Top Down (sec/bolt)	30	Assumed
Labor Time Through Bolting (sec/bolt)	60	Assume twice as long per bolt
Labor Premium (¢/W)	0.54	Calculation
Measure Premium Total (¢/W)	0.59	Calculation

This value aligns closely with anecdotal estimates of 0.20¢/W and 0.50¢/W from conversations with field practitioners.

Table 15. Roof-Mount Cost Calculation for Measure 3: Through Bolting

Metric	Value	Source
Top Down T-Clamp Set Cost (¢/clamp)	176	SolarisShop.com, GoGreenSolar.com, EcoDirect.Com, SolarWholesale.com
Number (clamps/module)	2.6	SEI solar electric handbook. Assume rows of 10+ modules
W/Module	320	Market trends
Top Down Materials Cost (¢/W)	1.43	Calculation
Through Bolt Stack Cost (Bolt, Flange Nut, 2 Washers) (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
Through Bolt Stacks/Module	4	Standard installation
Through Bolt Materials Cost (¢/W)	1.21	Calculation
Materials Premium (¢/W)	-0.22	Calculation
Labor Rate ($/hr)	42.44	Site operator provided data, NREL Solar Benchmark
Labor Time Top Down (sec/bolt)	45	Assumed
Labor Time Through Bolting (sec/bolt)	90	Assume twice as long per bolt
Labor Premium (¢/W)	0.90	Calculation
Measure Premium Total (¢/W)	0.68	Calculation

Through bolting on a roof-mounted system proves much more challenging due to the difficulties of accessing the rails after the modules are mounted.

3.4 Measure 4: Use Marine-Grade Steel Fasteners

> "Common stainless-steel alloys corrode in coastal areas, leading to eventual weakening and failure. A best practice is to request 316-grade stainless steel fasteners, which are made from an alloy designed for marine environments." (Robinson 2018)

In marine environments, salt in the water and air can quickly corrode system hardware and reduce its performance, leading to ineffective fasteners and structural components. Our research indicates that most systems installed in maritime regions already use marine-grade steel and are accustomed to using it as standard practice.

Regardless, using marine-grade (316) steel does come with a cost premium over standard (304 or 18-8) grade steel. Racks and frames are typically made from aluminum and are thus not a concern, so the bolts, washers, and nuts are the main components under consideration here. Fasteners should comply with ASTM F593G–Stainless Steel Alloy Group–316 and 316L Bolts and Nuts or the corresponding ISO standard. Bolts should be marked according to appropriate standard; a 316 marking does not necessarily comply with any specific industry standard.

The costs of this measure involve replacing 18-8 grade bolts, nuts, and washers with 316-grade stainless steel hardware. Table 16 and Table 17 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Table 16. Ground-Mount Cost Calculation for Measure 4: Use Marine-Grade Steel Fasteners

Metric	Value	Source
Bolt Stack Unit Cost (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
Stacks / W	0.0113	Site Operator Data
Baseline Cost per Watt (¢/W)	1.10	Calculation
316 Stainless Stack Cost (¢/stack)	199	McMaster Carr, Grainger, Fastenal, May 2019
Measure Premium (¢/W)	1.1	Calculation

Table 17. Roof-Mount Cost Calculation for Measure 4: Use Marine-Grade Steel Fasteners

Metric	Value	Source
Bolt Stack Unit Cost (¢/stack)	97	Site operator provided data, cross-referenced with costs sourced from online hardware providers: Fastenal, McMaster Carr, Grainer, Tanner Bolt, Bolt Depot, Zoro Feb 2020
Stacks / W	0.0119	Site Operator Data
Baseline Cost per Watt (¢/W)	1.15	Calculation
316 Stainless Stack Cost (¢/stack)	199	McMaster Carr, Grainger, Fastenal, May 2019
Measure Premium (¢/W)	1.2	Calculation

3.5 Measure 5: Select Panels With Appropriate Resistance to Design Wind Loading

> "Post-storm field inspections showed that high wind speeds caused some models of photovoltaic modules to burst from strong wind pressures. The ability of a module to withstand these wind pressures varies greatly between manufacturers. One critical strength rating for modules is front and back pressure." (Robinson 2018)

In high wind environments, modules experience periodic uplift that will flex the modules within their frames and from their mounting fixtures. Should this uplift pressure be strong or persistent enough, it could damage the modules or crack the glass top sheet. While there is not an industry-mandated effective dynamic wind load standard, some modules are tested for uplift using a push-pull pressure test. The "pull" rating here is more representative of in-field wind loads, representing the uplift static load tolerance of the module. Modules are typically rated for a 2,400 Pa pull test (Standard ASTM E1830-15), though a rating of 3,600-5,000 Pa or more is likely necessary in a severe weather-prone location (Robinson 2018). Still, many industry experts feel that there is not an appropriate PV module test for dynamic loading that simulates high wind conditions and that one needs to be developed.

The push-pull load tolerance is also dependent on mounting and clamping, which can drastically impact the load a module can withstand. Through different mounting and clamping designs, it is possible to increase the tolerance of the module/attachment system (Figure 3). For this specific module in Figure 3, the "Rear" or uplift pressure rating ranges from 1,800 Pa–5,400 Pa, depending on the clamping type.

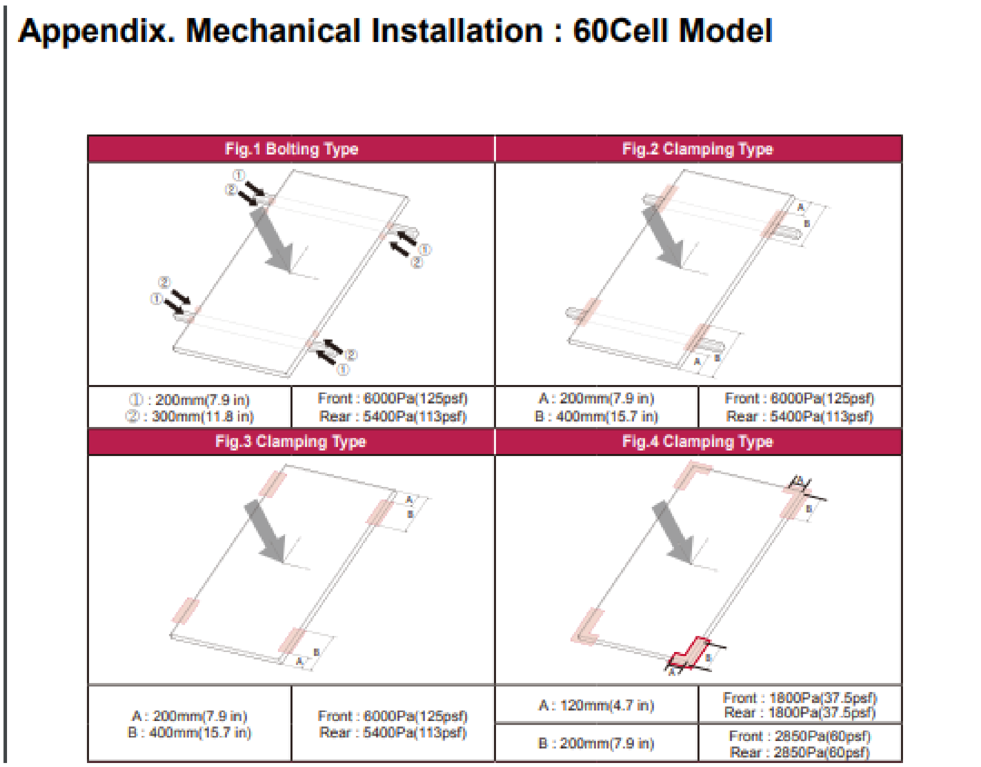

Figure 3. Excerpt from a module installation manual. Depending on the attachment design, the module has drastically different push (Front) and pull (Rear) load tolerance.

Image from LG https://www.lg.com/global/business/solar/business-resources/download

It is important to select modules appropriate for the site's location and wind speeds. The topography and surrounding structures will have an impact on the actual loads on the modules. In an area often exposed to Category 3 or higher hurricanes, however, we encourage selecting the highest pressure rated modules.

There is ongoing research aimed at developing more durable solar modules, through the Office of Energy Efficiency and Renewable Energy's SunShot Initiative, which has funded the International PV Quality Assurance Task Force (PVQAT) and the Durable Module Materials Consortium (DuraMAT). This targeted research could lead to mainstream production of more durable modules for severe weather regions, though presently only a few module manufacturers offer modules with higher than 2,400 Pa uplift ratings.

The cost premium for this measure is the increased cost of a module with a higher pull (uplift) rating. A stronger module is more costly, generally. The costs here represent an average premium for modules with an uplift rating at or above 3,600 Pa. Table 18 gives cost calculations for ground-mounted and roof-mounted systems.

Table 18. Ground-Mount Cost Calculation for Measure 5: Module Selection

Module	Value	Source
Module Cost (Baseline, 2,400 Pa Rated) (¢/W)	47	NREL Solar PV System Cost Benchmark 2018
Wind-Resistant Module Cost (>3,600 Pa Rated) (¢/W)	57.1	Premium percentage calculated from a survey of online solar wholesale websites.
Measure Premium (¢/W)	10.1	Frist row subtracted from the second row

Another consideration here is the recent rapid decline in solar module costs. Prices are falling quickly that the increased cost of a stronger module is comparable with the cost of a standard module from just a couple of years ago (Stone 2018).

Within this report, this measure is the most expensive measure analyzed. This is not likely reflective of the actual cost of hardening modules, however. These data are based on a very small data set, because very few modules are tested to higher standards. Those that were tested to and passed these higher standards are perhaps designed and built better than modules that either were not tested to these higher standards or did not pass them. This overall higher quality of engineering could account for a significant portion of their higher costs. So, the cost here may represent the cost of higher quality modules overall, not simply the cost of storm hardening.

Module manufacturers currently do not have much incentive or motivation to design modules that can withstand high wind loads. If industry standard is to pass a 2,400 Pa static (snow) load test, manufacturers have little to no reason to spend more money and time to test to a higher tolerance, under which their product could fail. One aim of this work is to spur the industry towards incentivizing and encouraging manufacture and testing of hardier modules. Also, as more PV systems are installed in severe weather regions, there will come a higher demand for hardier modules (and other system components).

3.6 Measure 6: Use a Three-Framed Rail System

> "Many modules were found to be poorly supported by underlying frame elements, which led to bending and twisting and then breakage in high winds. Most solar racking systems provide two frame rails for module mounting. Consider using a three-frame rail system to provide greater rigidity and support in order to reduce bending and twisting." (Robinson 2018)

Solar PV systems typically use a two-rail system, where each module is supported and attached to the two racking rails. Adding a third rail increases the strength of the system by giving the modules more attachment points, reducing the amount modules can flex in high winds, and transferring more load to the underlying structure (Figure 4).

Figure 4. A solar installation in hurricane-prone Florida using a three-framed rail system to support the solar modules.

Image from Commercial Solar Guy 2019

Adding an extra rail comes with extra costs of 50% more materials (rails, clamps, bolts, nuts, washers) and added labor time for the “east-west” rails that support the modules (Figure 5).

Figure 5. Standard two-rail racking frame

Photo by James Elsworth, NREL

Table 19 and Table 20 give cost calculations for ground-mounted and roof-mounted systems, respectively.

Table 19. Ground-Mount Cost Calculation for Measure 6: Use a Three-Framed Rail System

Metric	Value	Source
Module Racking Cost (¢/ft)	170	wholesalesolar.com, solarisshop.com, and ecodirect.com, assume 100% markup
Length of Rail (ft/W)	0.021	GRID Alternatives Bill of Materials and Specs
Baseline Cost (¢/W)	3.47	Calculation from previous two rows
3rd Rail Extra Cost - Ground Mount (¢/W)	1.74	Calculation (.5* cost of baseline system, as 1.5* number of rails are used here)
Top Down Fasteners Cost (¢/W)	0.48	Half of the value from Measure 3 above, 50% as many if just accounting for the third rail
Labor Costs (¢/W)	3	Based on $0.12/W Install Labor and equipment (Ran Fu 2018)
Total Ground Mount 3rd-Rail Premium (¢/W)	5.2	Sum of values from previous three rows

Table 20. Roof-Mount Cost Calculation for Measure 6: Use a Three-Framed Rail System

Metric	Value	Source
Ground Mount W/Roof Mount W Ratio	1.20	Field observations + conversations with installation professionals at GRID Alternatives—same number of rails and fasteners per module but typically roof mount uses shorter (lower W) modules
3rd Rail Extra Cost Roof Mount (¢/W)	2.09	Calculation using ratio in previous line
Top Down Fasteners Cost (¢/W)	0.58	Calculation using ratio
Labor Costs (¢/W)	3	Same as above
Total Roof Mount 3rd Rail Cost Premium (¢/W)	5.7	Sum of three previous rows

For reference, NREL's Solar Photovoltaic System Cost Benchmark (Fu 2018) cites between 13¢/W and 28 ¢/W for total cost of structural components of a ground mount system and an average of 11¢/W for a roof mount. A site NREL visited in Towaoc, Colorado, was priced around 15¢/W for the racking materials, structural engineering, and freight of the racking system. Adding a third rail adds around 33% to the system racking costs.

3.7 Measure 7: Use Two Driven Steel Pile Supports

Many ground-mount PV systems are installed using only one driven support pile, as shown in Figure 6.

Figure 6. Solar PV racking with a single support pile.

Photos by James Elsworth, NREL

Two driven support piers (dual post piers) would provide more stability to the system, as shown in Figure 7.

Figure 7. A ground-mount solar array using a dual pier support system

Photo by Dennis Schroeder, NREL

This measure considers the cost premium of using two instead of one driven pile support. In-field practitioners have relayed the necessity of this measure in hurricane-prone regions. The cost estimate for this measure is representative of the costs of purchasing a dual-row racking system directly from a manufacturer, rather than purchasing additional hardware and piecing together a system, which comes with its own risks. The cost of two piles is not simply twice that of one pile for two reasons. A dual post system can have a larger span between piers due to the increased structural integrity, and costs of contracting and transporting equipment on site still only need to be paid once.

Table 21 gives cost calculations for ground-mounted and roof-mounted systems.

Table 21. Ground-Mount Cost Calculation for Measure 6: Use Two Driven Steel Pile Supports

Metric	Value	Source
Cost of One Driven Pile, Labor and so on Included (¢/ft)	3,000	*RS Means Building Construction Costs 2019.* "'H' Sections, 50' long, HP8 x 36". (used because they most closely resemble piles from baseline installation—see image below)
Length of Driven Pile (ft)	10	Assumption
Cost per Pile (¢/pile)	30,000	Calculation
Modules per Pile (mods/pile)	12	GRID Alternatives 1.17 MW installation
W per Mod (W/mod)	385	
Piles/W	0.00022	Calculation
Cost of One Pile (¢/W)	7.2	Calculation
Cost of Two Piles (¢/W)	10	Site Operator input
Labor Premium (¢/W)	3	Site Operator input
Measure Premium (¢/W)	5.9	Calculation

This aligns well with our expert estimates, which averaged 4¢/W.

3.8 Measure 8: Use Closed Form Frame Elements

> "The selection of framing members comprising a racking system were another determinant of survivability. Light gauge (14–16ga), cold-rolled steel "C" or hat channels are not durable enough to survive severe weather without extreme bending and twisting. These bending forces transfer to the mounted solar modules and lead to breakage. Consulting engineers need to specify frame elements that are sufficiently strong. In general, closed-form (tubular) frame elements with low drag coefficients have proven to be superior to openshaped "C" and hat channels." (Robinson 2018)

In PV support structures, there has been a trend towards lighter aluminum module frames, which save both material and shipping costs. A trade-off of this, however, is that the frames are thinner and structurally weaker on newer modules than on older modules. Traditional rolled steel or aluminum racking frame elements can be weak along certain axes. Tubular or square supports would be more structurally sound and less likely to twist, deform, and fail in storms. They do, however, come with a significantly higher cost and weight.

Baseline system components here will be cold-rolled steel Z-, C-, or U-channel stainless steel 14 ga., 2.0 mm, 0.080" (Figure 8, Figure 9).

Figure 8. C, Z, and U purlins for solar racking

Image from SolarMount

Figure 9. Cold rolled steel support structures are lightweight but can be weak along certain axes.

Photo by James Elsworth, NREL

This measure considers replacing these with tubular steel or aluminum rails (Figure 10).

Figure 10. Tubular steel could provide more strength to PV racking systems.

Image from Matthew Smith

While tubular rails undoubtedly increase the rigidity of the system, there is significant proprietary data around racking costs and complications around assembling systems piecemeal. Our industry experts expressed concerns that using tubular steel could potentially void warranties and insurance and the compatibility with existing mounting system components. Furthermore, while there are cases of tubular racking used for PV systems, the practice is rare.

Because of these factors, we hold low confidence in our cost estimate for this measure.

Table 22. Cost Calculation for Measure 8: Use Closed Form Frame Elements

Metric	Value	Source
Baseline Rail Cost ($/W)	3.4748	From measure 5 calculations
U Channel Aluminum Baseline ($/l.f.)	10.00	Grainger, McMaster Carr Jun 2019 Thickness Range, average of middle 8 of 12 samples ($" wide, 14-16 ga)
Square Tube Stainless Steel ($/l.f.)	24	Grainger June 2019, average of 5 samples (4" wide, 12 ga)
Square Tube Aluminum ($/l.f.)	15	Grainger June 2019, average of 7 middle from 9 sampled (4” wide, 1/8 inch thick – 8.5 ga)
Linear Feet/ W	0.0239	GRID Alternatives 1.17 MW install bill of materials
Measure premium Steel (¢/W)	34	Calculation from above
Measure Premium Aluminum (¢/W)	12	Calculation from above

3.9 Measure 9: Use a Wind Calming Fence

> "Structural engineers experienced with wind dynamics and solar arrays have noted a highly destructive type of turbulence that acts on perimeter rows. This type of turbulence can amplify forces and lead to loss propagated from the perimeter of an array inward. On the Western plains, wind-calming and slowing fences are used to prevent snow accumulation on highways. This same technique could be used around the perimeter of photovoltaic systems to slow damaging winds, prevent perimeter turbulence, and provide the added benefit of stopping loose debris from entering an array field." (Robinson 2018)

One method to increase a PV system's resistance to strong winds is to decrease the amount of strong winds that impact the system. A wind-calming fence or wind break can help achieve this. There are different types of wind-calming fences, ranging from highway snow and wind fences (Figure 11) to porous, mesh screen fences (Figure 12).

Figure 11. Highway snow fence

Image from Minnesota Department of Transportation District 4 (2019). Structural snow fence I-94 and Hwy 336 near Moorhead, Minnesota.

Figure 12. Porous wind-calming fence

Photo from WeatherSolve Solutions Solar Brochure

Wind-calming fences are porous. They are designed to let some wind pass through, so as not to create a low-pressure void downwind of the fence, which ultimately deflects more wind, as depicted in Figure 13.

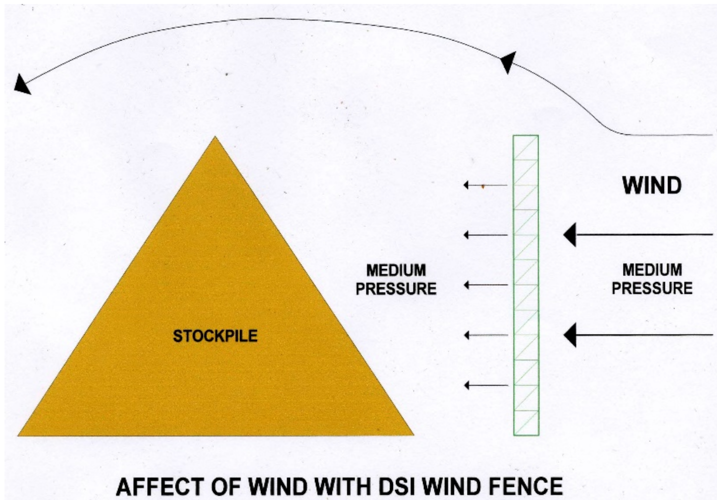

Figure 13. Wind-calming fences are porous and let some of the incoming wind pass through, so as not to create a low-pressure region downwind of the fence. Overall, this deflects more wind above the protected area.

Image from Dust Solutions, Inc.

There are ancillary benefits of wind-calming fences as well. They will block some dust and other debris from penetrating the solar field and soiling the panels, leading to less required cleaning and higher average output. Wind fences could stall wildfire ember migration, as well, providing some fire protection to the array. Wind fences could be made to double as security fences around systems, too.

Wind-calming fences have been used in the power industry, most commonly to protect coal stockpiles, but also have been used to protect solar arrays (Figure 14).

Figure 14. Wind and dust fences surrounding solar installations

Image 1 by WeatherSolve Solar Brochure; Image 2 by DCT-Dust Solutions, Inc.

Typically, the perimeter row of a PV array is engineered to higher load thresholds than the remainder of the array because the perimeter rows are usually subject to the highest loads (Figure 15). A wind-calming fence can reduce the loads on these outer loads, obviating the need for more robust design and leading to some system cost savings as well. It is also important to consider topographical effects and more complex wind factors that may lead to nonperimeter rows being more heavily loaded.

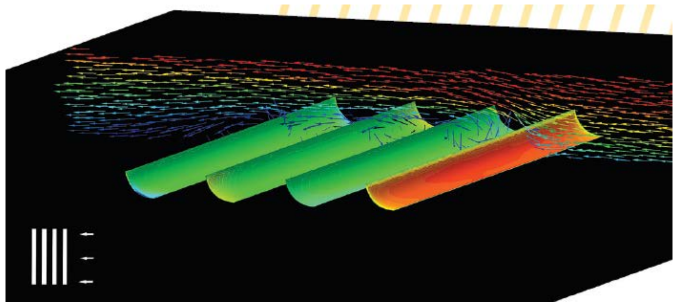

Figure 15. Flow visualization for wind loading a PV array. Perimeter rows are 2.25 times more heavily loaded than inner rows of the array.

Image from WeatherSolve Solutions Solar Brochure

This measure considers ground mount only; other structures such as wind deflectors are better suited as wind blocks for roof-mount systems. We estimated perimeter fencing around an entire array to reduce the extra perimeter loading on ground mount arrays. Typically, chain link fences are installed around a PV system for protection and security, so they serve as the baseline here. Depending on location, sometimes simpler animal blocking fences are used (goats can chew through electrical wires and jump onto arrays) (Walker 2016).

Table 23 gives cost calculations for ground-mounted and roof-mounted systems.

Table 23. Cost Calculation for Measure 9: Use a Wind-Calming Fence

Metric	1 MW	5 MW	10 MW	Source
Land Use Area (acres/MW)	5.5	5.5	5.5	https://www.nrel.gov/docs/fy13osti/56290.pdf
Total Length of Fence (ft)	2000	4500	6000	https://www.nrel.gov/docs/fy13osti/56290.pdf, Calculations based on square array
Base Case Cost per Foot (¢/ft)	29,500	29,500	29,500	*RS Means Building Construction Costs 2019* "Fence, Chain Link Industrial, Schedule 40, including concrete, 3 strands barb wire, 2" post at 10' OC, set in concrete, 6' H, 9 ga. wire, galv. steel, in concrete
Base Case Cost: (¢/W)	5.90	2.66	1.77	Calculation
Wind-Calming Fence (¢/Running Foot)	10,000	10,000	10,000	Mesh type wind calming fence—conversations and actual project quotes from two wind fence installers. 12' high fence
Measure Premium: (¢/W)	14.1	8.469	5.823	Calculation

Site conditions vary drastically and will determine the installation and labor cost. According to one source, an extremely challenging site could lead to costs near $150/running foot. The $100/running foot cost used here is for a 12' fence in normal conditions.

Opinions in the field vary as to whether wind fences are an effective solution for storm hardening. There are engineering, cost, and system liability concerns with this approach. For example, for outside-of-system measures such as this, it is important to ensure where the ownership and liability of such a measure lies—on the developer, contractor, or owner—and lay out ground rules for such beforehand. Developers should consider all the implications of installing a wind fence before proceeding.

3.10 Measure 10: Use Enclosures With Integrated and Contiguous Rubber Door Seals and Compression Latches on All Sides

> "Significant damage was caused by enclosure doors opening in strong winds or by water seeping into enclosures with insufficient gasketing and latching hardware. Specify enclosures with integrated and contiguous rubber door seals and compression latches on all sides." (Robinson 2018)

Flooding and water saturation can cause significant damage to PV systems, even in non-severe weather-prone regions. In severe weather regions, all enclosures containing electronic components—inverter boxes, combiner boxes, DC disconnect boxes—should be rated to withstand wind-driven rain and submersion (i.e., NEMA 4, 4X, or higher rated). These enclosures should be specified at design and installed with the system, as attempting to retrofit enclosures would likely void warranties and UL listings (Lopata 2019).

This measure should be a standard feature of PV systems and already incorporated into the cost, thus there is no premium for this measure. We include it here because lower NEMA-rated structures are often used, and flooding of system electronics is a common and expensive failure mode.

3.11 Measure 11: Install Equipment on Elevated Pads

> "While damage from some recent hurricanes was mainly caused by high winds, damage from other hurricanes came from localized flooding. FEMP recommends that equipment be installed on elevated pads and entire sites have well-designed and maintained drainage systems." (Robinson 2018)

Installing electrical equipment on elevated pads will reduce the likelihood of water damage. This measure looks at the cost of installing all electrical equipment on elevated pads.

We take a system using a central inverter as our baseline. We estimate that the area to be elevated is around five times the footprint of the actual inverter, or 125 ft^2 for a 1-MW array and 1,000 ft^2 for a 10-MW array.

This measure only applies to ground-mounted systems, as roofs typically have existing drainage systems. This measure represents the total cost of installing equipment on 18" deep square concrete pads. In the field, pads may not need to be uniform depth due to topographical features. Also note that this cost is compared to not pouring any concrete for an elevated pad (baseline of nothing).

Table 24 gives cost calculations for ground-mounted and roof-mounted systems.

Table 24. Cost Calculation for Measure 11: Install Equipment on Elevated Pads

Metric	1 MW	10 MW	Source
Concrete Area (ft^2)	125	1000	Product specifications http://files.sma.de/dl/25585/SC1000CP-DEN1751-V23web.pdf and conversations with site operator.
Array Size (W)	1000000	10000000	Assumption
Concrete Area (yd^2/W)	0.0000139	0.0000111	Calculation and unit conversion
Concrete Depth (yd)	2.0	2.0	Assumption
Concrete Volume (yd^3/W)	0.0000278	0.0000222	Using above value, based on 18” deep concrete.
Concrete Cost per Area (materials and labor) ($/yd^3)	375	375	RS Means “concrete in place, foundation mat, >20 C.Y.” All in cost.
Measure Cost (¢/W)	1.0	0.83	Calculation from previous two rows

There is a trend, even with larger systems, in shifting to the use of string inverters rather than central inverters. String inverters are typically mounted on a vertical surface high enough to be above the storm surge height and thus would not use elevated pads. This measure considers central inverters only.

It is important for the site engineer to define the storm surge height and ensure to raise all equipment at least to that height. Steel platforms would also be an effective solution and would likely be more cost-effective (Lopata 2019).

3.12 Measure 12: Ensure Site Has Well-Designed and Maintained Drainage Systems

While there are various types of drainage systems, moving water away from the foundation of a ground-mounted PV system and preventing flooding in the installation area can significantly aid storm survivability. Flooding after a severe weather event can lead to longer system downtimes and also block roads to sites, preventing access of maintenance crews and delivery of equipment necessary to get an array back online. Figure 16 shows how extreme site flooding can be after a hurricane. It also shows how critical it is to raise inverter boxes above standard design height—these inverters just barely escaped potential damage from high water, possibly saving significant repair costs and system downtime.

Figure 16. Post-hurricane flooding.

Photo from Strata Solar Services

Vegetation planning can play a role in preventing PV system washout. This will lead to more soil stability and less runoff, though maintaining the vegetation may incur higher sustained O&M costs.

Due to large variability in sites and local conditions, it is not feasible to calculate a reliable cost for designing and maintaining drainage systems. Furthermore, this measure should be common practice and thus does not come with a cost premium. Well-designed drainage systems are crucial, however, and should be considered in and budgeted for in site design and maintenance plans.

3.13 Measure 13: Take Pre- and Post-Storm Measures

> "Pre-storm measures:
>
> - Perform a torque audit of all fasteners.
> - Power down all components by opening breakers, fuses, and switches.
> - Remove debris and tie down loose material in and around arrays.
>
> Post-storm measures before energizing the system:
>
> - Dry and clean all electrical systems.
> - Perform a torque audit of fasteners.
> - Test for electrical faults in all systems.
> - Replace all damaged electrical systems before energizing." (Robinson 2018)

Because of the variability in systems, these measures vary in cost substantially. At the very least, systems should be powered down before a storm. A torque audit before and after a severe weather event will greatly increase the survivability during and after a storm. The post-storm replacement costs for damaged electrical and structural systems will also vary greatly. Due to this, no cost estimates are available. In any case, these measures should be considered high priority, as they are very low cost compared to the benefit they provide—a torque audit is the cheapest of the measures analyzed in this report and can prevent significant damage to the system.

4 Cost Comparison of Measures

These storm hardening measures come with an added up-front cost. Some are simpler and less costly than others, while some measures also provide more structural strength benefit than others. When prioritizing measures, a system designer should consider both cost and structural benefit. It is important to perform a careful structural engineering analysis of the strength benefits of each measure compared to their costs and how they can help a system meet its design wind loads. Nevertheless, Figure 17 gives a comparison of the costs of each of the measures estimated in this report. These values are an attempt to provide an initial estimate of the cost premium for each individual measure. Combining measures can have cost savings compared to the combined costs of individual measures. Combining measures will also have impacts on the overall rigidity of the system.

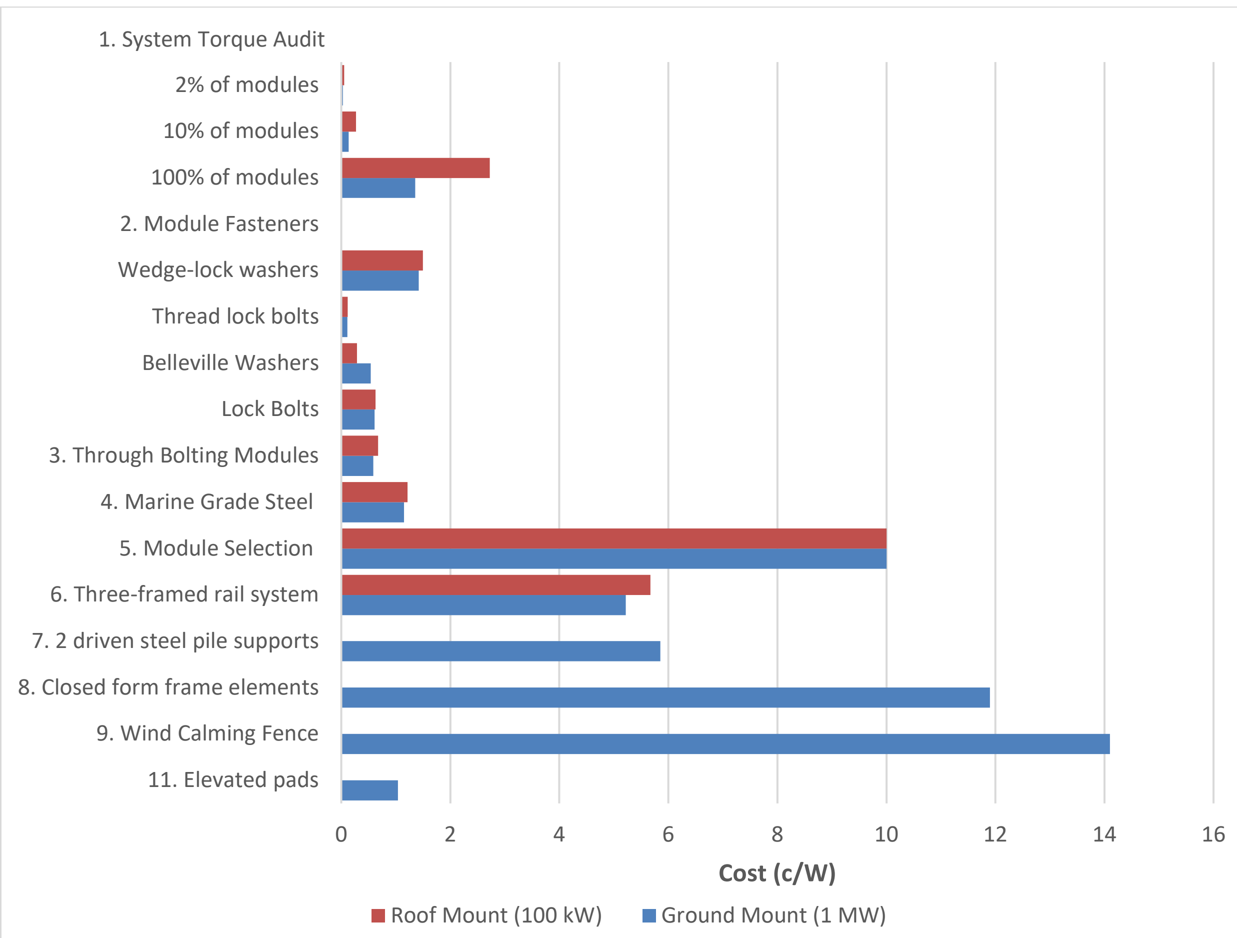

Figure 17. A comparison of the per-Watt premiums for each of the measures estimated in this report

In general, the core of the system measures appear to be less expensive than outside of system measures. Performing system audits and focusing on appropriate fasteners are the least expensive of the storm hardening measures we analyzed. In regions with a high likelihood of severe weather, however, additional measures, such as a three-rail system or two-pier mounting, may be necessary to protect a PV array.

We have low confidence in the high module premium estimate for the reasons mentioned in Section 3.5.

5 Costs of System Including All Measures

While each of these measures should increase the strength of a PV system, implementing several of the measures can have an even greater impact. Conversely, some measures may be redundant and unnecessary on individual installations. If a module is rated to 5,000 Pa uplift, say, that may be sufficient to withstand site conditions, perhaps obviating the need for a three-rail system.

There is no one-system-fits all solution and it is crucial for system engineers to design to the site conditions, project constraints, and the developer's acceptable level of risk.

In any case, a system installed featuring all of these measures is less likely to suffer as much damage in a severe weather event than one without. Table 25 gives the cost premium for implementing all 13 measures.

Table 25. Cost Premium of a PV System Containing All of the Recommended Measures Individually

Metric	Ground Mount 1 MW	Roof Mount 100 kW	Notes
Cost Premium of All Measures Combined (¢/W)	54	18	Fewer of these measures apply to roof-mount systems
Overall System Installed Cost (¢/W)	106	183	NREL System Benchmark
Percentage of Total System Cost	51%	10%	Calculation

An independent estimate cited storm hardening of a system using some similar measures to those analyzed in this report as

> "…that a 1 MW ground mount project on suitable soil and flat terrain in the Eastern Caribbean would incur an increase of approximately 5 percent in engineering, procurement, and construction (EPC) costs when these best practices are implemented versus the standard category IV rated installation… implementing the best resiliency practices would add approximately $90,000 in EPC costs to the budget. This overall project price increase is about the difference in module pricing from 2017 to 2018, and for Caribbean projects that procure modules later in 2018, the price drop could completely net out the additional resilient mitigation costs by year's end." (Stone 2018)

This system was installed with some similar measures to those described in this report, some different. Furthermore, while these values likely more accurately represent the cost of installing a system with multiple storm hardening measures in place than the values in Table 25, every system is unique and will require different design features and incur different costs.

6 Other Considerations

6.1 Modules

The recent trend in module manufacturing has been towards thinner and lighter aluminum frames. This has added advantages of using fewer raw materials and decreasing the shipping weight, but modules are weaker as a result. For instance, some older modules were manufactured with thicker frames and occasionally even with cross-bracing support frames (Figure 18). Reverting to techniques such as this could yield modules able to withstand higher uplift pressures.

Figure 18. An older PV module featuring thicker frames and cross supports. This design on today's modules would add strength.

Photo by James Elsworth, NREL

6.2 Through Bolt Pull-Out

With these lighter and thinner frames, the risk of "through bolt pull-out" is increased. With force on the module, through bolts could pull through the frame or off the flange of the module frame. Bolt holes are often drilled larger than needed, as well, necessitating other practices, such as using large washers to add surface area to the bolted joint. This is one of the major root failures in through-bolted PV systems and needs to be addressed through more attention to the module-racking bolted joint interface.

6.3 Wire Management

Securing electronic components during installation and conducting an electronics system audit before a storm could also help system survivability. In certain cases, wind has dislodged electrical wiring and connections, leading to more costly and longer repairs.

6.4 Insurance

Theoretically, a storm hardened system should be able to realize cost savings through reductions in insurance premiums. The life cycle costs of these proposed storm hardening measures could, in theory, be lower as a result. Furthermore, through some innovative, nascent financing mechanisms, these insurance savings may even be able to be made available upfront for investment in the higher initial costs. A report from Lloyd's of London proposes and describes four innovative insurance mechanisms that can be used to finance resilience efforts: "insurance-linked loan packages," "resilience impact bonds," "resilience bonds," and "resilience-service companies." (Lloyd's 2018)

6.5 Risk Acceptance

At some point, the costs of storm hardening an array for any conceivable site conditions will become prohibitive. An installer will never be able to ensure system survival in all conditions—sites are always subject to a force majeure event. The recommendations in this report should increase the likelihood of survival when compared to a baseline installation. Every installation is unique, as are the developers who must decide what level of risk they are willing to accept with their installation. Designing a more robust system will reduce the likelihood of failure and decrease the necessary repair costs, but this comes with a cost premium. Some installers may be willing to risk system failure or loss and potential higher rebuilding costs over the increased costs of a hardened system.

Critical facilities (hospitals, storm shelters, water treatment plants) will place a higher value on resilient power, because the consequences of power loss are higher. These facilities are some of the primary candidates for storm hardened PV installations.

6.6 O&M

While this report only specifically considers increases in up-front costs, it is also important to consider lifetime cost implications; investing in a stronger system upfront will almost always decrease O&M and repair costs in the future. Furthermore, with up-front costs of solar modules decreasing drastically in recent years, the outyear expenses weigh ever more heavily on system cost, emphasizing the importance of investing in better systems (NREL 2016).

PV systems in storm-prone regions assume greater risks, but also could potentially deliver greater benefits by providing power post-storm (as compared to a centralized grid reliant on fewer key assets—generation stations, transmission lines). These are important factors in calculating lifetime system costs (both monetary and societal).

6.7 Warranty and Liability

There may be warranty concerns with employing some of these measures. For example, module installation manuals may need to be consulted to determine if the manufacturer warranties different mounting and racking configurations (Figure 19). Retrofitting a system to incorporate these recommendations may also void system warranties.

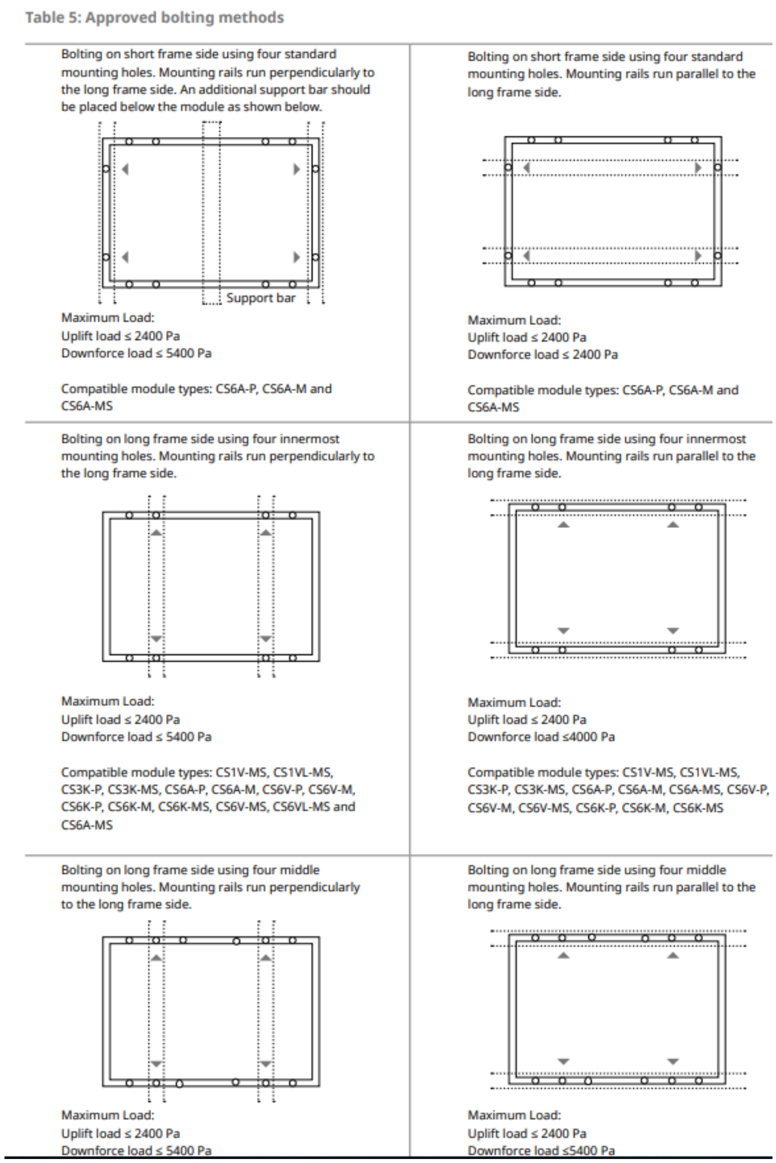
Table 5: Approved bolting methods

Bolting on short frame side using four standard mounting holes. Mounting rails run perpendicularly to the long frame side. An additional support bar should be placed below the module as shown below. Support bar Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 5400 Pa Compatible module types: CS6A-P, CS6A-M and CS6A-MS	Bolting on short frame side using four standard mounting holes. Mounting rails run parallel to the long frame side. Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 2400 Pa Compatible module types: CS6A-P, CS6A-M and CS6A-MS
Bolting on long frame side using four innermost mounting holes. Mounting rails run perpendicularly to the long frame side. Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 5400 Pa Compatible module types: CS1V-MS, CS1VL-MS, CS3K-P, CS3K-MS, CS6A-P, CS6A-M, CS6V-P, CS6V-M, CS6K-P, CS6K-M, CS6K-MS, CS6V-MS, CS6VL-MS and CS6A-MS	Bolting on long frame side using four innermost mounting holes. Mounting rails run parallel to the long frame side. Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤4000 Pa Compatible module types: CS1V-MS, CS1VL-MS, CS3K-P, CS3K-MS, CS6A-P, CS6A-M, CS6A-MS, CS6V-P, CS6V-M, CS6V-MS, CS6K-P, CS6K-M, CS6K-MS
Bolting on long frame side using four middle mounting holes. Mounting rails run perpendicularly to the long frame side. Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 5400 Pa	Bolting on long frame side using four middle mounting holes. Mounting rails run parallel to the long frame side. Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤5400 Pa

Figure 19. Module installation manual showing different approved attachment methods and rated loads for each

Image from Canadian Solar

Some of these measures may raise liability disputes as well. If an independent company installs a wind fence around a PV array, say, which entity would be liable for damage to the system? Will insurance still honor or treat original agreements?

6.8 Alternate Clamping and Bolting Methods

Clamp location, length, number, and type can have significant impacts on the loads a module can tolerate (Figure 19); it is possible to increase the wind load a module can tolerate simply with different clamping configurations. This may skirt the need to pay for a hardier module or invest in a three-rail racking system, for example, if altered clamping alone is enough to meet the design wind loads.

7 Conclusion

Severe weather poses a threat to all power system infrastructure; however, there are advantages to using solar PV as a resilient power source, such as its distributed nature and no need for fuel. To fully benefit from these advantages, it is vital that solar arrays are designed and installed in a manner that gives them the greatest likelihood of surviving severe weather events and thus being able to produce power afterwards.

Solar PV has grown and developed so rapidly, and the industry has become so competitive, that sometimes common design, engineering, and construction practices are overlooked in an effort to reduce up-front costs and complete projects quickly. The main takeaway from discussions with site designers, installers, and operators was the importance of designing for resilience and designing and building a system correctly from system inception (rather than retrofitting it after install). Ensuring a high standard of maintenance is also crucial.

Bolted joints were regularly cited as the most common initial point of failure in systems that did fail in severe weather (and for some in nonsevere weather as well). These fasteners and how they specifically support PV systems requires special attention, further research, and appropriate standards development. In general, new, stronger, and clearer standards could support and drive the PV market towards more robust system design.

Furthermore, while installing a storm hardened PV system will likely come with a cost premium over a baseline system, costs of system components have decreased drastically over the last several years. As a result, O&M (planned and unexpected) shares a higher burden of the lifetime system costs. While this report focuses on upfront cost premiums, hardening measures will reduce outyear expenses for systems in any location, leading to O&M savings and a reduction in lifecycle costs. Most importantly, when weighing investment in storm hardening measures, their costs must be compared to the extreme costs of system damage or total loss at the hands of a storm.

This report offers suggestions to help a PV system survive a severe weather event or decrease the damages resulting from a storm. We cannot predict all the failure modes and environmental conditions an installation will face over its lifetime and following the recommendations in this report in no way guarantees a system's survival. This report aims to shed light on the suite of measures from which PV designers and developers can choose to customize their sites through providing direct comparisons between various storm hardening measures.

The value resilient power systems can deliver in the face of severe weather events and after their impacts is ever more important. Severe weather-prone regions could benefit from resilient solar PV. Solar PV offers many benefits as a resilient power source. To be effective as a resilient power solution, though, the system needs to survive the weather event. To survive, it must be designed, installed, and maintained to a higher standard. While doing so will likely come with an increased cost, in many cases the benefits may outweigh the cost.

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