U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# PV System Owner's Guide to Identifying, Assessing, and Addressing Weather Vulnerabilities, Risks, and Impacts

September 2021

FEMP
Federal Energy Management Program

# Disclaimer

# Acknowledgments

This document was sponsored by the U.S. Department of Energy's (DOE) Federal Energy Management Program (FEMP) and the General Services Administration (GSA). Lawrence Berkeley National Laboratory (LBNL) is the lead author with GSA and the National Renewable Energy Laboratory (NREL) as contributors, and FEMP is the corresponding author. This activity was supported by an AAAS Science & Technology Policy Fellowship served at DOE/FEMP.

### Project Team Members

Gerald Robinson, Program Manager, LBNL

Kevin J. Watson, Research Associate, LBNL

Kevin Powell, Director, GSA Center for Emerging Building Technology

Joseph Skach, GSA Project Manager, GSA

James Elsworth, Research Engineer, NREL

Rachel Shepherd, FEMP Program Manager, DOE

Nichole Liebov, AAAS Science & Technology Policy Fellow, DOE

### Limitations on Use of this Document

This document is intended as a guide. It is not a code or regulation nor is it intended to be prescriptive in its scope or implementation. It is intended to act as a guide to establishing a structured process to plan, inspect, identify, document, and address commonly known vulnerabilities found in, on, and around solar photovoltaic systems. Consequently, it should not be considered exhaustive to encompass every actual or potential condition that may be found in the field. Its intended audience is experienced agency facility management professionals, their professional consultants, funding, asset, and portfolio professionals, as well as decision makers. Any material or language used from this guide in developing a construction, services, or other contract must be reviewed by local facility, technical, and procurement professionals and verified regarding their applicability to the particular and unique circumstances found at each facility or site.

Neither GSA, LBNL, NREL, nor DOE accepts any responsibility for use of materials or language from this guide in a prescriptive manner as part of a construction, maintenance, services, or other type of contract between system owners and other third parties.

Any products or manufacturers mentioned are for illustrative purposes only and are not endorsed by the federal government.

# List of Acronyms

| | |
|---|---|
| AC | alternating current |
| ASTM | American Society for Testing and Materials |
| BOD | basis of design |
| BOM | bill of materials |
| BOS | balance of system |
| CA | corrective action |
| CALE | corrective action labor estimate |
| CALR | corrective action labor range |
| CAME | corrective action materials estimate |
| CAMR | corrective action materials range |
| DC | direct current |
| DIN | Deutsches Institut für Normung |
| DOE | Department of Energy |
| EL | electroluminescence |
| EPDM | ethylene propylene diene monomer |
| FEMA | Federal Emergency Management Agency |
| FEMP | Federal Energy Management Program |
| GSA | General Services Administration |
| HVAC | Heating, ventilation, and air conditioning |
| IEC | Independent Electrical Contractors |
| IBC | International Building Code |
| I-V | current-voltage |
| IR | infrared |
| kW | kilowatt |
| kWh | kilowatt-hour |
| LBNL | Lawrence Berkeley National Laboratory |
| mph | miles per hour |

| | |
|---|---|
| MW | megawatt |
| NEC | National Electrical Code |
| NEMA | National Electrical Manufacturers Association |
| NREL | National Renewable Energy Laboratory |
| O&M | operations and maintenance |
| Pa | pascal |
| PV | photovoltaic |
| PVC | polyvinyl chloride |
| QMS | quality management systems |
| R&A | repair and alteration |
| SSF | site-specific factor |
| SSLC | site-specific labor cost |
| SSLR | site-specific labor range |
| SSMC | site-specific materials cost |
| SSMR | site-specific materials range |
| SWM | stormwater management |
| UL | Underwriters Laboratories |
| W | watt |

# Executive Summary

More than 3,000 solar photovoltaic (PV) systems have been installed at federal facilities to serve site loads and have proven to be cost-effective, reliable, and safe power sources. In order to ensure that a PV system performs optimally throughout its 30-year service life, system owners must identify any latent vulnerabilities that might make a PV system susceptible to weather damage.

This guide is intended to help federal managers and personnel responsible for PV system operations and maintenance through the process of identifying and correcting commonly known vulnerabilities in order to reduce life-safety risks and improve performance. This guide covers many of the most common vulnerabilities that have been discovered from field auditing existing solar PV systems. It also provides example corrective actions to facilitate any needed upgrades. Procedures for estimating costs of these corrective actions and guidelines for hiring consulting engineers and contractors to perform the required measures are often an important part of the process and are covered in detail.

Guide users should know that this is not an exhaustive list of vulnerabilities and corrective actions. Agencies may discover additional vulnerabilities and corrective actions through following the process outlined in this guide.

# Table of Contents

# List of Figures

# List of Tables

# Codes and Standards Referenced

| Code # | Code Purpose |
|---|---|
| ASTM 1830-15 | American Society for Testing and Materials (ASTM) 1830-15 applies to the standard test methods for snow and wind loading resistance on photovoltaic (PV) modules. |
| DIN 65151 | Fastener code covering vibrational loosening. Describes use of the Junker test as a testing method. |
| IEC 62548 | Independent Electrical Contractors (IEC) 62548 applies to design requirements for PV systems including direct current (DC) wiring. |
| IEC 62852 | Applies to connectors used in the DC wiring of PV systems. |
| TUV | TUV is an international company that tests, inspects, and certifies technical products, systems, and facilities in an effort to mitigate potential hazards and avoid damages. |
| UL 1703/61730 | Underwriters Laboratories (UL) 1703/61730 applies to the testing characteristics of PV modules. |
| UL 2703 | Applies to the standard for racking assemblies, clamps/module fasteners, and grounding lugs used in PV systems. |
| UL 6703 | Applies to connectors used in the DC wiring of PV systems. |
| NEC/NFPA | The National Electric Code (NEC) provides standards for the safe installation of electrical wiring and equipment in the United States. Codes are updated every three years and adopted regionally. It is part of the National Fire Code series produced by the National Fire Protection Association (NFPA). |

# 1 Introduction

There are approximately 3,000 PV systems on federal sites throughout the country and in U.S. territories. Since 2010, there has been significant growth in the PV industry, with many new entrants. Currently, codes and standards do not reflect field experience. There are many minor and major deficiencies (e.g., structural, electrical, civil) that make existing solar PV systems vulnerable to forces present in weather events.

Severe weather events are not just endemic to one region such as the tropics. From coast to coast, every region of the United States and U.S. territories experiences significant storm events (e.g., high winds, hail, lightning, snow).

Post-storm damage field inspections conducted by U.S. Department of Energy (DOE) national laboratories show that failures are occurring from various weather events.

This is a process guide that is intended to help federal managers and consultants identify the most common vulnerabilities that could lead to mild to catastrophic loss of PV systems during severe weather events. It will:

- Focus on deficiencies that can be field corrected to not only improve general performance and safety but also lead to enhanced durability of PV systems during weather events
- Provide tools to enable asset owners to field-survey and document existing PV systems for vulnerabilities—a risk-impact category is assigned to each type of vulnerability
- Help users understand the type and severity of severe weather that can occur at any given location
- Help users identify scope and costs—each vulnerability has a prescribed repair scope of work and associated estimated cost factor that range from minor (low-cost) items that can be self-performed by the agency to major (moderate-to-high cost) repairs requiring skilled technicians
- Provide a standard scope of work and basis of design (BOD) language to help agencies when procuring outside services from consulting engineers, contractors, and operations and maintenance (O&M) providers
- Provide pre- and post-storm O&M measures to reduce the potential for damage to a PV system during a severe weather event and post-storm O&M measures to help speed up the recovery of a PV system damaged during a storm
- Emphasize safety in responding to damage from severe weather events.

The target audience of this guide is federal facility managers and engineers as well as consultants and contractors responsible for operating and maintaining PV systems at federal facilities. This guide is also for contractors and consultants that may work closely with federal facility managers and engineers seeking to take proactive and preemptive actions to reinforce PV systems before weather or storm damage occurs. This guide is also for federal agencies and their stakeholders seeking to recover or rebuild their PV system due to weather or storm damage.

It is assumed that users of this guide are experienced facility managers, facility engineers, contractors, and/or consultants.

# 2 How to Use This Guide

## 2.1 Guide Structure

As stated in Section 1, this guide is intended to help agency managers and consultants identify, prioritize, and correct existing vulnerabilities of a PV system while also aiming to reduce the complexity of this process. The guide is organized into the following sections:

- Hiring a consulting engineer to assist in the process of identifying and correcting vulnerabilities
- Increasing weather awareness to understand the potential impacts of severe weather events
- Preparing the proper documentation prior to conducting the field audit
- Conducting a field audit to identify existing vulnerabilities
- Prioritizing which vulnerabilities to correct based on the risk-impact methodology
- Identifying costs associated with each corrective action that corresponds to a vulnerability
- Identifying simple O&M measures that can be done before and after a severe weather event that can minimize damage to a PV system and speed up the post-storm recovery process
- Hiring a contractor that can assist with correcting PV system vulnerabilities and storm recovery
- Financing and procurement options for PV system reinforcement or rebuild projects.

The variety of tools and methods described in this guide can further assist users with identifying and correcting PV system vulnerabilities. The end of the guide has the following appendices that enhance its effectiveness:

- Appendix A: Weather Awareness Worksheet
- Appendix B: Field Audit Form
- Appendix C: Basis of Design Template Language.

**HELPFUL TIP**

As discussed in Section 1, there are different types of users of this guide. There are **three common scenarios** where an agency will need this guide:

1. Agency seeks to be proactive and fix existing vulnerabilities in its onsite solar PV system(s)
2. Agency seeks to minimize damage to their PV system from an impending storm event such as a hurricane, blizzard, or derecho (See Section 8 for pre-and post-storm O&M measures)
3. Agency seeks to recover and/or rebuild their PV system from damage caused by a recent storm event (See Section 8 for storm recovery guidance).

### 2.1.1 Process Flow Diagram

The process to identify and correct vulnerabilities can be complex; however, a goal of this guide is to categorize the process into the successive steps shown in the Process Flow Diagram (Figure 1).

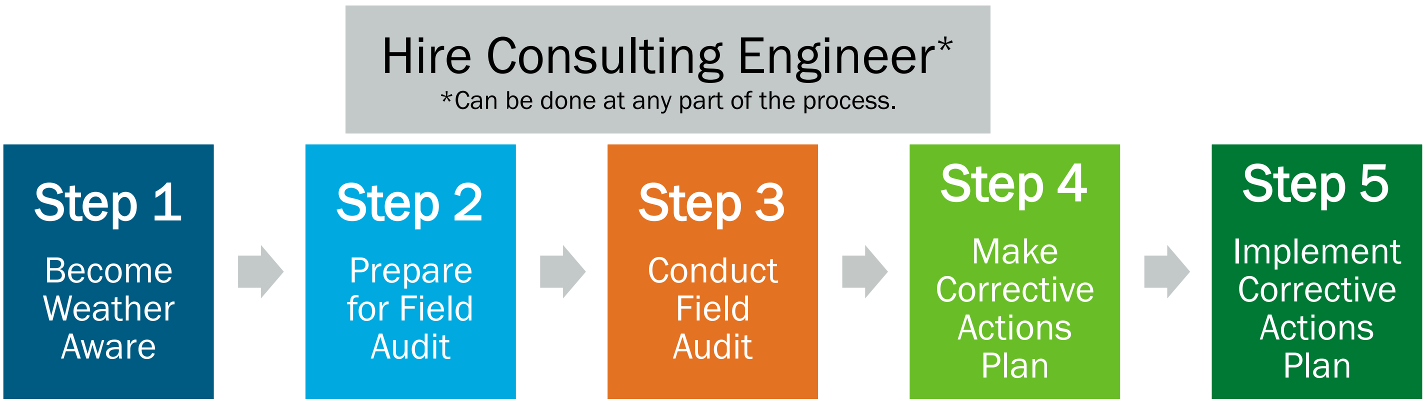
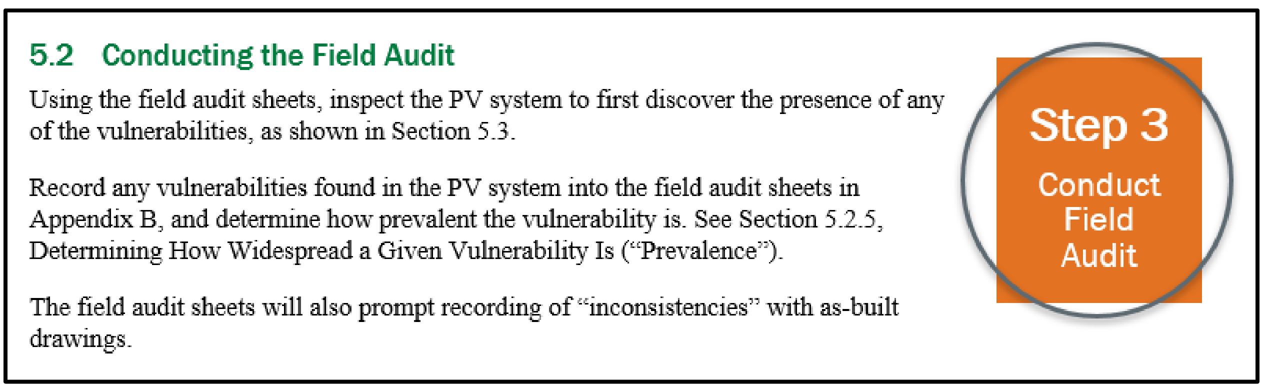



**Figure 1. Process Flow Diagram**

#### 2.1.2 Process Flow Diagram Excerpts

Guide users will see excerpts from the Process Flow Diagram at the top of corresponding sections. In the example in Figure 2, the Step 3 box is inserted at the beginning of the Conducting the Field Audit section. This will indicate which step in the process the user is in.



5.2 Conducting the Field Audit

Using the field audit sheets, inspect the PV system to first discover the presence of any of the vulnerabilities, as shown in Section 5.3.

Record any vulnerabilities found in the PV system into the field audit sheets in Appendix B, and determine how prevalent the vulnerability is. See Section 5.2.5, Determining How Widespread a Given Vulnerability Is ("Prevalence").

The field audit sheets will also prompt recording of "inconsistencies" with as-built drawings.



**Figure 2. Excerpt of process flow diagram**

## 2.2 Risk-Impact Methodology: Assessing Risk Levels

In Table 3, an estimated risk-impact assessment is provided for each vulnerability to help users assess the risk impacts of three main categories: (1) safety risk (i.e., life-safety), (2) performance risk, and (3) financial risk. Figure 3 provides an example. Readers should consider risk type and level (low, moderate, or high) in prioritizing the identified vulnerabilities.

### 2.2.1 Type of Risk

There are three major types of risk identified in this guide for each vulnerability: safety, performance, and financial.

1. **Safety Risk:** Bodily harm to persons and property
2. **Performance Risk:** PV system failure (e.g., the system goes offline and becomes unavailable permanently or for an extended period of time). This can extend to the entire system (100% performance loss) or just affect a certain part of it (e.g., ~50% performance loss).
3. **Financial Risk:** Incurring avoidable costs. This risk denotes the potential cost of repair, rebuild, or sometimes replacement of the solar PV system and other government property.

### 2.2.2 Level of Risk

The relative level of risk (low, moderate, and high) is distinguished with three colors: red for "high risk;" orange for "moderate risk;" and green for "low risk." The level of risk for each vulnerability is based on the potential damage if the vulnerability results in a failure.

### 2.2.3 Interpreting and Using the Estimated Risk-Impact Methodology

The example in Figure 3 shows the potential for poor installation practices to lead to damage of PV and other DC wires. If the vulnerability resulted in a failure (i.e., a metal wire tie cut through wire insulation and caused an electrical fault), the impacts to safety, performance, and financial costs would be high, low, and moderate, respectively.

| |
|---|
| Safety– High risk |
| Performance – Low risk |
| Financial – Moderate risk |

**Figure 3. Estimated risk-impact diagram for "poor installation practices leading to damage of PV and other DC wires"**

# 3 Hiring a Consulting Engineer

Hire Consulting Engineer

## 3.1 When a Consulting Engineer Is Needed

There are instances when a consulting engineer will need to be retained to devise a repair or rebuild. Government facility personnel can use this guide to identify if a vulnerability exists and then retain a qualified engineer to design and specify a repair.

Although there are likely other situations not contemplated by this guide, here are five instances in which a consulting engineer should be retained:

1. Agency managers, facilities engineers, and/or O&M contractors lack time or expertise to successfully inspect an existing PV system.
2. Failures with fasteners and bolted joints are a prominent vulnerability and one in which simple corrective actions are insufficient to resolve the vulnerability.
3. It is suspected that the PV system has significant structural deficiencies that will require a qualified engineer to design the extensive reinforcement scope required.
4. The manufacturer of an affected component (e.g., racking assembly) will require evidence before allowing modification to strengthen a PV system.
5. Wiring issues on the DC and/or alternating current (AC) sides continue to cause outages and/or the wire scheme is based on an architecture that is no longer supported (e.g., bipolar-inverter DC wiring scheme).

### 3.1.1 Need for Experienced and Specialized Engineers

Hire only engineers that have the requisite credentials and experience working on solar PV systems. See the sample language in Appendix C: Basis of Design Template Language.

**HELPFUL TIP**

Another good source of engineering services can be a qualified O&M contractor. Agencies may choose to include site inspections and repairs in the scope of work of an O&M contract.

## 3.2 Important Qualifications for a Consulting Engineer

There are four types of specialized engineers that may need to be retained, depending on the vulnerability and corrective action involved. The fast-growing solar PV industry has outpaced the ability of codes and standards-making committees to capture key lessons learned in updates. Simply following current codes and standards is **not** adequate and engineers with direct experience with solar PV systems are required. It is recommended that these requirements be applied even in situations where engineers are subcontractors to a prime contract holder. The following qualifications should be sought for all types of consulting engineers when undertaking the following work:

1. Understanding severe weather events (e.g., hurricanes, severe thunderstorms) and how these storms can affect the resilience of a PV system (Process Flow Diagram - Step 1)
2. Helping with the site audits and documentation (Process Flow Diagram - Step 2)
3. Working with the agency to prioritize corrective actions (Process Flow Diagram - Step 3).

#### 3.2.1 Bolted Joint Engineer Qualifications

1. Minimum of five years' experience designing bolted joints similar to those found in common PV racking assemblies
2. Direct experience with PV module mounting and racking assembly applications
3. Demonstrated knowledge of the challenges surrounding critical bolted joints in solar PV systems
4. Evidence of leadership in engineering through publications, as well as codes and standards work.

See the "How to Find a Bolted Joint Engineer" section for resources on how to contact a qualified bolted joint engineer.

#### 3.2.2 Structural Engineer Qualifications

1. Extensive design experience working with PV systems and severe weather
2. Experience working with racking assembly manufacturers' product lines to implement retrofits and changes needed to improve durability
3. Understanding of where existing codes and standards are limited. The engineer must never rely on calculations that are performed to meet code, and instead call upon wind tunnel testing and computational fluid dynamics.

#### 3.2.3 Civil Engineer Qualifications

1. Experience with the unique landscape, foundation, and siting of ground mounted PV systems
2. Experience interpreting common flood maps and local information to select equipment elevations and stormwater management features. The engineer must understand the rationale behind what flood levels are prudent beyond use of a simple Federal Emergency Management Agency (FEMA) lookup table.

#### 3.2.4 Electrical Engineer Qualifications

1. Experience with designing the electrical aspects of solar PV systems similar in size and complexity to the PV system under investigation
2. Experience with repowering and redesigning existing solar PV systems.

## 3.3 Manufacturer Approval on Product Retrofits

There are two primary scenarios where a facility manager may need to consult with manufacturers to obtain concurrence on needed modifications:

1. The proposed modification might void the existing product manufacturer's warranty
2. The original construction warranty period has expired, and the installation contractor will no longer honor their warranty of workmanship per the contract.

**HELPFUL TIP**

In cases where the manufacturer's involvement will be required, it is likely the agency will need to retain the services of a consulting engineer to coordinate with the manufacturer's engineers.

# 4 Increase "Weather Awareness"

**Step 1**

Become Weather Aware

While facility managers are most likely aware of weather events that impact their sites, a full accounting of such events will help make sure all damaging weather elements are identified. Appendix A contains a worksheet designed to help agencies take a full accounting of all the possible weather events at a site. This will allow agencies to conduct their "due diligence" towards identifying and correcting PV system vulnerabilities.

## 4.1 Wind as a Primary Damaging Element

Wind is the most common damaging weather element among many others (e.g., flooding, lightning, hail, snow). However, it is also the most complex force to understand and plan for, and varies greatly based on the storm type (e.g., hurricane, tornado, derecho) that produced it. The following factors must be considered when planning for corrective actions:

1. Comparing wind speeds between different types of storms and the common damage done by each is not a useful metric for PV systems. For example, even F0-rated tornadoes on the Fujita scale with wind speeds of less than 73 miles per hour (mph) can easily destroy a PV system, while the same wind speeds from a hurricane would do little damage. This is due to the high-pressure differentials generated by a tornado in a short distance.

2. Wind damage depends on factors such as the topography of the site and the tilt of the array. PV arrays with high tilt angles on exposed roof areas can be damaged by relatively low wind speeds.

3. Module mounting fasteners that are of inadequate strength will fail even at low wind speeds, based on field audits of damaged PV systems.

**HELPFUL TIP**

Remember that PV systems are subjected to the same types of severe weather events your facilities will encounter, and may even experience more severe impacts depending on their location and orientation.

## 4.2 Instructions for How to Become Weather Aware at a Site

1. Use the weather worksheet in Appendix A.

2. Follow the links provided to look up the values (e.g., wind speed, frequency).

3. Record the values in the worksheet.

4. Compare the values found in the tables to summarize the weather events that must be accounted for.

# 5 Assessing Vulnerabilities

**Step 2**
Prepare for Field Audit

## 5.1 Collecting and Reviewing System Documentation

Prior to conducting a field audit, collect and review all original documentation of the PV system that includes but is not limited to:

1. Original design documents
2. As-built drawings
3. Approved product submittals
4. Equipment manuals (e.g., inverters, modules, meters)
5. Commissioning reports
6. O&M log records
7. Performance data (preferably more than one year)
8. Photo records.

That information will be valuable for assessing vulnerabilities and identifying corrective actions, if required. It will first be used to verify that what was installed was "as specified" and "as approved." Some differences between design and as-built drawings might include items such as array layout, wiring configurations, or brand of PV modules.

### 5.1.1 Missing As-Built Drawing Sets

It is highly recommended that missing as-built drawings be replaced, as they can be useful for O&M contractors servicing the PV system. They also can help a consulting engineer if any repairs are needed, as these drawings typically have complete information on the PV system.

**HELPFUL TIP**

If a consulting engineer will be involved with reinforcing the PV array(s), then the site should consider tasking the engineer to produce new as-built drawings of the PV system.

### 5.1.2 Prepopulating Audit Sheets (Appendix B) to Reduce Field Work

Before entering the field, it is recommended that the audit sheets (found in Appendix B) be prepopulated to the greatest extent possible. This is important for auditing of such common components as bolted joints and wire management clips.

## 5.2 Conducting the Field Audit

**Step 3**
Conduct Field Audit

Using the field audit sheets, inspect the PV system to first discover the presence of any of the vulnerabilities, as shown in Section 5.3.

Record any vulnerabilities found in the PV system into the field audit sheets in Appendix B, and determine how prevalent the vulnerability is. See Section 5.2.5, Determining How Widespread a Given Vulnerability Is ("Prevalence").

The field audit sheets will also prompt recording of "inconsistencies" with as-built drawings.

### 5.2.1 Safety

*Potential Shock Hazards*

Inspections must be undertaken by qualified and trained electrical technicians. Electrical shock hazard symbols are placed throughout this guide, particularly in the Field Audit Instructions sections, to remind the user that the inspection of solar PV systems presents electrical shock hazards, and all personnel should proceed with caution.

*Safety Training Required*

Audits should be conducted by facility personnel and/or electrical technicians that have requisite training that matches the activities involved with the audit activities described herein. Audits may involve the use of basic tools to measure values on roofs, ladders, and around ground mounted PV systems.

**HELPFUL TIP**

Under no circumstances shall any untrained personnel or a consultant touch **<u>any</u>** electrical component of a PV system, including both AC and DC sides of the system, regardless of whether or not it is presumed de-energized.

**<u>SPECIAL SAFETY NOTICE: STORM-DAMAGED PV SYSTEMS</u>**

**Handling of Electrical Components**

Under no circumstances shall any untrained personnel or a consultant touch **<u>any</u>** electrical component of a PV system, including both AC and DC sides of the system, regardless of whether or not it is presumed de-energized.

**Danger from Electrical Components After Storm Damage**

Storm-damaged PV systems are dangerous because torn wires and other damaged electrical components may feed electricity into unpredicted pathways (e.g., metal racking, module frames, wet surfaces, neighboring heating, ventilation, and air conditioning [HVAC] equipment, and conduit). Some designs utilize high voltage DC wiring (e.g., 600–1,000 volts), which can be dangerous. Any PV system that has been storm damaged should be considered unsafe until rendered safe by a qualified electrician/technician before any field inspection is done.

**Danger from Loose/Damaged Components**

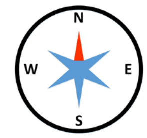
Loose/heavy components of a PV system, if touched, could come dislodged and fall atop a site inspector. This risk is especially a concern for solar shaded carports. If on a sloped roof, any modules or parts that can fall present a risk of serious injury to personnel below. Ground areas below sloped roofs and carports should be blocked off from pedestrian use with caution tape and barriers.

### 5.2.2 Basic Tools Needed to Conduct a Field Audit

Conducting a field audit requires a basic set of tools, shown in Table 1.

Any products or manufacturers mentioned in this section are for illustrative purposes only, and are not endorsed by the federal government.

**Table 1. Field Audit Tools**

| Tool | Uses | General Cost | Example |
|---|---|---|---|
| **Inclinometer** | Used to measure the tilt of the PV array | <$20 or use smartphone app |  **Figure 4. Inclinometer** *Source: Apex Instruments* |
| **Compass** | Used to confirm the orientation of the PV array in relation to the direction of due south | Use compass or smartphone app |  **Figure 5. Compass** *Source: Kevin J. Watson, Lawrence Berkeley National Laboratory (LBNL)* |
| **Metal Gauge Reader** | Used to measure the thickness of sheet metal in various parts of the PV system, like the racking assembly | <$5 |  **Figure 6. Metal gauge measures thickness of metal** *Source: Amazon* |
| **Current-Voltage (I-V) Curve Testing Device** | Used to examine module performance along a power curve | >$5,000 |  **Figure 7. I-V curve tracer** *Source: Solmetric* |
| **Handheld Infrared (IR) Imaging Camera** | Used to detect hot spots in electrical equipment and modules. See Section 5.2.3 for minimum specifications of an IR camera | >$5,000 |  **Figure 8. Infrared imaging camera** *Source: FLIR* |
| **Digital Torque Wrench with Data Collection Output** | Used to provide accurate torque settings to bolted joints and fasteners, saves field data and provides downloadable reports | ~$200 to $500 |  **Figure 9. Digital torque wrench** *Source: Home Depot* |

### 5.2.3 Imaging Tools and Methodologies for Module and Electrical Equipment Inspections

Two types of professional imaging inspections must be performed by trained imaging professionals. Training is required to effectively perform the imaging tests and interpret the results.

Use of IR imaging is a well-established and common practice in the inspection of electrical equipment (e.g., disconnect switches, service panels), as seen in Figure 10. IR imaging is now used extensively for the inspection of solar modules and DC wiring (Figure 11). However, this type of inspection requires trained personnel and highly specialized scopes.

1. **IR imaging:** This imaging can be done using aerial or handheld cameras. It is used to identify hot spots on modules and can spot many different types of failure modes. Many module failure modes will show a thermal hot spot viewable by scope. While an untrained technician (using the right IR camera) can see hot spots on the face of a solar module, it requires a trained imaging professional to properly inspect and interpret the resulting images and data. Facilities engineers commonly use IR cameras to inspect electrical equipment for hot spots. The same type of inspection can be used on module connectors and junction boxes to identify hot spots.

2. **Electroluminescence (EL):** Another imaging technology used less often than IR imaging to identify the extent of cell cracking is electroluminescence. It is typically only used if there is suspicion of widespread physical damage to the modules. This is done by ground, aerial, or laboratory techniques that require expensive equipment, extensive setup, and a high degree of skill to operate.

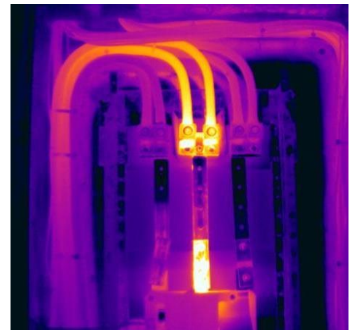


**Figure 10. Hot spot detected on busbar with IR camera**

*Source: Infrared Imaging Service, LLC*

**Figure 11. Hot spots detected in PV modules with IR camera**

*Source: Western Infrared*

*Storm Damage and Aerial Inspections*

If there is concern about significant module damage from a storm event (e.g., hail, wind, ice, snow) that may not be easily identifiable at ground level, consider conducting inspections via aerial photography (e.g., drone or aircraft).

### 5.2.4 Walking through the Site

The first part of the site audit is a visual inspection that consists of walking through, identifying, and documenting every vulnerability using Section 5.3 as a basis for the audit. It is important to note that no list is comprehensive, as specific vulnerabilities can arise based on unique circumstances at a site. Guide users should document any identified vulnerability, including any that are not listed in Section 5.3.

Pictures should be taken of any vulnerability found, including any identifying information (e.g., information plates with serial and model numbers) on components like inverters and modules.

*Components*

The auditor should **never** walk, climb, or lean on any modules to inspect interior fasteners or repair other inaccessible components that are found in the interior part of a PV array (Figure 12). If interior access is required in order to perform a repair for an existing solar array that is flat and contiguous or located on low-sloped roofs, always follow the manufacturer's instructions. In instances where instructions are not provided, agency managers should attempt to contact the manufacturer. In instances where the manufacturer is not willing or able to provide instructions, the following method can be used to access interior zones:

Lay a pathway of 4" thick 4' X 8' sheets of extruded polystyrene board (XPS) from the perimeter of the array to the area in need of repair. One person can access the interior of the array by crawling on the foam board. Crawling distributes the weight of that person across the wide surface area of the 4' X 8' sheets. Do not walk on top of the foam as this would damage the cells and greatly reduce the useful life of the module.

**Figure 12. Never walk or lean on a module, as damage can occur**

*Source: Longi Solar*

#### 5.2.5 Determining How Widespread a Given Vulnerability Is ("Prevalence")

Because even small PV systems can have thousands of individual components, it may not be practical to take exact counts of hardware components involved in a given vulnerability. Instead, obtaining enough information to gain a general sense of how widespread a vulnerability is may be sufficient. Prevalence involves estimating a proportion to the whole.

*Instructions for Establishing Prevalence*

1. Identify sections that are accessible to audit. These are usually sections that can be reached from the perimeter or through a walking path between rows.
2. Catalog the type and quantity of each type of component to be inspected.
3. Count the number of times a vulnerability is found during the field audit.
4. Divide the number of vulnerabilities by the quantity of that hardware item found in the audit area.
   a. If the vulnerability is found to exist among more than 5% of the hardware counted, then this should be considered "prevalent."

**Table 2. Levels of Prevalence**

| Relative Prevalence | |
|---|---|
| Not Prevalent | Less than 5% |
| Prevalent | 5%–10% |
| Moderately Prevalent | 10%–20% |
| Extremely Prevalent | Greater than 20% |

#### 5.2.6 Documenting Design Inconsistencies

The field audit sheets in Appendix B prompt the user to record vulnerabilities found during the field audit relative to what was designed, approved, and shown on as-built drawings.

### 5.2.7 First Movement Method of Fastener Field Auditing

The First Movement method is a torque auditing process applicable to bolted joints. It measures the torque value when a fastener is moved in the tightening direction.

The following procedure is recommended:

1. Using a metal marker pen, mark the top of the bolt nut and material as shown in Figure 13.

**Figure 13. Marked nut and washer for torque audit**

*Source: Bolt Science*

2. Set the torque wrench to a value well above that specified by the drawing and/or racking installation manual.
3. With the torque wrench, turn the nuts in the "tighten" direction until the nut moves a few degrees. Record the torque value seen upon first movement at this point into the field audit sheet. Make sure the audited fastener is left at the proper torque value.
4. Document if any signs of corrosion on the nut and bolt are visible.

## 5.3 Vulnerabilities Commonly Seen in the Field

The summary table below is meant to provide an overview to the user of the vulnerabilities and their associated corrective actions covered in this guide.

**Table 3. Summary of Vulnerabilities and Associated Corrective Actions**

| List of Vulnerabilities | Safety Risk | Performance Risk | Financial Risk | Associated Corrective Actions |
|---|---|---|---|---|
| **1. Fasteners and Critical Bolted Joints** | | | | |
| Vulnerability 1: Fastener loosening from transverse slip | High | High | High | Corrective Action 1: Replacing inadequate fasteners with rated locking fasteners |
| Vulnerability 2: Loss of fastener preload due to improper field assembly | High | High | High | Corrective Action 1: Replacing inadequate fasteners with rated locking fasteners |
| Vulnerability 3: Top-down module clamp assemblies with soft joint issues | Moderate | Moderate | High | Corrective Action 4: Fixing top-down clamp vulnerabilities |
| Vulnerability 4: Inadequate bolted joint design | Moderate | Moderate | High | Corrective Action 3: Modifying bolted joints in racking assemblies to avoid bolt shearing |
| Vulnerability 5: Top-down module clamps susceptible to vibrational loosening | High | High | Moderate | Corrective Action 4: Fixing top-down clamp vulnerabilities |
| Vulnerability 6: Module clamps and rails not installed properly | High | High | Moderate | Corrective Action 5: Modifying weak subframing with high deflection issues |
| Vulnerability 7: Top-down module clamps bent open due to inadequate strength | High | High | Moderate | Corrective Action 4: Fixing top-down clamp vulnerabilities |
| Vulnerability 8: Top-down module clamp failure leading to "row-domino" | High | High | Moderate | Corrective Action 4: Fixing top-down clamp vulnerabilities |
| Vulnerability 9: Use of back side clamping devices to fasten the module frames to rails | High | High | High | Corrective Action 6: Replacing specialty clamps and self-tapping sheet metal screws with through-bolts |
| Vulnerability 10: Deflection of subframing from heavy winds causing top-down clamps to fail and/or damaging mounted modules | Low | Moderate | Moderate | Corrective Action 5: Modifying weak subframing with high deflection issues |
| **2. Racking Assemblies** | | | | |
| Vulnerability 11: Use of clamping devices to fasten racking assembly together | Moderate | High | High | Corrective Action 6: Replacing specialty clamps and self-tapping sheet metal screws with through-bolts |

| | | | | |
|---|---|---|---|---|
| Vulnerability 12: Self-tapping sheet metal screws used to hold the racking assembly together | Moderate | High | High | Corrective Action 6: Replacing specialty clamps and self-tapping sheet metal screws with through-bolts |
| Vulnerability 13 - Presence of soft joints in the array's racking assembly | Moderate | Moderate | High | Corrective Action 2: Strengthening soft joints in racking Assemblies |
| Vulnerability 14: Unbraced racking assemblies causing bolted joint failures from large lateral movements | Moderate | Moderate | Moderate | Corrective Action 5: Modifying weak subframing with high deflection issues |
| **3. Special Considerations for Roof Mounted PV Arrays** | | | | |
| Vulnerability 15: Inaccessible and wind damage prone PV array | High | High | High | Corrective Action 7: Reconfiguration of PV array to allow interior access |
| Vulnerability 16: Inadequate structural attachment to building | High | High | High | Corrective Action 8: Adding mechanical attachments to the building structure to improve the structural integrity |
| Vulnerability 17: Mounting position of PV array resulting in high wind exposure | High | High | High | Corrective Action 9: Redesigning a PV system to reduce potential for damage from heavy wind forces |
| Vulnerability 18: Array tilts (>15°) resulting in high turbulence and front and back pressure on modules | Moderate | Moderate | Moderate | Corrective Action 10: Redesigning a PV system to a lower tilt angle to reduce potential wind damage |
| Vulnerability 19: Flexible PV array glued to roof membrane | Moderate | Moderate | High | Corrective Action 11: Removing and/or replacing a flexible PV system glued to the roof |
| **4. Modules** | | | | |
| Vulnerability 20: Damaged modules from inadequate resistance to wind/snow loading and hail | Low | High | Moderate | Corrective Action 12: Replace module(s) showing signs of degradation |
| Vulnerability 21: Cracked or failed backsheet | Low | Moderate | High | Corrective Action 12: Replace module(s) showing signs of degradation |
| **5. Wire Management** | | | | |
| Vulnerability 22: Improperly supported wires | High | Low | High | Corrective Action 13: Proper wire management support and protection |
| Vulnerability 23: Corroded grounding components due to environmental conditions or dissimilar metals | Moderate | Low | Low | Corrective Action 14: Ensuring the equipment grounding system is functional |
| Vulnerability 24: Poor installation practices leading to damage of PV and other DC wires | High | Low | Moderate | Corrective Action 15: Replacing damaged DC wiring |

| | | | | |
|---|---|---|---|---|
| Vulnerability 25: Animals nesting under modules, chewing and damaging wires | Moderate | Low | Moderate | Corrective Action 16: Removing and preventing animal nesting under the PV array |
| Vulnerability 26: PV connector failure | Low | Low | Moderate | Corrective Action 17: Replacing damaged PV connectors |
| **6. Electrical Enclosures and Conduit** | | | | |
| Vulnerability 27: Electrical equipment located below the site's 100-year flood level | High | High | High | Corrective Action 18: Relocating electrical equipment above 100-year flood level to prevent flooding |
| Vulnerability 28: Conduit draining water into downhill electrical equipment from flooded uphill locations | Moderate | Moderate | Moderate | Corrective Action 18: Relocating electrical equipment above 100-year flood level to prevent flooding |
| Vulnerability 29: Common issues with electrical enclosures | High | Low | High | Corrective Action 19: Replacing inadequate and/or corroded electrical equipment |
| Vulnerability 30: Conduit-related vulnerabilities | High | Low | High | Corrective Action 20: Preventing damage to the PV conduit |
| Vulnerability 31: Field-applied labels and markings showing signs of significant degradation | Moderate | Low | Low | Corrective Action 21: Replacing all field labels and markings that are showing signs of degradation |
| **7. Topography** | | | | |
| Vulnerability 32: Unobstructed wind forces on the PV system | High | High | High | Corrective Action 22: Install wind calming fence to reduce wind forces on PV system |
| **8. Site Management** | | | | |
| Vulnerability 33: Clogged roof drainage system | Moderate | Low | Moderate | Corrective Action 23: Inspecting and clearing roof drains to avoid electrical and structural damage |
| Vulnerability 34: PV equipment in direct contact with the roof membrane | Low | Low | Moderate | Corrective Action 24: Protecting against and/or repairing roof damage from PV system |
| Vulnerability 35: Loose debris and/or equipment scattered around a PV array | High | Low | Moderate | Corrective Action 25: Clearing debris and securing loose equipment around the PV system |
| Vulnerability 36: Improper site stormwater management around a ground mounted PV system | Low | Low | High | Corrective Action 26: Improving stormwater management around a ground mounted PV array |
| Vulnerability 37: PV array covered in snow, making it susceptible to damage | Moderate | Moderate | Moderate | Corrective Action 27: Clearly mark the presence of the PV array and its boundaries to prevent damage to snow-covered modules |

### 5.3.1 Fasteners and Critical Bolted Joints

Provides information on vulnerabilities related to fasteners and critical bolted joints of a solar PV system.

**Critical Bolted Joints**

Many bolted joints in a PV system (Figure 14) can be classified as "critical." Critical bolted joints are those that maintain the structural integrity by holding the racking assembly together and securing modules to frame rails. Failure of critical bolted joints presents serious risk to life and property, particularly in severe weather-prone regions.

Issues with fasteners appear to be the most common and potentially serious vulnerability that must be addressed in a PV system. Fastener issues with roof mounted systems are a significant operational and safety concern, as modules and structural components that fail can result in dangerous wind-borne debris in addition to system failure.

Bolted joint design is a specialized discipline of engineering. In the automotive industry, bolted joint engineering is a mature practice governed by well-developed quality management systems (QMS). These QMS practices in the automotive industry govern the entire life cycle of a bolted joint from design, installation, and on through operation of the vehicle. With the rapid development of the PV industry, QMS, as well as codes and standards that govern these practices, currently lag behind other industries. Given that the solar PV industry is still maturing, all critical bolted joints and fasteners in a PV system must be checked for common weaknesses found in these joints.

**Figure 14. Bolted joints highlighted in red circles**

*Source: Jon Ness, Matrix Engineering*

*Vulnerability 1: Fastener loosening from transverse slip*

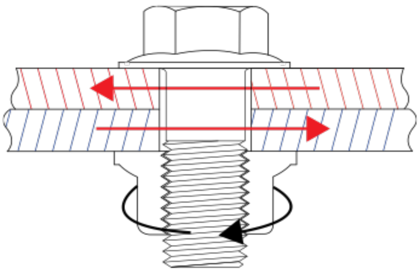


**Figure 15. Transverse slip causing bolt loosening**

*Source: Jon Ness, Matrix Engineering*

**Figure 16. Structural element of array with bolts missing from transverse slip**

*Source: Gerald Robinson, LBNL*

**Description:** Structures exposed to wind take on vibrations and vibrate at a regular frequency. This can commonly be observed on a sailboat with sail masts and rigging taking on a vibration when exposed to winds.

When two surfaces are clamped (fastened) together, this vibrating can cause movement between the two parts, which is commonly referred to as ***transverse slip***. When the forces of transverse vibration are strong enough, the friction between the two parts can be overcome and result in movement between the clamped surfaces, as seen in Figure 15. Transverse slip is very effective at causing loosening of threaded fasteners to a degree that the entire fastener can fail.

Loosening from transverse slip can affect many of the common critical fastened joints found in both module mounting and racking assemblies.

Bolted joints in the perimeter rows of a PV array are subjected to stronger wind-induced turbulence and vibrations than interior rows. This is due to a ***self-shielding phenomenon*** where perimeter rows act as a windbreak to interior rows. In storms with winds greater than 70 mph, all array rows may show signs of vibrational loosening.

### Corrective Action 1

Replace inadequate fasteners with rated locking fasteners

**Field Audit Instructions:**

1. Inspection of all threaded fasteners should be done using the ***Finger Loose*** and ***First Movement method,*** as described in Section 5.2.7.
2. Determine the quantity of loose fasteners using steps described in Section 5.2.5.
3. Take count of the prevalence of finger-loose fasteners.
4. Use a torque wrench to determine the prevalence of inadequately torqued fasteners.
5. Determine if a formal assembly process was used involving a torque wrench with prescribed values. Torque values may be found on as-built drawings and/or product specification manuals. If the field audit shows a wide range of values coming from the First Movement method, then it can be concluded that no formal assembly process was used during construction.
6. Make sure to photo-document all visible conditions.

Bolted joints with vibrational loosening will have any of the following unmistakable characteristics:

- Threaded fastener assemblies (nuts, washers, and/or bolts) will be found on ground or roof surfaces directly underneath or near the arrays. Heavy rain can scatter fasteners or wash them aside. A thorough walk around the array and perimeter areas should be conducted to spot fasteners.

  Fasteners found on the ground can be matched quickly to those still in place in the racking assembly. This provides a quick clue as to which bolted joints have the greatest number of fastener losses. It can also provide important information on what is taking place on "stranded" sections of the array (e.g., not accessible from the perimeter of the array).

  For arrays that only can be accessed from the perimeter, it is important to look under the structures to identify fasteners that have fallen out and are lying on surfaces underneath.

- As shown in Figure 16, there will be fasteners missing from bolted joints, leaving empty holes. Some racking systems come predrilled with extra holes to accommodate adjustability of such features as tilt angle. There are clear differences that can be seen between holes that had once contained fasteners and those that are "extra" to provide adjustability. Previously occupied fastener holes will show clear markings of the bolt head, nut, and or washer scarring of metal around the hole (Figure 16). Compare sections of racking that are intact to those with missing fasteners. A consultant or O&M contractor may need to review as-built drawings, installation manuals, and product submittals to understand where fasteners should be placed in each critical bolted joint. Confirm that the location, quantity, and type of fasteners are as specified.

- Loose fasteners are those that are in the process of disassembly from wind-induced vibrations but are still populating the bolted joint holes. Upon inspection, some fasteners will be loose to the touch and can be hand-turned freely without tools. Nuts will often spin freely on severely loosened fasteners.

*Vulnerability 2: Loss of fastener preload due to improper field assembly*

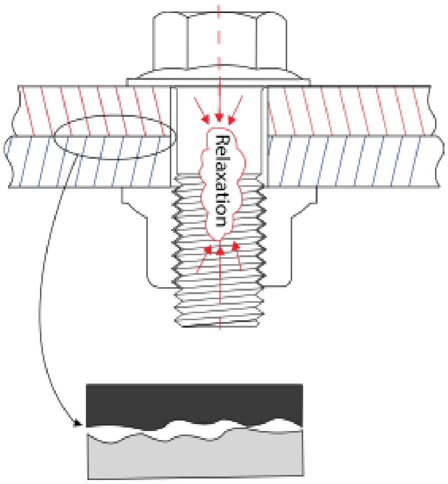



**Figure 17. Loss of preload on the fastener**

*Source: Jon Ness, Matrix Engineering*

**Description:** When a fastener loses preload (and thus the ability to clamp and hold joint surfaces together under friction), the friction between bolted joint surfaces drops and becomes susceptible to transverse slip generated at almost any wind speed. This will in turn result in fastener loss discussed above in Vulnerability 1. Maintaining design clamping forces in a bolted joint requires that the fastener achieve and maintain preload on the fastener. Achieving and maintaining preload with conventional threaded fasteners is complex and requires the following design and construction features:

- Fastener assembly should be engineered to accommodate some joint relaxation from metal embedment that occurs between surfaces (Figure 17).
- Installer is trained to use rated assembly tools that can apply a metered torque value.
- Thread assembly lubricant is used to prevent galling of thread metals.

**Corrective Action 1**

Replace inadequate fasteners with rated locking fasteners

**Field Audit Instructions:**

While looseness of fasteners is common among other vulnerabilities, improper field assembly and loss of preload is the result of highly random tightening that is indicative of manual wrenches and impact drivers.

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. Using the First Movement Torque Audit method, look for any signs of fasteners having been assembled with a torque value.
3. Determine if a formal assembly process was used involving a torque wrench with prescribed values. Torque values may be found on as-built drawings and/or product specification manuals. If the field audit shows a wide range of values coming from the First Movement method, then it can be concluded that no formal assembly process was used during construction.
4. Look for signs of extremely overtightened fasteners, which can often be the result of impact drivers. In addition to high torque values found during audit, there might be damage to the fastener or bolted joint such as deflected metal.

*Vulnerability 3: Top-down module clamp assemblies with soft joint issues*

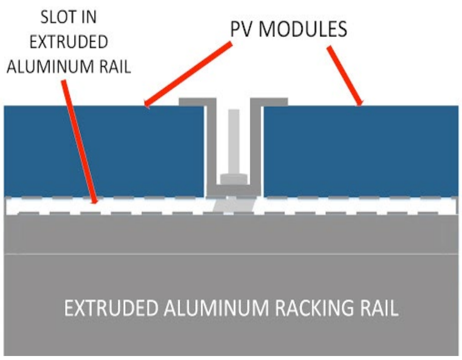



**Figure 18. Common top-down clamp with soft joint characteristics**

*Source: Kevin Watson, LBNL*

**Figure 19. Slotted T-bolt**

*Source: Grainger*

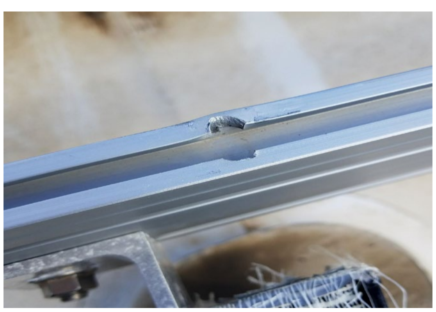


**Figure 20. Top-down clamp with T-bolt torn out of rail**

*Source: Gerald Robinson, LBNL*

**Description:** Taken together, the top-down clamp assemblies, module frame, and underlying mounting rails (which are most often aluminum) present what bolted joint engineers characterize as "soft-joints." One or more of these aluminum parts will relax when the fastener (often a slotted steel T-bolt) reaches pre-load. Wind pressures on the front or back of the module would also likely compound deformation on one or more of the aluminum parts (Figure 18).

Slotted T-bolts (Figure 19) are often made of a specific grade of stainless steel. In order for the top-down clamping assembly to adequately hold modules in place under compression, the bolt would need to be pre-loaded (put under tension). However, the pre-load on the bolt cannot be achieved as the soft aluminum components yield or bend. This causes the joint to relax before the bolt achieves or sustains its rated pre-load. In the case of Figure 20, the extruded aluminum yielded under pressure to the point of total failure with the T-bolt breaking through.

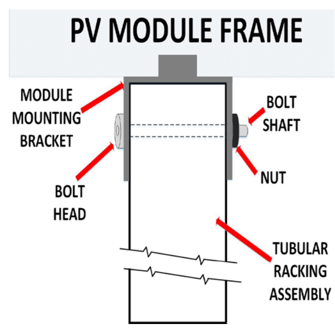



**Figure 21. Racking assembly design with soft joint and tube stock**

*Source: Kevin J. Watson, LBNL*

There is another commonly observed hardware setup that is similar to a soft joint. Figure 21 depicts a bracket attached to a square tube on one end and attached to a module on the other. Both ends of the bracket suffer from soft-joint issues. This setup has presented persistent fastener loosening problems.

## Corrective Action 4

Fixing top-down clamp vulnerabilities

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. Catalog the type and quantity of each bracket mounted to tubular stock prior to entering the field into the audit sheet.
3. Follow the tips and instructions provided in Vulnerability 1.
4. Remove bolt, nut, and washer passing through bracket and look for chronic loosening, using the finger tight test.
5. Using the First Movement method, identify if there is a wide range of torque values, ranging from finger loose to overtightened. In this case, overtightened would be well above the torque values shown in the installation manuals and design documents.
6. Look for the following signs of deformation:

- Signs that wall of tube and bracket has been collapsed inward under the force of the nut and bolt
- Signs that bolt holes in tube wall have been elongated from movement
- Metal erosion from movement and friction.

*Vulnerability 4: Inadequate bolted joint design*

**Figure 22. Bolt shaft worn out by joint movement**

*Source: Bolt Science*

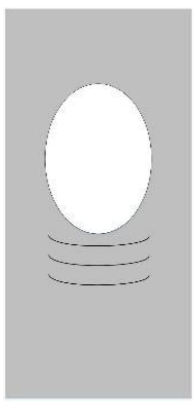


**Figure 23. Excessive hole elongation**

*Source: Kevin J. Watson, LBNL*

**Description:** When movement in a bolted joint occurs, the fastener can be abraded (most often a bolt shaft), resulting in weakening of the joint.

The movement can also abrade the fastener holes in brackets and clamp parts. The holes can become elongated, which in turn allows more joint movement and further metal loss to the point where either the bolt shaft shears off or the hole breaks through, leading to catastrophic failure.

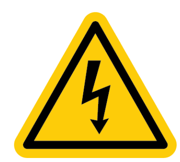
When enough metal is lost, the fastener is susceptible to failure from loading conditions during a weather event. "Shearing off" is a phenomenon occurring when the bolt fails under shear stress, which can result in total loss of the fastener. Look for fasteners that are still in place but are loose. Note and photograph any areas of the bolt shaft that are worn. These fasteners must be replaced.

A second clue and vulnerability for joints that have experienced a large amount of slip is elongation of bolt holes through the joint, which subjects the entire bolted assembly to vibration and torsional stress. Joints with elongated holes must be counted and then addressed during the repair phase. Note that depending on the component and the location of the elongated bolt hole, this could involve more expensive repair.

Corrective Action 3

Modify bolted joints in racking assemblies to avoid bolt shearing

**Field Audit Instructions:**



1. To determine "Prevalence" of this vulnerability, use Section 5.2.5.
2. Follow the tips and instructions provided in Vulnerability 1.
3. Look for bolts showing signs of metal loss (Figure 22) and/or bolt holes that have become elongated, torn out, or split open (Figure 23).
4. Note which types of bolted joints these vulnerabilities exist in. Note the pervasiveness of a vulnerability.
5. Note if the vulnerability is more prevalent in perimeter rows.

*Vulnerability 5: Top-down module clamps susceptible to vibrational loosening*

**Figure 24. Misaligned module clamp caused by vibrational loosening**

*Source: Gerald Robinson*

**Description:** Some styles of top-down module clamps are particularly vulnerable to vibrational loosening. As with other bolted joints, module fasteners can loosen when exposed to vibrations, causing modules to be "liberated" and thus pose a serious life-safety issue from flying debris, as seen in Figure 24. Modules that become liberated from racking also pose potential electrical hazards as the lead wires are severed, leaving exposed wires in contact with metal racking. In the presence of sunlight, this will create dangerous ground faults, as well as electrical shock and fire hazards.

Spotting top-down fasteners that have loosened from exposure to vibrations but are separate from other factors (soft joint vulnerabilities, embedment, installation) is difficult. These fasteners will be found finger loose, and either partially or completely disassembled from the joint. This vulnerability is very similar to Vulnerability 1.

Another indicator of possible vibrational loosening can be observed if serrated flange nuts are used. If the metal directly underneath the flange nut shows signs of scraping, that is a good indication of vibrational loosening.

Corrective Action 4

Fix top-down clamp vulnerabilities

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. Use the First Movement method to perform a torque audit—record both under- and over-torqued fasteners.
3. Note any signs of metal scrapping underneath flange nuts.

*Vulnerability 6: Module clamps and rails not installed properly*

**Figure 25. Module end clamp not properly installed or loosened from winds**

*Source: LG Energy*

**Description:** Improper installation of module clamps, both middle and end, can lead to failure. A variety of factors can contribute to the inadequate installation of these clamps.

Module mounting rails will often come with special thermal expansion joints that allow movement from thermal cycling without damaging the modules. The specifications and positioning of the expansion joints should be covered in the installation manual and/or the design drawings.

If they are missing or improperly installed, they will put forces on module clamps. Lack of thermal expansion unions can force end clamps off or partially dislodge them, as shown in Figure 25.

If even one top-down clamp is loose and/or not installed properly, a module can loosen over time from heavy winds and dislodge, becoming airborne and producing a life-safety and property threat.

Corrective Action 5

Modify weak subframing with high deflection issues

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. For a racking assembly using extruded aluminum module rails, use the installation manual and confirm the existence and location of the expansion joints. An expansion joint should be located at about every 25′ to 50′ of rail; the product manual should be consulted for exact specifications of the expansion joint locations.
3. When expansion joints are missing and not installed properly, or do not have the minimum gap, look for mid and end clamps that have been forced aside, such as those shown in Figure 25.

*Vulnerability 7: Top-down module clamps bent open due to inadequate strength*

**Figure 26. Bent module end clamp (right) compared to an unbent end clamp (left)**

*Source: Gerald Robinson, LBNL*

**Description:** Some top-down clamps may be inadequately designed to resist the load forces applied such as wind pressure on the back of modules that are susceptible to uplift. These clamps are often fabricated from aluminum and are small, with 1″ or less of clamp surface area.

Figure 26 compares two of the same aluminum end clamps, one of which has been bent open from wind forces (right) while the other is unbent. This bending process can be spotted even before the module becomes liberated, and replaced with a fastener option of sufficient strength.

**Corrective Action 4**

Fix top-down clamp vulnerabilities

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. For aluminum clamps, document the fastener by drawing a simple sketch and add the dimensions.
3. Document the number of clamps that are bent or displaced.

## *Vulnerability 8: Top-down module clamp failure leading to "row-domino"*

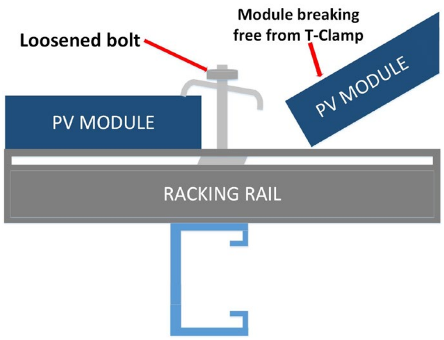



**Figure 27. Module mid-clamp failure causing adjacent module to dislodge from racking**

*Source: Kevin J. Watson, LBNL*

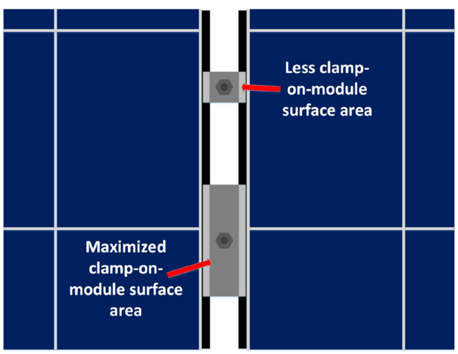



**Figure 28. Comparing module mid-clamp sizes**

*Source: Kevin J. Watson, LBNL*

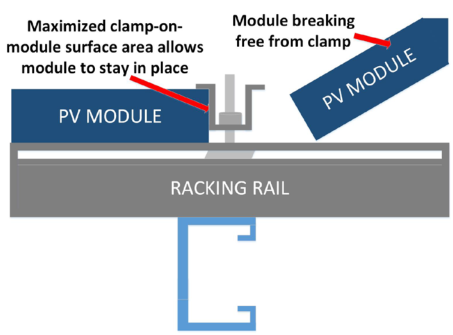



**Figure 29. Testing is needed to confirm if a U-shaped module clamp prevents row-domino effect**

*Source: Kevin J. Watson, LBNL*

**Description:** Some styles of module mid-clamps will not hold unless both modules are in place. If, for example, debris strikes an array and dislodges one module, the mid-clamp will tilt off the adjacent module. When one module is lost in a row, the full row of modules will be liberated, creating multiple modules that can become airborne in the wind. Some styles of top-down clamps are more susceptible to this vulnerability than others. Any clamp with a profile similar to that seen in Figure 27 is the most vulnerable, as this style lacks any feature to prevent the clamp from tipping off once the neighboring module is lost.

Another vulnerability to look for is top-down clamps that have little contact surface area with the module frame or glass (i.e., frameless modules). There are several styles of top-down clamps with very small profiles—some with as little as 1″ of clamp width. Small contact area means that even if the clamp is properly torqued, there is little surface friction and less ability of the clamp to secure the module to the racking. Figure 28 shows two module clamps in comparison; the top clamp has less surface area than the clamp on the bottom.

**Important Note:** It is not yet fully understood which fasteners will and will not prevent "row domino," as the testing needed has not yet been done. Testing standards have not been developed. The current assumption is that top-down clamps with large surface areas and a "U" (Figure 29) or "H" shape may do better, but testing is needed to make any firm conclusions. It has become evident from field audits that top-down fasteners that are highly susceptible have a profile similar to what is seen in Figure 27. There are likely other top-down clamp profiles that could be of concern.

### Corrective Action 4

Fix top-down clamp vulnerabilities

**Field Audit Instructions:**

1. If the vulnerability exists, it is likely pervasive throughout the entire array unless the contractor used a mix of different mid-clamps. This is unlikely, though it has been seen in the field.
2. Look for mid-clamps that have a profile similar to Figure 27, as they are the most susceptible to "row domino." Aluminum mid-clamps with a small surface (sometimes as small as 1″) should also be recorded in the field audit process.
3. Using a trained electrical technician or electrician, remove a module and retighten the mid-clamps. Check the mid-clamps holding only the one module and note how susceptible they are to holding the neighboring module. If the inspected mid-clamp appears vulnerable to loss, then this should be documented and photographed.

*Vulnerability 9: Use of backside clamping devices to fasten the module frames to rails*

**Figure 30. Inadequate sizes of clamps used to hold structural elements together**

*Source: Gerald Robinson, LBNL*

**Figure 31. Use of clamping devices on structural elements**

*Source: Gerald Robinson, LBNL*

**Description:** A few products have been or are currently sold that involve some kind of clamp to mount modules to underlying frame elements. These clamps mount the backside of module frames to the underlying racking rails. Attention should be paid to the efficacy of these products to safely hold the modules in place. Figures 30 and 31 show one example of a product that appears to have insufficient clamping strength in climates that experience even moderate wind events. If these systems are located in moderate wind zones, serious consideration needs to be given toward a reinforcement or replacement effort due to the life-safety implications.

If there is any possibility of modules becoming airborne and striking a pedestrian, then there is a potential for a life-safety issue that must be addressed immediately. Modules that are liberated from racking will leave string wiring torn apart, with energized copper exposed to metal parts. Once the storm passes and sunlight returns, this vulnerability could lead to ground and/or structure fires. These backside mounted module frame clamps are easy to spot. During the field audit, check underneath the array to spot one of these devices clamped to the module frame and underlying mounting rail.

In two examples examined by one of the authors of this guide, the TUV and UL 2703 rating provided covered electrical bonding but not mechanical strength. In one instance, the author found reference to a mechanical strength rating, but upon close examination the value provided appeared to be the tensile strength of the metal used to fabricate the clamp. The maximum clamping forces were not provided.

### Corrective Action 6

Replace specialty clamps and self-tapping sheet metal screws with through-bolts

**Field Audit Instructions:**

1. Backside mounted module clamps are easy to spot and should be fully documented with pictures and sketches.
2. Record the metal gauge of the clip and then the gauge of metal purlin they are mounted to.

*Vulnerability 10: Deflection of subframing from heavy winds causing top-down clamps to fail and/or damaging mounted modules*

**Figure 32. Row of modules experiencing high deflection**

*Source: First Solar*

**Figure 33. A C-channel distorted from high winds, leaving the frame rails deflected**

*Source: Gerald Robinson, LBNL*

**Figure 34. Top-down module clamp bent due to wind forces**

*Source: Andy Walker, NREL*

**Figure 35. High wind deflection caused several module glass top-sheets to fracture**

*Source: Gerald Robinson, LBNL*

**Description:** As structural engineering and construction practices are highly variable and are yet to be governed by a set of clear codes and standards, agency managers are likely to find racking frame members to be too weak to support modules in dynamic winds. Some racking systems lack adequate structural integrity, which can be from (1) use of light-gauge members that are torsionally weak, (2) light gauge frame members that are insufficient, (3) frame members with wide spacing, and (4) use of soft metal alloys.

Structural vulnerabilities with the underlying racking can lead to a number of failures. The impacts on fasteners will be addressed in this section, with broader structural vulnerabilities addressed in the "Racking Assemblies" section.

When solar modules are mounted to framing members that lack strength, severe deflection and twisting (Figure 32) will occur, causing fasteners to be levered open. Figure 33 shows a tilted fastener, which appears to have been forced off from the prying action during times when the framing members deflected. In cases where fasteners stay in place during episodes of deflection and twisting, modules may suffer from cell cracking or even shatter. Look for the following deflection clues:

**1. Top-down fasteners pried out and away from the module frame.**

In Figure 34, the mid clamp is showing signs of a prying action, causing the clamp to slide off and tilt away from the frame. If this vulnerability is found, it is a clue that can be combined with others to make a more definitive conclusion.

**2. Frame deflection when tested.**

In the field, pushing on racking from various angles and noting how easily frame members deflect is an indication of structural instability.

**3. Module glazing fractured.**

Modules mounted to racking rails with high deflection will sometimes have broken module glazing. Some modules will fall out as fasteners weaken while others may stay mounted and relieve the bending forces by cracking or even shattering (Figure 35).

Corrective Action 5

Modify weak subframing with high deflection issues

**Field Audit Instructions:**

1. Look for a common cold-rolled channel type: C-channel, hat channel, and Z-channel.
2. Using the metal gauge tool, record the metal thickness of each racking frame element.
3. Note the spacing intervals of the bracing and measure between each. Note each brace's method of fastening. How are the braces attached? Do they use self-tapping sheet metal screws or nuts and bolts? Are all the fasteners installed?
4. Perform a deflection test of an area as close to the center of two posts as possible. Carefully push on the front and then back side of the racking assembly and note any tendency to deflect.
5. Push on the racking from the east, west, and then north side. Note any movement from pushing on any of the sides. Note also any bolted joints that are loose and move freely when pressure is applied to the sides.
6. Look for top-down clamps that appear to be bent up and open. This might be seen most pronounced on end clamps.
7. Inspect for damage done to modules from subframe deflections. Using the IR scope, the cracked cells should appear as a hot spot and take the shape of the affected cells.
8. If there is evidence of extensive module cell cracking from the IR scope, an EL imaging consultant may be needed to determine which modules are affected. Any modules found with extensively cracked cells should be tagged with an indelible mark to facilitate future audits.
9. Modules with cracked cells are not necessarily candidates for replacement. Certain cracking patterns are more impactful on the long-term performance of the module than others. It takes time for performance issues to develop. Use an electrician to spot-check known modules with cracks using a purpose-built I-V curve testing meter.

### 5.3.2 Racking Assemblies

Provides information on vulnerabilities related to the racking assembly of the PV array (e.g., rails, C-channels).

*Vulnerability 11: Use of clamping devices to fasten the racking assembly together*

**Figure 36. View showing clamp size compared to the structural element**

*Source: Gerald Robinson, LBNL*

**Figure 37. Damaged clamp used to hold structural elements together**

*Source: Gerald Robinson, LBNL*

**Description:** Some racking assembly designs utilize clamps as a means to fasten structural members together, as seen in Figure 36. Given the critical nature of the frame-bolted joints, field audits have shown that these types of structural clamps are a significant concern for any array that is exposed to even moderate weather events.

Figure 36 shows the size of the clamp relative to the size of the C-channel, an important part of the racking assembly. The structural clamps are insignificant to the size of the C-channel, which was determined as a key cause of failure during the 2017 hurricane season. Figure 37 shows a structural clamp that was severely deformed from the forces exerted on the racking assembly.

**Corrective Action 6**

Replace specialty clamps and self-tapping sheet metal screws with through-bolts

**Field Audit Instructions:**

1. Look for clamps that are used to hold racking assembly components together. These need to be documented for gauge of metal. Photographs and a simple sketch with dimensions should be taken. Note any designations stamped into the metal (e.g., UL, TUV)
2. Compare the clamps to the product literature to make sure what was installed is as specified.
3. These designs may also use braces to stabilize framing. Count the number and positioning of the braces, and compare them to the drawings and/or product literature. Check the fasteners used to attach braces against those in the installation manual. Confirm if the type and quantity is the same as those specified from the installation manuals or engineer's drawings.

*Vulnerability 12: Self-tapping sheet metal screws used to hold the racking assembly together*

**Figure 38. Corroded self-tapping sheet metal screws used to hold racking assembly together**

*Source: Gerald Robinson, LBNL*

**Description:** The use of self-tapping sheet metal screws to fasten structural elements in the racking assembly together is a serious vulnerability that must be corrected. These screws are often made of a special hardened galvanized steel. The galvanized coating can scrape off during installation. Hardened steel is very susceptible to corrosion (Figure 38).

### Corrective Action 6

Replace specialty clamps and self-tapping sheet metal screws with through-bolts

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. Self-tapping sheet metal screws are often used extensively. Catalog where and how many are used.
3. Note the age and condition of screws. Check for signs of corrosion.
4. Note and photograph the corrosion around the screw. Determine if any of the screws are loose.

*Vulnerability 13: Presence of soft joints in the array's racking assembly*

**Figure 39. Example of common tube stock used in racking systems**

*Source: Home Depot*

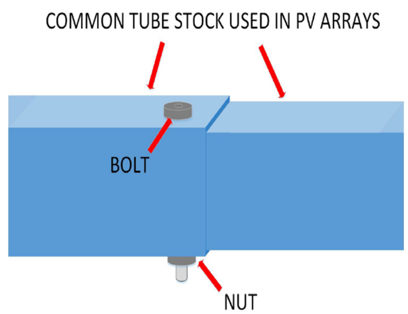



**Figure 40. Exterior view of common soft joint and bolting system**

*Source: Kevin J. Watson, LBNL*

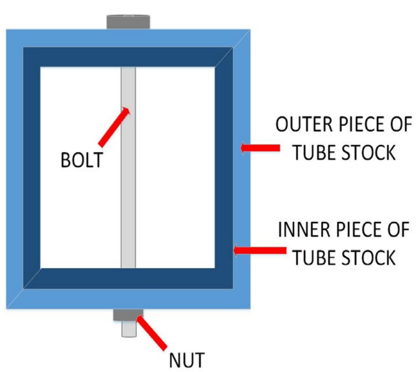



**Figure 41. Sectional view of classic soft joint and bolting system**

*Source: Kevin J. Watson, LBNL*

**Description:** Many racking systems utilize tubular (tube) or square stock as the main racking element (Figure 39). When tube stock is used extensively, several types of soft joints may be present in an array.

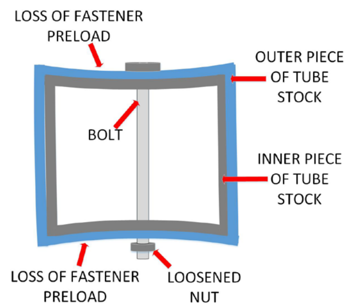



**Figure 42. Classic soft joint and bolting system collapsing under clamping forces**

*Source: Kevin J. Watson, LBNL*

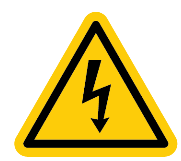
Some racking systems utilize a type of slip joint created when one tube or square stock of metal slides and fits inside another, allowing field adjustments (Figures 40 and 41).

It is very difficult for a threaded fastener to be placed, tightened, and achieve and maintain preload with any kind of tube stock. The wall of the tubular stock collapses under the clamping forces of the fastener, resulting in loosening. Special attention is required to investigate loosening of fasteners (Figure 42).

## Corrective Action 2

Strengthen soft joints in racking assemblies

**Field Audit Instructions:**



1. Look for tubular stock in the framing.
2. Note and photograph any through-bolting and check for finger-loose fasteners.
3. Look for any tubular frame elements where the walls have collapsed in, as shown in Figure 42.
4. Remove the fastener temporarily from a few bolted joints and note any signs of elongated holes. Photograph and note this vulnerability on the field audit sheet.
5. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.

*Vulnerability 14: Unbraced racking assemblies causing bolted joint failures from large lateral movements*

**Figure 43. No lateral bracing causes undue stresses on bolted joints**

*Source: IAEI Magazine*

**Description:** Racking assemblies that are not designed and/or constructed with braces to resist lateral movement will put stresses on the bolted joints (Figure 43). In these instances, the bolted joints should be inspected, as they have the potential to fail. Failures will show signs of bolt shear and/or hole elongation. There could also be signs of vibrational fastener loosening.

It is critical to note that simply upgrading fasteners with bolted joints that are exposed to powerful lateral forces will not solve underlying problems.

Corrective Action 5

Modify weak subframing with high deflection issues

**Field Audit Instructions:**

1. Gently push on the array racking to note lateral movement. Push from the east, west, and north sides. Note which joints move. Note any sounds that come from bolted joints as the array moves. Movement will be in the bolted joint and will make the sounds of metal surfaces rubbing.
2. Examine the bolted joints that show signs of movement. Check the fasteners for looseness. Temporarily remove a fastener and examine the bolt and bolt holes for signs of shear and elongation, respectively.
3. Note and photograph any bent parts of a bolted joint.

### 5.3.3 Special Considerations for Roof Mounted PV Arrays

Provides information on unique vulnerabilities for roof mounted PV arrays.

**Background**

Given the high risks of life-safety issues, roof mounted arrays must be given special attention during field audits in order to spot all significant vulnerabilities. The types of vulnerabilities include but are not limited to:

1. Vulnerabilities presented by ballasted roof arrays, including instances where ballasting is combined with some mechanical attachment points to a building
2. Arrays mounted in positions that result in exposure to accelerated winds, turbulence, and extreme positive/negative pressure differentials
3. No access to interior of array.

*Vulnerability 15: Inaccessible and wind damage-prone PV array*

**Figure 44. This array design provides no interior access for maintenance and repairs**

*Source: Gerald Robinson, LBNL*

**Figure 45. A similar array design provides no access for maintenance and is susceptible to wind lift**

*Source: Gerald Robinson, LBNL*

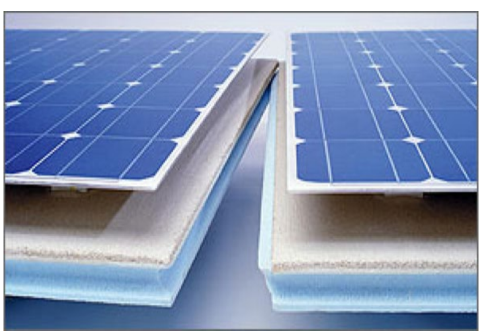


**Figure 46. A cross section of array design that allows for limited interior access**

*Source: Powerlight*

**Description:** Though they are not currently on the market, a very popular concept for roof arrays sold broadly in the 2001–2012 timeframe. These products were believed at the time to offer many cost and roof compatibility advancements in roof arrays. The design involved mounting an unframed solar module atop interlocking polystyrene insulation and a layer of fire-rated cementitious material that also provided weight and ballasting. The arrays were held together under tension through cables, and the perimeter wire trays were designed to act as wind shields. Designers of concepts like this believed that the arrays could be completely self-ballasted, with no mechanical fasteners to the roof structure, and that the ballasting, interlocking system and perimeter wire tray/wind shielding were adequate.

Field experience has shown that this array type is vulnerable to wind events. There are several installations of this style of array that remain in service and pose a significant concern around dislodgement during moderate to severe wind events. Figure 44 above shows a roof array located in New York where large sections of the array became dislodged during a routine summer thunderstorm.

Even in cases where the wind does not remove sections of this style of self-ballasted arrays from the roof altogether, there are instances of some movement. There is concern that these arrays can shift slowly over time, leading to damage of the underlying roof membrane and/or strain on the DC wiring.

### Corrective Action 7

Reconfiguration of the PV array to allow interior access

**Field Audit Instructions:**

1. Draw a simple sketch of roof array(s) and note the rough distance from the perimeter to the interior of the array.

2. Note on the drawing the presence and location of cabling running through the array.
3. Note the general location of each point of the mechanical attachment to the building.
4. Compare the attachments and cabling found in the field against those shown on the as-built drawings and note differences on the field sketch.
5. Photograph and note on the field sketch any weed growth.
6. Interview facility staff about any ongoing roof leaks blocked off by the PV array.
7. Look at the roof condition around the perimeter of the array. Photograph and note any unusual roof decay from chemical reactions, dirt buildup, and plant or moss growth.
8. Note the condition where roof membrane sections overlap to create seams. Look for signs of separation at seams.

*Vulnerability 16: Inadequate structural attachment to the building*

**Figure 47. Ballasted roof array**

*Source: Solar Power World*

**Figure 48. Ballasted roof array destroyed from high winds**

*Source: Renewable Energy World*

**Description:** On low-sloped roofs, ballasted roof arrays (Figure 47) have become popular as a means to reduce roof penetrations. This results in less maintenance and reduces the potential for water leaks during severe weather events like hurricanes and blizzards. Ballasted PV systems use heavy blocks, typically made of concrete, to hold the array in place. This is done in lieu of mechanical attachments to the roof structure.

Unfortunately, in regions that experience moderate to severe wind events, ballasted PV systems can experience damage, as seen in Figure 48, and potentially cause significant property damage and pose very serious life-safety issues. The original designs did not account for powerful wind dynamics common to low-sloped roofs. Hybrid designs employing both ballasting and mechanical attachments to the building structure can be a preferable way to reduce roof penetrations while not relying solely on ballasting.

### Corrective Action 8

Add mechanical attachments to building structure to improve structural integrity

**Field Audit Instructions:**

1. Ballasted arrays are easily identifiable, as they will have rectangular blocks, usually made of concrete, in the racking assembly.
2. Look at the back of each row of modules and confirm the presence of ballasting blocks.
3. Identify if any part of the racking assembly is mechanically attached to the roof's structure.
4. Look for any signs that the PV system has moved as a result of heavy wind forces by noting any scraping that has occurred with the underlying roof.

*Vulnerability 17: Mounting position of a PV array resulting in high wind exposure*

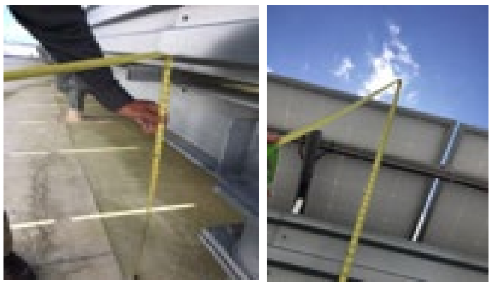


**Figure 49. Elevated PV array highly exposed to wind damage**

*Source: Gerald Robinson, LBNL*

**Figure 50. A similar PV array design elevated above the parapet, making it susceptible to heavy winds**

*Source: Gerald Robinson, LBNL*

**Description:** Elevation of the PV array above the roof deck will expose the array to full unobstructed wind speeds and possibly winds that accelerate over and around a building and the parapet. Wind speeds flowing up and over a building accelerate exposure of an array to forces higher than the recorded wind speeds found in nearby weather stations.

The top edge of the array in Figure 49 is situated at 11′ elevation above the roof deck. This array was exposed to 70 mph winds and severely damaged during a 2017 hurricane.

Figure 50 shows a PV system on a four-story building located in a hurricane-prone region. The array was mounted to a subframe assembly, leaving the bottom of the array at a 3' elevation off the roof deck.

Make note of arrays that protrude fully or partially above the parapet.

### Corrective Action 9

Redesign PV system to reduce potential damage from heavy wind forces

**Field Audit Instructions:**

1. For any array mounted above the elevation of the roof parapet, measure and record the height of both the lower and upper edges of the array from the roof surface.
2. Measure and record the height of the parapet from the roof surface.
3. Determine the slope using a smartphone app or inclinometer.
4. Note any loose or damaged fasteners.

*Vulnerability 18: Array tilts (>15°) resulting in high turbulence and front and back pressure on modules*

**Figure 51. High tilt of modules makes the array more susceptible to wind damage**

*Source: Gerald Robinson, LBNL*

**Figure 52. Low positioning of the module's top rail and a high array tilt can make the modules susceptible to wind damage**

*Source: LG Energy*

**Description:** Some PV system designers will select tilt angles that maximize annual solar kilowatt-hour production without consideration to the high pressures and turbulence created by these tilt angles. Tilt angles will often be equal to the latitude of the site, and so angles of 35° or more are commonly seen in the field, as seen in Figures 51 and 52.

These high tilt angles produce enormous pressures when exposed to wind events and will create life-safety risks, the most serious of which is modules becoming airborne debris. Turbulent wind forces cause a rapid cycling of pressure on the modules. Over time, this constant change in pressure can cause microcracking in the modules.

Most common angles on roof arrays range from 5° to 10°. This range of angles is common, as wind pressures and inter-row shading is low, and roof power density of watts per square foot is higher. An array with a tilt angle significantly higher than 10° is a vulnerability that should be noted during the field audit.

**NOTE:** In areas with heavy snow, high tilt angles might also be used as means to shed snow to increase system performance.

Corrective Action 10

Redesign PV system to a lower tilt angle to reduce potential wind damage

**Field Audit Instructions:**

1. Using an inclinometer tool (or smartphone app), measure and record the array tilt.
2. Photograph and document the racking assembly. Test for lateral weakness by pushing on the end of the racking assembly.
3. Photograph and make a simple sketch of the module fasteners. Look for damaged module fasteners and document them.
4. Examine bolted joints in the racking and look for looseness in the joint and fastener. Look for damage to any part.
5. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.

*Vulnerability 19: Flexible PV array glued to roof membrane*

**Figure 53. Peel-and-stick modules degrading rapidly over time**

*Source: Gerald Robinson, LBNL*

**Description:** While modules that adhere to the underlying roof membrane are no longer in production, there are still a few of these arrays in service (Figure 53). If you have one of these arrays, the following vulnerabilities should be noted for further consideration:

1. Areas within an array where water ponds and leaves standing water after a rainstorm can lead to electrical shorts and melt small holes in the underlying roof membrane. This is evidenced by chronic roof leaks and ponded areas, along with blown fuses at the combiner boxes.
2. Areas where leafy debris buildup not only shades modules but also (and most significantly) increases the potential for a roof fire.

Corrective Action 11

Remove and/or replace the flexible PV system glued to the roof

**Field Audit Instructions:**

1. Interview site facility managers and document any existing roof leaks.
2. Speak with any electricians to discover if string fuses are often failing; this is a sign of electrical faults.
3. Note the general condition of any of these flexible modules. Look for signs of dirt and leafy debris buildup.
4. Create a simple sketch and note where water ponds, which is evidenced by either standing water or dried dirt left by water. Mark areas where there is roof damage.

#### 5.3.4 Modules

Provides information on vulnerabilities related to the PV modules of the array.

*Vulnerability 20: Damaged modules from inadequate resistance to wind/snow loading and hail*

**Figure 54. Module with broken glass top-sheet**

*Source: NREL*

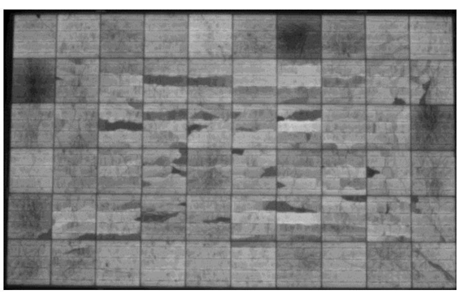


**Figure 55. Module testing reveals cell cracking from wind loading**

*Source: BrightSpot Automation*

**Description:** Modules that experience sustained heavy winds can be damaged from the strong uplift and downdraft forces that cause flexing. In highly turbulent wind events, the flexing can occur in rapid succession.

Damage can come in the form of broken glass top-sheets but often is seen in the form of microcracking of the cells. Broken glass can be identified visually, but microcracks will need to be located with either IR or EL imaging technology. Note that modules that have experienced extensive microcracking may not suffer from serious long-term power loss.

According to the standard ASTM E1830-15, most modules are rated for a 2,400-Pa front pressure. However, PV systems located in severe weather-prone regions should have modules with wind and snow load ratings of 3,600–5,000 Pa or more (Robinson 2018).

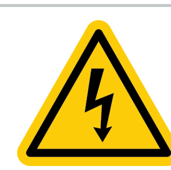
The wind load tolerance of a module is also influenced by the mounting, clamping, and stiffness/strength of the racking assembly. More robust mounting and clamping designs may be able to increase the module's wind and snow load ratings.

Figure 54 shows a module with a broken glass top-sheet from hail impacts. Figure 55 is an IR image showing microcracks of the cells in the module.

**Corrective Action 12**

Replace module(s) showing signs of degradation

**Field Audit Instructions:**



1. Count the number of modules with broken glass top-sheets. Count the number that have no obvious debris strikes as the root cause of the breakage versus those that appear to be broken from over-flexing.
2. Retain the services of a trained imaging professional that can conduct an IR inspection of all the modules and look for signs of cell cracking or other module vulnerabilities. See Section 5.2.3.

*Vulnerability 21: Cracked or failed backsheet*

**Figure 56. Cracked back sheet with burn mark**

*Source: Solar Power World*

**Figure 57. Damaged backsheet, exposing cells**

*Source: DuPont*

**Description:** Module manufacturers (like all PV equipment manufacturers) are under intense price pressures. Because of this, common materials with chemical instabilities are used by some module manufacturers to cut costs. Failures with such materials as backsheets, encapsulants, glues, and gaskets can pose serious life-safety and financial risks to PV system owners and hosts (e.g., a third-party-owned system). If exposed to weather, these vulnerabilities can result in significant damage.

In the case of module backsheets, some brands degrade quickly in the field, vastly underachieving their expected lifespan. Degraded backsheets crack and peel, exposing the energized cell busways in the modules to moisture, and in worse cases, to salt water that can act as a corrosive agent.

Degraded and cracked backsheets rapidly worsen when exposed to weather events like hurricanes, thunderstorms, and blizzards. Moisture from these storms can easily penetrate into a cracked backsheet and cause electrical faults in the module. This is a major threat of fire and other life-safety issues. The power output of modules with cracked backsheets will quickly drop off as the cell busways corrode.

Figures 56 and 57 show damaged module backsheets. The most likely causes of this degradation are the manufacturer's use of poor-quality materials and severe weather events.

Corrective Action 12

Replace module(s) showing signs of degradation

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5. The majority of PV installations procure modules in large quantities. Therefore, if some modules are showing signs of backsheet degradation, it can be assumed that all modules with the same bill of materials (BOM) will soon show signs of degradation and eventually need to be replaced.
2. Visually inspect the backside of the modules. Look for material cracking and blistering. Photograph and record the vulnerabilities found on audit sheets.
3. Using the handheld IR scope, look for hot spots. Record any vulnerability found on the audit sheets.
4. Review the BOM of the installed modules and verify if the backsheet material used in the modules is of known poor quality.

### 5.3.5 Wire Management

Provides details on vulnerabilities related to wire management of the PV system (e.g., module wire, home runs).

#### Background

This section focuses on wire management that covers the DC wiring of a PV system.

#### Why Is Wire Management So Important?

An effective wire management system is one of the simplest ways to prevent dangerous electrical faults that can result in fires, shock hazards, and substantial financial loss, as well as pose a threat to life-safety.

#### Relevant Codes and Standards

Many vulnerabilities can arise from improper wire management due to inadequate materials and poor workmanship. Although some NEC codes include requirements on wire management, these codes leave key details unaddressed and subject to the interpretation of the installer. Additionally, these codes serve more as a basis for evaluation and inspection post-installation, and do not guarantee long-term performance.

Properly installed wires should not be visible unless you are viewing the PV array up close. Wires should be supported at intervals pursuant to the NEC so there is no exposure to damaging elements like sunlight, wind, and snow. It is critical that best practices and relevant codes in wire management are followed.

*Vulnerability 22: Improperly supported wires*

**Figure 58. Poor wire management**

*Source: IAEI Magazine*

**Figure 59. Unsupported PV wires submerged in water**

*Source: Cadmus Group*

**Figure 60. Broken plastic wire ties, allowing PV wires to move freely**

*Source: Gerald Robinson, LBNL*

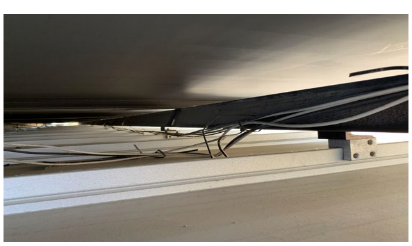


**Figure 61. Broken plastic wire ties from thermal movement**

*Source: Gerald Robinson, LBNL*

**Description:** Poor wire management is a serious vulnerability that can affect the longevity and safe performance of a PV system. There are four main vulnerabilities associated with improper wire management. All four vulnerabilities, when exposed to severe weather, can contribute to wire damage when the wire insulation is abraded, exposing the inner copper which carries electricity. Electrical faults can occur and create dangerous scenarios for both infrastructure and life-safety of site personnel.

**1. Loose hanging wires**

Some PV systems have been installed without proper wire management support. Weather elements like heavy winds and snow have the potential to cause loose hanging wires to rub against other surfaces and abrade the wire insulation, exposing the inner energized copper strands. Figures 58 and 59 show the effects of PV systems without proper wire management.

**2. Widespread use of plastic wire ties**

Plastic wire ties were a commonly used method to secure PV wires to the racking assembly. While considered to be a cost-effective option, these plastic wire ties have become problematic, as they quickly fail under high-heat environments (common for rooftops) by becoming brittle and breaking, leading to a failure to hold the wires securely.

Additionally, with such short life spans, plastic wire tie failures may cause contractors to replace them frequently, driving up O&M costs and ultimately lowering a project's economic viability.

Figures 60 and 61 show what happens to plastic wire ties after only a few years from the time the PV system was installed.

**3. Improper routing of PV wires**

Improper routing of PV wires can come in two forms: (1) wires pulled too tight against a sharp edge or surface, and (2) wires pulled too tightly overall, causing significant strain.

Figure 62 shows PV wire entering conduit without a proper fitting on the end of the pipe. These conduit ends have sharp edges, and can be jagged from poor workmanship during the installation. In Figure 63, the blue arrows indicate points at which wires are routed over sharp edges. In this instance, the sharp edges are the modules themselves and the end of the conduit does not have the proper fitting. These wires are also strained from being pulled too tightly.

Strained PV wires entering electrical enclosures can also cause the inner copper wire to become bent and brittle. This can reduce overall system performance.

Figure 62. PV wires routed out of conduit with no protective bushing

*Source: Bill Brooks, Brooks Engineering*

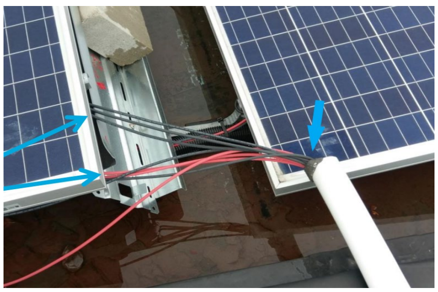


Figure 63. Wires routed over a sharp module edge

*Source: Cadmus Group*

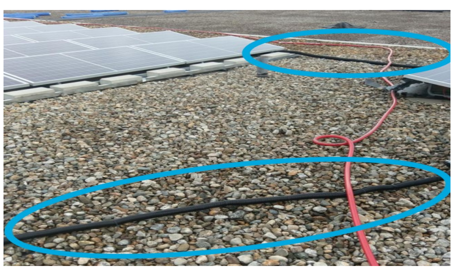


Figure 64. Exposed PV wires lying on an abrasive roof surface

*Source: Cadmus Group*

Figure 65. PV wire exposed to weather elements

*Source: LG Energy*

**4. Wires unprotected and exposed to weather elements (e.g., sunlight, rain, wind)**

PV wire that is exposed to direct sunlight will degrade, and the wire insulation will become brittle. When subjected to severe weather, the brittle wire insulation will fall apart, exposing the energized copper strands. There are two concerns with this vulnerability:

- Exterior rated wires not supported and routed properly, resulting in sunlight and weather exposure
- Use of non-rated wiring in exterior applications.

During the field audit, if any of the following vulnerabilities exist, then they must be remedied:

- For exterior-rated wires, under no circumstances should wire be exposed directly to sunlight. There are instances where non-exterior rated wire is used, creating not only a dangerous scenario but also a code violation. Wires should be routed and supported in a manner that protects them from direct sunlight exposure.
- In most applications, interior wires shall not be used in exterior applications. The one exception is grounding wire, which can be identified as wire with green insulation or solid bare copper.

Figure 64 shows nonrated PV wires routed across a gravel roof, creating a dangerous scenario.

Figure 65 is an example where the installer routed PV wires outside of a conduit. Leaving PV wires exposed to the weather elements (e.g., sunlight, rain, wind) can cause significant damage.

Corrective Action 13

Proper wire management support and protection

**Field Audit Instructions:**

**General instructions**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. As discussed in Section 5.2, note these vulnerabilities in the audit sheets and photograph them.

**Loose-hanging wires**

1. Based on Figures 58 and 59, identify this vulnerability by looking for PV wires that are hanging loosely from the modules and/or racking assembly.
2. It is recommended that PV wires be supported every 12 inches. When inspecting the PV system for unsupported PV wires, these spacing intervals should be considered.

**Widespread use of plastic wire ties**

1. All plastic wire ties must be replaced. Even if they have not broken, their short lifespan will cause them to eventually be removed and replaced with a proper wire management product such as an ethylene propylene diene monomer (EPDM) rubber-lined clamp.

**Improper routing of PV wires**

1. Inspect the routing of PV wires and look for wires coming in contact with sharp edges such as conduit ends, modules, racking assemblies, and other balance-of-system (BOS) components.
2. Inspect module junction boxes and other electrical enclosures for signs of wire strain. These are the most common locations for wires to be strained.

**Wires unprotected and exposed to weather elements (e.g., sunlight, rain, wind)**

1. Look for PV wires that are unprotected and exposed to weather elements. These wires should be protected by the modules, racking, or conduit and supported by a proper wire management product.
2. Look for wires that are not rated for exterior use. Exterior rated wiring is usually in carbon black insulation.

*Vulnerability 23: Corroded grounding components due to environmental conditions or dissimilar metals*

**Description:** Corroded equipment grounding system components, from the wires to the grounding lugs, can inhibit the PV system's ability to hold continuity to ground. Interfering with this continuity can allow potential ground faults to cause damage to the PV system and adjacent infrastructure, as well as pose a threat to life-safety of site personnel. It is important to identify the root cause of a grounding component's failure. Marine environments can cause significant corrosion, as seen in Figures 66 and 67.

**Figure 66. Corroded grounding lug**

*Source: Gerald Robinson, LBNL*

**Figure 67. Corroded grounding wire and lug**

*Source: Miller Solar*

### Corrective Action 14

Ensure the equipment grounding system is functional

**Field Audit Instructions:**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. Grounding system components are typically installed on the racking system underneath the modules. Tilted arrays will make the field audit easier, as there is visual access to these components. Flush mounted arrays make it difficult to inspect all grounding system components. However, it can be assumed that if one component (e.g., a grounding lug, Figure 66) is showing signs of corrosion, the rest of the grounding system is experiencing the same level of corrosion (if made of similar materials).

*Vulnerability 24: Poor installation practices leading to damage of PV and other DC wires*

**Figure 68. PV wire bent at tight radius**

*Source: Bill Brooks, Brooks Engineering*

**Figure 69. Metal wire tie compromising wire insulation**

*Source: Hellerman Tyton*

**Figure 70. Pinched wire between the module and the racking assembly**

*Source: Solar Novus*

**Description:** While improper wire management support typically leads to wire damage, wires can also be damaged in other ways. The following three vulnerabilities, when exposed to severe weather, can potentially damage wires when the wire insulation is abraded, exposing the inner copper, which may be energized. Electrical faults can thus occur and create dangerous scenarios for life-safety of site personnel and infrastructure.

**1. Overly tight bending radius of wires**

When wires are bent at a tight radius, damage can be done to the insulation and interior copper strands. Prolonged exposure to weather elements like heavy winds and snow can cause movements of the wires, thereby exacerbating the damage to the copper strands. Overly bent wires (less than five times the diameter of the wire) can cause excessive heat at the bend, due to increased resistance, and lead to stress on the wire connection point. The resistance in the wire can reduce PV system performance.

This vulnerability may be seen in all DC wiring, from the module wires to the DC wires leading from the combiner boxes to the inverters. Figure 68 shows a PV wire bent at a tight radius. This wire bend does not meet NEC requirements.

**2. Metal wire tie is overly tightened and cutting through wire insulation**

Metal wire ties, some with a plastic coating, are often used to support PV wires to prevent movement and potential damage. While these metal wire ties often have a longer lifespan than plastic wire ties, installers sometimes overtighten them. If the plastic coating peels away, the metal wire ties can abrade the wire insulation. Figure 69 shows an overly tightened metal wire tie cutting into the wire's insulation.

**3. Wires pinched between the module and the racking assembly**

When a module is installed, there is the possibility that one of the module wires gets caught and pinched between the module and the racking assembly, as seen in Figure 70. This can cause a drop in performance almost immediately. It can also damage the wire insulation and expose the energized copper.

Corrective Action 15

Replace damaged DC wiring

**Field Audit Instructions:**

**General instructions**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. As discussed in Section 5.2, note these vulnerabilities in the audit sheets and photograph them.
3. If an I-V curve test shows low performance on a string, this may indicate a damaged wire.

**Overly tight bending radius of wires**

1. During the field audit, look for overly bent wires on the back of modules and along the routing of the string wiring. The NEC states that the "radius of the curve of the inner edge of any bend, during or after the installation, shall not be less than five times the diameter of the cable" (Brooks 2010).

**Metal wire tie is overly tightened and cutting through wire insulation**

1. If metal wire ties are found during the field audit, they should be carefully examined to determine if they are overtightened, causing damage to the wire insulation and exposing the energized copper inside.
2. If metal wire ties with vinyl or other plastic coatings were used, these should be examined to see if the coatings have started to peel away from the metal inside.

**Wires pinched between the module and the racking assembly**

1. Interfaces of the modules and racking should be examined to identify if any module's wires have been pinched between the two surfaces.

*Vulnerability 25: Animals nesting under modules, chewing and damaging wires*

**Figure 71. An animal nest under a PV module can cause damage to wires**

*Source: Van der Valk Systems*

**Figure 72. Birds pulled PV wires up between the modules**

*Source: Gerald Robinson, LBNL*

**Description:** Birds, squirrels, and other small animals have been known to build nests under or behind PV arrays. These spots are ideal for nesting animals as they are shielded from weather elements (e.g., rain, snow, sunlight) and predatory animals. Wires in nesting areas are often chewed, creating a very dangerous scenario of exposed wires and nesting materials made of dry, leafy debris. Compromised wire insulation can expose the copper strands in the wires and possibly lead to electrical shock hazards and faults if a damaged wire comes in contact with the nest.

Figure 71 shows a large nest built under the modules. Figure 72 shows a PV array that had animal nesting under the modules. The modules' wires were pulled loose from underneath the modules and then pulled up to the surface of the array. The wire in Figure 72 is most likely degrading rapidly, as it is now exposed to sunlight, wind, and snow.

Corrective Action 16

Remove and prevent animal nesting under PV array

**Field Audit Instructions:**

1. During the field audit, look for signs of animal nesting, which include piles of sticks, leaves, feathers, and other dry debris. An animal will usually leave signs of nesting around the perimeter if the nest is located in the center of the array.
2. Look for wires that have been pulled up between the modules, as shown in Figure 72.
3. Confirm if the site has had past issues with animal nesting, which may indicate the presence of animal nests underneath the PV array(s).

*Vulnerability 26: PV connector failure*

**Figure 73. Incompatible module connectors visibly melted from a buildup of heat**

*Source: Affinity Energy*

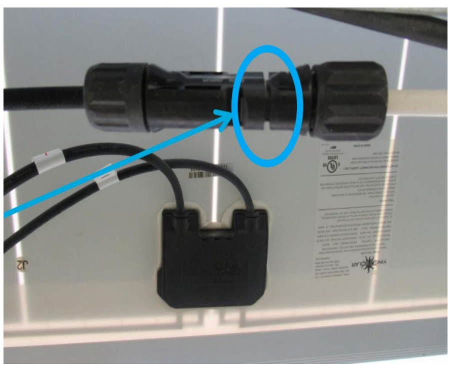


**Figure 74. PV connectors not fully secured to each other**

*Source: Cadmus Group*

**Description:** PV connectors and crimps are the single largest cause of DC wiring failures in PV systems. These connectors and crimps are also often found to be responsible for low performance. Most of the failures observed occurred during the first five years of the installation. Root causes for field-installed connectors include:

1. Poor contact crimps or crimps that have pinched some of the wire insulation
2. Contacts not installed properly into the connector, causing higher contact resistance (heat)
3. Water intrusion from improperly assembled connectors (Moser et al. 2017).

Incompatibility issues are frequently seen in the field, and often arise when connectors from different manufacturers are mated, a term also known as "cross-mating." Some connector manufacturers and standards such as UL 1703/6703, IEC 62548, and IEC 62852 advise against cross-mating. Although many connectors are considered compatible, there is no industry standard for a uniform connector design. The variations between brands introduce incompatibilities that can cause life-safety and performance issues. The vulnerabilities include the use of dissimilar metals (i.e., galvanic action), the need for specific tools and watertight seals, and the inability to fully connect (Moser et al. 2017).

PV connectors are required to be tested to UL 6703. Unfortunately, this standard does not cover cross-mating unless specifically tested, which is usually not done by manufacturers. Figure 73 shows the result of a PV connector failure, possibly due to cross-mating and/or poor installation practices.

Figure 74 shows two PV connectors that are not fully seated, as evidenced by the gap circled in blue. There is a likelihood that moisture from wind-driven rain and snow accumulation can enter through this gap and cause damage to connector terminals. This can be worse in marine environments, as the saline content of the water nearby can act as a corrosive agent. The poor connection of these two components can also cause electrical resistance (heat), which produces a drop in system efficiency. However, more severe scenarios like arc faults can occur from compromised connectors.

Corrective Action 17

Replace damaged PV connectors

**Field Audit Instructions:**

1. To determine the "Prevalence" of these vulnerabilities, use Section 5.2.5.
2. Survey each set of connectors and:
    - Look to see if two different brands/models are mated together
    - Look to see if connectors are fully connected
    - Look for signs of overheating and damage (deformed connectors) from melting
    - Use the handheld IR scope to look for hotspots on each connector.

### 5.3.6 Electrical Equipment and Conduit

Provides information on vulnerabilities related to electrical equipment (e.g., inverters, switchgear) and conduit.

**Background:**
**Equipment located below flood levels**

Unbeknownst to many PV system owners, BOS equipment like inverters and switchgear can be mounted below the site's flood levels. This can be a dangerous scenario, particularly as severe weather events (e.g., hurricanes, thunderstorms) become more common. Current design practices may not have incorporated local flooding data and may rely solely on FEMA's 100-year flood maps. As weather patterns change, greater consideration should be given to potentially higher flood levels.

*Vulnerability 27: Electrical equipment located below the site's 100-year flood level*

**Figure 75. Flooded central inverters**

*Source: Nikkei Business Publications*

**Description:** As the name indicates, a 100-year flood has a 1%, or 1 in 100, chance of occurring or being exceeded in any given year. It is critical for PV system developers to install electrical equipment in accordance with the site's 100-year flood level to account for increasing severity of flooding and a growing understanding of local flood potential. If installed without these levels in mind, equipment such as inverters, switchgear, and transformers could be vulnerable to flooding (Figure 75), and can become a major threat to infrastructure and site personnel if they are severely water-damaged. Repairing and/or replacing flooded electrical equipment can be extremely costly.

**Corrective Action 18**

Relocate electrical equipment above 100-year flood level to prevent flooding

**Field Audit Instructions:**

1. Examine the original design documents for civil engineering details (i.e., what flood level was planned for).
2. Estimate the current elevation of the bottom of all major BOS components and record on the audit sheet. If the inverter is on a concrete equipment pad, measure from the ground level to the top of the pad.
3. Use a topographic map and/or FEMA flood maps to assess for 100-year flood levels.
4. Compare the elevation of the equipment to the 100-year flood level.
5. Add localized flood information from planning departments to develop a flood risk profile.

*Vulnerability 28: Conduit draining water into downhill electrical equipment from flooded uphill locations*

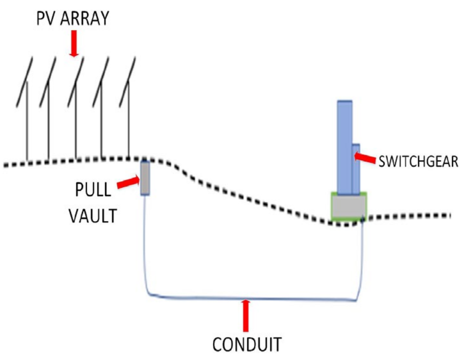



**Figure 76. Water can enter electrical equipment at a high elevation and flood equipment at a lower elevation**

*Source: Gerald Robinson, LBNL*

**Figure 77. A frog nesting in an electrical enclosure post-flood**

*Source: Gerald Robinson, LBNL*

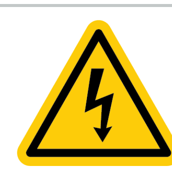
**Description:** During heavy rains, standing water will develop, even on well-drained landscapes, and flood into pull boxes, conduit, and any BOS equipment located at lower elevations. Underground conduit is often routed into the bottom of electrical equipment, through concrete pads.

Figure 76 shows a ground mounted PV system where the pull vault (commonly known as a *pull box*) is mounted at a higher elevation than the switchgear. The two pieces of electrical equipment are connected by the underground conduit pipe. If the pull box is flooded, the water will naturally move downhill and enter the switchgear, causing damage. Figure 77 shows the aftereffects of a flooded electrical enclosure which allowed a frog to swim into it.

### Corrective Action 18

Relocate electrical equipment above 100-year flood level to prevent flooding

**Field Audit Instructions:**



1. Upon field audit, if any BOS components appear to be lower in elevation than the array field, a site surveyor will be needed to determine the exact differences in elevation among the electrical equipment.

2. Using a qualified electrician, note if the conduit is routed through the underside of the cabinets. Note also if the conduit is routed from one piece of equipment underground and through the bottom of the cabinets.

3. Using a qualified electrician, note any signs of water having entered the bottom of the cabinets through the conduit.

*Vulnerability 29: Common issues with electrical enclosures*


**Figure 78. Inadequate combiner box flooded with water and froze in the winter**

*Source: North American Clean Energy*

**Figure 79. Corroded central inverter**

*Source: Gerald Robinson, LBNL*

Corrective Action 19

Replace inadequate and/or corroded electrical equipment

**Description:** It is important to verify that all electrical enclosures installed outdoors are rated for severe weather events. Electrical faults can occur if inadequate electrical enclosures experience damage and create dangerous scenarios for life-safety of site personnel and infrastructure.

1. **Inadequate NEMA ratings for outdoor electrical enclosures**

The National Electrical Manufacturers Association (NEMA) provides a rating system for electrical enclosures. Electrical enclosures without the proper NEMA rating will be unable to prevent water intrusion during a storm and will often collapse under heavy winds. Figure 78 shows a combiner box that was installed outdoors but did not have the proper NEMA rating to prevent water intrusion. The combiner box filled halfway with water and then froze during the winter.

Electrical enclosures have many conduit and fastener penetrations. It is critical that these penetrations are properly sealed to prevent water entry.

Low-cost and thin-walled electrical cabinets with a poor NEMA rating will use simple peel-and-stick foam gaskets. These gaskets are very ineffective at keeping water out, especially if they are pinched or not contiguous around the seal perimeter.

2. **Corroded electrical enclosures**

Some electrical enclosures corrode quickly due to coating failures. If the corrosion is significant enough, the integrity of the enclosure can be compromised, allowing wind-driven rain to penetrate and damage electrical equipment. This vulnerability poses a potential shock hazard and risk of electrical faults.

Figure 79 shows a central inverter experiencing a severe level of corrosion, thereby compromising its ability to withstand weather elements like rain, snow, and hail.

3. **Electrical enclosures not equipped with proper drainage for condensation**

Condensation can form in a tightly sealed electrical enclosure when there are high variations in temperature and pressure between the interior of the enclosure and the outside air. The electrical enclosure must have the ability to drain out the condensation to avoid damage to interior electrical components. Vent plugs and weep holes installed on the bottom are two ways that an electrical enclosure can drain condensation out. The combiner box in Figure 78 could have avoided water damage if one of these solutions had been used.

NOTE: Self-tapping sheet metal screws may also have been used to hold electrical enclosures to walls, racking assemblies, and other structural elements. These screws are weak and can fail during severe weather events.

**Field Audit Instructions:**

**General instructions**

To determine the "Prevalence" of this vulnerability, use Section 5.2.5.

As discussed in Section 5.2, note these vulnerabilities in the audit sheets and photograph them.

**Inadequate NEMA ratings for outdoor electrical enclosures**

1. Confirm the NEMA rating of electrical equipment by looking at the installer's product submittal, if available, to verify if they are adequate for the site's environmental conditions.
2. Examine any specification labels on the electrical equipment for more information on whether or not the equipment is rated for outdoor use.
3. If the labels are missing or have degraded beyond recognition, consult a qualified electrician for verification on outdoor ratings.
4. Check all electrical enclosures that are equipped with a rubber gasket and determine if the gasket has been compromised.
5. Check penetrations into the electrical equipment and identify if a sealant was used on the penetrations to prevent water intrusion. Identify if any self-tapping sheet metal screws were used on the electrical enclosure.
6. Open and examine the interior of all electrical enclosures for any signs of damage from water intrusion.

**Corroded electrical enclosures**

1. Corrosion in electrical equipment can commonly be seen as rust. However, there are other forms of corrosion, like discoloration, that should be identified.
2. The exterior of the enclosure should be examined with a sharp putty knife to slightly skim the cabinet's surface to see if there is excessive loose and blistering paint.
3. Some corrosion occurs within electrical equipment and is not readily visible from the exterior. The site inspector, along with a trained electrician, can open the electrical enclosure and verify if there are any signs of corrosion.

**Electrical enclosure is not equipped with proper drainage for water intrusion**

1. Check all electrical enclosures like combiner boxes, junction boxes, and switchgear to ensure they have the proper drainage in case of water intrusion.
2. With the help of a trained electrician, open the electrical enclosure and verify if a weep hole or one-way vent/drain was installed, by either the contractor or manufacturer, at the bottom of the enclosure.

*Vulnerability 30: Conduit-related vulnerabilities*

**Figure 80. Conduit supports degraded from prolonged weather exposure**

*Source: Roofers Coffee Shop*

**Figure 81. Conduit separated at connectors from thermal movement**

*Source: IAEI Magazine*

Corrective Action 20

Prevent damage to the PV conduit

**Description:** There are a number of vulnerabilities related to conduit in a PV system; however, this guide will focus on the three most commonly seen in the field. All three vulnerabilities, especially when exposed to severe weather, can potentially damage the wires inside of the conduit. Electrical faults can occur and create dangerous scenarios for life-safety of site personnel and infrastructure.

**1. Improperly supported conduit runs on low sloped roofs**

Conduit runs across the surface of a low sloped roof are often not adequately supported, and this results in bending or separation at the fittings. Conduit leading to electrical equipment, as per the NEC, must be supported at a specified intervals based on conduit sizes.

Figure 80 shows wooden blocks used to support conduit. Unfortunately, due to severe weather, the wood has rotted significantly, compromising its ability to support the conduit. Without proper support, conduit can sag and/or be crushed from foot traffic, and potentially cause connectors and couplings to separate. The wires inside the conduit will be forced up against the sharp edges of the exposed conduit ends and abrade. Conduit that has separated at the union will also allow water to enter.

**2. Conduit installed without the proper fittings for the site's environmental conditions**

Conduit pipe holding energized wires must have the proper fittings for two reasons: thermal movement, and prevention of water intrusion.

Although it may be difficult to identify if a conduit fitting is rated for thermal movement, one clear example can be seen in Figure 81. One piece of conduit has completely separated from the fitting, causing the conduit to sag toward the roof. Unfortunately, the wires inside the conduit will be forced up against the sharp edges of the conduit ends and abrade, exposing the energized copper inside.

It is critical in wet environments and locations that see frequent severe weather involving rain and snow that the proper conduit fittings are installed for outdoor use. If a conduit fitting is used outdoors but is not rated as "watertight" or rated for its environment, water from rain and snow can enter the conduit. Because all conduit raceways eventually enter an electrical enclosure, the intruding water can flow toward the enclosure and cause damage.

**3. Roof mounted PV conduit showing physical damage**

With a continuous rotation of personnel working on the roof for different purposes, there is a potential for conduit that is part of the PV system to be damaged (e.g., crushed or bent). This can happen in a variety of ways: being stepped on, run over by a hand truck carrying a heavy load, or pushed aside to make room for other non-PV equipment. If conduit is damaged, it can damage the energized wires inside of it.

**Field Audit Instructions:**

**General instructions**

1. To determine the "Prevalence" of this vulnerability, use Section 5.2.5.
2. As discussed in Section 5.2, note these vulnerabilities in the audit sheets and photograph them.

**Improperly supported conduit runs on low-sloped roofs**

1. Follow conduit runs and examine supports. Look for locations where the fittings have slipped off.
2. Measure the distance between supports and record that information on the audit sheets.
3. Count the number and note the types of conduit damage.

**Conduit installed without the proper fittings for the site's environmental conditions**

1. Look for separation between a piece of conduit and the conduit fitting. This is evidence that the wrong conduit fitting was used for this application. Some conduit fittings may not have been tightened properly upon installation, or may have loosened over time.
2. It may be difficult to visually identify that a conduit fitting is not rated for outdoor use. One option is to read the original as-built drawings and determine if the developer specified which type of conduit fittings were to be used in the construction of the PV system.
3. Because as-built drawings do not always match what is actually installed, the purchase lists of the conduit fittings should be sought from the developer, if possible, and checked to see if the fittings allowed for thermal movement. Original product submittals from the installer may not accurately reflect what is in the field.
4. Adjacent electrical equipment (e.g., a combiner box into which a conduit pipe feeds) may show signs of corrosion, which can indicate that improper conduit fittings were used and water penetrated inside.

**Roof mounted PV conduit showing physical damage (e.g., crushed, bent)**

1. Inspect all conduit for signs of damage, especially in high-traffic areas near other roof equipment and across walkways. Dents and sharp kinks may indicate that the conduit has been damaged and needs to be replaced.

*Vulnerability 31: Field-applied labels and markings showing signs of significant degradation*


**Figure 82. Degraded field label on switchgear**

*Source: IAEI Magazine*

**Description:** Labels and markings installed on electrical equipment and conduit are important for the safe operation of a PV system. These labels typically provide information on the location of disconnect switches, electrical shock hazards, and other electrical details.

Figure 82 is an example of engraved placards used to identify shock hazards and DC power source ratings. The placards are showing significant degradation due to the local environmental conditions. Also note that the screws used to install the placards are severely rusted.

### Corrective Action 21

Replace all field labels and markings that are showing signs of degradation

**Field Audit Instructions:**

1. Look for labels showing signs of degradation such as discoloration, faded paint, and rust.
2. Photograph each label that is showing signs of degradation.
3. Mark the location of each label by the equipment it is mounted to. Record that information on the field audit sheet.

### 5.3.7 Topography

Provides information on vulnerabilities related to a site's topographical effects on the PV system.

*Vulnerability 32: Unobstructed wind forces on the PV system*

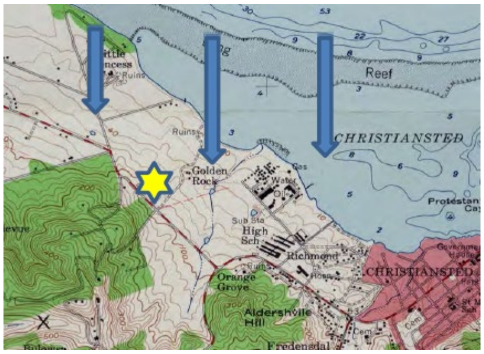



**Figure 83. An unobstructed wind path, indicated by the blue arrows, destroyed an array located at the location identified by the yellow star**

*Source: Gerald Robinson, LBNL*

**Description:** Topography that provides few or no obstructions to the full force of wind can leave solar PV systems highly exposed (Figure 83). Particularly in regions that experience hurricanes, unobstructed winds coming off the ocean will gain considerable speed.

Land features such as elevation, windward side of a slope, or features that funnel and accelerate wind (e.g., between hills and over bluffs) can affect wind speeds and impact PV arrays.

It is important to note that neighboring trees and buildings can act as breaks to strong winds and gusts. PV arrays located on sites with no neighboring obstructions will experience the full force of the winds and gusts.

Perimeter rows of PV arrays have been found to experience the greatest destructive wind turbulence. The turbulence can amplify forces and cause module loss from the perimeter inward (Robinson 2018).

**Corrective Action 22**

Install a wind calming fence to reduce wind forces on PV system

**Field Audit Instructions:**

1. The site inspector should observe and note if there are any neighboring obstructions that can act as a break to strong winds and gusts. Obstructions can include fences, buildings, trees, and any other physical objects that can slow winds and gusts.
2. The site inspector should determine if the PV array is located at a high elevation, like a hill or cliff, or in a canyon that will concentrate and rapidly accelerate winds.

### 5.3.8 Site Management

Provides information on vulnerabilities related to the management of the site where the PV system is located.

*Vulnerability 33: Clogged roof drainage system*

**Figure 84. Clogged roof drain**

*Source: Commercial Roof USA*

**Figure 85. Lack of maintenance to the roof drain can cause a buildup of water from rain and snow**

*Source: Advanced Roofing Inc.*

**Description:** Clogged roof drains not only cause undue weight and leaks into the building below but also create a risk of flooding the PV system's electrical equipment.

Without continual maintenance of a roof mounted PV system, it is easy to overlook the importance of clearing roof drains of debris. When roof drains are clogged, water from heavy rains and melting snow builds up and can penetrate into electrical enclosures like combiner boxes and conduit.

In addition to damaged electrical equipment, the weight load from the excess water buildup can adversely affect the roof's structural integrity. It can cause sagging, which will allow even more water to pool in a more concentrated spot, creating a positive feedback loop.

Roof drains may also not be visible when the roof is covered in snow. It is critical during heavy snowfall events that roof drains are kept clear so melting snow does not build up and cause the roof to sag (NREL et al. 2018).

Figures 84 and 85 show the effects that a lack of roof drain maintenance can have. A significant amount of water has pooled and poses a threat to the PV system and the roof's structural integrity.

Corrective Action 23

Inspect and clear roof drains to avoid electrical and structural damage

**Field Audit Instructions:**

1. Inspect roof drains and the areas surrounding the drains for buildup of leafy debris.
2. Inspect areas under the array for leafy debris accumulation.
3. Look for signs of water ponding and water spots that will reveal where ponding occurs.

*Vulnerability 34: PV equipment in direct contact with the roof membrane*

**Figure 86. Racking component in direct contact with the roof membrane**

*Source: Andy Walker, NREL*

**Description:** It is important that a roof mounted PV system not cause any damage to the roof membrane. Over time, movement from wind and thermal activity can cause PV equipment such as modules and racking to damage the roof membrane.

In Figure 86, the racking component is in direct contact with the roof membrane, causing it to abrade. Without proper installation practices and continual inspections, a small vulnerability like this can lead to a much larger problem if the compromised section of roof allows moisture to penetrate. Water damage can be significant and expensive to fix if major renovations are required (NREL et al. 2018).

Corrective Action 24

Protecting against and/or repairing roof damage from PV system

**Field Audit Instructions:**

1. Check for any part of the PV system that is in direct contact with the roof membrane. Some of these parts may include the modules, racking assembly, and conduit supports.
2. If water damage is observed from the interior of the building, look for obvious roof damage caused by array contact and abrasion. Because water moves from the spot of a leak horizontally before appearing inside the structure, a professional inspection by a waterproofing company might be required.
3. Use the IR scope to inspect the roof. Moisture underneath the roof membrane may appear under IR inspection and show up as either a hot or cool spot.

*Vulnerability 35: Loose debris and/or equipment scattered around a PV array*

**Figure 87. A communications tower fell onto this PV array during a hurricane**

*Source: Gerald Robinson, LBNL*

**Description:** Debris and abandoned in-place roof mounted equipment can dislodge and become airborne under high winds. This debris can travel across a roof array, causing a large amount of damage during a wind event.

Airborne debris also poses a serious threat to life-safety and to the PV system. Loose debris and various types of inadequately secured equipment can become airborne during a high wind event and strike a PV system, potentially causing significant damage (Robinson 2018).

Figure 87 shows damage to a PV array after an abandoned in-place communications tower was knocked down by a hurricane and fell onto the modules.

### Corrective Action 25

Clear debris and secure loose equipment around PV system

**Field Audit Instructions:**

1. Identify the presence of any roof debris and abandoned in-place HVAC equipment, communication towers, and staging items stored on a roof. Photograph and catalog all items that could become airborne during a wind event. It is critical that the facility determine if any of the roof mounted equipment is not adequately secured to the roof. Document obvious signs like rusted-out or missing screws and bolts used to fasten the equipment to the roof.

2. Ground mounted PV systems may have different equipment than roof mounted systems, but the general rule for the site inspector is to identify any equipment that is not adequately secured. Vegetation debris, stored materials, and old fences should be cleaned up, and any nearby trees that are susceptible to storm damage should be documented as a possible source of damage to the PV system.

*Vulnerability 36: Improper stormwater management around a ground mounted PV system*

**Figure 88. Soil erosion on a perimeter road around a ground mounted PV array**

*Source: Andy Walker, NREL*

**Figure 89. Poor stormwater management of a ground mounted PV array**

*Source: ESE Magazine*

**Figure 90. Scouring occurring around concrete foundations of a PV array**

*Source: Firstgreen Consulting*

**Description:** Stormwater management (SWM) should be factored into the design and construction of a ground mounted PV array. Soil erosion from weather events like hurricanes and thunderstorms can pose a serious threat to the system's structural integrity (NREL et al. 2018). Several vulnerabilities can arise from improper SWM:

**1. Compaction of soil**

Construction activity during the installation can cause soil to compact, leading to an increase in runoff and sediment transport if site vegetation has not been adequately established.

**2. Removal of topsoil**

The removal of topsoil and loss of organic matter during construction can lead to less vegetative ground cover and/or a prolonged time to revegetate the site. Without the necessary vegetation, bare soil can experience more erosion and washouts.

**3. Shaded conditions**

Uneven growth of vegetation, particularly grasses, can occur if the site is planted with one type of grass or plant. The areas under the arrays are shaded and inhibit vegetation growth.

**4. Erosion of perimeter roadways**

Roadways around a ground mounted PV system are important for personnel to be able to access and work on the system. Oftentimes, due to a lack of planning, these roads are located on the perimeters of the site. Because runoff needs to be directed outside of the site to a ditch or drainage basin, the water may flow via culverts across the roadway. The culverts create a narrow and concentrated flow of runoff that can lead to significant erosion on the perimeter roads.

**5. Long, uninterrupted flow of runoff**

Long stretches of smooth surfaces created from soil compaction and grading activities can result in an increased velocity of runoff due to a lack of natural obstructions (e.g., pockets, depressions). Concentrated flows of high-velocity runoff can create rills and gullies around the site.

**6. Scouring**

This occurs when water runoff removes soil around the concrete foundations of the PV array and compromises its structural stability under heavy winds. Exposed concrete will then be subject to the site's environmental conditions, and may degrade faster.

Corrective Action 26

Improve stormwater management around a ground mounted PV array

**Field Audit Instructions:**

1. Evidence of insufficient SWM can be seen after a storm hits a site. Photograph and sketch locations where water flows around the site. Even small amounts of water will indicate the direction of the drainage.
2. Walk the whole perimeter and between each row of the array(s) to identify any areas where soil may be eroding. Figures 88, 89, and 90 are common representations of what soil erosion around a ground mounted PV array look like. Look for rills, gullies, and washed-out areas, as well as exposed concrete foundations. Nearby water bodies like streams and ponds may have an increased level of sediment deposited in them, increasing the water's turbidity and possibly degrading the water body.
3. Look at the vegetation cover and identify any barren, loose, open-soil spots, particularly under the arrays, due to a lack of sunlight and shade-tolerant plantings.

*Vulnerability 37: PV array covered in snow, making it susceptible to damage*

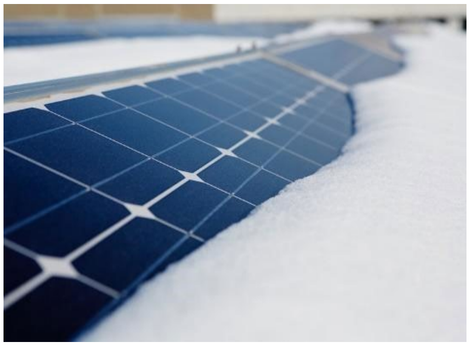


**Figure 91. Modules covered in snow can be damaged if not clearly marked**

*Source: Solar Power Authority*

**Description:** Damage to a PV array can occur when the modules are covered in snow and not visible to site personnel (Figure 91). Roof- and ground mounted PV arrays can experience damage in different forms.

PV arrays installed on low-sloped roofs are typically designed and built at a low tilt angle. The higher end of the module may not be more than 24 inches above the roof. Additionally, some PV arrays can be installed flush, or parallel, to the roof, with an approximate 6″ clearance. During blizzards, low-tilt and flush mounted PV arrays can be covered in snow and not visible to site personnel.

Snow removal crews can easily miss unmarked arrays and end up walking onto the modules and/or damaging them with shovels.

Ground mounted PV systems are typically designed and built so that the low end of the array is approximately 18″ above ground level. Snowplows moving between rows of ground mounted arrays can damage the modules if the lower ends are covered in snow and not marked for the driver to see. This creates a scenario for the snowplow to hit the modules and cause significant damage. Snow removal vehicles should not be removing snow unless the array is specifically designed with the appropriate pavement, clearances, and protections (e.g., curing, stations, bollards).

**Corrective Action 27**

Clearly mark the presence of PV array and its boundaries to prevent damage to snow covered modules

**Field Audit Instructions:**

**Roof mounted arrays**

1. Look for markings and/or signage that indicates the presence of a PV array on the roof. These markings and signage should be posted in visible areas, such as access hatches, roof doors, and ladders that any person accessing the roof will see.

2. Look for snow stakes that mark the location/perimeter of the PV array so anyone walking on the roof knows where the modules are and avoids walking on and/or shoveling snow off of them.

**Ground mounted arrays**

1. Look for snow stakes or any markings that can indicate the location of the lower end of the PV array, because this is the part most susceptible to damage.

# 6 Corrective Actions for Vulnerabilities

**Step 4**
Make Corrective Actions Plan

## 6.1 Factors That Go into Prioritizing Corrective Actions

While assessing and identifying vulnerabilities in a PV system can be a challenge, coming up with corrective actions that can fix these vulnerabilities can be even more of a challenge without proper guidance.

This section is intended to help agencies prioritize which vulnerabilities need to be fixed, with a focus on immediate, near-term, and long-term strategies. Please note that each vulnerability may have more than one option as a potential corrective action. Each agency site will be different and therefore needs to account for the factors identified in the following subsections.

### 6.1.1 Costing for Corrective Actions

Financial limitations can be burdensome to an agency. Section 7 provides an estimated cost range for each corrective action based on a variety of factors. Please see Section 7 for more information on associated costs for corrective actions.

### 6.1.2 Skill Level Required to Perform Corrective Action

Some corrective actions will be more complex and thus require specialized personnel such as qualified electricians, bolted joint engineers, and solar PV contractors. Each corrective action specifies which skill level may be needed.

The ability for an agency to perform any of these actions will most likely be determined at the site level. Such corrective actions like cleaning and installing roof drains and clearing the site of any debris and loose equipment can be performed by the agency without any specialized training. However, some corrective actions like retrofitting a racking assembly will most likely require the help of a qualified engineer and solar PV contractor to design and perform the work.

### 6.1.3 Risk-Impact Diagram

As discussed in Section 2.3, use the Risk Impact assessments when prioritizing which vulnerabilities to correct.

### 6.1.4 Safety

Safety is always paramount when working with solar PV systems, especially when performing corrective actions. As discussed in Section 6.1.2, minimal skill work can be performed without qualified personnel. However, any electrical, structural, or civil engineering and/or construction work **must** be performed by qualified personnel.

All photos and images used in this section are for illustrative purposes only. This guide does **NOT** recommend any particular product or manufacturer.

## 6.2 Critical Background

### 6.2.1 Fasteners and Bolted Joints Corrective Actions

*Fasteners and Bolted Joints*

Chronic fastener loosening seen with several types of bolted joints is due to underlying and fundamental design and/or installation problems. These bolted joints often lack the ability to achieve and sustain the minimum clamping forces needed to hold when exposed to weather events. Simply replacing fasteners with, for example, a rated locking version will not address underlying joint design deficiencies, which eventually lead to joint failure.

This guide has identified the most common bolted joint design deficiencies with recommended corrective actions that largely involve consultations with professional bolted joint engineers.

*Warning about Locking Fasteners*

It cannot be stressed enough that the connections in a PV system are the most likely cause of or contributor to failures. Fasteners are part of a bolted joint assembly and perform the job of clamping two surfaces and maintaining a bond through a combination of friction and the actual fastening forces. Some bolted joint designs have fundamental problems such as the inability to resist movement even when properly installed. In these cases, a bolted joint and/or structural engineer will need to specify the strengthening of the bolted joint and associated racking assembly to prevent failure. Even when rated locking fasteners are used, vulnerabilities with the bolted joint can still persist with issues such as bolt holes becoming elongated or the fasteners failing in shear due to movement of structural members.

*Gaining Approval from Manufacturers*

For any retrofits or replacements to existing fastener assemblies, check to see if any manufacturers may still be involved. Once equipment is modified, any remaining warranty will likely be voided, even in situations where the existing setup is inadequate. Gaining concurrence from equipment manufacturers (under the advisement of a consulting engineer) is critical prior to making any changes. Ideally, manufacturers should work collaboratively to specify any needed retrofit or replacement.

### 6.2.2 Top-Down Module Clamps

There are array designs that only provide access to the front of the module, and therefore require a top-down clamp solution. As of yet, industry designers lack a set of standard tests to determine how well any top-down clamp product can sustain suitable clamping forces through field (thermal cycling) and weather conditions.

Performing field audits enables system operators to have a sense of what a "more effective" top-down fastener looks like. However, this information is not based on publicly available test data. Facility managers should consult with a bolted joint engineer. See the section "How to Find a Bolted Joint Engineer" for additional information.

## 6.3 Fasteners, Critical Bolted Joints, and Racking Assemblies

**Corrective Action 1: Replace Inadequate Fasteners with Rated Locking Fasteners**

**Rationale:** Objects exposed to wind take on a natural vibration. This vibration can loosen threaded fasteners that are not designed and/or constructed properly. Common threaded fasteners (e.g., nuts, bolts) will loosen under vibration. A vibration-resistant fastener shall comply with DIN-65151. Rated fasteners must also be installed properly as per manufacturer's instructions.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 1: Fastener loosening from transverse slip
- Vulnerability 2: Loss of fastener preload due to improper field assembly.

**Skill Level Required:** Facilities engineer with mechanical skills or trained electrical or PV technician

**Specialized Tools Required:** Torque wrench or specialized installation tool for "lock bolts"

**Engineering Services:** Bolted joint engineer is required to specify an engineered solution

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Add wedge-locking washers to existing nut and bolt assembly**

**Figure 92. Wedge-locking washer**

*Source: Nordlock*

**General Application:** One washer is placed under nut and a second under bolt head.

**Advantages**

- Easy to select

**Disadvantages**

- Must be applied with a torque wrench
- Threads will need treatment with anti-galling compound.

**Replace entire assembly with a lock bolt**

**Figure 93. Lock bolt**

*Source: Huck*

**Figure 94. Hydraulic lock bolt gun**

*Source: Aerobolt*

**General Application:** Remove and discard existing fastener with a new lock bolt.

**Advantages**

- Bolt can be specified based on bolted joint characteristics
- With right bolt and tool setting, installation results are dependable

**Disadvantages**

- Requires specialized tools and training.

<table>
<tr>
<td>Use pre-applied thread locking compound</td>
<td><br>Figure 95. Thread locking compound on bolt shaft<br>Source: ND Industries</td>
<td>General Application: Remove and discard existing fastener for a version that has a pre-applied thread locking compound.<br>Advantages<br>• Adds extra resistance to loosening<br>Disadvantages<br>• Once set, the fasteners cannot be adjusted<br>• Unknown longevity when exposed to weather.</td>
</tr>
<tr>
<td colspan="3">Instructions</td>
</tr>
</table>

**Wedge Washers**

Wedge washers require the following steps to use:

1. Specify a washer that has an inner diameter that matches the existing bolt and an outer diameter to provide adequate contact surface area. The outside diameter should never be less than the diameter of the nut and bolt head. A technical document from the manufacturer should be used to select the right sized washer.
2. Use the same torque values provided with original design documents and/or product manuals.
3. Follow torque audit procedures using the First Movement method in Section 5.2.7.

**Lock Bolts**

Lock bolts require the following steps to use:

1. Technical assistance from the lock bolt manufacturer and other resources can be used to specify replacement bolt.
2. The specialized tool must be acquired and set to the specified bolt size.
3. It is highly recommended that any technician unfamiliar with lock bolt installations practice on scrap material first.
4. With a properly specified bolt and installation tool, this style of fastener can be very effective, as each one installed will have the same clamping forces.

**Pre-applied Locking Compounds:**

Nuts and bolts with pre-applied locking compounds require the following steps to use:

1. The replaced nut and bolt will be identical in size except for the pre-applied thread locking compound. Use the existing fastener to size and procure the replacement unless there is a known deficiency.
2. Use the torque specifications that were provided with the original design drawings and product manuals.
3. Follow torque audit procedures using the First Movement method in Section 5.2.7.

### Corrective Action 2: Strengthen Soft Joints in Racking Assemblies

**Rationale:** There are several racking assembly products that are made of tubular or square stock. Creating a robust bolted joint with this material is very difficult, as these tubes are very weak under side compression. Racking assemblies made from these profiles often have severe and chronic fastener loosening problems as preload on the bolt cannot be maintained easily.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 13: Presence of soft joints in the array's racking assembly

**Skill Level Required:** Facilities engineer with mechanical skills or trained electrical or PV technician

**Specialized Tools Required:** Torque wrench

**Engineering Services:** A bolted joint engineer is required to specify an engineered solution.

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

#### Corrective Action Options

**Use of Belleville washers with locking capability/feature**

**Figure 96. Belleville washer**

*Source: Grainger*

**General Application:** This will likely require replacement of the original threaded fastener, as the two must be matched and work with the strength characteristics of the tubular frames.

**Advantages**

- A wide range of products can allow maintenance of the bolt preload

**Disadvantages**

- Must be applied with a torque wrench
- Threads will need treatment with anti-galling compound.

#### Instructions

Belleville washers require the following steps to use:

1. Work with a bolted joint engineer or with the fastener manufacturer to develop the entire fastener assembly, including washer, bolt, and nut. The engineer or manufacturer should provide torque ratings and assembly details. The washer assembly will need to be selected so that bolt preloads are maintained without causing the walls of the metal tube to collapse.
2. Always use an anti-galling thread compound as part of assembly.
3. Follow torque audit procedures using the First Movement method in Section 5.2.7.

Note: See the Additional Resources section "Technical Assistance from Fastener Manufacturers."

## Corrective Action 3: Modify Bolted Joints in Racking Assemblies to Avoid Bolt Shearing

**Rationale:** Some bolted joints are not adequately designed and see high movement during weather events. This movement will eventually erode the bolt surfaces and holes, and then cause total shearing. When there is evidence of bolt shear in a significant number of bolted joints within the racking assembly, an effective corrective action will need to be engineered by a consulting engineer.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 4: Inadequate bolted joint design

**Skill Level Required:** Facilities engineer with mechanical skills or trained electrical or PV technician

**Specialized Tools Required:** Torque wrench

**Engineering Services:** Bolted joint engineer is required to specify an engineered solution

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Bolted joint modification**

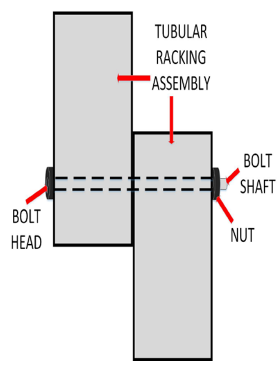



**Figure 97. Bolted joint modification**

*Source: Kevin J. Watson, LBNL*

**General Application:** A specialized bolted joint engineer will need to be consulted to develop needed modifications that can then be installed by a qualified technician. Reinforcement to the racking assembly may be needed to reduce stresses on a given bolted joint.

**Advantages**

- A qualified engineer can coordinate with the racking manufacturer to get concurrence on a solution

**Disadvantages**

- Need to find a qualified engineer with experience in this subject.

### Instructions

Resolving this vulnerability will require a professional bolted joint engineer.

1. Start with the Basis of Design template language provided in Appendix C. Update the template language to address any specific concerns.
2. Implement an engineered solution with a qualified bolted joint engineer. See Additional Resources section "How to Find a Bolted Joint Engineer."
3. Always require the contractor to use an anti-galling thread compound as part of the assembly.
4. Follow assembly and torque instructions prescribed by the bolted joint engineer.
5. Follow torque audit procedures using the First Movement method in Section 5.2.7.

**Corrective Action 4: Fix Top-Down Clamp Vulnerabilities**

**Rationale:** There are a several module clamp failures that can be addressed through this corrective action. Top-down clamps are cited in many weather-related failures.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 3: Top-down module clamp assemblies with soft joint issues
- Vulnerability 5: Top-down module clamps susceptible to vibrational loosening
- Vulnerability 7: Top-down module clamps bent open due to inadequate strength
- Vulnerability 8: Top-down module clamp failure leading to "row domino."

**Skill Level Required:** Facilities engineer with mechanical skills or a trained electrical or PV technician
**Specialized Tools Required:** Torque wrench
**Engineering Services:** A bolted joint engineer that can specify an engineered solution

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Through-bolting module frames to mounting rails where possible**

**Figure 98. Nuts and bolts used to through-bolt modules to rails**

*Source: Trailer Spares*

**General Application**: Through-bolt the modules to the rails with either nut, bolt, and wedge washer or lock bolt or fastener with pre-applied thread locking compound.

**Advantages**

- Eliminates concerns with top-down clamps

**Disadvantages**

- Must be applied with a torque wrench
- Threads will need treatment with anti-galling compound
- Requires access to back of module and racking rails.

**Use top-down clamps with improved features**

**Figure 99. Mid-clamp with a more robust design**

*Source: Spyder Racking*

**General Application**: Replace the top-down fastener assembly with one with the features listed below in the instructions.

**Advantages**

- Requires use of specialized engineering services to specify correctly

**Disadvantages**

- Must be applied with a torque wrench
- Threads will need anti-galling compound applied.

| Instructions |
| --- |
| **Through-Bolting**<br>Through-bolting requires the following steps to use:<br>1. The module manufacturer installation manual should be consulted for bolt, nut, and washer size. A wedge-locking fastener of the same inner and outer diameter should be used.<br>2. The manufacturer installation manual should be consulted for use of predrilled mounting holes on the frame.<br>3. Use the torque values provided in the module installation manual.<br>4. Follow torque audit procedures using the First Movement method in Section 5.2.7.<br>**Upgraded Top-down Fastener**<br>Top-down fasteners require the following steps to use:<br>1. A bolted joint engineer* should be consulted to properly specify any top-down fastener.<br>2. In general, it is suspected** that a superior top-down clamp has the following features:<br>• Large contact area with the module, for example using 4″ long clamp versus those often much shorter, in the 1″ to 1.5″ range<br>• H- or U-shaped mid-clamps that can resist "row domino"<br>• Threaded fastener that is matched to the strength of the module clamp so that preload and clamping forces can be achieved and maintained<br>• Wedge-locking washer under the head of the slotted T-bolts<br>• Addition of a third rail where possible, and where extruded aluminum is used with a slotted T-bolt.<br>*Given that module fasteners are ALL critical bolted joints with severe life-safety implications, it is recommended that agency managers consult with a bolted joint engineer. See Section 3.<br>**All configurations of module fasteners and module types have not been tested, so the above recommendations are based solely on field observations. |

### Corrective Action 5: Modify Weak Subframing with High Deflection Issues

**Rationale:** Racking assembly manufacturers select frame members for strength, often along one or two axes. Highly cyclical and dynamic wind forces put loads on frame members in a nonuniform manner. The strength of light-gauge cold rolled metal framing is often insufficient to withstand wind events that create these dynamic and compound forces. High deflection in underlying frame elements causes pressure on the mounted modules, either prying open clamping fasteners or breaking the modules. Array racking comprised largely of this light-gauge framing will need to be strengthened through added bracing.

Bolted joints in racking with deflection and lateral movement will likely fail. These joints will need to be braced to reduce the forces and movement that leads to failure.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 6: Module clamps and rails not installed properly
- Vulnerability 10: Deflection of subframing from heavy winds causing top-down clamps to fail and/or damaging mounted modules
- Vulnerability 14: Unbraced racking assembles causing bolted joint failures from large lateral movements.

**Skill Level Required:** Facilities engineer with mechanical skills or trained electrical or PV technician

**Specialized Tools Required:** Torque wrench

**Engineering Services:** A structural engineer is required to specify an engineered solution.

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

| | |
|---|---|
| **Add stiffening braces** | **General Application**: For racking with insufficient strength and stiffness, a structural engineer can specify the addition of braces.<br>**Advantages**<br>• Reduces deflection to an acceptable level<br>• Reduces stresses on weak bolted joints<br>• Eliminates concerns with top-down clamps<br>**Disadvantages**<br>• Must be applied with a torque wrench<br>• Threads will need treatment with anti-galling compound.<br>• Requires access to back of module and racking rails. |
| **Use top-down clamps with improved features** | **General Application**: High deflection is likely to have damaged any top-down module fasteners, and they should be replaced. Replace them only after the subframing has been stiffened.<br>**Advantages**<br>• Requires use of specialized engineering services to specify correctly |

| | |
|---|---|
| | **Disadvantages**<br>• Must be applied with a torque wrench<br>• Threads will need treatment with anti-galling compound. |
| **Instructions** | |
| **Reinforcing Framing with High Deflection and Associated Fastener and Module Damage**<br>1. Reinforcing an existing racking assembly to increase strength must be done by a consulting structural engineer, as this will involve an engineered solution. The engineer will provide drawings and construction scopes of work.<br>2. When mounting modules, the manufacturer's installation manual should be consulted for bolt, nut, and washer size. A wedge-locking fastener of the same inner and outer diameter should be used.<br>3. Self-tapping sheet metal screws holes must be drilled out to accommodate a full-sized fastener.<br>4. Use the torque values provided in the module installation manual.<br>5. Follow torque audit procedures using the First Movement method in Section 5.2.7.<br>6. Torque audits are not performed on lock bolts.<br>7. If soft joints are a problem, use Belleville washers. | |

## Corrective Action 6: Replace Specialty Clamps and Self-Tapping Sheet Metal Screws with Through-Bolts

**Rationale:** Some manufactures offer "fast assembly" products that utilize clamps to join rack frame elements and to mount solar modules. These products are not adequate solutions for critical bolted joints where there is a potential for serious life-safety issues and risk of high economic loss. These products should be replaced with either bolt, nut, and wedge washer assemblies, or lock bolts or fasteners with pre-applied thread locking compound. Because this involves modification to an existing fastener system, a bolted joint engineer should be consulted. See the Additional Resources section.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 9: Use of backside clamping devices to fasten the module frames to rails
- Vulnerability 11: Use of clamping devices to fasten the racking assembly together
- Vulnerability 12: Self-tapping sheet metal screws used to hold the racking assembly together.

**Skill Level Required:** Facilities engineer with mechanical skills or a trained electrical or PV technician

**Specialized Tools Required:** Torque wrench

**Engineering Services:** A bolted joint engineer is required to specify an engineered solution.

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Replacing specialty clamps and self-tapping sheet metal screws with through-bolts**

**Figure 100. Through-bolting modules can increase resistance to heavy wind forces**

*Source: Home Depot*

**General Application:** Through-bolt with either nut, bolt, and wedge washer or lock bolt or fastener with pre-applied thread locking compound.

**Advantages**

- Eliminates concerns with clamps and self-tapping sheet metal screws

**Disadvantages**

- Must be applied with a torque wrench
- Threads will need treatment with anti-galling compound
- Requires access to back of module and racking rails.

### Instructions

Through-bolting require the following steps to use:

1. Drill holes at locations of existing clamps and/or self-tapping sheet metal screws.
2. For existing clamps, look up the rated clamping forces, which will be expressed as either coefficient of friction or axial bolt clamp force (lbs). Add a 50% safety factor to the value. Use an online fastener calculator (Engineer's Edge) to calculate the bolt size.

3. Install nut, bolt, and locking washers using anti-scaling compound on threads. Use the torque value found with the online tool (Engineer's Edge) to tighten the fastener.
4. Consult with a bolted joint engineer to specify a solution.

## 6.4 Special Considerations with Roof Arrays

**Corrective Action 7: Reconfiguration of PV array to allow interior access**

**Rationale:** Without access to interior rows, many critical parts of the PV system (e.g., fasteners, modules, DC wiring), as well as the roofing material, cannot be inspected or maintained.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 15: Inaccessible and wind damage-prone PV array

**Skill Level Required:** Qualified solar PV contractor with an in-house design engineer
**Specialized Tools Required:** N/A
**Engineering Services:** A structural engineer and electrical engineer with experience in solar PV systems

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Reconfiguration – opening the layout to allow interior access**

**Figure 101. This design allows for O&M access to the PV system and roof material**

*Source: Sunlink*

**General Application:** Where there is no physical access to the array's interior, the layout may need to be reconfigured if there is an ongoing need to maintain the system and roof and/or clean out leafy debris. Reconfiguration can be done when mechanical attachment points are added.

**Advantages**

- Allows access to maintain all parts of array, as well as the underlying roof

**Disadvantages**

- Major reconfiguration and cost that could result in a smaller array size
- The new layout will need to be engineered by both an electrical engineer and structural engineer.

**Instructions**

1. If there is need to reconfigure the array to allow access to interior sections for repair and maintenance of the array and roof, the agency will need to retain both electrical and structural engineering services.

2. It is critical that the structural engineer retained has experience with solar PV array designs, and can demonstrate that experience.

**Corrective Action 8: Add Mechanical Attachments to Building Structure to Improve the Structural Integrity**

**Rationale:** Ballasted PV systems on low-sloped roofs are at high risk of movement from strong, dynamic winds.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 16: Inadequate structural attachment to the building

**Skill Level Required:** Qualified solar PV contractor
**Specialized Tools Required:** N/A
**Engineering Services:** A structural engineer with a unique background in solar PV is required.

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Add mechanical attachments to the building structure**

**Figure 102. Mechanical attachment to building structure**

*Source: Ecofast*

**General Application:** Roof arrays that rely mostly on ballasting should be examined carefully, given their potential to become dislodged in a wind event. For regions that experience severe weather events with heavy winds, these roof arrays should be a high priority for retrofit.

**Advantages**

- Prevents dislodged array components in a wind event from becoming dangerous flying debris

**Disadvantages**

- Array will need to be partially disassembled to add the attachments
- Modifications will need to be specified by a structural engineer.

**Instructions**

1. Due to the significant life-safety issues involved, it is highly recommended that any array on a low-sloped roof be evaluated by a structural engineer experienced with wind and solar PV systems.
2. Redesign should be guided by SEAOC guidance (Wind Design for Solar Arrays PV2-2017), which is a compendium to the ASCE 7-16 standard.
3. See Section 3, Hiring a Consulting Engineer.

## Corrective Action 9: Redesign a PV System to Reduce Potential Damage from Heavy Wind Forces

**Rationale:** If the elevation of an array is partially or fully above the parapet or roof peak (in the case of sloped roofs) then the front and backside will likely receive very strong wind forces, resulting in catastrophic failure and dangerous flying debris. Top-down module clamps can easily fail under wind pressures seen with arrays that sit prone above the roof parapet or peak.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 17: Mounting position of a PV array resulting in high wind exposure

**Skill Level Required:** Qualified solar PV contractor

**Specialized Tools Required:** N/A

**Engineering Services:** A structural engineer and electrical engineer with experience in solar PV systems

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Redesign and reconfigure array**

**Figure 103. Roof mounted PV array**

*Source: Solar Panels Plus*

**General Application:** A consulting structural and electrical engineer will need to develop a scope of work with a full set of design drawings that will result in the array's modification.

**Advantages**

- Resolves a serious life-safety issue
- Results in an array less visible from the ground

**Disadvantages**

- Costly
- Potential to result in a reduced PV system size (kilowatt-hours).

### Instructions

1. See Section 3, Hiring a Consulting Engineer and Appendix C for BOD language.
2. The engineer will generate a set of new design documents that will prescribe the modifications needed.
3. See Section 9, Considerations for Hiring a Contractor for tips on soliciting a contractor.

### Corrective Action 10: Redesigning a PV System to a Lower Tilt Angle to Reduce Potential Wind Damage

**Rationale:** In regions with a large snowfall, it is not uncommon to find array tilts >15% as a means to help shed snow accumulations. High tilt angles in regions that experience hurricane-force winds or even strong summer thunderstorms should be a concern. Wind forces, particularly from the northern direction, can be very heavy on arrays with high tilt angles.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 18: Array tilts (>15°) resulting in high turbulence and front and back pressure on modules

**Skill Level Required:** Qualified solar PV contractor

**Specialized Tools Required:** N/A

**Engineering Services:** A structural engineer with experience in solar PV systems

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

#### Corrective Action Options

| | | |
|---|---|---|
| **Redesign and reconfigure array to a lower-tilt angle** |  **Figure 104. The low-tilt angle of a PV array reduces chances for wind damage** *Source: Sunlink* | **General Application:** Redesigning PV systems with high tilts (>15%) in high wind regions is critical to ensure their survivability during severe weather events.<br>**Advantages**<br>• Will greatly reduce wind drag and associated stresses on the array<br>**Disadvantages**<br>• Substantial cost and procurement effort to undertake the array's reconfiguration. |

#### Instructions

1. See Section 3, Hiring an Engineer, and use BOD language in Appendix C.
2. The engineer will generate a set of new design documents that will prescribe the modifications needed.
3. See Section 9, Considerations for Hiring a Contractor on tips for soliciting a contractor.

### Corrective Action 11: Remove and/or Replace a Flexible PV System Glued to the Roof

**Rationale:** While most of these glued-down arrays have been removed since their installation, a few remain. If a site still has this kind of array and there is a history of damage to the underlying roof from electrical faults, then this is a candidate for removal of all modules and roof repair.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 19: Flexible PV array glued to roof membrane

**Skill Level Required:** Qualified solar PV contractor

**Specialized Tools Required:** N/A

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Removal and replacement of modules and racking assembly and refurbishment of BOS**

**General Application:** This option would require removal of modules, repair to roof, refurbishment of BOS components, and installation of new modules and a "roof friendly" racking system.

**Advantages**

- Eliminate modules causing electrical shorts and roof damage
- Install new modules on roof friendly racking, utilizing any existing equipment to reduce cost

**Disadvantages**

- High cost
- High procurement effort.

**Complete replacement of PV system**

**Figure 105. New construction PV system**

*Source: Solar Builder Magazine*

**General Application:** The agency may choose to remove all solar PV components and replace them with an entirely new system. The roof would be either repaired or replaced.

**Advantages**

- The array achieves a safe performance for its expected 30-year lifespan

**Disadvantages**

- High cost
- High procurement effort.

<table>
<tr>
<td>Complete removal of the PV system and restoration of the site to its original condition</td>
<td><br>Figure 106. New roof<br>Source: Roofing.com</td>
<td>General Application: This would be a complete removal of the PV system and a restoration of the site to its original condition.<br>Advantages<br>• Eliminate modules causing electrical shorts and roof damage<br>Disadvantages<br>• The agency no longer has a PV system to reduce energy costs.</td>
</tr>
<tr>
<td colspan="3">Instructions</td>
</tr>
<tr>
<td colspan="3">1. Consider hiring a consultant to understand the technical and financial implications of each option before making a decision.<br>2. Consider using an ESPC-ENABLE contract for O&M. See Section 10 for financing and procurement options.</td>
</tr>
</table>

## 6.5 Modules

**Corrective Action 12: Replace Module(s) Showing Signs of Degradation**

**Rationale:** PV systems can experience broken glass top-sheets and cracked cells if they are located in regions with high wind and snow loads, as well as in regions experiencing hail events. Upon cell or glass top-sheet cracking, modules may still be able to perform to their expected production level. Unfortunately, however, these vulnerabilities will start to worsen over time and reduce the performance of the modules. Additionally, modules with cracked backsheets will show similar signs of degradation over time.

These vulnerabilities can quickly become more serious when exposed to severe weather events like hurricanes and blizzards. Water intrusion from rain and snow in broken glass top-sheets and cracked backsheets will create electrical faults within the modules, potentially creating a dangerous scenario for life-safety of site personnel.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 20: Damaged modules from inadequate resistance to wind/snow loading and hail
- Vulnerability 21: Cracked or failed backsheet

**Skill Level Required:** Trained electrical or specialized PV technician and IR imaging professional trained in PV module inspections

**Specialized Tools Required:** Torque wrench, PV connector assembly tool, I-V curve testing device, IR camera

**Engineering Services:** An electrical engineer with a solar PV background

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

| | |
|---|---|
| **Replace any module with a broken glass top-sheet** | **General Application:** Any module with a broken glass top-sheet should be replaced immediately before water intrusion causes electrical faults within the module.<br>**Advantages**<br>• Reduces the chance that module failure will create a dangerous life-safety issue<br>• Replacement module will achieve expected performance level<br>**Disadvantages**<br>• Manufacturer warranty may not cover labor and logistical costs to replace module. |
| **Replace module with a cracked or failed backsheet** | **General Application:** Any module with a cracked or failed backsheet should be replaced immediately before water intrusion causes electrical faults within the module.<br>**Advantages**<br>• Reduces chance that the module failure will create a dangerous life-safety issue |

| | |
|---|---|
| | • Replacement module will achieve the expected performance level<br>**Disadvantages**<br>• Manufacturer warranty may not cover labor and logistical costs to replace the module. |
| **Conduct an I-V curve test on the string and module level**<br><br>**Figure 107. I-V curve testing**<br>*Source: Seaward Group* | **General Application:** Perform an I-V curve test on the string and module level to determine what modules need to be replaced or marked for retesting at a later date.<br>**Advantages**<br>• Confirms whether or not a module with cracked cells needs to be replaced<br>• Can be less costly than module replacement if no underperformance is detected<br>**Disadvantages**<br>• Can be labor intensive if a large number of strings and modules need to be tested. |
| **Replace module with cracked cells** | **General Application:** A module with cracked cells that is found to be underperforming by at least 10% should be replaced.<br>**Advantages**<br>• Reduces the chance that the module failure will create a dangerous life-safety issue<br>• Replacement module will achieve expected performance level<br>**Disadvantages**<br>• Manufacturer warranty may not cover labor and logistical costs to replace the module. |

**Instructions**

Modules with broken glass top-sheets and/or cracked/failed backsheets should be replaced immediately. Although many of these modules can still perform as expected, it is inevitable that water from rain and snow will penetrate into the module and cause electrical faults. There may be instances where repairing a cracked module backsheet is an option. However, these solutions are temporary and only prolong an inevitable replacement of the module.

The site should identify if the module replacement(s) can be covered under a manufacturer's warranty. It is important to note that most module warranties only cover the replacement module and not the associated labor and logistical costs.

Note that modules that have experienced cell cracking may still perform to their expected performance level. However, as stated above, these will gradually begin to degrade, especially if cell cracking gets worse through high winds, snow loads, or hail events. The site should conduct the following steps to identify if modules with cracked cells need to be replaced:

1. Use an IR camera to scan the modules and identify if any of them show signs of cell cracking. An EL imaging consultant may be needed to determine which modules are affected.

2. Perform an I-V curve test on every string in the array that has at least one module with cracked cells to measure underperformance on a string level.
3. If a string is found to be underperforming, an I-V curve test must be performed on each module in the string.
4. Any module found to have a performance decline of 10% or greater should be replaced.
5. If modules are found to have cracked cells via IR or EL imaging and have no performance issues based on I-V curve testing, they should be marked and retested at a later date to see if the pattern of cell cracking has worsened, resulting in a drop in performance of more than 10%.

IMPORTANT: All replacement modules should be electrically and physically compatible with the rest of the modules in the array. Electrical mismatch occurs when there are modules installed in the same array with different electrical characteristics (i.e., current, voltage). This can create problems for the PV system and should be avoided. Physical mismatch is due to the varying dimensions of different brands of modules. Even modules from the same manufacturer can have different physical characteristics like height, width, and frame thickness. Installing modules with different physical characteristics must also be avoided.

## 6.6 Wire Management

**Corrective Action 13: Proper Wire Management Support and Protection**

**Rationale:** All DC wiring should be protected and not left exposed to weather elements like heavy winds, snow, rain, and sunlight. Some sites may find that a combination of options best suits their wire management needs, as there is no single best option. The NEC requires DC wires be supported at a specified interval (typically 12″) to prevent movement and chafing of insulation, resulting in electrical faults. It is recommended that the solution take into account ultraviolet exposure, humidity, and temperature variations.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 22: Improperly supported wires

**Skill Level Required:** Trained electrical or specialized PV technician

**Specialized Tools Required:** Impact driver, flat-headed screwdriver, channel lock pliers

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**EPDM rubber-lined clamps**

**Figure 108. EPDM rubber-lined clamp support wires**

*Source: Fastronix Solutions*

**General Application**: Clamps are anchored with screws into the racking assembly to support wires and prevent movement.

**Advantages**

- Rubber-lined for wire insulation protection
- Durable material can survive environmental conditions

**Disadvantages**

- Requires access to the back of the module and the racking assembly.

**Metallic module wire clip**

**Figure 109. Module wire clips can last the life of the PV system**

*Source: Solar Builder Magazine*

**General Application**: Clips are attached to interior frame of the module, and wires are secured into the clip.

**Advantages**

- Easy to install
- Durable material can survive environmental conditions

**Disadvantages**

- Only holds up to two wires per clip
- Requires access to the back of the module and the racking assembly

| | | |
|---|---|---|
| Metallic rail wire clip | <br>**Figure 110. Rail clip can hold up to four PV wires**<br>*Source: AltE Store* | **General Application**: Clips are attached to the channel on top of the rail, and wires are secured into the clip.<br>**Advantages**<br>• Easy to install<br>• Durable material can survive environmental conditions<br>• Can hold up to four wires per clip<br>**Disadvantages**<br>• Requires access to the back of the module and the racking assembly. |
| Metallic wire tie | <br>**Figure 111. Metal wire ties must be installed properly to avoid damaging wire insulation**<br>*Source: NetZero Tools* | **General Application**: The metal wire tie is wrapped around bundle of wires and secured firmly to the racking assembly.<br>**Advantages**<br>• Easy to install<br>• Durable material can survive environmental conditions<br>**Disadvantages**<br>• Poor installation method can cause sharp metal to be overtightened and cut into wire insulation<br>• Requires access to the back of the module and the racking assembly. |
| Conduit | <br>**Figure 112. PV wires routed properly into a conduit body for protection**<br>*Source: CED Greentech* | **General Application**: Conduit pipe and bodies provide covered support for wires and can be installed on the racking assembly and/or the roof.<br>**Advantages**<br>• Protects wires completely from weather conditions<br>• Durable material can survive environmental conditions<br>**Disadvantages**<br>• More labor intensive than other options. |

**Instructions**

1. Best practices and workmanship must be followed by the contractor to ensure that the wire management product will last the full life of the PV system. For example, metallic cable ties may be an effective solution, but if tied too tightly, they can damage the wire insulation and lead to electrical hazards.
2. All wire management options, if used, should not cause any stress or strain to the module wires.
3. All wires should be routed in ways that do not cause them to fail against any sharp or abrasive surfaces (e.g., modules, rails, shingle roof).

## Corrective Action 14: Ensure the Equipment Grounding System is Functional

**Rationale:** Corroded grounding components can hinder a PV system's ability to properly defuse ground faults, which can lead to damage to infrastructure and life-safety threats.

**Associated Vulnerabilities Addressed by This Corrective Action:**

- Vulnerability 23: Corroded grounding components due to environmental conditions or dissimilar metals

**Skill Level Required:** Trained electrical or specialized PV technician

**Specialized Tools Required:** Electrical wire strippers, torque wrench

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Replace corroded grounding components with non-corrosive components**

**Figure 113. Solid ground wire**

*Source: Home Depot*

**Figure 114. Grounding lug**

*Source: Home Depot*

**General Application**: Functional equipment grounding components will last the expected life of the PV system.

**Advantages**

- Protection from ground faults
- Significantly reduces potential for ground faults to cause damage to infrastructure
- Ensures life-safety of site personnel

**Disadvantages**

- Requires access to the back of the module and the racking assembly.

### Instructions

1. Corrosion in the grounding system is most often due to dissimilar metals corrosion (called *galvanic corrosion*) on one component of the grounding system. Any grounding lug, splice, and wire not of copper, brass, or stainless steel set screws on lugs shall be replaced.
2. If some grounding components are showing little to no corrosion but are made of the same material, it is likely that the non-corroded components will fail at some point. In this scenario, it is recommended that the entire grounding system be replaced.

## Corrective Action 15: Replace Damaged DC Wiring

**Rationale:** Damage to DC wiring can affect the performance of the PV system, and if left unattended can cause damage to infrastructure and pose a threat to the life-safety of site personnel.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 24: Poor installation practices leading to damage of PV and other DC wires

**Skill Level Required:** Trained electrical or specialized PV technician

**Specialized Tools Required:** Electrical wire strippers, MC4 connector assembly tool, MC4 crimping tool

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

| | |
|---|---|
| **New PV wire**  **Figure 115. PV wire** *Source: Solar Panel Store* | **General Application**: PV wiring is used to connect modules and home run leads together to bring electricity from the PV array to the combiner boxes.<br>**Advantages**<br>• Significantly reduces the potential for electrical faults from damaged PV wire<br>**Disadvantages**<br>• Requires access to the back of the module and the racking assembly. |
| **New DC wiring in BOS equipment** | **General Application**: DC wiring in the BOS is critical to bringing electricity from the PV array to the inverters.<br>**Advantages**<br>• Significantly reduces the potential for electrical faults from damaged PV wire<br>**Disadvantages**<br>• May require access to the back of the module and the racking assembly. |

### Instructions

Any wires that have been damaged should be replaced with the same type of wire.

**Corrective Action 16: Remove and Prevent Animal Nesting Under PV Array**

**Rationale:** Animal nests must be removed immediately from the PV array, as animals are likely to chew on and use the wires as part of their nest, thus causing damage and reducing system performance. Damaged wires and dry material in the nests have the potential to start a fire, causing damage to the infrastructure and creating life-safety issues for site personnel.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 25: Animals nesting under modules chewing and damaging wires

**Skill Level Required:** Can be performed by any site personnel

**Specialized Tools Required:** Face mask/respirator, gloves, cardboard box to temporary shelter infant animals, metal shear scissors, tape measure

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools
- Possible contact with disease-carrying animals.

**Corrective Action Options**

**Remove any existing animal nest(s)**

**Figure 116. Animal nests must be removed from the array**

*Source: Bird Barrier*

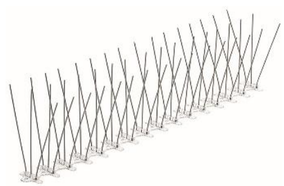
**General Application:** Animal nests must be manually removed from under or behind the PV array.

**Advantage**

- Reduces potential for animals to damage wires
- Reduces potential for birds to soil modules

**Disadvantages**

- Must wear face mask and gloves to prevent contact with animals
- Sometimes requires access to the back of the module and the racking assembly
- May have to provide temporary shelter for infant animals until further guidance is given by local animal shelter or wildlife organization.

| | |
|---|---|
| **Install wire-based critter guard or netting to flush mounted arrays**<br><br>**Figure 117. Critter guards prevent animal nesting**<br>*Source: Bird Barrier*<br><br>**Figure 118. Metal wire critter guards are durable in severe weather environments**<br>*Source: Amazon* | **General Application:** These guards and netting are installed around flush mounted PV arrays to prevent animals from nesting under or behind the modules.<br>**Advantages**<br>• Reduces potential for animals to damage wires<br>• Can be installed by site personnel<br>• Reduces potential for birds to soil modules<br>**Disadvantages**<br>• Labor intensive to install. |
| **Install bird spikes on top of the array**<br><br>**Figure 119. Bird spikes can be installed to prevent bird perching**<br>*Source: Bird-B-Gone* | **General Application:** Prevents perching of birds on the top of array.<br>**Advantages**<br>• Reduces potential for animals to damage wires<br>• Can be installed by site personnel<br>• Reduces potential for birds to soil modules<br>**Disadvantages**<br>• Labor intensive to install. |

**Instructions**

1. Removal of animal nests will require the use of gloves and face masks, as animals such as birds and squirrels are known to carry diseases.
2. Before any removal of animal nests, consider contacting a local animal shelter or wildlife organization, as some of these animals, particularly birds, may be endangered and require special care.
3. The site will need to have continual O&M to make sure that animals have not found new spots to nest after old nesting sites were cleaned out and sealed up.

### Corrective Action 17: Replace Damaged PV Connectors

**Rationale:** Failures in the PV connectors can occur in a variety of ways. It is important that these failures are found early on, before they can become a serious problem.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 26: PV connector failure

**Skill Level Required:** Trained electrical or specialized PV technician

**Specialized Tools Required:** PV connector assembly tool, MC4 crimping tool, IR camera

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

#### Corrective Action Options

**Replace damaged PV connector(s)**

**Figure 120. PV connectors**

*Source: CED Greentech*

**General Application:** Replace all damaged PV connectors with new ones, ensuring the installer employs the best installation practices.

**Advantages**

- Replaces failed component that reduces system performance and creates life-safety issues

**Disadvantages**

- Costly
- Labor intensive.

#### Instructions

1. Replacement connectors must be of the same make and manufacturer as the originals to avoid cross-mating.
2. If PV connector failures are found to be prevalent, the site should determine whether to replace all of the connectors at once, even before signs of damage are visible, or replace the connectors as they fail. Replacing the connectors as they fail will require continual inspection and replacement, and may become a more burdensome cost to the site than if all connectors are replaced at once.
3. Connectors might also have damage that is not readily visible. A more thorough field audit of connectors can be performed with an IR camera to identify if any of them have internal damage.
4. PV connectors that have not been fully secured together may not visibly shows sign of damage. However, water from wind-driven rain and snow, as well as the possibility of internal corrosion from being located in a marine environment, will compromise connector performance. Any PV connectors that are not fully secured together should be marked for replacement.
5. If available, the site inspector should look at product submittals for connectors used and identify any cross-mating problems. The site may have to contact the manufacturer for information on cross-mating.

## 6.7 Electrical Enclosures and Conduit

**Corrective Action 18: Relocate Electrical Equipment Above 100-Year Flood Level to Prevent Flooding**

**Rationale:** Electrical equipment below the site's 100-year flood level should be relocated to a higher elevation.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 27: Electrical equipment located below the site's 100-year flood level
- Vulnerability 28: Conduit draining water into downhill electrical equipment from flooded uphill locations

**Skill Level Required:** Trained electrical technician, crane operator

**Specialized Tools Required:** Full set of standard electrician tools, crane, masonry tools for concrete pad

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools and heavy equipment/machinery.

**Corrective Action Options**

**Relocate ground mounted electrical equipment to a higher elevated concrete pad**

**Figure 121. Crane picking up central inverter for concrete pads to be installed**

*Source: Solar Power World Magazine*

**Figure 122. String inverters mounted behind PV array**

*Source: PV Magazine*

**General Application:** Ground mounted electrical equipment can be reinstalled on elevated concrete pads and reduce potential damage from a 100-year flood.

**Advantages**

- Reduces chance for flood damage

**Disadvantages**

- Costly
- Labor intensive.

**Relocate wall mounted electrical equipment to a higher elevation**

**Figure 123. Wall mounted inverters can be installed higher up**

*Source: Solar Edge*

**General Application:** Wall mounted electrical equipment can be reinstalled higher up the wall and reduce potential damage from a 100-year flood.

**Advantages**

- Reduces chance for flood damage

**Disadvantages**

- Costly
- Labor intensive
- May not have available space to install equipment higher up on the wall.

| Instructions |
| --- |
| 1. Transformers and central inverters are typically installed on concrete pads. This equipment can be temporarily removed and reinstalled on concrete pads that are above the site's 100-year flood level.<br>2. It is also common for large PV systems to install multiple string inverters, in lieu of central inverters, on similar concrete pads or steel structures, as seen in Figure 122.<br>3. Wall mounted electrical equipment like string inverters and switchgear can be remounted higher up on the wall, if possible, or reinstalled inside of the facility, if space is available.<br>4. If underground conduit is acting as a transport for water to flood downhill electrical equipment, the lower-elevated electrical equipment should be reinstalled at a higher elevation. |

**Corrective Action 19: Replace Inadequate and/or Corroded Electrical Equipment**

**Rationale:** All electrical enclosures that are installed outdoors must be able to resist the impacts of severe weather events and particularly, prevent damage from wind-driven rain, snow, and flooding. Failure of these components can have a significant impact on performance and create life-safety issues if left uncorrected.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 29: Common issues with electrical enclosures

**Skill Level Required:** Trained electrical technician

**Specialized Tools Required:** Full set of standard electrician tools

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Replace inadequate and/or corroded enclosures with ones that have contiguous rubber seals and compression latches**

**Figure 124. Electrical enclosure with rubber seal and compression latch**

*Source: USA Blue Book*

**General Application:** An electrical enclosure with a contiguous rubber seal and compression latches will prevent wind-driven rain and snow from intruding.

**Advantages**

- Contiguous rubber seals and compression latches reduce chances for water damage
- Available in variety of sizes

**Disadvantages**

- Can be costly if many replacement enclosures are needed.

**Apply outdoor-rated sealant to penetrations in electrical enclosures**

**General Application:** Outdoor-rated sealant can be used on inadequate electrical enclosures that are installed outdoors. Penetrations in the enclosures like wall-mounting screws and conduit penetrations should be sealed.

**Advantages**

- Less costly than replacing electrical enclosure
- Low skill
- Versatile applications

**Disadvantages**

- Should be considered a temporary measure.

**Install a weep hole in the electrical enclosure**

**Figure 125. Combiner box with weep hole at the bottom corner**

*Source: Kevin J. Watson, LBNL*

**General Application:** A weep hole in an electrical enclosure will allow water ingress to drain out and not cause damage to any of the internal components.

**Advantages**

- Reduces potential for water damage to electrical equipment
- Easy to install

**Disadvantages**

- May void warranty of certain electrical equipment if the manufacturer disallows such retrofits.

**Install a vent or drain plug in the electrical enclosure**

**Figure 126. Vent plug for an electrical enclosure**

*Source: Newark*

**Figure 127. Drain plug**

*Source: Newark*

**General Application:** Allows moisture from condensation buildup or water ingress to drain out and not cause damage to any of the internal components while preventing intrusion through its one-way valve.

**Advantages**

- Less costly than replacing the electrical enclosure
- Available in different sizes
- Easy to install

**Disadvantages**

- May void warranty of certain electrical equipment if the manufacturer disallows such retrofits.

## Instructions

**Inadequate NEMA ratings for outdoor electrical enclosures:**

1. Electrical enclosures should, at a minimum, be equipped with contiguous rubber seals and compression latches that will prevent the intrusion of water from wind-driven rain and snow.
2. It is recommended that any new electrical enclosures have a NEMA rating of 4 or better.

**Corroded electrical equipment:**

In corrosive environments (i.e., marine/coastal areas) electrical enclosures should be a minimum of 4X, as the "X" indicates additional corrosion resistance.

**Electrical enclosure is not equipped with proper drainage for water intrusion:**

1. Drilling a weep hole into the bottom corner of a small (e.g., 6″ x 6″) electrical enclosure or installing a one-way vent/drain plug on a medium-to-large electrical enclosure (e.g., switchgear, combiner box) will allow moisture to drain out and avoid damage to the PV system.
2. Weep holes should be no larger than ¼″ diameter.
3. Weep holes should only be installed on electrical equipment if the site has verified that a weep hole does **NOT** void the manufacturer's warranty. Do not modify inverters without concurrence from manufacturer.

## Corrective Action 20: Prevent Damage to the PV Conduit

**Rationale:** It is critical for conduit to be properly supported with durable supports that can withstand the site's environmental conditions (e.g., rain, snow, sunlight).

Conduit raceways should have the proper fittings to accommodate thermal movement where necessary. Thermal movement, if not originally included in the PV system's design, can cause the conduit to separate from the fittings and potentially cause significant damage to the energized wires in the conduit. Additionally, the PV system should have watertight conduit fittings to prevent water intrusion and avoid damage to the internal components of electrical equipment.

When conduit is damaged, there is a possibility that the energized wires inside of the conduit can be damaged as a result. This can reduce system performance and pose a threat to the life-safety of site personnel. Conduit can be damaged in a variety of ways, as rooftops can be heavily trafficked areas for non-PV O&M activities.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 30: Conduit-related vulnerabilities

**Skill Level Required:** Trained electrical technician

**Specialized Tools Required:** Full set of standard electrician tools

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

### Corrective Action Options

**Install durable conduit supports**

**Figure 128. Conduit supports made of a mix of rubber and steel**

*Source: Arlington Industries*

**General Application**: Conduit supports made of materials like rubber and steel can last the full life of the PV system.

**Advantages**

- Will not degrade during the life of the PV system
- Ensures support of conduit that carry energized wires

**Disadvantages**

- Costly
- Labor intensive.

| | |
|---|---|
| **Install expansion joints to accommodate thermal movement**<br><br>**Figure 129. Polyvinyl chloride (PVC) expansion joint**<br>*Source: Home Depot*<br><br>**Figure 130. Exterior rated metal conduit expansion joint**<br>*Source: Eaton* | **General Application**: Installing expansion joints in runs of conduit will allow for thermal movement and prevent separation of the pipe from the fittings.<br>**Advantages**<br>• Reduces potential for damage to energized wires in the conduit<br>• Comes in a variety of sizes to accommodate different PV system sizes<br>**Disadvantages**<br>• Labor intensive to install<br>• Can be costly if multiple expansion joints are needed. |
| **Replace conduit fittings with ones that are watertight**<br><br>**Figure 131. Watertight conduit fitting**<br>*Source: Home Depot*<br><br>**Figure 132. Watertight conduit coupling**<br>*Source: Home Depot* | **General Application**: Watertight conduit fitting will greatly decrease any potential for water intrusion that can cause damage to internal components of electrical equipment.<br>**Advantages**<br>• Reduces potential for damage from water intrusion<br>• Comes in a variety of sizes to accommodate different PV system sizes<br>**Disadvantages**<br>• Labor intensive to install<br>• Can be costly if a significant number of fittings need to be replaced. |
| **Replace damaged conduit**<br><br>**Figure 133. Exterior-rated metal conduit**<br>*Source: Home Depot*<br><br>**Figure 134. PVC conduit**<br>*Source: Home Depot* | **General Application**: Any damaged conduit must be replaced immediately.<br>**Advantages**<br>• Reduces potential for wire damage in the conduit<br>• Comes in a variety of sizes to accommodate different PV system sizes<br>**Disadvantages**<br>• Costly<br>• Labor intensive. |
| **Install ramp or walkway over roof mounted conduit**<br><br>**Figure 135. Walkway over conduit**<br>*Source: Eaton* | **General Application**: Installing a walkway over rooftop conduit provides a pathway for site personnel and other workers to traverse the roof without damaging the conduit from the PV system.<br>**Advantages**<br>• Reduces potential for damage to conduit from non-PV O&M activities<br>• Better access to roof equipment<br>**Disadvantages**<br>• Costly<br>• Labor intensive. |

| Instructions |
|---|
| **Installing durable conduit supports:**<br>1. All rapidly degradable conduit supports like wooden blocks should immediately be replaced with non-degradable supports made of rubber, steel, and/or aluminum.<br>2. To avoid causing unforeseen damage to the roof, slip sheets or another roof-friendly material should be placed under each support and sealed to the roof with caulk.<br>3. As per the NEC, there is a maximum distance between conduit supports that is based on the size of the conduit (e.g., 10' maximum distance between supports for 3/4″ conduit). It is recommended to add additional supports and reduce these intervals to provide more support for the conduit.<br>**Conduit installed without the proper fittings for the site's environmental conditions:**<br>If it is found that the conduit fittings are **not** rated for thermal movement or to prevent water intrusion, they should be replaced with fittings that can perform these necessary functions.<br>**Roof mounted PV conduit showing physical damage (e.g., crushed, bent):**<br>1. There is a need for quick action as the conduit is carrying energized wires from the PV array to inverters.<br>2. Any roof mounted conduit showing evidence of damage must be replaced immediately.<br>3. To prevent future damage, walkways and ramps should be placed over all roof mounted conduit, so site personnel can safely move about the roof to perform various non-PV O&M activities. |

### Corrective Action 21: Replace All Field Labels and Markings that are Showing Signs of Degradation

**Rationale:** Field markings and labels are required on various components of the PV system (i.e., inverters, switchgear) as per the NEC. According to the NEC, label materials must be durable enough to withstand the local environmental conditions. However, label materials are not always sufficient to withstand these conditions. Field labels and markings need to be readable in the event that emergency responders need to de-energize and work around the PV system.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 31: Field-applied labels and markings showing signs of significant degradation

**Skill Level Required:** Trained electrical technician

**Specialized Tools Required:** None required

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

#### Corrective Action Options

| | |
|---|---|
| **Replace field labels and markings** | **General Application:** Field labels and markings should be readable for any PV O&M contractors and emergency responders.<br>**Advantages**<br>• Provides clarity to O&M personnel and emergency responders on the details of the PV system<br>• Visible labels help the PV system meet NEC standards<br>**Disadvantages**<br>• None. |

#### Instructions

1. Any labels that are showing signs of significant degradation must be replaced.
2. All recurring preventative maintenance performed on the PV system should include the inspection of labels and markings to ensure they are still readable and not degrading.
3. Replacement field labels and markings should be made of durable material and to withstand the site's environmental conditions (e.g., rain, ultraviolet exposure, heat).

## 6.8 Topography

**Corrective Action 22: Install a Wind Calming Fence to Reduce Wind Forces on the PV System**

**Rationale:** Unobstructed wind forces can significantly impact a PV system and potentially cause catastrophic damage. Efforts must be taken to reduce the wind forces on the PV system in order to avoid these losses and reduce the risk to life-safety of site personnel.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 32: Unobstructed wind forces on the PV system

**Skill Level Required:** Fence installer

**Specialized Tools Required:** General fence building equipment

**Engineering Services:** A structural engineer with experience in solar PV systems

**Safety considerations that must be planned for include:**

- Presence of large landscaping equipment and vehicles
- Underground utilities around the PV system area.

**Corrective Action Options**

**Install a wind calming fence around the perimeter of the PV array(s)**

**Figure 136. Porous wind fence around a PV array**

*Source: WeatherSolve Structures*

**Figure 137. Fencing reduces wind speeds and snow accumulation on roads**

*Source: Minnesota Department of Transportation District 4*

**General Application:** A wind calming fence can reduce the effects of turbulent wind forces on the PV system while also achieving other benefits.

**Advantages**

- Reduces effects from turbulent wind forces
- Reduces potential for catastrophic damage to the PV array(s)
- Reduces O&M costs associated with module cleaning
- Provides additional security to the PV system

**Disadvantages**

- Costs increase with the PV system size
- Liability issues need to be addressed before installation.

**Instructions**

1. Installing a wind calming fence will reduce the turbulent wind forces on the PV array(s) and greatly reduce the potential for damage. Wind calming fences are porous and allow wind to pass through them. This avoids the potential for the creation of a low-pressure zone on the downwind side of the fence. Winds are then deflected above the perimeter rows, which are the most vulnerable to turbulent wind forces.
2. A solid wall would create a large pressure differential between the upwind and downwind sides, causing turbulence on the perimeter rows of modules.
3. The differences between solid and porous walls for wind calming effects can be seen in Figure 138.

4. Because a wind calming fence reduces the wind load on the perimeter rows of modules, this may reduce the needed strength of the retrofit to the racking assembly and fasteners to withstand high winds and gusts (Elsworth and Van Geet 2020).

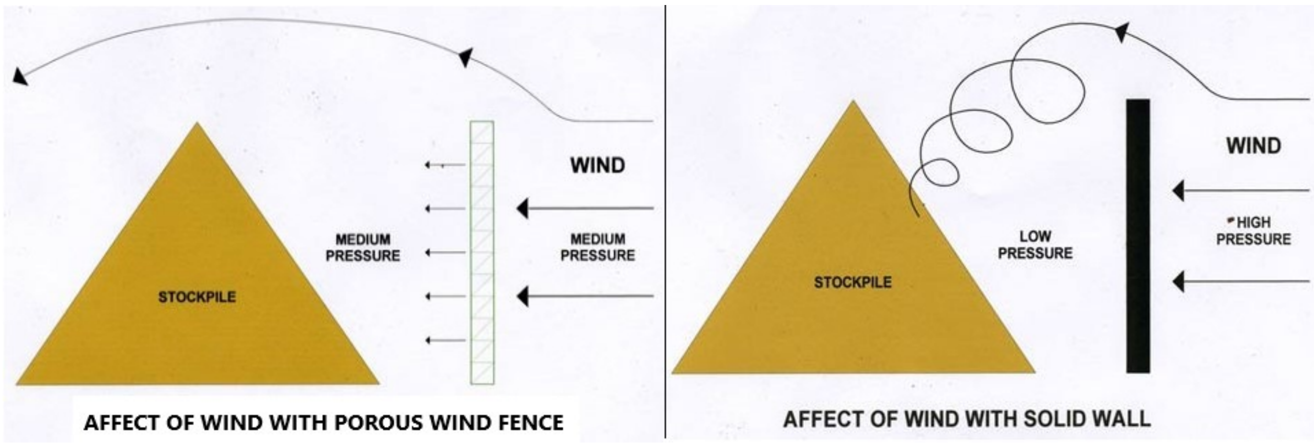



**Figure 138. Wind forces become less turbulent with porous fencing and are better suited for a PV system**

*Source: Dust Solutions, Inc.*

## 6.9 Site Management

### Corrective Action 23: Inspect and Clear Roof Drains to Avoid Electrical and Structural Damage

**Rationale:** Clogged roof drains can cause a buildup of water and flood conduit and electrical enclosures, while also potentially causing damage to the roof via pooling water.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 33: Clogged roof drainage system

**Skill Level Required:** Can be performed by any site personnel

**Specialized Tools Required:** Face mask/respirator, gloves, impact driver, drill

**Engineering Services:** A structural engineer with experience in solar PV systems

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools
- Contact with debris in drains.

**Corrective Action Options**

<table>
<tr><td>Clear roof drains of any debris</td><td>General Application: Roof drains must be cleared of any debris that is impeding the flow of water.<br>Advantages<ul><li>Allows water from rain and snowmelt to properly drain off roof</li><li>Prevents water pooling that can lead to structural damage of the roof</li></ul>Disadvantages<ul><li>Must be performed throughout the year.</li></ul></td></tr>
<tr><td>Install roof drain cover<br><br>Figure 139. Flat roof drain cover<br>Source: Home Depot</td><td>General Application: A roof drain cover must be installed over every drain to prevent debris from entering and clogging it.<br>Advantages<ul><li>Protects roof drains from becoming clogged with debris</li></ul>Disadvantages<ul><li>Requires recurring maintenance to be conducted.</li></ul></td></tr>
</table>

| | | |
|---|---|---|
| **Mark roof drain(s) with snow stake for site personnel to locate** |  **Figure 140. Snow marker for roof drains** *Source: Amazon* | **General Application:** Installing a stake on or next to a roof drain is useful for any site personnel that needs to clear it out to allow for snowmelt to drain off the roof.<br>**Advantages**<br>• Makes access to drains easy when roof is covered in snow<br>**Disadvantages**<br>• None. |

**Instructions**

1. Recurring maintenance is essential for the safe and reliable performance of a PV system. In particular, roof drains must be inspected, preferably more than once per year, and cleared of any debris that has accumulated.
2. If the site has not already done so, entering into an O&M contract with an O&M provider can ensure that maintenance tasks like clearing roof drains are not deferred.
3. All roof drains must be equipped with a cover to prevent the buildup of debris.
4. If the roof has experienced significant and prolonged water accumulation, it is recommended that a structural engineer conduct an inspection/analysis of the roof's structural integrity. Subsequent reports should be provided to the site with the results of the analysis.
5. Additionally, some roof material may have become warped due to prolonged inundation of water. Careful examination of the roof material should be conducted.

## Corrective Action 24: Protect against and/or Repair Roof Damage from PV System

**Rationale:** PV equipment that comes in direct contact with the roof can cause damage if left uncorrected. A compromised roof membrane can allow for water intrusion and significant damage to the structure of the roof.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 34: PV equipment in direct contact with the roof membrane

**Skill Level Required:** Qualified roofing contractor

**Specialized Tools Required:** Roofing contractor will have proper tools and equipment

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders.

### Corrective Action Options

**Roof repair**

**Figure 141. Roof repair**

*Source: ClipArt Library*

**General Application:** Repairs to the roof may be necessary if the PV system has caused any damage.

**Advantages**

- Prevents damage from water intrusion
- Potentially addresses other deferred maintenance issues with the roof

**Disadvantages**

- Can be costly
- Labor intensive.

**Install a protective sheet under any part of the PV array that comes in contact with or is close to the roof membrane**

**General Application:** The sheet acts as a barrier between any part of the PV system that comes in contact with the roof membrane and has the potential to cause damage to it.

**Advantages**

- Protects the roof membrane from sharp/abrasive parts of the PV system
- Reduces the potential for roof leak caused by a PV system

**Disadvantages**

- Can be costly
- Labor intensive.

### Instructions

1. If any PV equipment is seen coming in direct contact with the roof membrane, a thorough inspection must be conducted to identify if any damage has been done. If damage to the roof membrane is confirmed, the site must repair the damage done in a timely manner.

2. Additionally, the cause of the damage to the roof membrane must be solved in order to prevent additional damage to the roof.
3. Slip sheets made of a material suitable for the site's environmental conditions should be used abundantly around the PV system where contact with the roof may occur.

**Corrective Action 25: Clear Debris and Secure Loose Equipment Around the PV System**

**Rationale:** Proper site maintenance is critical in reducing the chances that airborne debris damages a PV system or harms site personnel during a high wind event.

**Associated Vulnerabilities Addressed by This Corrective Action:**

- Vulnerability 35: Loose debris and/or equipment scattered around a PV array

**Skill Level Required:** Can be performed by any site personnel

**Specialized Tools Required:** Face mask/respirator, gloves, impact driver, drill, torque wrench (if necessary)

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

| | |
|---|---|
| **Securing or removing equipment and debris from the area around the PV system** | **General Application:** Recurring maintenance should be performed to secure or remove any loose or defunct equipment and debris, as well as to identify objects that could become airborne hazards.<br>**Advantages**<br>• Removes objects that can become airborne and damage the PV system<br>• Removes the potential for airborne objects to threaten the life-safety of site personnel<br>**Disadvantages**<br>• May require relocating equipment in space-constrained sites. |

**Instructions**

1. The site must ensure that these objects are secured and/or removed from the area to prevent them from becoming airborne.
2. A roof mounted PV system is usually surrounded by other non-PV-related equipment like HVAC units and communication towers. These must also be adequately secured to prevent them from becoming airborne and causing damage to the array. Defunct equipment, oftentimes an old antenna or air conditioning unit that is no longer used, should be removed from the roof.
3. A ground mounted PV system may see similar conditions, with objects like utility poles and trees having the potential to become sources of airborne debris and cause damage to the PV system.

**Corrective Action 26: Improve Stormwater Management Around a Ground Mounted PV Array**

**Rationale:** Soil erosion and scouring around foundations can have a significant impact on the stability of the PV system and cause damage to the local environment (e.g., increased turbidity from soil erosion into waterways). Best practices for SWM are most effective when done during the design and construction phases. However, given the scope of this guide, the following recommended corrective actions are remediation efforts that can be performed after construction of the PV arrays.

**Associated Vulnerabilities Addressed by this Corrective Action:**

- Vulnerability 36: Improper stormwater management around a ground mounted PV system

**Skill Level Required:** Landscaping contractor familiar with pollinator friendly habitats

**Specialized Tools Required:** General landscaping equipment

**Engineering Services:** Civil engineering services will be required

**Safety considerations that must be planned for include:**

- Presence of large landscaping equipment and vehicles
- Underground utilities around the PV system area.

**Corrective Action Options**

**Pollinator plantings**

**Figure 142. Pollinator plantings around a PV system**

*Source: Fresh Energy*

**Figure 143. Pollinator habitat**

*Source: Fresh Energy*

**General Application**: Pollinator plantings are a very effective method to reduce soil erosion and scouring, as well as achieve other non-energy benefits.

**Advantages**

- Relatively low-cost measure
- Provides structural stability to the soil
- Reduces soil erosion and scouring around foundations
- Lower O&M costs than turf grass
- Provides habitat for pollinator species
- Can improve system performance by reducing heat island effect

**Disadvantages**

- May require the addition of topsoil
- Need an experienced vendor for the design, installation, and management of the vegetation.

<table>
<tr>
<td>Installation of site stormwater management (SWM)</td>
<td><br>Figure 144. Bioswale is an effective SWM feature<br>Source: Tata & Howard</td>
<td>General Application: SWM features can be retrofitted into an existing site. This will require retaining a civil engineer who can produce construction drawings and guide environmental compliance and scopes of work.<br>Advantages<br>• Provide a permanent solution and prevent damage to the array and environmental harm<br>Disadvantages<br>• Modifying site landscape to accommodate SWM features is costly and requires an involved solicitation.</td>
</tr>
<tr>
<td colspan="2">O&M</td>
<td>General Application: Continual O&M must be conducted to ensure that the site is not experiencing any soil erosion and scouring vulnerabilities.<br>Advantages<br>• Frequent monitoring and inspections will ensure SWM features are performing as expected<br>Disadvantages<br>• Need to find a qualified solar contractor or vendor that installs and designs pollinator plantings.</td>
</tr>
<tr>
<td colspan="3">Instructions</td>
</tr>
</table>

**Pollinator Plantings:**

1. Reestablishing vegetation on bare soil is essential to reducing soil erosion and controlling water runoff. Based on existing soil conditions, adding topsoil with sufficient organic matter may be required.
2. While turf grass is commonly used to add vegetation to the soil, it should be avoided due to its shallow root structure (~3–6 inches) and high O&M costs from required mowing and fertilization. Pollinator plants and grasses compatible to the region should be used, as their root structures are deeper (~4–6 feet deep). With a deeper root structure, the pollinator plants give the soil more structural integrity and make it less susceptible to erosion. Pollinator plantings, once established, have fewer O&M costs as they require less mowing.
3. It is recommended that the seed mix to establish pollinator plantings include shade-tolerant plants and grasses for the areas underneath the PV arrays.
4. Pollinator-friendly seed suppliers are an excellent source of information on qualified landscape contractors that are able to install pollinator-friendly habitats.

**Installing Stormwater Management Landscape Features**

1. This option will require hiring a civil engineer to design the landscape modifications and guide the process through the environmental compliance requirements.

**Operations and Maintenance**

1. Vegetation, outlets for water runoff, and other SWM features should be monitored and inspected throughout the project's life. This site monitoring should be incorporated into the O&M staff's annual operating plan.

2. It is recommended that the site and O&M provider establish a contingency plan to address any concerns and potentially perform inspections more frequently throughout the year if problems arise.
3. Metrics of soil erosion should be established that will prompt actions to be taken if the soil erosion levels are higher than an agreed-upon threshold.

**Corrective Action 27: Clearly Mark the Presence of the PV Array and its Boundaries to Prevent Damage to Snow-Covered Modules**

**Rationale:** When a PV array is covered in snow, whether it be roof or ground mounted, there is a possibility for damage to be done if a team is hired to clear the snow. The team can unknowingly walk on the modules and/or damage them with their shovels.

**Associated Vulnerabilities Addressed by This Corrective Action:**

- Vulnerability 37: PV array covered in snow, making it susceptible to damage

**Skill Level Required:** Can be performed by any site personnel

**Specialized Tools Required:** Impact driver, drill, torque wrench (if necessary)

**Safety considerations that must be planned for include:**

- General electrical shock hazard
- Fall hazard on roofs and ladders
- Use of power tools.

**Corrective Action Options**

**Mark the perimeter of the PV array with snow stakes**

**Figure 145. Snow markers can be used to mark the perimeter of a PV array**

*Source: Blackburn Flag*

**General Application:** Using snow stakes to mark the perimeter of the PV array can help prevent damage from site personnel and O&M providers.

**Advantages**

- Prevents damage to the roof mounted PV array from shovels and foot traffic of site personnel
- Prevents damage to the ground mounted PV array from snowplows

**Disadvantages**

- Inadvertently shade modules if installed too close to array.

**Install signs indicating the presence of a PV array at various access points to the roof**

**General Application:** Placing signs at various roof access points like hatchways, ladders, and roof doors can alert site personnel to the presence of a roof mounted PV array, especially if the array is covered in snow and not visible.

| | |
|---|---|
| | **Advantages**<br>• Prevents damage to the PV array from shovels and site personnel<br>**Disadvantages**<br>• Outdoor sign must be made of durable material. |
| **Instructions** | |
| 1. Snow stakes should be installed around the perimeter of the PV array so site personnel can identify the array's location. This is especially important for arrays that have low or no tilt angles. These arrays can easily be covered in snow and should be clearly marked.<br>2. Ground mounted PV arrays need snow stakes at the lower end because this is most likely the part of the array that will be covered in snow.<br>3. The snow stakes should be close enough to the PV array but not too close as to cause shading on the modules.<br>4. Signs installed at roof access points to indicate the presence of a PV array should be made of durable material that can withstand the site's harshest environmental conditions. These signs should be continually inspected and replaced if they are showing signs of degradation. | |

# 7 Costing

Step 4
Make Corrective Actions Plan

Constructing, maintaining, and retrofitting PV systems comes at a cost. Over the lifetime of the system these investments should save money through reduced repair, maintenance, and loss of production/downtime, while also strengthening the PV system and reducing vulnerabilities. The actual costs for the various corrective actions mentioned will vary significantly based on factors such as geographic location, PV system size, type of PV system (i.e., roof mount, ground mount, carport), and specific system attributes such as the type of racking system. Costs differ also based on whether the work is preventative or for repairing a damaged system. The latter will require damage assessment, safety inspection, and removal of damaged parts before rebuilding the array. Furthermore, prices are always changing, especially in a younger industry such as PV.

For these reasons, providing precise costs for the corrective actions recommended in this report is not feasible or useful. Instead, to provide decision support for system owners, we provide cost range estimates for the corrective actions for a model, a "representative" PV array, and factors to help account for the various system differences.

## 7.1 Baseline System

Our baseline system is modeled to be a "representative PV array" in that it is an approximate average of existing federal installations. Installations vary greatly. The factors discussed in Section 7.2 help adjust costs to account for the variation in array types, sizes, geographic location, and specific features (Table 4).

**Table 4. Baseline Representative System Attributes**

| | |
|---|---|
| System Size | 50 kilowatts (kW) |
| System Type | Roof mounted |
| Roof Description | Flat roof with parapet |
| System Tilt | Low tilt (<10°) |
| Racking | Self-contained racking systems |
| Mounting | • Ballasted with distributed roof attachments<br>• Top-down T clamps to attach modules to the racking system. 3/8″ hex bolt, 2 flat washers, flange nut on racking attachments<br>• (420) module-racking attachments for top down clamps<br>• (800) module-racking attachments for through-bolting<br>• (800) racking fasteners. |
| Inverters | String. ~10 kW each. NEMA 4-rated enclosure with a water resistant seal |
| Electrical | Use of conduit on all exposed wiring |
| Module Size and Layout | • 250-W modules (200 total)<br>• 20 rows of 10 modules |
| Location | Washington D.C. |

## 7.2 Cost Factors to Consider

The baseline system identified in Section 7.1 is intended to be representative of typically installed federal systems. PV systems vary greatly—to account for maintenance and repair cost differences for different types of systems, apply the factors below for regional variations, differences in system sizes, array times, and difficulty of access to an array.

As noted, precise estimates are not practical, given the range of variables specific to a particular site; however, relative costs provide a basis to begin making decisions about prioritizing repair and maintenance issues and making preliminary decisions about whether to completely redesign a damaged system.

Consequently, adjustment factors are presented here to better facilitate preliminary order-of-magnitude budgetary estimates. It should be noted that the information presented in this section is not intended to be definitive but is provided as an initial structure to help facility managers develop a program in consultation with their senior management. It is highly recommended that cost estimating professionals, either within the organization or as consultants, are utilized to develop actual cost estimates once a repair program is identified.

### 7.2.1 Regional Cost Factors

Costs vary by region, largely due to differences in labor rates. Table 5 shows relative regional factors for all fifty states and Puerto Rico, compared to the cost of a system in Washington D.C.

**Table 5. Regional Factors for 50 States, Washington D.C., and Puerto Rico (NREL 2018)**

| State | Regional Cost Factor | State | Regional Cost Factor | State | Regional Cost Factor |
|---|---|---|---|---|---|
| Alabama | 0.57 | Kentucky | 0.76 | North Dakota | 0.81 |
| Alaska | 1.16 | Louisiana | 0.69 | Ohio | 0.90 |
| Arizona | 0.74 | Maine | 0.72 | Oklahoma | 0.70 |
| Arkansas | 0.61 | Maryland | 0.84 | Oregon | 0.93 |
| California | 1.10 | Massachusetts | 1.17 | Pennsylvania | 0.92 |
| Colorado | 0.77 | Michigan | 0.86 | Puerto Rico | 0.33 |
| Connecticut | 1.14 | Minnesota | 0.99 | Rhode Island | 0.96 |
| Washington D.C. | 1.00 | Mississippi | 0.58 | South Carolina | 0.62 |
| Delaware | 0.83 | Missouri | 0.92 | South Dakota | 0.58 |
| Florida | 0.64 | Montana | 0.83 | Tennessee | 0.64 |
| Georgia | 0.61 | Nebraska | 0.71 | Texas | 0.60 |
| Hawaii | 1.29 | Nevada | 0.96 | Utah | 0.74 |
| Idaho | 0.75 | New Hampshire | 0.81 | Vermont | 0.68 |
| Illinois | 1.22 | New Jersey | 1.29 | Virginia | 0.64 |
| Indiana | 0.93 | New Mexico | 0.73 | Washington | 1.04 |
| Iowa | 0.80 | New York | 1.09 | West Virginia | 0.80 |
| Kansas | 0.74 | North Carolina | 0.57 | Wisconsin | 0.97 |
| | | | | Wyoming | 0.81 |

**Example for a PV system in California**

*Baseline Cost (Washington D.C.) x Regional Cost Factor (Table 5) = Regional Factor*

1.00 x 1.10 (CA) = 1.10

The *Regional Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

**Exercise 7.2.1 to complete for the system in question**

*Regional Factor* = *Baseline Cost* x *Regional Cost Factor*

= *(Washington DC)* x *(Table 5)*

= 1.00 x ________________ = __________________

The *Regional Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

### 7.2.2 System Size Factors

To account for economies of scale, apply the factors from Table 6 based on the closest system size to the system under scrutiny.

**Table 6. Array Size Factors to Account for Economies of Scale (NREL 2020).**

| System Size | System Size Cost Factor |
|---|---|
| 10 kW | 1.13 |
| 20 kW | 1.07 |
| 50 kW | 1.00 |
| 100 kW | 0.95 |
| 200 kW | 0.90 |
| 500 kW | 0.84 |
| 1,000 kW (1 MW) | 0.80 |
| 2,000 kW (2 MW) | 0.76 |
| 5,000 kW (5 MW) or more | 0.70 |

**Example for a 200 kW PV system**

*Size Factor* = *Baseline Cost (50 kW array)* x *System Size Cost Factor (Table 5)*

= 1.00 x 0.90

= 0.90

The *Size Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

**Exercise 7.2.2 to complete for the system in question**

*Size Factor* = *Baseline Cost (50 kW array)* x *System Size Cost Factor (Table 5 )*

= 1.00 x ________________

= ________________

The *Size Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

### 7.2.3 System Type Factors

Different system types have different costs. Should a system differ from the baseline system type, apply the appropriate multiplier given in Table 7.

**Table 7. Array Type Cost Factors**

| System Type | System Type Cost Factor |
|---|---|
| Flat Roof | 1.0 |
| Pitched Roof | 1.1 |
| Ground Mount – Fixed Tilt | 0.8 |
| Ground Mount – Carport | 1.2 |
| Ground Mount – Tracker | 0.9 |

**Example for a carport PV system**

*Type Factor* = *Baseline Cost (flat roof)* x *System Type Cost Factor (Table 7)*

= 1.00 x 1.2

= 1.2

The *Type Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

**Exercise 7.2.3 to complete for the system in question.**

*Type Factor* = *Baseline Cost (flat roof)* x *System Type Cost Factor (Table 7)*

= 1.00 x ____________________

= ____________________

The *Type Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

### 7.2.4 Difficulty of Access Factors

Some system layouts may make access to the array more difficult: systems with the panels close to the roof surface or those with small spacing between rows of modules, for example. This can add to the labor time for a project. Apply the appropriate multiplier in Table 8.

Examples of systems that are easy/normal to access:

- Ground mount, no higher than 15′ from ground elevation
- Rooftop system on low sloped roof with stair and or freight elevator access.

Examples of systems that are moderately difficult to access:

- Rooftop system on low sloped roofs with access ladder
- Ground arrays on steep slopes.

Examples of systems that are difficult/very difficult to access:

- Steep sloped roofs
- Carports that require a lift system
- Ground arrays with height greater than 15′ from ground elevation
- Arrays without inter-row access walkways
- Low-tilt roof arrays.

**Table 8. Difficulty of Access Cost Factors**

| Difficulty of Access | Access Cost Factor |
|---|---|
| Difficult | 1.5 |
| Moderate | 1.0 |
| Easy | 0.75 |

**Example for a difficult-to-access PV system**

*Access Factor* = *Baseline Cost (moderate access)* x *Access Cost Factor (Table 8)*

= 1.00 x 1.5

= 1.5

The *Access Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

**Exercise 7.2.4 to complete for the system in question**

*Access Factor* = *Baseline Cost (moderate access )* x *Access Cost Factor (Table 8)*

= 1.00 x ________________

Access Factor = ________________

The *Access Factor* will be combined with the other factors in this section and multiplied by the corrective action costs presented in Section 7.3.

### 7.2.5 Combining All Cost Factors to Calculate Site-Specific Factor

The four factors determined in Sections 7.2.1–7.2.4 are combined into a single site-specific factor (SSF) by multiplying them together.

**Example for a 200-kW carport PV system with difficult access in California**

*SSF* = *Regional Factor (Exercise 7.2.1)* x *Size Factor (Exercise 7.2.2)* x *Type Factor (Exercise 7.2.3)* x *Access Factor (Exercise 7.2.4)*

= 1.1 x 0.9 x 1.2 x 1.5

= 1.78

The SSF will be multiplied by the corrective action costs presented in Section 7.3.

**Calculation for the PV system in question**

*SSF* = *Regional Factor (Exercise 7.2.1)* x *Size Factor (Exercise 7.2.2)* x *Type Factor (Exercise 7.2.3)* x *Access Factor (Exercise 7.2.4)*

= __________ x ____________ x _________ ____________

*SSF* = ____________

The SSF will be multiplied by the corrective action costs presented in Section 7.3.

## 7.3 Baseline Costs of Corrective Actions

Cost estimates for each corrective action (see Section 7.3.1) are grouped into one of the four cost ranges shown in Table 9. Symbols are used for ranges to emphasize that the cost estimates in this report are only intended to serve as an "order of magnitude" calculation for rough project budgetary planning. While the given approximate values of costs can be used, it is important to keep in mind the range of costs that each symbolized category can actually represent. All prices in this table are given in 2020 U.S. dollars. Use the latest version of National Institute of Standards and Technology's "Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis" handbook to obtain the inflation rates.

**Table 9. Ranges for Estimating Corrective Action Costs**

| Symbol | Cost per Watt | Cost for a 50-kW PV System |
|---|---|---|
| $ | ≈ $0.01/W<br>*(± $0.01/W)* | ≈ $500<br>*(±$500)* |
| $$ | ≈ $0.06/W<br>*(± $0.04/W)* | ≈ $3,000<br>*(± $2,000)* |
| $$$ | ≈ $0.30/W<br>*(± $0.20/W)* | ≈ $15,000<br>*(± $10,000)* |
| $$$$ | ≈ $1.50/W<br>*(± $1.00/W)* | ≈ $75,000<br>*(± $50,000)* |

**Example:** You have a rooftop PV system that is 200 kW in size. The specific corrective action you are cost estimating has a total cost of "$$" in Table 9.

*Calculation:*

Convert the system size to watts.

200 kW * 1,000 W/kW = 200,000 W

Cost per watt (Table 9) x PV system size (the size of your system) = approximate cost

$0.06/W x 200,000 W = $12,000

Determine the range.

Range ($/W) from Table 9 x PV system size (the size of your system) = approximate range

±$0.04/W x 200,000 W = ± $8,000

Your estimated cost for this measure is $12,000 ± $8,000.

*Note: You will apply the SSF from Section 7.2 to this number later.*

### 7.3.1 Table of Costs of Corrective Actions

Table 10 shows symbolic cost range estimates for the corrective actions described in detail in Section 6 of this report. Costs are broken out into materials and labor costs. This approach can help project managers who plan to use their staff for the necessary labor to eliminate extra labor costs from the corrective action. If you plan to outsource the work or have it completed through an O&M contract, you can simply use the total cost column.

Note: These costs are given for the baseline 50-kW system defined in Section 7.1.

Note: The "$" cost symbols represent cost ranges of different sizes, so they cannot be added by themselves. For example, $ materials + $ labor does *not* necessarily equal $$ total cost. The symbols are intended to compare relative costs to each other.

**Table 10. Estimated Material Costs, Labor Costs, and Total Costs for Corrective Actions Presented in Section 6**

| Corrective Action (CA) | Material Cost Estimate | Labor Cost Estimate | Total Cost Estimate |
|---|---|---|---|
| **Bolted Joints and Fasteners** | | | |
| CA 1: Replace inadequate fasteners with rated locking fasteners | $$ | $ | $$ |
| CA 2: Strengthen soft joints in racking assemblies | $$ | $ | $$ |
| CA 3: Modify bolted joints in racking assemblies to avoid bolt shearing | $$ | $$ | $$ |
| CA 4: Fix top-down clamp vulnerabilities | $ | $ | $$ |
| CA 5: Modify weak subframing with high deflection issues - Add stiffening bracing | $$ | $$ | $$ |
| CA 5: Modify weak subframing with high deflection issues - Use top-down clamps with improved features | $$ | $ | $$ |
| CA 6: Replace specialty clamps and self-tapping sheet metal screws with through bolts | $$ | $ | $$ |
| **Special Considerations with Roof Arrays** | | | |
| CA 7: Reconfiguration of PV array to allow interior access | $ to $$ | $$ to $$$ | $$ to $$$ |
| CA 8: Add mechanical attachments to the building structure to improve the structural integrity | $ | $$ | $$ |
| CA 9: Redesign PV system to reduce potential for damage from heavy wind forces | $$ | $$ | $$$ |
| CA 10: Redesign PV system to a lower tilt angle to reduce potential wind damage | $$ | $$ | $$$ |
| CA 11: Remove and replace modules and racking assembly + refurbishment of BOS | $ to $$$$ | $$ | $$ to $$$$ |
| CA 11: Completely replace the PV system | $$$$ | $$$ | $$$$ |
| CA 11: Completely remove the PV system and restore the site to its original condition | $ | $$$ | $$$ |
| **Modules** | | | |
| CA 12: Replace module with broken glass top-sheet | $$$$ | $$ | $$$$ |

| Corrective Action (CA) | Material Cost Estimate | Labor Cost Estimate | Total Cost Estimate |
|---|---|---|---|
| CA 12: Replace modules with cracked or failed backsheet | $ to $$$$ | $ to $$ | $ to $$$$ |
| CA 12: Conduct an I-V curve test on string and module level | $$ | $$ | $$ |
| CA 12: Replace modules with cracked cells | $ to $$$$ | $ to $$ | $ to $$$$ |
| Wire Management | | | |
| CA 13: EPDM rubber-lined clamps | $ | $ | $$ |
| CA 13: Metallic module wire clip | $ | $ | $ |
| CA 13: Metallic rail wire clip | $$ | $ | $$ |
| CA 13: Metallic wire tie | $ | $ | $ |
| CA 13: Conduit | $ | $$ | $$ |
| CA 14: Replace corroded grounding components with non-corrosive components | $ to $$ | $$ | $ to $$$ |
| CA 15: Replace damaged DC wiring | $ | $ to $$ | $ to $$ |
| CA 16: Remove any existing animal nest(s) | $ | $ | $ |
| CA 16: Install wire-based critter guard or netting to flush mounted arrays | $$ | $ | $$ |
| CA 16: Install bird spikes on top of array | $$ | $ | $$ |
| CA 17: Replace damaged PV connector(s) | $ to $$ | $ to $$ | $ to $$ |
| Electrical Enclosures and Conduit | | | |
| CA 18: Relocate electrical equipment above 100-year flood level to prevent flooding | $$ | $$ | $$$ |
| CA 19: Replace inadequate and/or corroded enclosures with ones that have contiguous rubber seals and compression latches | $$ | $$ | $$$ |
| CA 19: Apply outdoor-rated sealant to penetrations in electrical enclosures | $ | $ | $ |
| CA 19: Install weep hole in electrical enclosure | $ | $ | $ |
| CA 19: Install a vent or drain plug in electrical enclosure | $ | $ | $ |
| CA 20: Install durable conduit supports | $$ | $$ | $$ |
| CA 20: Install expansion joints to accommodate thermal movement | $$ | $$ | $$ |
| CA 20: Replace conduit fittings with ones that are watertight | $$ | $$ | $$ |
| CA 20: Replace damaged conduit | $ | $ to $$ | $ to $$ |
| CA 20: Install a ramp or walkway over roof mounted conduit | $ | $ | $ |
| CA 21: Replace all field labels and markings that show signs of degradation | $ | $ | $ |

| Corrective Action (CA) | Material Cost Estimate | Labor Cost Estimate | Total Cost Estimate |
|---|---|---|---|
| **Topography** | | | |
| CA 22: Use a wind calming fence to reduce wind forces on the PV system | $$ | $$ | $$$ |
| **Site Management** | | | |
| CA 23: Inspect and clear roof drains to avoid electrical and structural damage | $ | $ | $ |
| CA 24: Roof repair | $ to $$ | $ to $$$ | $ to $$$ |
| CA 24: Install protective sheet under any part of the PV array that comes in contact with or is close to the roof membrane | $ | $$ | $$ |
| CA 25: Clear debris and secure loose equipment around the PV system | $ | $ | $ |
| CA 26: Plant pollinator habitat | $ | $ | $ |
| CA 26: Install site water management | $$ | $$ | $$$ |
| CA 26: Conduct O&M *(cost given as a per-year amount)* | $ | $$ | $$ |
| CA 27: Clearly mark the presence of the PV array and its boundaries to prevent damage to snow covered modules | $ | $ | $ |

### 7.3.2 Applying Factors to Corrective Action Costs

Regional, size, type, and access factors should be applied to the corrective action estimated costs from Section 7.3.1 as follows:

a. Identify the symbolic ($–$$$$) cost of the desired corrective action from Table 10.

b. Find the corresponding cost and range ($/W) for the $–$$$$ symbol from Table 11.

c. Calculate the actual estimated cost for your array size (for both materials and labor costs).

d. Calculate the cost range for your array size (for both materials and labor costs).

e. Apply the SSF calculated in Section 7.2.5 to estimated cost and cost range calculated in steps C and D.

f. Repeat separately for all corrective actions desired.

g. Sum the corrective action estimated costs for an approximate total cost.

Look up corresponding corrective action materials estimate (CAME), corrective action labor estimate (CALE), corrective action materials range (CAMR), and corrective action labor range (CALR) from Table 9, reproduced in Table 11.

**Table 11. Costs and Ranges**

| Symbol | Cost (for CAME and CALE) | Range (for CAMR and CALR) |
|---|---|---|
| $ | $0.01/W | ± $0.01/W |
| $$ | $0.06/W | ± $0.04/W |
| $$$ | $0.30/W | ± $0.20/W |
| $$$$ | $1.50/W | ± $1.00/W |

Note: For corrective actions with a range in cost in Table 10, estimate the percentage of the array that needs to be repaired and choose the "$" category based on that. For example, if the range from Table 10 is $–$$$ and only 10% of your array needs repair, choose "$."

**Example**

Corrective Action 1 – Rated Locking Fasteners for a 200-kW PV array

a. Symbolic cost from Table 10

Materials: $$ Labor: $

b. Look up corresponding *CAME*, *CALE*, *CAMR*, and *CALR* from Table 11.

*CAME* = $.06/W *CALE* = $0.01/W

*CAMR* = ± $0.04/W *CALR* = ± $0.01/W

c. Calculate estimated cost for your system

*System Size* = 200 kW = 200,000 W

*Materials-Cost* = *CAME* x *System Size*
= $0.06/W x 200,000 W
= $12,000

*Labor-Cost* = *CALE* x *System Size*
= $0.01/W x 200,000 W
= $2,000

d. Calculate cost range

*Materials-Range* ≈ *CAMR x System Size*
= ± $0.04/W x 200,000 W
= ± $8,000

*Labor-Cost* ≈ *CALR x System Size*
= ± $0.01/W x 200,000 W
= ± $2,000

e. Apply site-specific-factor (SSF) calculated in section 7.2.5 (SSF = 1.15 used here) to calculate site-specific materials cost (SSMC), site-specific labor cost (SSLC), site-specific materials range (SSMR), and site-specific labor range (SSLR).

*SSMC* = *Materials-Cost x SSF*
= $12,000 x 1.15
= $13,800

*SSLC* = *Labor-Cost x SSF*
= $2,000 x 1.15
= $2,300

*Total Cost* = *SSMC* + *SSLC* = $ 13,800 + $2,300
= $16,100

*SSMR* = *Materials-Range x SSF*
= ± $8,000 x 1.15
= ±$9,200

*SSLR* = *Labor-Range x SSF*
= ±$2,000 x 1.15
= ±$2,300

*Total Range* = Sum of two ranges = $9,200 + $2,300
≈ $11,500

*Approximate Project Cost* = *Total Cost* ± *Total Range*
≈ $16,100 ± $11,500

Notes:

*If you have on-site personnel to perform the labor, you can skip the labor side of the calculations.

*This cost is an approximate value. Use this as a decision-making aid rather than for determining specific budgets.

Calculation

Corrective Action: ________________________________________

a. Symbolic cost ($–$$$$)

Materials: _________ Labor: __________

Calculation

*CAME* = $__________/W *CALE* = $__________/W

*CAMR* = ± $________ /W *CALR* = ± $________ /W

a. Calculate estimated cost for your array

System Size: ________kW = ________ W

*Materials-Cost* = *CAME* x *System Size* *Labor-Cost* = *CALE* x *System Size*

= $________/W x _______ W = $_______/W x ________ W

= $__________ = $__________

b. Calculate cost range

*Materials-Range* = *CAMR* x System Size *Labor-Range* ≈ *CALR* x *System Size*

= ± $_______/W x ______ W = ± $_______/W x _______ W

= ± $__________ = ± $__________

c. Apply the *SSF* calculated in Section 7.2.5 to calculate *SSMC*, *SSLC*, *SSMR*, and *SSLR*.

Look up SSF from Section 7.2.5. *SSF* = ___________

*SSMC* = *Materials-Cost* x *SSF* *SSLC* = *Labor-Cost* x *SSF*

= $_________ x _______ = $_______ x ______

= $__________ = $_________

*Total Cost* = *SSMC* + *SSLC*

= $ _______ + $_________

= $________________

*SSMR* = *Materials-Range* x *SSF* *SSLR* = *Labor-Range* x *SSF*

= ± $__________ x _____ = ± $__________x _______

= ± $ _____________ = ± $ ___________

*Total Range* = *SSMR* + *SSLR*

= $________ + $________

= $___________

*Approximate Project Cost* = *Total Cost* ± *Total Range*

= $___________ ± $ ___________

d. Repeat this calculation process for all corrective actions

e. Sum up corrective action estimated costs for approximate total cost.

### 7.3.3 Cost Comparison of Corrective Actions

The best use of the cost estimating guidance in this section may be in comparing costs between candidate corrective actions. Specific costs are ever changing and project specific, so a direct comparison between costs may be more useful than numeric values in guiding system owner's decisions. While these relative costs of measures will also change over time, they are likely more durable than the actual costs of corrective actions. Figures 146 and 147 provide a graphical overview of the comparison of different corrective actions. These numbers are based on the 50-kW baseline system size described in Section 7.2.

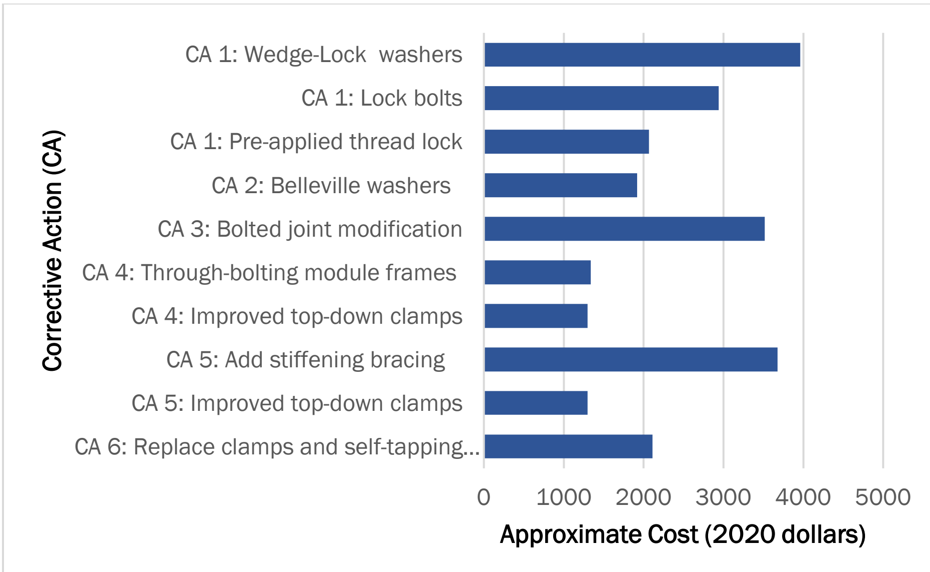



**Figure 446. Estimated costs for fastener, critical bolted joint, and racking assembly corrective actions**

Even though certain measures may be more inexpensive than others, it is important that the measure is appropriate for the vulnerability. This report estimates that there are 420 module-to-racking bolted joints for a top-down clamped system, 800 module-to-racking bolted joints for a through-bolted system, and 800 bolts within the racking system of a 50-kW PV system.

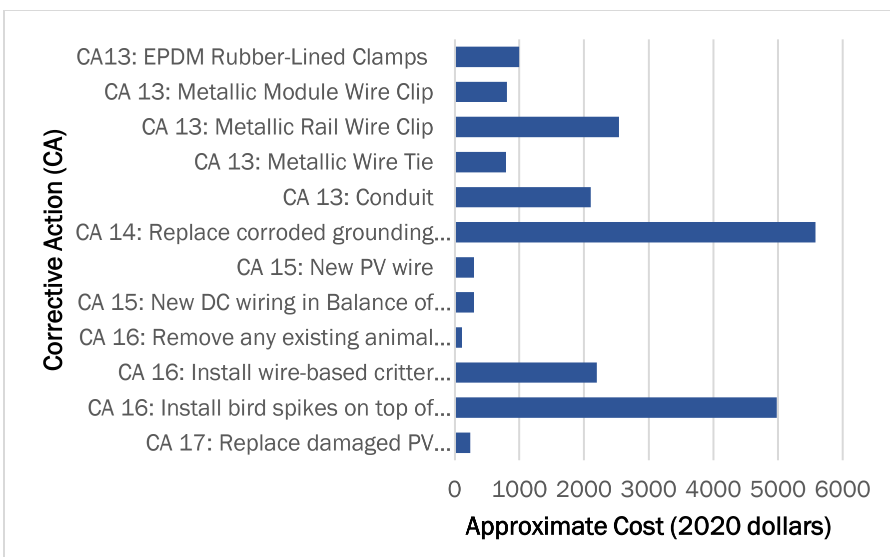



**Figure 147: Estimated costs for wire management corrective actions**

This report only provides these two figures on estimated comparative costs for fastener, critical bolted joint, and racking assembly and wire management corrective actions because of the prominence of these issues in the field and the higher level of confidence the authors have in the actual costs of these measures compared to others. These charts are intended only to provide more information that can aid in budgetary planning and should be treated as rough estimates.

## 7.4 Takeaways

The system materials and labor cost estimates provided in this section are intended to serve as a decision-making guide for estimating approximate ranges in project retrofit costs. Costs are ever-changing and vary greatly, and this report cannot account for all the potential factors that will contribute to actual invoice costs. Actual cost quotes should be procured before final decisions are made.

While the corrective actions in this report will all come with an upfront cost, they should help protect PV systems against future damage, system downtime, repair, and maintenance costs. PV systems are designed to produce power for 20–30 years or more, and the decision to repair and maintain a system is not only a safety measure, but will also help the system produce as expected throughout its life. For sites that depend on solar PV for backup power, ensuring these systems are best prepared to survive a weather event and continue providing power afterwards carries even more importance.

# 8 Considerations for Hiring a Contractor

**Step 5**
Implement Corrective Actions Plan

## 8.1 Contractor Qualifications and Experience

Hiring the right contractor for the job is important for a successful recovery process and the safe performance of the PV system. The contractor should have the experience and personnel to be able to complete a recovery project given the unique challenges involved when compared to a new construction PV project.

It is important for the contractor to be able to locate hard-to-find components or components from out-of-business manufacturers. If the contractor is to use subcontractors at any part of the recovery process, the same standards must apply to the subcontractors as they do to the prime contractor.

## 8.2 Manufacturer Approval on Product Modifications

As discussed earlier, if the agency does **not** hire an engineering firm to help with Steps 2 and 3, then the hired contractor must be able to gain concurrence from manufacturers to perform modifications on their products in accordance with the scope of work.

## 8.3 Warranty Claims

A qualified contractor should be able to help the agency with any warranty claims for damaged components of the PV system. This is just one of the reasons why hiring a full-scope contractor is beneficial. The contractor, specializing in solar PV recovery, can handle every aspect of the project, including interacting with manufacturers to fulfill warranty obligations.

## 8.4 Estimate Costs Ahead of Time

Section 7 provides costing information on each corrective action. Agency personnel, with the help of an engineering firm (if applicable), should use these cost estimates to get a sense of what the recovery efforts might cost. Please note that these costs are approximate values, and the actual costs may vary based on a variety of factors.

An agency will benefit from developing its own cost estimates for the corrective actions to be completed. It is important to tell the bidders what vulnerabilities exist so they can confirm and factor them into their quotes. Having a sense of what it will cost will also reduce the potential for any change orders during the recovery phase, when the contractor is working onsite.

### 8.4.1 Removal/Dismantling of Damaged Equipment

Bids must include removing and/or dismantling any damaged or obsolete components of the PV system, as the removal process can be costly and time consuming.

**HELPFUL TIP**

If some or all of the bids received are not what the agency expected, it is possible that the agency missed something significant during the site audit process. Cross-compare the agency (or engineering firm, if applicable) generated scope of work to the bidders' scopes of work and identify any significant differences.

### 8.4.2 Receiving Low Estimates from Bidders

Be cautious of bids very far below the competitive range, as there may be a chance that the contractor does not understand the full scope of work required to complete all the corrective actions in the recovery process. This could lead to costly change orders further on in the project.

## 8.5 Strong Safety Culture

Solar PV recovery efforts are unique and should be treated that way. New construction projects are generally similar from start to finish. However, recovery projects can be complex and have a variety of scopes of work. Some contractor personnel may not have performed PV recovery work before. That is why the agency should choose a contractor with the following attributes:

- A strong and effective safety culture
- Workers with solid safety records
- Commitment to ongoing safety trainings
- Continuous safety inspections by the contractor throughout the project.

It is essential for each worker to be familiar with the site and be given a site orientation at each phase, regardless of when they started on the project. Hiring a contractor with a strong commitment to safety will greatly reduce the potential for issues to arise during the recovery phase.

# 9 Storm Preparation and Recovery

After completing the Severe Weather Awareness worksheet in Appendix A, an agency manager should have a better understanding of the storm events that occur at their location(s). This section will discuss steps an agency can take that can have a significant impact on reducing the potential for storm damage to a PV system and speeding up the recovery process (Robinson 2018). As discussed earlier, if the agency determines that the storm recovery phase is too complex to handle alone, they should consider hiring a consulting engineer that is experienced in severe weather and PV system recovery.

Although certain pre- and post-storm O&M measures like site cleanup and torque auditing can be done by agency personnel, it is highly recommended that the agency employ appropriate specialized professionals either through their O&M contractor or by contracting out the recovery actions to a qualified consultant/contractor. Considerations in selecting a contractor to perform the corrective actions identified in the recovery phase are discussed in Section 9.2 and are always subject to particular agency procurement regulations.

## 9.1 Pre- and Post-Storm O&M Measures

### 9.1.1 Pre-Storm Measures

Table 12 provides descriptions of pre-storm measures.

**Table 12. Pre-Storm Measures**

| O&M Measure | Description |
|---|---|
| De-energize PV system | Turn all electrical equipment into the open position to prevent electrical fault damage and shock hazards. This electrical equipment includes:<br>• Combiner box fuses<br>• All main disconnects at the point of interconnection<br>• Switchgear<br>• Weather stations and metering specific to the PV system. |
| Clear debris and/or secure loose equipment | Remove any loose debris and tie down any equipment or objects that can become airborne during high-wind storm events. |
| Perform a torque audit | Conduct a torque audit using a specified torque wrench to check the settings of a minimum 5%–10% of all fasteners and critical bolted joints throughout the PV system. If fasteners and bolted joints are found to be loose, they should be tightened to specified torque ratings. Use the First Movement method discussed in Section 5.2.7. |
| Clear roof drains | Make sure all roof drains are clear of debris so water can properly exit the roof. This will prevent flooding of electrical equipment and conduit and also prevent damage to the roof's structural integrity due to excess water buildup. |
| Install a ratchet strap and tarp on electrical enclosures | Improperly rated electrical enclosures located outside can be covered with a tarp and tied down with a ratchet strap. This is intended to prevent water intrusion from wind-driven rain but should not be considered a permanent solution. |

### 9.1.2 Post-Storm Measures

Table 13 provides descriptions of post-storm measures.

**Table 13. Post-Storm Measures**

| O&M Measure | Description |
|---|---|
| Check the integrity of the wires | The technicians should conduct tests on the wires with Megger testing equipment and identify and replace all damaged wires. |
| Check for ground faults | The technicians should conduct ground testing to ensure that there are no ground faults. |
| Clean and dry all electrical equipment | If any electrical enclosures have been inundated with water and/or salt from saline rain, the electrical equipment should be dried and cleaned immediately. |
| Check for flooded conduit | All conduit should be checked for flooding/water penetration. If any conduit has been compromised, it should be cleaned and the wires inside the conduit should be inspected and tested to ensure no damage occurred. |
| Perform a torque audit | A torque audit should be conducted on all fasteners and critical bolted joints using the First Movement method discussed in Section 5.2.7. |
| Visual inspection of the PV system | The agency should conduct a visual inspection of the site to identify if damage has been done to any component of the PV system. |
| Re-energizing the PV system | The PV system should be re-energized slowly and carefully. No string should be re-energized if modules and/or wires have been broken or compromised. |

## 9.2 Recovery Process

### 9.2.1 Assessing the Level of Storm Damage to your PV System

After a severe storm event, the agency should, with the help of a consulting engineer (if applicable), determine what level of damage the PV system has experienced. As always, a qualified electrician shall determine if the PV system is safe to access. Once this is confirmed, the agency can use the four levels shown in Table 14 as criteria to determine the extent of damage. Once the level of damage is determined, the agency can move ahead with the next step of the recovery process.

**Table 14. Damage Levels**

| Level of Damage | Likely Field Observations |
|---|---|
| PV system undamaged with minor production issues | String of modules or an inverter may be offline, but the system is producing electricity. |
| Minor damage | Approximately 5%–10% of the PV system has been damaged. There could be a few inverters offline or some damage has occurred to the modules and/or BOS. |
| Significant damage | Up to half of the PV system has been damaged. The other half may be generating power, but extensive damage to other sections may require the undamaged sections to be turned off for repairs to the damaged sections. |
| Total destruction | The entire PV system is not operational. Total remediation of the system is required before any power can be produced. |

### 9.2.2 Cataloging the Vulnerabilities

The agency, with the help of a consulting engineer (if applicable), shall conduct a thorough site audit and use the same process described in Section 5.2, or Step 2B of the Process Flow Diagram, to document any existing vulnerabilities and damage to the PV system.

**HELPFUL TIP**

The Risk-Impact Methodology, coupled with Section 7: Costing, should be used to prioritize which vulnerabilities need to be corrected and included in the recovery scope of work.

### 9.2.3 Salvaging versus Replacing Components

An agency will be mission driven to correct any existing vulnerabilities to its PV system while also keeping recovery costs as low as possible. That is why determining what components can be salvaged and what components need to be replaced is critical to overall project costs. The agency will benefit from a thorough initial site audit if they are able to identify salvageable components that would have otherwise been replaced. New components (e.g., inverters, modules) can be expensive, while salvaged components may cost nothing more than labor and materials (e.g., fuses, PV wire). Some components, such as the combiner box in Figure 148, are beyond salvageable and must be replaced.

### 9.2.4 Partially Operable PV Systems

As described above, some PV systems may experience damage but can still generate power. In events like this, it is beneficial that any operable part of the PV system be left on and running while the rest of the system is undergoing recovery efforts. However, it must be determined safe to operate by a qualified electrician. Even if only half the PV system is able to offset the site's power use, it will be less costly to the agency than purchasing all of their electricity from the electric utility provider.

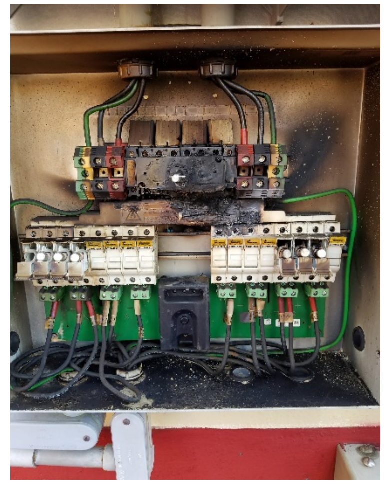


**Figure 148. Combiner box damaged from backfed current after a hurricane**

*Source: Gerald Robinson, LBNL*

### 9.2.5 Minimizing the PV System Downtime

The contractor should have all necessary materials onsite before they start to take a partially operable PV system offline for recovery efforts. Potential delays in shipping of materials and replacement components could keep a PV system offline longer than anticipated. Minimizing the PV system's downtime should be a top priority.

### 9.2.6 Recommissioning Phase (if applicable)

Storm damage to a PV system may be extensive enough that the system needs to be recommissioned after all the vulnerabilities have been corrected and the recovery phase is almost complete. This phase will provide the agency with the assurance that the PV system is back up and running to its normal operating conditions.

**HELPFUL TIP**

It is critical that the contractor perform a recommissioning test with agency personnel onsite as witness. The contractor should provide the owner with written confirmation that the system is back up and running to its normal operating conditions and all recovery work is completed.

# 10 Financing and Procurement Options

Agencies facing significant costs to reinforce a PV system should consider one of the financing options shown in Table 15.

**Table 15. Financing Options**

| Option | Description | Factors to Consider |
|---|---|---|
| **Appropriations** | Use an annual funding cycle to pay repair and alteration (small) or capital construction (large) project costs. | • Easiest to implement<br>• Competes with other priorities<br>• Agency will play role of general contractor |
| **Integrate with the O&M contract** | Issue a solicitation for O&M that includes the repairs and reinforcements. | • Easy scope for O&M contractor<br>• O&M staff is skilled to undertake the repair |
| **Combine with current energy project** | Integrate repair and reinforcement upgrades into an energy efficiency or renewable energy project. | • Design and skilled labor can be managed by the contractor |
| **Performance contract** | For an array that is underperforming, use a performance contract to have the PV system taken over by a contractor. The agency pays on a $/kilowatt-hour (kWh) basis for refurbishing the PV system and regaining lost performance. | • More complicated procurement pathway<br>• Contractor can manage all design and skilled labor needed to undertake the project<br>• Contractor is incentivized to maintain system performance, as payment is based on $/kWh delivered to the agency |

# Glossary

| Term | Definition |
|---|---|
| Alternating Current (AC) | A type of electrical current characterized for a constant change of direction and magnitude. The rate at which the current changes its direction in the United States is about 60 times a second or 60 Hz. |
| Backsheet | The sheet material adhered to the back of a module designed to protect the interior components from damage due to abrasion and weathering. |
| Balance of System (BOS) | Includes all of the components of a solar photovoltaic (PV) system other than the PV modules. This includes everything from the wiring, electrical equipment, conduit raceways, and racking assembly. |
| Basis of Design (BOD) | Primary document developed by system owner to describe the objective and technical requirements that engineers must design to. Development of the BOD can be done interactively through discussion with engineers and/or by use of a request for information process. The BOD is included in the solicitation and contract documents when soliciting for engineering services. |
| Bill of Materials (BOM) | List of raw materials, subcomponents, parts, and quantities of each that comprise a major component. The BOM for solar modules is often an area of interest. |
| Bolted Joint | A combination of components attached together using an assembly of fasteners, frame elements, and clamps. |
| Busway | An electrically conductive metal bar or cable used to tie together breaker or fuse devices and main source circuit. |
| Coefficient of Friction | The ratio between the minimum force needed to move one surface across another and the clamping pressure between the two surfaces. |
| Commissioning | Most often refers to the standard of practice described in IEC 62446 undertaken by an independent certified commissioning agent. Used to confirm all PV systems are installed properly and performing as intended. |
| Conduit | A tube used to protect, guard, and route electrical wires. It can be metallic or non-metallic (plastic) and categorized as rigid or flexible. |
| Cross-Mating | Occurs when PV connectors from different manufacturers are connected, sometimes causing incompatibility issues that lead to failure. |
| Direct Current (DC) Wiring | A type of electrical current characterized for being unidirectional and usually with constant amplitude. |
| Electrical Equipment | Any equipment that is used in the PV system that includes but is not limited to: inverters, combiner/junction boxes, switchgear boxes, transformers, weather stations, meters, and |

| Term | Definition |
|---|---|
| | any equipment associated with a battery storage system. Other terms used to describe electrical equipment are "enclosures" and "cabinetry." |
| Energized | Describes electrical conductors that are connected to a closed circuit and actively carrying current. The inverse of this is "de-energized," which occurs when those same wires are not actively carrying electrical current. |
| Engineer | In this context, refers to one of the professional engineering designations in the electrical, mechanical, structural, bolted joint, and civil disciplines. |
| Facility Manager | The person responsible to ensure overall safe, effective, and efficient facility operations. |
| Failure | The resulting occurrence when a component or system is unable to fulfill its intended function. |
| Fastener Preload | The tensile load applied to a fastener when it is first installed. |
| Field Audit; Audit | For purposes of this guide, the process of visually inspecting the PV system and documenting any vulnerabilities present. |
| First Movement Method | A type of torque auditing that records the energy needed to tighten the threaded fastener. |
| Flexing | Used to describe the bending of solar modules when exposed to wind pressures or from movement of the racking assembly. |
| Flush Mount | A PV array that is installed where the modules are parallel to the surface of the roof. |
| Galling | Occurs when the friction between mating threads (often nuts and bolts) causes metal to release and shavings accumulate, and thereby increase turning resistance. |
| Hot Spot (Electrical) | A location of high electrical resistance that leads to an increase in temperature which can be caused by such things as loose connections, dirt, corrosion, or damaged wires. |
| Infrared (IR) Imaging | IR imaging is the process of using a specialized imaging tool that is tuned to register infrared wavelengths. It is useful in inspecting components of a PV system like the modules and BOS components. |
| Inverter | Converts the DC generated by the PV module into AC which is the grid-compatible form of electricity used by consumers. |
| Junker Test | Mechanical test used to measure the point in which a bolted joint loses its preload when exposed to vibrations. This helps design engineers to be able to specify fasteners that will perform under extreme conditions without failing. |

| Term | Definition |
|---|---|
| Levered | Occurs when a fastener is exposed to a force that results in leverage-type forces. |
| Liberated | Occurs when a module breaks free from mounting and becomes airborne. |
| Microcrack | Microcrack (measured in microns) in the cell of a PV module that can occur during production, transportation, installation, or performance in the field. Cracks can worsen over time and cause a PV module to underperform. |
| Module (panel) | The component of a PV system that converts sunlight into DC electricity. A module may also be commonly referred to as a "panel." A group of interconnected PV cells comprises a module. |
| Normal Operating Conditions | Refers to the baseline condition at which a PV system performs before any issues arise, such as storm damage or equipment failure. |
| Operations and Maintenance (O&M) | Refers to the services that are required for a solar PV system to achieve its expected performance and lifespan, as well as those that address any unexpected issues that may arise during the system's performance period. O&M services include, but are not limited to: annual electrical inspections, module cleaning, monitoring of system production, and corrective maintenance actions such as inverter and module repair or replacement. |
| Pascal (Pa) | A unit of measurement for pressure. |
| Photovoltaic Array | A group of PV modules connected together in series and/or parallel. |
| Photovoltaic System | The PV modules and the BOS components. For the purposes of this guide, wherever "PV" appears, it is referencing solar PV unless specified otherwise. |
| Prevalence | The proportion of something to the whole. Can be expressed as a percentage. (Note: This is not to be confused with Incidence, conveying a rate, for example, of a particular failure). |
| Prying Action | A force that results in separation or bending of fasteners or racking assembly. |
| Racking Assembly | Structural components that are used to support the PV modules. Most racking assemblies are made of aluminum, steel, or a combination of both. There are variations in racking assembly designs among manufacturers, as well as array types (e.g., roof, ground, carport) |
| Repair and Alteration | A class of projects generally smaller in dollar value executed to repair and/or maintain an asset. |
| Resonance | Occurs when objects are exposed to wind and take on a natural vibration frequency. |
| Row-Domino Effect | Occurs when fasteners holding a module to the racking assembly fail under high wind loads, allowing the module to pry loose. Because most top-down module clamps hold two modules to the racking, once one module comes loose, the adjacent module will not be secured. This can lead to a chain reaction of modules loosening and falling out of the array. |

| Term | Definition |
|---|---|
| Self-Shielding Phenomenon | A phenomenon discovered in solar arrays where interior rows are shielded by perimeter rows from the wind forces. |
| Stormwater Management | Variety of techniques that are used to reduce soil erosion and/or scouring from water runoff due to excess rainfall and snowmelt. Proper design, monitoring, and maintenance will allow stormwater management features of a site to perform as expected. |
| String of Modules | Combination of modules that are connected. The number of modules that can be connected together depends on the electrical characteristics of the modules and BOS components. |
| Soft Joint | A bolted joint that is unable to maintain preload and clamping forces due to the presence of soft metals (e.g., aluminum, brass) and/or insufficiently strong clamped material (e.g., tubular stock). |
| String Wiring | Includes all of the wiring from the PV modules and the "home run" wires that connect a string of modules to the wires at the combiner box(es). |
| Torque | Measure of turning forces often expressed in pascals (Pa) that is related to achieving a targeted bolt preload and clamping force in a bolted joint. |
| Transverse Slip | A phenomenon that occurs when wind induced vibrations overcome the coefficient of friction between two surfaces and result in movement. |
| Vulnerability | A defect (latent or patent), damage, or other condition that if subjected to a weather event could severely compromise the operability of the PV system or case system failure. |

# References

ASTM International (2019). E1830-15(2019) Standard Test Methods for Determining Mechanical Integrity of Photovoltaic Modules. Retrieved from https://doi.org/10.1520/E1830-15R19.

Brooks Engineering (2010). *Field Inspection Guidelines for PV Systems.* http://brooksolar.com/files/PV-Field-Inspection-Guide-June-2010-F-1.pdf.

Elsworth, J., and Van Geet, O. (2020). *Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience.* Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy20osti/75804.pdf.

Engineer's Edge. (n.d.). Estimated Fastener Bolt Clamp Force Torque Calculator. Accessed June 3, 2021. https://www.engineersedge.com/calculators/torque_calc.htm.

Federal Emergency Management Agency. (n.d.). Flood Map Products. Accessed June 3, 2021. https://www.fema.gov/flood-maps/tools-resources/flood-map-products.

Moser, D., Belluardo, G., Del Buono, M., Bresciani, W., Veronese, E., Jahn, U., and Richter, M. (2017). *Technical Risks in PV Projects: Report on Technical Risks in PV Project Development and PV Plant Operation.* February 27. https://www.tuv.com/content-media-files/master-content/services/products/p06-solar/solar-downloadpage/solar-bankability_d1.1_d2.1_technical-risks-in-pv-projects.pdf.

National Renewable Energy Laboratory, Sandia National Laboratory, SunSpec Alliance, and the SunShot National Laboratory Multiyear Partnership (SuNLaMP) PV O&M Best Practices Working Group. (2018). *Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems*, 3rd Edition. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-73822. https://www.nrel.gov/docs/fy19osti/73822.pdf.

Robinson, G. T. (2018). Solar Photovoltaic Systems in Hurricanes and Other Severe Weather. Accessed June 2, 2021. https://www.energy.gov/sites/prod/files/2018/08/f55/pv_severe_weather.pdf.

# Additional Resources

American Society of Civil Engineers (2017). Minimum design loads and associated criteria for buildings and other structures, ASCE/SEI 7-16. https://www.asce.org/structural-engineering/asce-7-and-sei-standards/.

Burgess, C. Detweiler, S. Needham, C. Oudheusden, F. (2020). *Solar Under Storm Part II: Selected Best Practices for Resilient Roof-Mount PV Systems with Hurricane Exposure.* Rocky Mountain Institute. https://rmi.org/insight/solar-under-storm/.

Burgess, C. and Goodman, J. (2018). *Solar Under Storm: Select Best Practices for Resilient Ground-Mount PV Systems with Hurricane Exposure*. Rocky Mountain Institute. https://rmi.org/solar-under-storm-designing-hurricane-resilient-pv-systems/.

Maxwell, K., S. Julius, A. Grambsch, A. Kosmal, L. Larson, and Sonti, N. (2018). *Built Environment, Urban Systems, and Cities. In Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*. pp. 438–478. U.S. Global Change Research Program. Washington DC, USA. DOI: 10.7930/NCA4.2018.CH11. https://nca2018.globalchange.gov/chapter/11/

National Academies of Sciences, Engineering, and Medicine (2016). *Attribution of Extreme Weather Events in the Context of Climate Change.* The National Academies Press. Washington DC, USA. DOI: 10.17226/21852.

Structural Engineers Association of California (2017). *Wind Design for Solar Arrays. SEAOC PV2-2017.* https://www.seaoc.org/store/ViewProduct.aspx?id=10228815.

Wuebbles, D.J., D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, and Maycock, T.K. (2017). *Climate Science Special Report: Fourth National Climate Assessment, Volume I.* U.S. Global Change Research Program. Washington DC, USA. DOI: 10.7930/J0J964J6. https://science2017.globalchange.gov/

# Technical Assistance from Fastener Manufacturers

Manufacturers of fasteners often maintain technical assistance customer support. The manufacturers should be consulted with regard to any proposed solution. The solution shall include hardware and field assembly instructions.

# How to Find a Bolted Joint Engineer

Bolted joint engineering is a highly specialized discipline. These engineers work in house or as consultants designing a wide variety of bolted joint assemblies for a multitude of industries. This specialized engineering practice is just starting to be applied to solar PV systems.

This guide cannot list specific names of engineers. The easiest way to find one of these specialized engineers is to type some keywords into a browser search tool. Here are some example search words that turn up articles and companies' names involved with bolted joint engineering:

- "bolted joint engineer"
- "solar PV"
- "fasteners challenges"
- "high wind."

# Appendix A: Weather Awareness Worksheet

Which storms occur at your site?

| *Weather Event* | *Present? (Y/N)* |
|---|---|
| *Hurricane* | |
| *Thunderstorm/Monsoon* | |
| *Derecho* | |
| *Tornado* | |
| *Hail* | |
| *Lightning* | |
| *Blizzard* | |

Record your weather extremes based on historical events:

| *Weather Event* | *Value* | *Look Up Source* |
|---|---|---|
| *Wind (Risk Category IV - MPH)** | | https://hazards.atcouncil.org/ |
| *Flood levels (feet above sea level)* | | https://www.arcgis.com/apps/webappviewer/index.html?id=9c74eb252049463996360876caec2046 |
| *Hurricane storm surge flooding (feet above sea level)* | | https://www.nhc.noaa.gov/nationalsurge/ |
| *Tornado occurrence likeliness (low, medium, high)*** | | https://ncdp.columbia.edu/library/mapsmapping-projects/us-natural-hazards-index |
| *Tornado wind speed (MPH)* | | https://hazards.atcouncil.org/ |
| *Snow load (lbs/sq ft) – ASCE 7-16* | | https://hazards.atcouncil.org/ |
| *Hail severity at your location of >.75"diameter (Y/N)**** | | https://www.spc.noaa.gov/wcm/ |
| *Lightning (flashes/sq/mile/year)* | | https://www.spc.noaa.gov/wcm/ |
| *Blizzards – snow depths (inches/month & year)* | | https://www.ncdc.noaa.gov/snow-and-ice/daily-snow/CO/snowfall/20200101 |

**Risk category IV closely resembles max wind speeds seen for site.*

***Look up your county to determine likeliness.*

****Hail maps included with several other weather maps—reader should scroll through.*

# Appendix B: Field Audit Form

Site Name: ______________________________

Address: ________________________________

Agency Representative: ____________________

Date of Site Inspection: ___________________

**Important Things to Remember**

1. Follow all safety precautions, and use trained personnel where needed.
2. Take several photos from different vantage points.
3. Compare drawings to the installed conditions before conducting the field audit.

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| **1. Fasteners and Critical Bolted Joints** | | | | |
| Vulnerability 1: Fastener loosening from transverse slip | | | | |
| Vulnerability 2: Loss of fastener preload due to improper field assembly | | | | |
| Vulnerability 3: Top-down module clamp assemblies with soft joint issues | | | | |
| Vulnerability 4: Inadequate bolted joint design | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 5: Top-down module clamps susceptible to vibrational loosening | | | | |
| Vulnerability 6: Module clamps and rails not installed properly | | | | |
| Vulnerability 7: Top-down module clamps bent open due to inadequate strength | | | | |
| Vulnerability 8: Top-down module clamp failure leading to "row-domino" | | | | |
| Vulnerability 9: Use of backside clamping devices to fasten the module frames to rails | | | | |
| Vulnerability 10: Deflection of subframing from heavy winds causing top-down clamps to fail and/or damaging mounted modules | | | | |
| **2. Racking Assemblies** | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 11: Use of clamping devices to fasten the racking assembly together | | | | |
| Vulnerability 12: Self-tapping sheet metal screws used to hold the racking assembly together | | | | |
| Vulnerability 13: Presence of soft joints in the array's racking assembly | | | | |
| Vulnerability 14: Unbraced racking assembles causing bolted joint failures from large lateral movements | | | | |
| **3. Special Considerations for Roof Mounted PV Arrays** | | | | |
| Vulnerability 15: Inaccessible and wind damage-prone PV array | | | | |
| Vulnerability 16: Inadequate structural attachment to the building | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 17: Mounting position of a PV array resulting in high wind exposure | | | | |
| Vulnerability 18: Array tilts (>15°) resulting in high turbulence and front and back pressure on modules | | | | |
| Vulnerability 19: Flexible PV array glued to roof membrane | | | | |
| **4. Modules** | | | | |
| Vulnerability 20: Damaged modules from inadequate resistance to wind/snow loading and hail | | | | |
| Vulnerability 21: Cracked or failed backsheet | | | | |
| **5. Wire Management** | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 22: Improperly supported wires | | | | |
| Vulnerability 23: Corroded grounding components due to environmental conditions or dissimilar metals | | | | |
| Vulnerability 24: Poor installation practices leading to damage of PV and other DC wires | | | | |
| Vulnerability 25: Animals nesting under modules, chewing and damaging wires | | | | |
| Vulnerability 26: PV connector failure | | | | |
| **6. Electrical Enclosures and Conduit** | | | | |
| Vulnerability 27: Common issues with electrical enclosures | | | | |
| Vulnerability 28: Conduit draining water into downhill electrical equipment from flooded uphill locations | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 29: Electrical enclosures with inadequate NEMA rating located outdoors | | | | |
| Vulnerability 30: Conduit-related vulnerabilities | | | | |
| Vulnerability 31: Field-applied labels and markings showing signs of significant degradation | | | | |
| **7. Topography** | | | | |
| Vulnerability 32: Unobstructed wind forces on the PV system | | | | |
| **8. Site Management** | | | | |
| Vulnerability 33: Clogged roof drainage system | | | | |
| Vulnerability 34: PV equipment in direct contact with the roof membrane | | | | |

| Vulnerability Name | Prevalence (%) | Location of Vulnerability on System | Condition Needs Immediate Attention? (Y/N) | Notes |
|---|---|---|---|---|
| Vulnerability 35: Loose debris and/or equipment scattered around a PV array | | | | |
| Vulnerability 36: Improper stormwater management around a ground mounted PV system | | | | |
| Vulnerability 37: PV array covered in snow, making it susceptible to damage | | | | |

# Appendix C: Basis of Design Template Language

This appendix provides an example of basis of design language and suggested selection criteria for hiring consulting engineers.

**Note: This template is not intended to supersede any agency procurement guidance. It is simply a basis for consulting with procurement staff, writers of such contracts, and consultants, if applicable.**

## Bolted Joint Engineer: Basis of Design

The engineer is to design a retrofit that results in stabilization of affected bolted joints shown from a prior field audit to be unstable. The fastener engineer shall provide the following services:

1. For any affected products that are still under warranty for any reason where agencies need concurrence from the manufacturer, the fastener engineer shall communicate with the manufacturer to gain concurrence on all changes to the affected products.
2. Provide drawings and sketches of the retrofit for the contractor to implement.
3. Provide assembly specifications such as torque values and use of thread assembly compounds.
4. Specify vibration-resistant fastener assemblies to guard against loosening from transverse slip.
5. Specify fastener assemblies that can maintain bolt preloading after embedment and ensure that soft joint relaxation vulnerabilities are accounted for.
6. For fasteners used to mount solar modules to racking rails:
    a. The engineer is to consult with the module manufacturer to determine the fastener method that provides adequately secure mounting of the module.
    b. The engineer is to determine which fastener provides the greatest front and back pressure resistance to the mounted module.
7. For bolted joints with fundamental design weaknesses, the engineer shall design and specify a retrofit solution to strengthen the racking assembly.
    a. If the engineer needs to work cooperatively with a structural engineer to design bracing, then the fastener engineer shall be prime contractor and the structural engineer shall be subcontractor.
    b. For racking with high lateral movement, whereby bolted joints are subjected to unanticipated forces (e.g., wind or snow loading), the engineer shall design a lateral bracing system to stabilize the racking assembly.

## Structural Engineer: Basis of Design

The engineer is to design a retrofit that results in stabilization of the affected structure. The structural engineer shall provide the following services:

1. For any affected products that are still under warranty for any reason where agencies need concurrence from the manufacturer, the structural engineer shall interface with the affected manufacturer to gain concurrence on all changes to the affected products.
2. Provide drawings and sketches of the retrofit for the contractor to implement.

3. The structural engineer shall draw upon the following SEAOC guidance document that complements ASCE 7:
    a. Gravity Design for Rooftop Solar Photovoltaic Arrays PV3-2019
    b. SEAOC Wind Design for Solar Arrays PV2-2017
    c. Wind Design for Low-Profile Solar Photovoltaic Arrays on Flat Roofs PV2-2012
4. Ideally, proposed retrofits to existing arrays should be analyzed under computation fluid dynamics modeling.

## Civil Engineer: Basis of Design

The civil engineer is to design a retrofit of the site that results in effective stormwater management that will ensure the structural stability of the PV system. The civil engineer shall provide the following services:

1. For any affected products that are still under warranty for any reason where agencies need concurrence from the manufacturer, the civil engineer shall interface with the affected manufacturer to gain concurrence on all changes to the affected products.
2. Provide a detailed analysis of the site's landscape and how the current stormwater management is affecting the PV system.
3. Provide drawings and sketches of the retrofit for the contractor to implement.
4. Compare common flood maps to local information that will affect the re-siting of electrical equipment such as inverters, transformers, and switchgear.
5. Provide information on how the retrofit will be able to survive a 100-year flood.

## Electrical Engineer: Basis of Design

The electrical engineer is to design a retrofit of any electrical BOS components (e.g., inverters, PV connectors, DC wiring) in order to resist damage from weather elements (e.g., wind-driven rain, sustained winds, flooding). The electrical engineer shall provide the following services:

1. For any affected products that are still under warranty for any reason where agencies need concurrence from the manufacturer, the electrical engineer shall interface with the affected manufacturer to gain concurrence on all changes to the affected products.
2. Provide a detailed analysis on what electrical BOS components can be salvaged versus what need to be replaced following a severe weather event (e.g., hurricane, blizzard, tornado).
3. Provide detailed specifications on the proper NEMA-rated equipment to install per site's location.
4. Confirm the proper replacements for PV connectors if cross-mating is an issue at the site.
5. Provide drawings and sketches of the retrofit for the contractor to implement.
6. Work with civil engineer to confirm proper heights to raise electrical equipment out of floodplain.

U.S. DEPARTMENT OF ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

**For more information, visit:**
energy.gov/eere/femp

DOE/EE-2500 ▪ September 2021