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Weather impacts on solar PV operations summary of the current body of knowledge and implications for further investigation

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Weather Impacts on Solar PV Operations Summary of the Current Body of Knowledge and Implications for Further Investigation

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Preface

Weather is negatively affecting solar photovoltaic systems in ways that have not yet been anticipated and quantified by key industry stakeholders: product designers, installers, insurers, system operators, and others. Information about failures is limited and mostly held private, inhibiting the ability of broad data sharing. This report summarizes weather impacts information that is available today in an attempt to begin to address that data gap.

Table of Contents

Table of Figures

List of Tables

Acronyms and Abbreviations

AC	alternating current
AHJ	authority having jurisdiction
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
ATC	Applied Technology Council
Availability	A metric of solar performance that is a ratio of system time offline to online time expressed as a percentage (%)
Belleville washer	Type of corrugated washer designed to maintain compensate for bolted joint relaxation to maintain a design pre-loading
BOS	Balance of system. These are components other than the array and inverter needed to make a fully functioning system.
BTUS	Building Technology & Urban Systems
CFD	computational fluid dynamics
CM	center meter
DC	direct current
Derecho	Long lasting line of severe weather events
DML	dynamic module loading
DOE	U.S. Department of Energy
EAEI	Energy Analysis and Environmental Impacts
EF	Enhanced Fujita scale
EL	electroluminescence
ESDR	Energy Storage and Distributed Resources
ETA	Energy Technologies Area
FEMA	Federal Emergency Management Agency
FEMP	Federal Energy Management Program
Force majeure	A failure event beyond the ability to plan for and prevent
GW	gigawatt
HDT	hail durability test
IEC	International Electrotechnical Commission
IML	inhomogeneous mechanical loading
IR	infrared
ITRI	Industrial Technology Research Institute
KTI	key term identification
kV	kilovolt
kW	kilowatt
Lockbolt	A type of fastener likened to a rivet in terms of basic installation and operation
LBNL	Lawrence Berkeley National Laboratory
mph	miles per hour
MW	megawatt
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association

NFPA	National Fire Protection Association
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
NRTL	Nationally Recognized Testing Laboratory
O&M	operations and maintenance
pa	pascal
Performance	A metric of solar PV system that is the result of actual production in kilowatt-hours divided by modeled kilowatt-hours
psi	pounds per square inch
PM	preventative maintenance
psf	pounds per square foot
PV	photovoltaic
PVROM	PV Reliability Operations and Maintenance
PVRW	PV Reliability Working Group
RETC	Renewable Energy Test Center
RMI	Rocky Mountain Institute
SEAOC	Structural Engineers Society of California
SETO	Solar Energy Technologies Office
Severe Thunderstorm	A storm that produces at least 58 MPH or produces a tornado or hail greater than 1” in diameter.
Severe Weather Element	A specific feature of a severe weather event, e.g., wind, hail, flooding
Severe Weather Event	Weather that presents above-average elements that pose life-safety and infrastructures threats
SPD	surge protection device
Storm Resilience	Ability of buildings and infrastructure equipment to withstand storm forces resulting in minimal interruption in function
UV	ultraviolet
UL	Underwriters Laboratories
Wedge locking washer	Class of washers that use a camming action to resist vibrational loosening
WG	working group

Abstract

There is growing concern that severe weather events are negatively affecting solar photovoltaic (PV) systems and pose ongoing and unrecognized risks. Clearly research is needed to quantify and characterize the risks so that properly calibrated improvements can be implemented. To begin this process, this report is a collection of information of severe weather impacts on solar PV available today taken from research, insurance data, and field inspections. While it is not comprehensive enough to draw conclusions, this information provides a baseline for action and indicates an urgent need to investigate further.

Executive Summary

A growing body of evidence is revealing key weaknesses in solar photovoltaic (PV) systems due to weather exposure. These weaknesses include hardware designs, gaps in codes and standards, and highly variable construction practices. For this report, these weaknesses were revealed in insurance claim data, service repair ticket analysis, existing research, reports from industry journals, field investigations of storm damaged arrays, and phone interviews with two large national owner/operators. While there is a growing base of evidence, there is still a significant industry-wide need to fully characterize these weaknesses with data that will enable industry stakeholders to resolve these issues quickly and decisively.

This report discusses the implications of this evidence on several facets of solar PV technologies: plant operations, current design practices, and codes and standards where applicable.

The potential impacts of these weaknesses are quite serious for the solar PV industry, and if not addressed, they could proliferate along with the industry's current rapid pace of development. They present large unplanned operational costs and very serious life-safety issues, as airborne modules and racking components can pose a threat to pedestrians. Incidents of hardware failure due to weather events also pose a reputational threat, which could be politicized. Moreover, lost production and repair costs affect not only the financial prospect of individual systems, but also the ability of the entire solar industry to gain affordable surety products (insurance).

Many solar PV systems are not suitable generation components of a microgrid where resiliency is the primary interest, and solar PV systems could be offline for extended periods of time or completely destroyed.

While some storms (i.e., tornadoes and Category 5 hurricanes) are force majeure events, field inspections have found many examples of fundamental hardware weaknesses to be the root cause of failures, and these represent fully preventable and unnecessary losses.

1. Introduction

Efforts to improve the reliability of solar photovoltaic (PV) systems have, to date, largely focused on the core components of modules and inverters. With weather-related damage becoming a prominent industry issue, the importance of failures with other array components such as racking, fasteners, and wiring systems now deserves industry attention. The entirety of the solar PV system must be examined for reliability.

Statistically significant datasets of storm-caused failures validate and inform our understanding of weather effects and clarify conclusions and corrective actions. Emerging patterns of field failures as reported by stakeholder groups are beginning to provide evidence of current inadequacies in design, construction, and operations. These patterns of failures also are revealing ways to improve performance and durability related to severe weather events, which would help ensure that solar PV systems can be used as a resilient power source in diverse climates.

The ability of the solar industry to incorporate lessons learned in a timely manner is essential for continued technological and financial advancement. Many industry stakeholders now have direct experience with weather impacts and have gained valuable insights into root failure modes, cost impacts, and performance and availability reductions. These insights comprise critical lessons learned that should be widely shared, yet many firms keep this information private. Lack of dissemination of storm-damage data are a central barrier to widespread resolution of these issues.

Current industry practice reflects a wide variety and immaturity of codes, standards, and design principles that result in unpredictable long-term operational outcomes. Intense price pressures, along with many new industry entrants and exits, may provide some explanation. There is a wide variation in the understanding and application of codes and standards, design practices, construction methods, and operations. Most important, many engineers lack awareness of where serious code gaps exist and how to compensate for them. Similarly, buyers of manufactured racking systems are unaware of the design flaws inherent in the products they are procuring for a project. There are many examples of code-compliant arrays that did not withstand forces of even routine weather events such as summer thunderstorms.

The goal of this report is to provide an operations-focused synopsis of how solar PV systems are affected by both severe and regular weather events. The findings are drawn from an existing body of small research efforts and field observations that have implications for the design, construction, and operations life-cycle phases of a solar array.

Nearly every location in North America experiences at least one form of severe weather (or weather event with impactful elements such as winds). During the 30-year operating period of a solar PV system, it is statistically likely that a significant weather event will strike. Impacts stemming from severe weather events appear to present a serious hindrance to the continued advancement of solar PV as a resilient, cost competitive, and dispatchable energy source.

Implications of severe weather effects on solar PV technology not only amount to system performance and availability loss but also a potential impediment to continued cost reductions. The following section summarizes the data sources used to support the discussion and implications put forward in this report. Although the data sources are limited, they provide consistency in supporting this discussion. Still, more data are needed to fully characterize the issues.

This summary draws from six sources:

1. Insurance claim data
2. Literature review
3. PV Reliability Operations and Maintenance (PVROM) analysis by Sandia National Laboratories
4. Trade press articles
5. Field observations and root cause analysis
6. Interviews with two large national owner/operators

1.1 Insurance Claims Data

Insurance data supports the assertion that weather-related impacts should be a serious industry concern.

Insurance data are tied closely to weather events, but an examination of insurance claim data is often very sensitive to the time period selected. Years may go by with no problems, but a severe weather event like a hurricane or hailstorm will affect a large number of systems all at one time.

A research report by GCube, a leading insurance underwriter in renewable energy, highlights that weather-related losses are a leading cause of solar PV claims worldwide. Events such as tornadoes, floods, windstorms, and hail damage have all contributed to damages. From 2011 to 2015, weather-related events accounted for 49.8 percent of all insurance claims (Pickerel 2018). There are regional differences in these claims; within North America, approximately half of all solar PV claims are attributed to weather impacts, while the global percentage is approximately 25 percentage (GCube 2016).

Generally speaking, there has been a significant increase (87 percent) in weather-driven PV claims in the last five years (GCube 2016). The report also identified key factors that influence the financial impact, as well as recommendations for preventing failures in the future.

Another analysis of insurance claims indicated losses to solar equipment using claim information from Verisk, a leading compiler of property-casualty loss data. It showed that 95 percent of the 15,128 claims over the period of 2014 to 2019 had weather-related causes. Figure 1. Of those weather-related causes, the most frequent cause of loss was from hail (56 percent of claims), the second most frequent cause was wind (33 percent), and the third most frequent cause was fire (9 percent). The largest average claim size for losses including solar equipment was from fire ($639,000 total claim), followed by lightning ($253,000) (Verisk 2020). The fire claims in this collection of data concentrated around the dates of three large California wildfire events — indicating the significance of losses from these events.

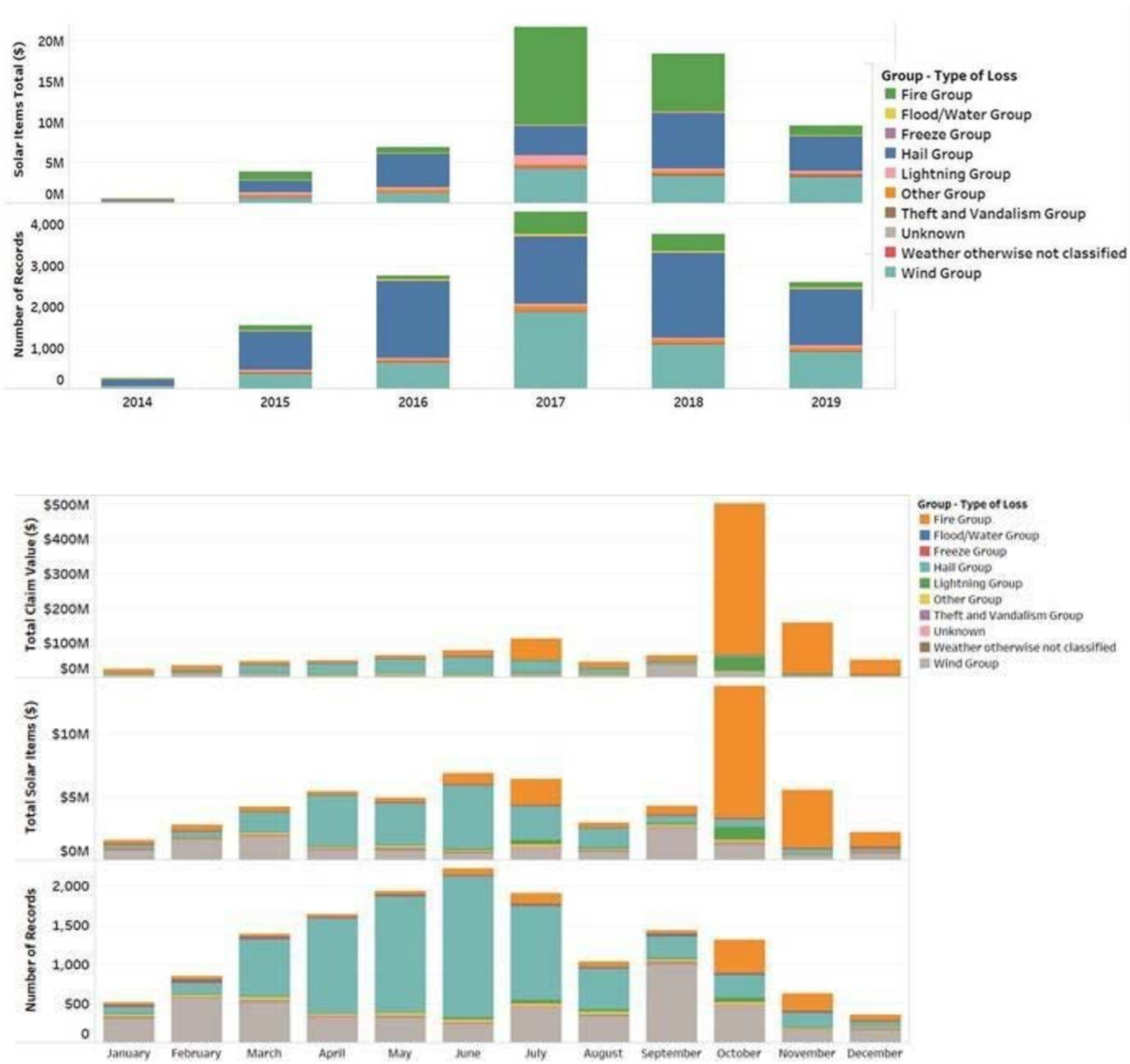


Figure 1. Total claim records and dollar amounts. Source: Jal Desai, NREL

Using the same dataset, the data for total claims ($), number of claims, and total losses ($) to solar equipment were broken out by month. In October, the highest loss was due to fire. In June, the highest total claim and loss was from hail, and in September the highest loss was from wind. When compared to other weather-related causes, the highest number of claims were from the June hailstorms.

1.2 Academic Literature Review

Peer-reviewed literature encompasses both experimental and field-related analysis regarding different influences of weather on PV systems. For example, Santhakumari and Sagar (2019) provided a comprehensive review of the impact of different environmental conditions (e.g., speed, humidity, and temperature) on PV module performance. With regard to extreme weather events of snowfall and ice buildup, the authors noted that orientation and tilt angle of the modules can greatly influence the amount of production loss (Santhakumari and Sagar (2019). Hail damage can also lead to power loss; up to 30 percent, due to impact cracks affecting electrical performance (Santhakumari and Sagar 2019; Gupta et al. 2019).

A number of snow events were also documented in the Northeastern United States, leading to significant underperformance in the region in 2011 (Jordan and Kurtz 2014).

Andrews et al. (2013) monitored the PV system for two winters in Canada and determined that the losses due to snowfall were dependent on the angle and technology being considered. Over the two years studied (when snowfall was relatively low compared to historical data), the losses ranged from -3.5 to +1 percent of expected yearly yield for sites in southeastern Ontario. The increase in expected energy was attributed to increased albedo for modules with higher inclinations (Andrews et al. 2013). Ground-mounting versus elevated modules also had an impact on energy losses. Heidari et al. (2015) quantified energy losses of PV systems with different architectures, and tilt angles were quantified for a test site located in Calumet, Michigan. Based on their study, the authors found that snow-related energy losses ranged from 5 to 12 percent for three unobstructed, elevated modules, and from 29 to 34 percent for comparably tilted modules mounted next to the ground (Heidari et al. 2015).

Although many of the researchers documented the influence of specific ambient conditions on PV systems (e.g., temperature influences and wind speeds in Karin et al. [2019]), the primary discussions for extreme conditions are generally limited to a survey of damages observed for a general event. For example, Ghazi and IP (2014) noted that precipitation higher than 12 millimeters (mm) and wind speed lower than 30 kilometers per hour (km/h) led to poor efficiency of PV panels in the southeast United Kingdom. However, this level of specificity is generally lacking in evaluation of extreme weather events, with limited information presented regarding the quantity, timing, or dimensions of the extreme weather events that led to specific PV system impacts and damages.

1.3 PVROM Analysis - Repair Record Analysis

This work draws on the PV Reliability Operations and Maintenance (PVROM) database managed by Sandia National Laboratories. It includes information about performance and operations and maintenance (O&M) activities conducted at 800+ sites across the United States (Figure 2). An evaluation of the O&M records within PVROM using a key term identification (KTI) for weather-related records identified that both extreme weather events and ambient conditions are identified as factors in the need for repairs (Figure 3). Frequency analysis indicates that extreme weather conditions (hurricanes, snow, and storms, as well as associated events such as high winds and lightning) dominate the database.

Figure 2. Distribution of PV sites within PVROM databases. Source: SNL 2020

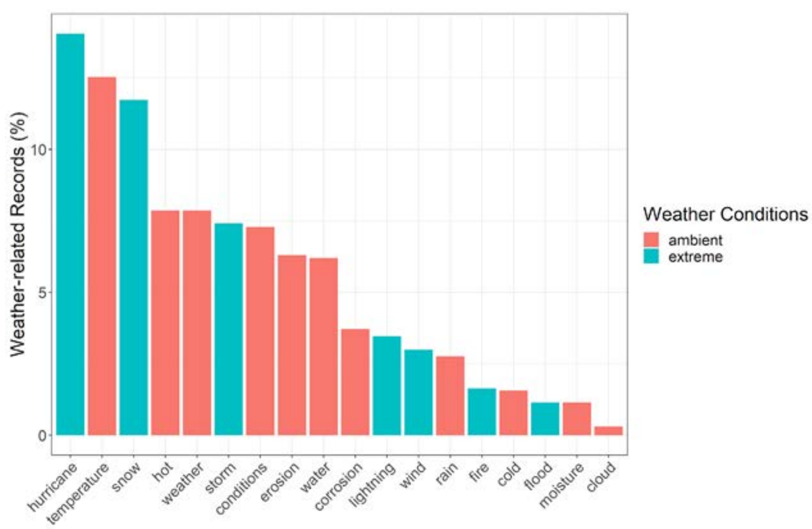


Figure 3. Percentage of records with weather-related terms. Source: Jackson and Gunda, 2020.

Hurricanes represented 15 percent of the weather-related tickets, with a majority of the tickets corresponding to sites located in North Carolina and South Carolina. These tickets can be categorized into three unique categories: (1) preventative maintenance (e.g., forced outages and voluntary offline activities), (2) inspections post hurricane, and (3) addressing hurricane-related damages.

Damages often result in sites offline (both Preventative Maintenance [PM] and Corrective Maintenance [CM]), trackers offline, modules offline (blown off or displaced), or caused by tree falls onto an array or onto power lines.

Generally, however, few details are captured in the tickets. For example, multiple tickets note “hurricane-related inspection” or “hurricane-related. Site offline,” indicating opportunities for capturing more details regarding the specific activities conducted or damages observed.

Unlike hurricane-related events, which predominantly occur in September and October, storm activities (which occur less frequently within PVROM) are more evenly spread throughout the year, and lightning impacts are concentrated in August (Figure 4). High winds are observed in the seasonal transitional periods (between winter and spring and between summer and fall) (Figure 4). Although sites can be offline from wind issues, more often single trackers or modules are offline or communications disruption is observed during high wind events. Interestingly enough, winds and hurricanes are not mentioned together in any of the entries, but some events do use more than one weather term within the same entry. These co-occurrences are generally very low, the most common co-occurrence (5 percent of tickets) contain both storm and wind terms within the same ticket (Jackson and Gunda, 2020).

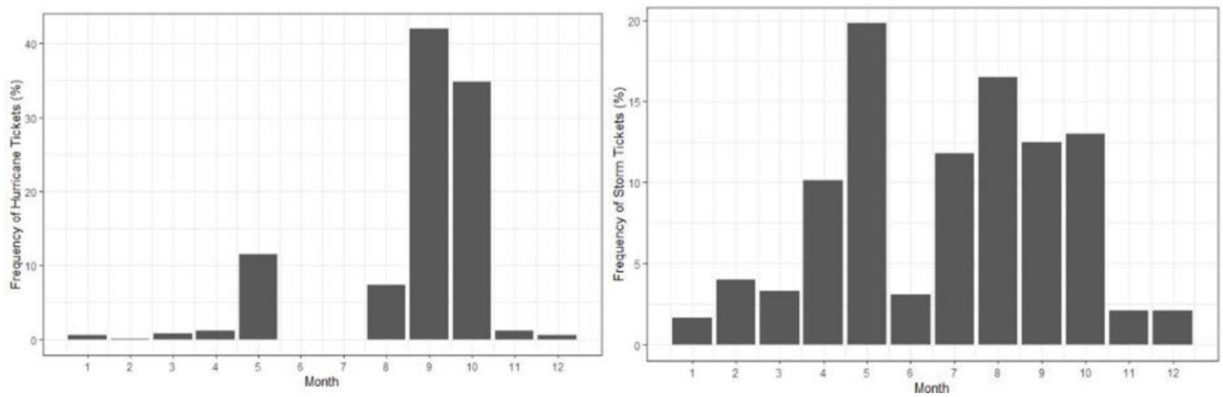


Figure 4. Timing of extreme weather events for (a) hurricanes, (b) storms.

As noted above, researchers have, thus far, explored the influence of ambient conditions on PV systems (Karin et al. 2019), but limited effort has focused on characterization and quantification of extreme weather conditions on PV sites, including geographic pervasiveness of issues (e.g., Santa Ana winds in the western United States). Although there is a limited presence of co-occurring weather terms in the maintenance tickets, the weather terms are often related to each other (e.g., high winds can be related to a hurricane, while lightning is often associated with storms). So, it would be beneficial to distinguish events (e.g., hurricanes and storms) from the associated impacts (e.g., high winds and lightning).

While some note that certain extreme weather events are rare, the specific impacts of weather events can vary greatly. Though there is a current lack of data sharing, what is available (ranging from ticket and claim data to research and field observations) provides meaningful insights into weather impacts on PV systems where tangible actions could be taken to reduce risk. The next few sections document specific opportunities for improvement within current codes, standards, and practices. These approaches will hopefully improve PV systems' resilience to avoidable aspects of these "act of God" events.

1.4 Articles Relating to Incidents of Severe Weather: Industry Press

A keyword search of four common renewable energy industry magazines — *Greentech Media,* *Renewable Energy World, Solar Power World,* and *PV Magazine* — show 42 articles dedicated to the topic of extreme weather. Figure 5 shows the number of articles discussing solar PV and severe weather-related topics.

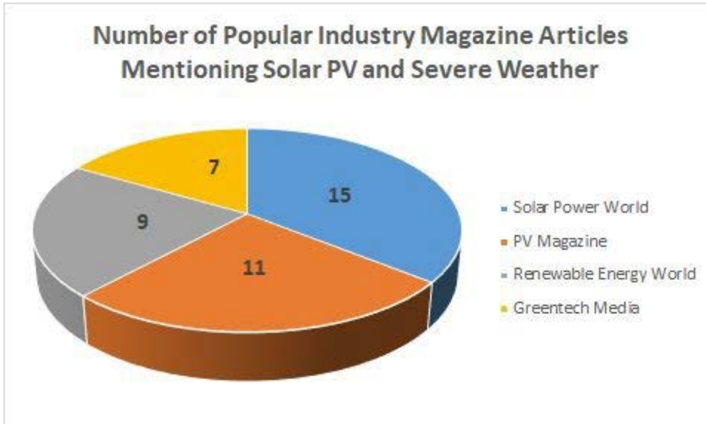


Figure 5. Number of popular industry magazine articles mentioning solar PV and severe weather

To best visually represent the data compiled by the authors in Figure 5, the following keywords related to solar PV and severe weather were chosen:

- Damage
- Storm
- Hurricane
- Wind
- Flood
- Hail

Figure 6 shows that "damage" and "storm" were the most common keywords identified in the 42 industry articles found for this study. The Appendix shows the list of articles and provides links.

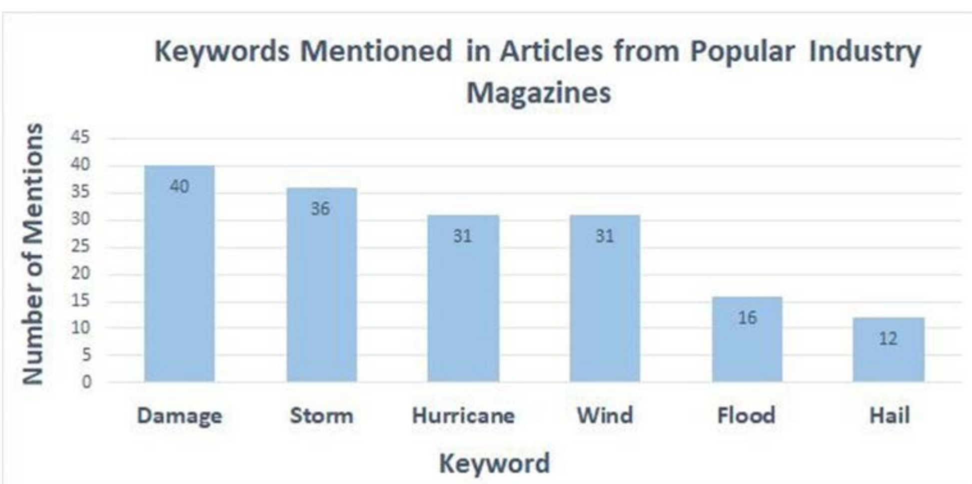


Figure 6. Keywords mentioned in articles from popular industry magazines

2. Field-Observed Hardware Failures from Weather Events

The field observations reported here were documented by both U.S. Department of Energy (DOE) laboratories and industry. The field-observed failures and a summary of the root cause failures is provided. The full list of field failures observed and discussed in this report is limited to examples that are considered by the authors to be the most common and serious, therefore, this is not a comprehensive list of field-observed failures. While this chapter presents an introductory overview, failures and losses from specific weather events are discussed in greater detail in subsequent chapters, and more suggestions for improvements are offered.

Various aspects of PV projects can contribute to their failure, ranging from materials and people to codes/standards and business models. In a 2018 study, the Rocky Mountain Institute (RMI) conducted field visits to investigate the root causes of PV system failures and survivals within the same region. They documented a number of recommendations (both specifications and collaborations) to improve the resilience of PV systems during hurricanes (Burgess and Goodman 2018). Failures during hurricanes were attributed to orientation issues, training, and module mounting hardware. For example, the report notes that systems that survived had bolted modules (with locking solutions) and lateral racking supports (Burgess and Goodman 2018). The authors noted that in addition to specifying the different hardware used, collaboration is also needed to ensure that module, racking, and equipment suppliers are implementing representative load tests and are documenting associated assumptions (Burgess and Goodman 2018). Specifications and construction guidance (including quality control) recommendations have also been made for rooftop systems, including the use of mechanically anchored PV rails and use of rated locking panel clamp bolts (FEMA 2018).

This report discusses hardware, design, and operational issues resulting from the following weather events:

1. Wind, as a common element to most weather events
2. Flooding, as a common element to most weather events
3. Hurricanes
4. Thunderstorms
5. Derechos
6. Tornadoes
7. Lightning
8. Hail
9. Blizzards

Because wind and flooding are part of most severe weather events, they are discussed separately. Some weather events, such as lightning, originate from storms such as thunderstorms but are broken out separately here because of the significance of their impact on solar PV systems.

2.1 Weather and Natural Disaster Events Not Covered

Many categories of weather events and or natural disasters are not covered in this report, as data for these events are scarce. These events are undoubtedly worth investigation, and include such events as:

1. Dust storms
2. Ice storms
3. Mudslides
4. Wildfires
5. Earthquakes

2.2 Severe Weather Events and Damaging Elements

Design and construction practices are evolving but are currently still highly variable. Related to this variability, the way in which weather events and forces for a given site are accounted for and integrated into a system's engineering, construction, and operations practices is not thorough. There appear to be several areas of weather awareness that are sometimes not fully accounted for:

1. Assuming a site does not experience any kind of significant weather altogether.
2. Wind speed design values. Common engineering design wind speed values (such as those of the Applied Technology Council [ATC]) are often exceeded by wind events. The recent derecho that ran through the Midwest in August 2020 exceeded design wind values. The ATC 25-year wind value for Cedar Rapids is 84 miles per hour (mph) yet was exceeded twice in 2020, with the August derecho event producing the most extreme wind speeds at 140 mph.
3. The full list of significant weather events that occur at a site and the associated probabilities of each over the 30-year life of a solar PV system.
4. Topology around the array site, and how winds are channeled and possibly speed up through canyons and rises.
5. The increasing frequency and or intensity of storms due to shifting climate.

2.3 Wind: The Most Common Element Weather Event

Wind is the most common damaging element stemming from nearly every significant weather event. Design engineers use simple wind speed values (usually in mph) plugged into software tools or hand calculations that are done to meet required codes. These simple wind speed values do not capture the unique wind dynamics that stem from different weather events, and thus the design of solar PV structures lack consideration of the highly dynamic forces that result from different storm types.

Comparing, for example the wind speeds and resulting damage between hurricanes, tornadoes, and derecho events illustrates the need for engineers to adapt updated design practices. Even an F-0 rated tornado on the Fujita scale of less than 73 mph can easily destroy a solar array, while the same wind speeds from a hurricane or routine thunderstorm would do little damage. This is due to the high-pressure differentials generated by a tornado over a short

distance with strong updrafts inside rotating winds.
Similarly, there appear to be unique and dynamic forces stemming from the powerful downburst clusters generated with derecho thunderstorm events. More investigation is needed to fully characterize wind forces from different storm events, and these insights must be used to inform and update design practices.

Hardware design and installation practices are key determinants for durability; however, the ability of an array to withstand a significant wind event, modules to stay mounted and undamaged, and the racking assembly to stay intact and in place depends on a variety of factors:

- Arrays located in highly exposed locations (e.g., mounted on roofs well above the elevation of the parapet or peak, or in ground locations on topology with no obstructions from neighboring buildings and vegetation).
- High tilt angles.
- Array sections on the perimeter row, or one or two rows in, and in high turbulence areas on the roof in proximity to parapets and penthouses.

2.3.1 Wind failures and code gaps

System owners and operators may be working under the false assumption that the bolted joints, fasteners, and racking systems can withstand the design wind speeds used to meet ASCE-7 code. Field evaluations of damaged arrays indicate failures are occurring at well below design wind speeds. Currently there appears to be poor correlation between design wind speed and actual wind speeds in terms of the survivability of solar structures.

Some engineers have recommended the use of stamped (sealed) structural drawing sets as a solution; however, there are concerns that the engineering process itself and underlying supporting calculations and software modeling tools need to be updated.

Operators should take a closer look at likely survivability given current field experience from other similar arrays. For low sloped roof (SEAOC 2017) and ground array (Cain et al. 2015) types, operators can utilize guidance produced by the Structural Engineers Society of California (SEAOC) to examine the integrity of existing structures. Though intended to be used for new systems, operators can use the guidance to identify weaknesses and then engineer a retrofit. System operators have been confronted with solar arrays vulnerable to even minor and routine wind forces, indicating a design or installation flaw more than a severe weather vulnerability.

Post-storm inspections of solar arrays have found significant damage from routine thunderstorms that had wind speeds of 70 mph or less. In one example, lab inspectors found a ground array in Prescott, Arizona (Figure 7) completely destroyed due to fastener and racking weaknesses. A weather station located within feet of the array recorded 70 mph winds from a summer monsoon storm that caused the damage. This array was also co-located next to an older tracking system that was unharmed by the storm.

Figure 7. A ground array in Prescott, Arizona

3. Field-Observed Module Losses

3.1 Wind Failure Mode: Module Loss from Wind Pressure and Debris Strikes

Under high front or back pressure, modules can implode, leaving the assembly of glass, encapsulants, cells, and backsheets fractured (Figure 8). Sometimes this kind of failure has been traced to racking frame deflection/twisting. Care should be taken to examine the racking frame stability as a root cause before assuming wind damage.

Figure 8. Imploded module

It is likely that the damage wind flexing causes is not visible and can only be fully evaluated using infrared (IR) and/or electroluminescence (EL) imaging technologies to examine cells and other components. In high wind events, and especially in long duration high wind events from hurricanes, the module glass / encapsulant / bus bar assembly flexes many thousands of times, probably causing material fatigue leading to failures.

3.1.1 Design and code implications

Using the ASTM E1830-15 prescribed test parameters is one resource designers can use to select a module suitably durable to front and back wind pressures. Table 1 shows the minimum recommended static test values.

At least two manufacturers exceed these ratings. ASTM E1830-15 also covers dynamic loading with 1,440 pascals (Pa) at 10,000 cycles. IEC-62782 is a dynamic mechanical load test that flexes the module assembly using 1,000 Pa cycling 1,000 times.

The Industrial Technology Research Institute (ITRI) of Taiwan has developed a typhoon-specific module test. It is a dynamic module loading (DML) test that subjects a module to 5,400 Pa front and back pressure at 200 cycles. The institute claims that this is equal to a hurricane on the Beaufort wind scale of 12.[1] Purportedly, only one module has passed this test (Pickerel 2016). When choosing a module, designers can investigate use of this test method at a module test lab that is nationally recognized (NRTL) for large projects.

Ultimately the ASTM test (and IEC 62782) should be field validated, particularly given that it is well understood that modules mounted in perimeter rows and on roofs located in zones with high turbulence are likely to see dynamic loads and cycling in excess of the tests. The sustained winds of a single hurricane would produce thousands of cycles alone.

Table 1. Minimum Front and Back Pressures: Static Test

Module Side	Pascals (Pa)	Pounds per Square Inch (psf)
Front Load (Push) Rating	6,000	125
Back Load (Pull) Rating	5,400	113

3.1.2 Reducing damage from debris strikes

Hail ratings might provide some indication of resistance to some debris strike damage. Some debris has enough mass and inertia (liberated modules) that damage will occur regardless of module rating. It can be reasonably assumed that heavier objects will break any module, but it may be possible to guard against lighter debris material. FM Global has a “Very Severe Hail Rating” (FM 4478) which uses a 2 inch ice ball propelled at 152 to 160 feet per second. An independent test lab, the Renewable Energy Test Center (RETC) has developed a hail test methodology called the Hail Durability Test (HDT) that is advertised to be more indicative of field conditions. During a November 17, 2020, *PV Magazine* Roundtable event, Daniel Chang of the RETC asserted that no modules fail the current versions of IEC hail test standards and therefore it should not be used as an indication of resistance to debris strike damage.

3.2 Wind Failure Mode: Lack of Mechanical Attachments to Building Structures

As discussed in the SEAOC report, *Wind Design for Solar Arrays,* winds flowing over parapets and penthouses can generate powerful turbulence (eddy currents and vortices) with pressure differentials that are known to remove ballasted solar arrays even in moderate winds. Figure 9 shows a ballasted rooftop array with inadequate mechanical attachment points to the building

[1] Beaufort Wind Scale. https://www.spc.noaa.gov/faq/tornado/beaufort.html

structure. Given the very serious life-safety implications, this is an area of structural engineering and wind dynamics that needs more investigation to fully characterize the problem.

Figure 9. Ballasted rooftop array with inadequate mechanical attachment points

3.2.1 Design implications

While design practices, codes, and tools evolve to properly capture the highly dynamic wind forces in severe weather events, conscientious engineers currently have a challenging job to produce durable designs. While code committees debate needed updates to ASCE 7, structural engineers need to undertake the extra efforts as described in such publications as the SEAOC guidance documents. Where clear guidance is missing, engineers will need to do almost custom design work for now. In engineering new arrays to replace those lost during hurricane Maria and Emma, structural engineers at Jacobs Engineering utilized computational fluid dynamics (CFD) modeling to examine and understand the dynamic forces placed on their design in high wind events. Jacobs engineers examined forces from multiple directions: north, south, east and west. Modeling with CFD software is a powerful tool, however researchers at the National Renewable Energy Laboratory (NREL) National Wind Technology Center involved with examining solar tracking technologies have observed the need to validate CFD models using field measurements.

3.2.2 Operational implications

Incidents of ballasted arrays detaching from underlying roof areas appear to be occurring in a broad geographical region well outside of hurricane zones. Figure 10 shows a ballasted array lifted off a roof surface in Cedar Rapids, Iowa, during the August 2020 derecho event.

Figure 10. Ballasted array lifted off a roof surface

This storm generated winds gusts equivalent to that of a Category 4 hurricane, at 140 mph. These winds exceeded the highest ASCE 7-16 Risk Category of 120 mph. There are multiple examples of this type of damage throughout the Caribbean, but it also is happening around the lower 48 U.S. states. From an owner/operational perspective, any ballasted roof array should be immediately evaluated by a qualified structural engineer that has experience designing wind-resistant roof arrays.

3.3 Wind Failure Mode: Ballasted Roof Arrays with No (or Few) Mechanical Attachment Points

The damaged array shown in Figure 11 is located in the Bronx borough of New York City and was damaged during a routine summer thunderstorm.

Figure 11. Thunderstorm damage

Several rows of modules were lifted off of the roof and strewn during this thunderstorm event. This design was originally thought to be very aerodynamic and not susceptible to damage from moderate wind storms. The system lays flat on low sloped roofs and consists of a module glued to a layered foam and cementitious fire-rated material (Figure 12).

Figure 12. The module construction, glued to a layered foam and cementitious fire-rated material

Each module assembly was keyed to neighboring units through a tongue-and-groove feature and held together by cabling. The perimeter metal wire tray served as a windbreak, providing what the original designers thought was a very aerodynamic design not susceptible to wind lift.

3.3.1 Design implications

These flat array concepts that cover large roof areas contiguously have many other serious design flaws in addition to wind vulnerability. Though wind vulnerabilities are the most serious (life threatening), covering large areas of a roof impedes facilities engineers from executing roof membrane repairs, and interior sections of the array are very difficult to reach and service. These concepts have proven to be incompatible with normal roof maintenance programs.

3.3.2 Operational implications

Owners and operators of this style of array should preemptively work with a structural engineer to devise a retrofit to properly mechanically fasten the array to the building. The life-safety ramifications are severe, and any owner or operator with a self-ballasted array should have it carefully examined by a structural engineer experienced with wind forces and solar arrays.

4. Critical Bolted Joints and Fasteners in Racking Systems

The application of fasteners and the design of bolted joints is an important area of racking engineering that is just now starting to mature. Even still, many racking systems on the market, and certainly a large installed base of systems, have critical bolted joints that have underlying issues. Figure 13 shows an example of where some critical bolted joints are located on a fixed racking system.

Figure 13. Critical bolted joints

Many bolted joints in a PV system can be classified as “critical.” Critical bolted joints are those that maintain structural integrity by holding racking assemblies together and holding modules to frame rails, often under clamping forces. Mechanical attachment points to a building are another location of critical bolted joints.

The following chapters discuss field-observed weather-related losses from bolted joints, fasteners, racking systems, and other PV system components. They also identify how weather events can compromise these components and offer suggestions to strengthen solar structures and reduce extent of harm from storm forces.

5. Wind

This chapter presents field-observed failures from wind events, focusing on top-down module mounting assemblies, top-down clamp assemblies, and racking assemblies. These failures mainly result from bolted joint and fastener failures, and all can be mitigated or resolved completely.

5.1 Top-Down Module Mounting Assemblies

One of the most commonly observed field failures involves issues with top-down clamp assemblies used to mount modules to underlying rails. Top-down clamps are part of an assembly of components that must work together to be effective. Incompatibilities in an assembly or a weakness on one component within the assembly will result in catastrophic failure, allowing modules to break free and become wind-borne.

Though no significant dataset yet exists to fully characterize failures with top-down clamps, there are consistencies in observations among multiple stakeholders (operators, engineering firms, DOE lab teams, and others) involved in the analysis of post storm field failures. Burgess and Goodman (2018) performed a statistical analysis of 26 Caribbean rooftop systems. Of the 26 systems, 22 used some type of top-down clamp system. Nearly all of these 22 arrays (21 out of 22) had failure on the top-down clamps. Operators that were interviewed (Constellation and Strata Solar) all reported top-down clamps as a key weak point. Post-damage field inspections done by DOE laboratories (NREL and LBNL) have also observed top-down clamp failures, adding evidence that this is an area of concern. During a presentation given at the PV Reliability Working Group (PVRW) in 2019, a bolted joint engineer (Jon Ness) of Matric Engineering reported many identifiable weaknesses with top-down clamping assemblies, most notably soft-joint characteristics.

Safety implications with top-down clamps that result in liberated modules during wind events are a severe life-safety issue.

5.2 Top-Down Clamp Assemblies: Five Categories of Suspected Failures

Five categories of failures are discussed below:

1. Loss of clamp loading from vibration and fastener loosening
2. Soft joint deformation, resulting in clamp load loss and loosening
3. Deformation of clamps (bending) with inadequate strength
4. Mid-clamps fail with loss of one module; the “row domino” effect
5. Clamps pried open from subframe deflection and torsional movement

5.2.1 Loss of clamp loading from vibration and fastener loosening

Though difficult to distinguish from other failure modes, vibrational loosening of top-down clamp fasteners is suspected to be an issue, as field inspections after storm events show a large number of loose fasteners. Vibrational loosening is at least a concern that needs further verification with regard to top-down module clamping fasteners. Vibrational loosening from transverse slip in racking frame bolted joints has been definitively identified from field inspections. Whether from transverse slip or other type of fastener movement, vibrational loosening may be a serious problem with top-down clamping fastener assemblies.

One clue seen from field inspections is the metal scraping that occurs between serrated flange nuts and the underlying clamp bracket. The serrations of the nuts are thought by some designers to provide locking capabilities. Field inspections have found signs that strong forces cause the flange nuts to spin off and force the serrations to scrape the metal; causing a tell-tale scarring of the metal (Figure 14).

Figure 14. Clamping bracket: evidence of flange nut scrapes from loosening. Source: G. Robinson, LBNL.

Serrated flange nuts (Figure 15) are known under the DIN 65151 standard (Junker test) to be an ineffective locking fastener that does not resist vibrational loosening. That appears to be supported by field observations.

Figure 15. Typical serrated flange nuts. Source: Pinterest.

Need for further investigation
The issue of vibrational loosening in bolted joints in racking is well understood but not as clear with top-down module clamps. Since the issue of vibrational loosening is not well understood with top-down clamps, by neither the solar PV racking design community nor field inspections, further testing and investigation is needed to better characterize the issue. Both wind tunnel testing and field testing are needed to fully characterize the issue.

Codes and standards implications

As of the date of publication, a few working committees are starting to examine fastener issues. To support clear and timely decision making, data obtained through testing of different assemblies are needed. These committees should be consulted to better understand the need for data to assist in decision making.

Design implications
Since vibrational loosening on top-down clamp fasteners is potentially a very serious life-safety issue and not well understood yet, the design community should adopt a conservative approach by specifying rated locking fasteners (DIN 65151) and assembly instructions with torque values and audit procedures.

Designers need to be cautious about other underlying weaknesses in the fastener assembly. If these underlying weaknesses are not addressed, then locking fasteners will have no benefit.

Operational implications
Retrofitting existing fastener assemblies with locking hardware can be expensive; however, significant life-safety issues may justify the cost. Two practical DOE/Federal Energy Management Program (FEMP) publications address cost issues with various storm hardening measures (Elsworth and Van Geet 2020; FEMP, forthcoming).

5.2.2 Soft joint deformation, resulting in clamp load loss and loosening

Taken together, the top-down clamp assemblies, module frame, and underlying mounting rails (which are most often comprised partially or wholly of aluminum components) present what bolted joint engineers characterize as “soft-joints.” One or more of these aluminum parts can relax when the fastener (a slotted t-bolt, most often) reaches pre-load. Wind pressures on the back or front of the module would also most likely cause one or more of the aluminum parts to relax or deform, thus resulting in loosening in the module clamp.

Slotted t-bolts (Figure 16) are often made of a grade of stainless steel.

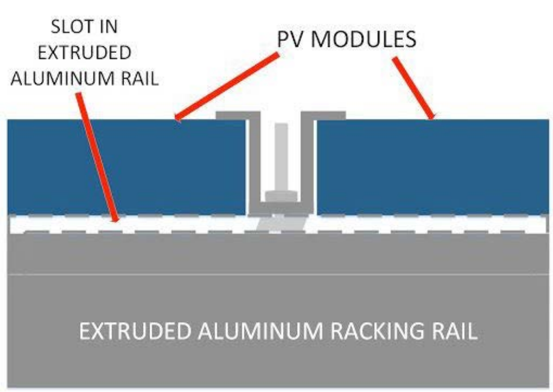


Figure 16. Soft joint: Top-down clamp

For the top-down clamping assembly to adequately hold modules in place under adequate clamping forces, the bolt would need to reach a pre-loaded state when tightened (put under tension). However, given the hardness of the stainless bolt, the pre-load on the bolt may not be achieved, as the soft aluminum components yield or bend, causing the joint to relax before bolt rated pre-loading is achieved or sustained.

One extreme example of how aluminum can yield is at the point where the slotted t-bolt contacts the slot in an aluminum extrusion. In the case of Figure 17, the extruded aluminum yielded under pressure to the point of total failure with the t-bolt breaking through. This condition has been noted a few times by field inspectors.

Figure 17. T-bolt breakthrough

Figure 18 shows a typical slotted t-bolt and an end profile of one type of slotted extruded aluminum mounting rail.

Figure 18. Typical slotted t-bolt and a type of slotted extruded aluminum mounting rail

Codes and standards implications
Loss of clamp loading has been observed on arrays exposed to both normal routine and severe weather events. Field inspections of two six-year-old roof arrays in two upstate New York locations (Albany and Syracuse) showed extensive fastener loosening. These arrays were exposed to normal (non-severe) weather events and showed loosening of fasteners across both arrays. Product literature from the racking manufacturer provided torque ratings for some critical fasteners; however, there is concern that even with proper installation, fastener loosing will be chronic due to fundamental design problems with the bolted joints.

Design implications
In place of top-down fasteners, through-bolting of modules to underlying frame rails should be considered. This could be especially effective if rated locking fasteners (DIN 65151) are used. There are many instances where through-bolting is not possible, such as where there is only access to the front of the module, forcing a top-down solution. One solution bolted joint

engineers use to address relaxation of metal parts that have “soft joint” characteristics is to apply a conical spring washer in the assembly (Figure 19).

Figure 19. Conical spring washer

Conical spring washers provide a means to maintain bolt pre-load should metal deform or embedment occur. This style of washer collapses flat under a properly tightened fastener and adjusts (within limits) open to maintain pre-loading. This style of washer is used in soft joints and is selected for a bolted joint, accounting for the style of joint and metals involved, and requires specialized engineering knowledge to specify.

Operational considerations

Given the severe life-safety issues involved with module fasteners, owners should consult with bolted joint engineers to fully evaluate vulnerabilities and prescribe any needed retrofits.

One solution is to through-bolt the module frames to the racking rails where possible. There are many instances where this is not possible, as the pre-drilled mounting holes located on the back of most modules do not line up with racking rails. Some racking systems, such as the extruded aluminum rails, are not designed for through-bolting. Many roof racking systems do not provide access to the back of the module, making a through-bolting solution impossible.

Successfully specifying a through-bolt retrofit solution requires a surprisingly highly specialized fastener and bolted joint knowledge. The complexity of the engineering challenges involved are clearly not yet reflected in industry common practice yet. For example, some module manufacturers provide specifications for a through-bolt assembly and call for the use of a star washer or other type of washer for electrical equipment bonding (WEEB) in order to meet UL 1703 grounding requirements, yet the star washer is a known source of problems leading to loss of pre-load and thus clamping forces. If a fastener assembly is to be modified by eliminating star washers (or WEEBS) to address excessive pre-load relaxation, consultation with an experienced bolted joint engineer will be essential.

5.2.3 Deformation of clamps (bending) with inadequate strength

Clamping brackets from some manufacturers have inadequate strength to resist the upward forces from module back pressure generated during moderate to high wind events. The upward forces on the modules forces the flange or clamp out. This has been a very common condition found from field inspections and reported also by system operators. While the prevalence of this condition is not yet fully known, many product designs utilize light-duty aluminum clamps. Figure 20 shows an end clamp bracket example; the one on the left is intact and undamaged, while the one on the right has been bent out.

Figure 20. End clamps, intact and damaged

A few racking designs utilize back-of-module frame clamps (Figure 21). These concepts have low strength, and in one field inspection failed under a 70 mph wind generated by an afternoon thunderstorm.

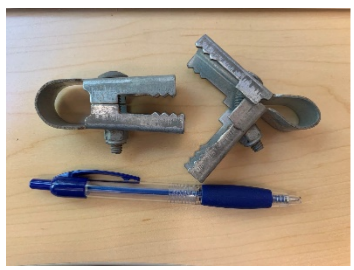


Figure 21. Back-of-module frame clamps

Codes and standards implications

In other industries, such as transportation, that also have large quantities of critical bolted joints, there is a well-developed quality management system that is reflected in codes and standards. The continuity of quality management systems used in the automotive industry are strong, from standards through to engineering, assembly, and audit. It is a full life cycle quality management system that ensures low cost, high assembly speed, and auditing with critical bolted joints. An appropriate quality management system for the solar industry has not been developed, but one is needed, given the severe life-safety and economic issues involved.

In a phone interview, Jon Ness, a bolted joint engineer with Matrix Engineering, characterized the practices in the solar PV industry as immature (from a design and assembly perspective) and still developing. The solar industry will need to reach a similar standard of practice where large volumes of low cost bolted joints can be produced under a comprehensive quality management system. With undeveloped codes and standards currently, and many new companies entering and exiting the market, attaining low cost with high reliability has become complicated. There is currently a UL working group looking to update UL-2703 corrosion testing so stronger (and lower cost) alloys can be used in racking systems. However there should be more activities with codes and standards than the few currently ongoing, given the wide number of complex issues.

Design implications

The level of awareness within the design community needs to be increased with regard to the current field failures being observed. Until such a time, when standards and practices improve and become “institutionalized,” product designers should consult with an experienced bolted joint engineer who can provide the specialized engineering needed to correctly specify adequate hardware and assembly practices. Designers also will need to prescribe assembly practices (with training) that can yield reliable, predictable outcomes during construction.

Operational implications

System owners and or operators should inspect existing solar PV systems and catalog the number and type of these components. Working with the racking manufacturer and a bolted joint engineer, these vulnerabilities will need to be addressed.

5.2.4 Mid-clamps fail with loss of one module; the “row domino” effect

Figure 22 illustrates a common style of top-down mid-clamp that is used to secure the inside edge of two neighboring modules.

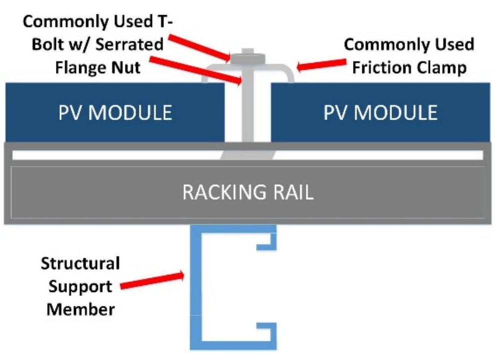


Figure 22. Common style of top-down mid-clamp

Figure 23 shows the clamp in a picture taken from the field holding the inside edges of the two modules.

Figure 23. Top-down mid-clamp in the field

Figure 24 shows the fastener assembly with the clamp, slotted t-bolt, and flange nut. This style (as well as several others like it) is particularly vulnerable to failure if and when one of the two neighboring modules breaks free (is dislodged).

Figure 24. Fastener assembly with clamp, slotted t-bolt, and flange nut

The fastener will tip off the remaining module (Figure 25) once one of the neighboring modules has broken free from such events as high wind pressure or a debris strike.

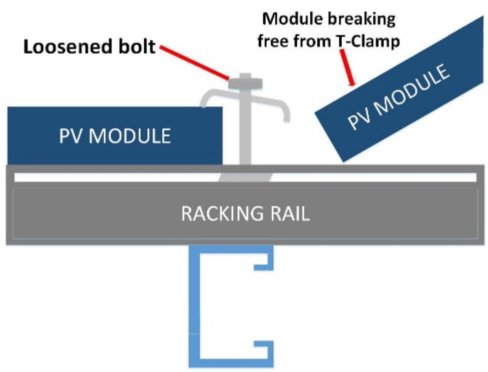


Figure 25. How module breaks free from a t-clamp

Modules are most often arranged in rows with end- and mid-clamps securing models to the racking rails. Once one module is dislodged during a weather event, the entire row will be found lost in a kind of “domino” effect. This “row domino” problem has been observed repeatedly by those that undertake field inspections, and it is suspected to be one the major causes of module loss during a storm.

Design and code implications

The design, surface area, positioning, and quantity of clamping fasteners may determine how well a module is mounted and secured for storm-force winds. Module manufacturers’ installation instructions show various allowable mounting schemes and the resulting front and back wind pressure ratings (in pascals, Pa) that will result. The guidance provided in the solar PV module instruction manual (Figure 26) is from a Canadian Solar installation manual and shows different mounting positions and the resulting module front and back pressure ratings. What is missing is any indication of how well secured the modules are to such phenomena as “row domino.”

Table 5: Approved bolting methods

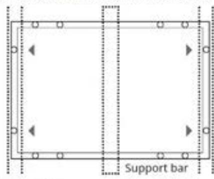
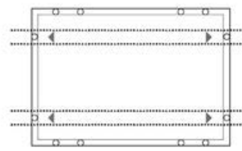
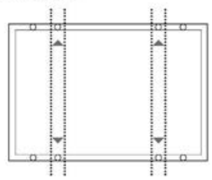
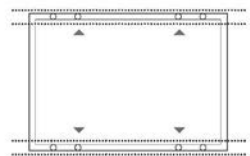
Bolting on the short frame side using four standard mounting holes. Mounting rails run perpendicularly to the long frame side. An additional support bar should be placed below the module as shown below.  Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 5400 Pa Compatible module types: CS6A-P, CS6A-M and CS6A-MS	Bolting on the short frame side using four standard mounting holes. Mounting rails run parallel to the long frame side.  Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 2400 Pa Compatible module types: CS6A-P, CS6A-M and CS6A-MS
Bolting on the long frame side using four innermost mounting holes. Mounting rails run perpendicularly to the long frame side.  Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤ 5400 Pa Compatible module types: CS1V-MS, CS1VL-MS, CS3K-P, CS3K-MS, CS6A-P, CS6A-M, CS6V-P, CS6V-M, CS6K-P, CS6K-M, CS6K-MS, CS6V-MS, CS6VL-MS, CS6A-MS and CS1HA-MS (Please refer to the separate manual for the KuLite CS3K-P which is a lightweight option for standard CS3K-P)	Bolting on the long frame side using four innermost mounting holes. Mounting rails run parallel to the long frame side.  Maximum Load: Uplift load ≤ 2400 Pa Downforce load ≤4000 Pa Compatible module types: CS1V-MS, CS1VL-MS, CS3K-P, CS3K-MS, CS6A-P, CS6A-M, CS6A-MS, CS6V-P, CS6V-M, CS6V-MS, CS6K-P, CS6K-M, CS6K-MS and CS1HA-MS (Please refer to the separate manual for the KuLite CS3K-P which is a lightweight option for standard CS3K-P)

Figure 26. Solar PV module instruction manual

Operational implications

There is an indication that first costs are not properly balanced with life-cycle costs. Operating firms report maintenance staff revisiting fasteners for retightening on a recurring basis and at high cost. First-cost considerations should also be balanced against the risk to loss in performance, availability, resilience (in cases where array is part of a backup power scheme), and life safety.

First-cost considerations without factoring in impacts on insurance risk premiums is shortsighted, as premiums industry-wide will go up and remain artificially high.

O&M implications

Owner operators should audit existing arrays to determine the type of module fasteners in use. Look to spot fasteners that could result in “row domino.”

Given that fasteners and attachment points are such a highly specialized engineering field, owners should consult with a bolted joint engineer. There are likely compound issues involved; for example, a fastener with inadequate strength to resist wind forces and one that is vulnerable to “row domino.”

5.2.5 Clamps pried open from subframe deflection and torsional movement

This type of failure can result in deformation of the array's mounting rails and subframing, as well as module damage.

As evidenced by field inspection, array assemblies are exposed to highly dynamic wind forces that cause unanticipated load paths along racking members and through modules. Some designs utilize light gauge (20–22 gauge) cold rolled metal channels. Common profiles seen are often C-channel, hat channel, or Z channel (Figure 27).

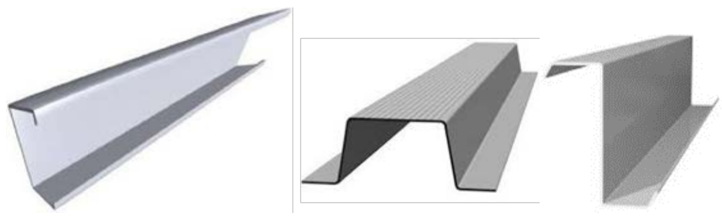


Figure 27. C-channel, hat channel, and Z channel

Based on damage observed in the field, it appears that structural engineers generally consider loads along the Y-axis (shown in Figure 28); however, the actual load paths under dynamic wind loading result in uneven lateral forces across an array.

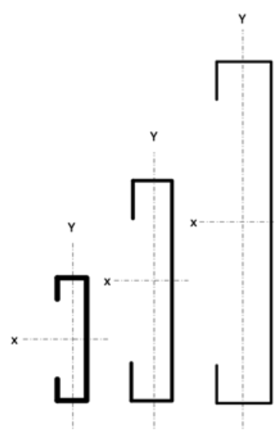


Figure 28. Sectional view of c-channel: Loading on the y-axis.

Figure 29 shows one such example of a carport from St. Johns in the U.S. Virgin Islands, where the top flange of the c-channel bent. This condition was found throughout the array.

Figure 29. Bent top flange of a c-channel

Also, field inspection revealed that these same c-channels had experienced loading that resulted in torsional forces that twisted the beams.

The unintended deflection, bending, and twisting of the structural channel (c-channel in this case) resulted in putting the modules mounted above under forces; the deflection was transferred to the modules mounted above and caused a fair number to burst from overflexing.

Instability with racking systems comprised of light gauge structural channels was also reported in a December 2020 phone interview with a representative of a large owner/operator of 5 gigawatts (GW) of utility-scale systems under management. This large owner/operator had several arrays that were retrofitted to reinforced structural channels in order to stabilize the racking systems against dynamic loading.

In Figure 30, several burst modules can be seen. Those damaged from a debris strike can be differentiated from those broken from deflection of the underlying racking framework.

Figure 30. Burst modules

Severe frame deflections can also be seen from bent top-down module clamps. When the frame members deflect, top-down module clamps can be unevenly pried up. Figure 31 shows one example of a top-down module clamp bent unevenly from frame deflection.

Figure 31. Top-down module clamp bent unevenly from frame deflection

Codes and standards implications
Racking assemblies are covered by codes and standards mostly addressing grounding issues, with UL 2703 covering clamping forces of the bolted joints. However arrays are subjected to non-uniform dynamic loading, yet there are no well-developed standard and accompanying testing methods. This situation leaves designers without the tools they need to select appropriate racking systems for a given site.

Design implications
Racking designers should account for all the load paths through the entire system, including those into fasteners and mounted modules. The load paths under dynamic loading need to be accounted for, along with the effects of vortices and eddy currents between rows. Systems that rely on use of light-gauge structural channel frame elements need to include large amounts of well-placed bracing to prevent failure (twisting and deflection) on these members.

O&M implications
Services of a structural engineer with experience in solar PV racking systems should be utilized to evaluate existing installations to identify latent weaknesses. The engineer will need to prescribe retrofit brackets and bracing to address weaknesses with light-gauge frame elements and unintended lateral movement.

5.3 Racking Assemblies

Field inspections and phone interviews with two large national owner/operators revealed two common failures with racking assemblies: (1) vibrational loosening and (2) soft bolted joint relaxation.

5.3.1 Vibrational fastener loosening

While vibrational loosening is suspected to be an issue with top-down module mounting clamp fasteners, it is clearly an issue with the racking fasteners. Vibrational loosening on racking bolted joint fasteners is widely seen and talked about among operators, field inspectors, and bolted joint engineers active in the solar industry.

Structures exposed to wind take on a natural vibration frequency or oscillations. The substructures of many solar arrays are populated with bolted joints that take on a type of vibration that can lead to transverse slip, where the clamped surfaces of the bolted joint slide past each other. In these cases the intense vibrations set up during a wind event overcome the coefficient of friction between the bolted surfaces. Transverse slip is very effective in loosening threaded fasteners. When winds speeds reach a critical threshold, the clamping forces between two metal surfaces is defeated, and slippage occurs (Figure 32).

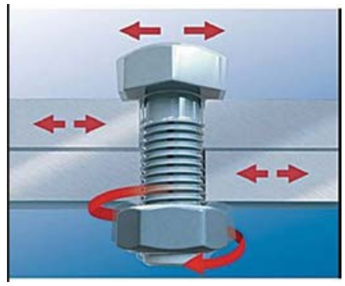


Figure 32. Transverse slip

Corroborations between system operators and field inspections have illustrated the prevalence of chronic fastener loosening. Fastener loosening, if left unchecked, will often result in the entire loss of fastener assembly (bolt, nut, and washer); the entire threaded system will vibrate out and fall to the surface below.

Figure 33 is a picture of a bolted joint found in Puerto Rico after hurricanes Maria and Irma, showing the results of vibrational loosening. Several bolt holes are missing fasteners, and those remaining in place were found finger loose, with the nuts spinning freely. This racking system had a large quantity of fasteners that loosened and fell out of bolt holes, leaving nuts, bolts, and washers scattered around the roof.

Figure 33. Vibrational loosening of a bolted joint

Codes and standards implications

Ideally, critical bolted joints found in array structures would be engineered to prevent slip from transverse vibrations, and thus, threaded fastener loss. Purpose-built bolted joints are needed to reduce both first cost and costly operational retrofits. Certainly the life-safety issues involved are profound. Other industries (automotive, rail) have obtained very reliable bolted joints at high volumes and low cost. Getting to high reliability and low cost should be the goal in the solar PV industry. There is some activity taking place with a UL-2703 working group to examine updates to corrosion testing to allow stronger and lower cost fasteners. A multitude of issues with unanswered questions have yet to be addressed, and progress is currently slow.

Design implications
In the interim, while codes and standards-making committees work to make updates, there is need for stop-gap guidance that can incorporate bolted joint engineering from other industries. Specialized bolted joint engineers should be consulted to provide input if and when a manufacturer chooses to update a product line. Designers need to admit and recognize gaps in codes, standards, and field assembly practices and compensate for those gaps until such time as the industry matures.

Operations implications
Retrofitting bolted joints successfully requires a high degree of specialized engineering knowledge. In some instances, it appears there are structural issues in a racking assembly that lead to over-stressing a bolted joint. Simply retrofitting with a rated (DIN 65151) locking fastener, for example, would not solve the problem.

Given the many thousands of fasteners in a racking system, ignoring fastener loosening and instead deploying maintenance staff to periodically tighten fasteners is extremely expensive. The NREL study *Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience* (Elsworth 2020) estimates a cost of $.045/watt to install a simple but effective wedge locking washer and $.069/watt for the conical spring washers sometimes used together to solve complex bolted joint problems. On a typical 1 megawatt (MW) ground array this could lead to retrofit costs of $45,000 to $114,000 — a large amount.

With the lack of purpose-built vibration resistant bolted joints being the norm in most arrays, much of the existing population of solar arrays needs to be retrofitted. Use of rated (DIN 65151) locking fasteners is inevitable for existing arrays as a retrofit solution to prevent losses. Choice of locking fastener systems to use as an appropriate retrofit solution is complicated and requires careful consideration of different factors. One prime example of the complications involved in retrofit choices center on pre-load loss from soft joint relaxation. With soft joints, given the potential for a high degree of relaxation, a locking fastener that allows some periodic tightening, and thus adjustability, would need to be considered. Soft joint retrofits would most likely preclude thread locking compounds and huck bolts.

5.3.2 Soft joints

Many racking systems utilize tubular (tube) or square stock as the main racking element (Figure 34). When tube stock is used extensively, several types of soft joints may be present in an array, posing serious storm vulnerabilities.

Figure 34. Typical square stock racking element

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. Figure 35 shows a side view of a slip joint, and Figure 36 shows the end profile of a slip joint.

When tubular stock is through-bolted and fastened, the hollow shape will deform easily, causing the loss of pre-load and a resulting loosening. Figure 37 shows a wall of square tube stock deforming when the fastener is pre-loaded.

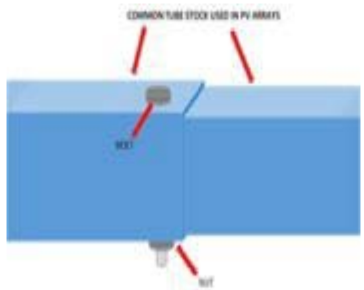
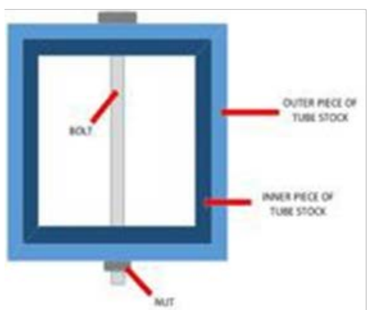


Figure 35. Slide view of a slip joint



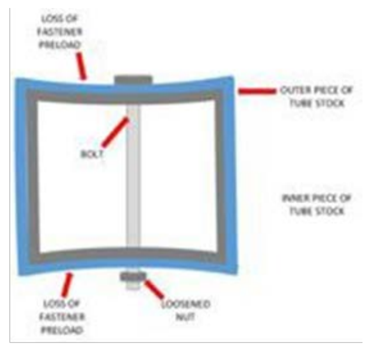


Figure 36. End profile of a stock deforming   **Figure 37. Wall of square tube slip joint**

Once this kind of bolted joint loosens, the fastener can easily disassemble and fall out. In cases where the fastener stays in place, the joint is loose, and the tubular elements will move, elongating the bolt hole and wearing down the bolt shaft, eventually leading to full shear off.

Another common type of soft joint seen in the field, and commonly reported to be an issue, is when a bracket is attached to tubular stock (Figure 38). If the module mounting bracket is attached to tubular stock, this can create a very dangerous situation, where modules are easily liberated from the racking, even in light winds.

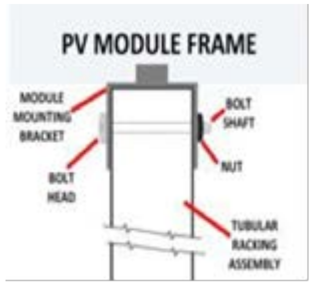


Figure 38. Bracket mounted to square stock

Design implications
Fastening tubular frame elements requires that a special assembly of fasteners be combined to ensure this kind of bolted joint can maintained pre-load after relaxation occurs. One example of a key feature of the fastener used in this kind of joint is a spring-type washer (Figure 39) that can maintain bolt pre-load even after some relaxation. Design of these kinds of fastener assemblies requires the specialized skills of a fastener engineer to ensure success with what is a very challenging application.

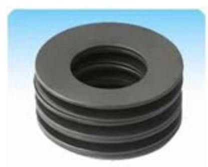


Figure 39. Spring-type washer

Operational implications
A December 2020 phone interview with one large national owner/operator of distributed generation systems revealed that retrofitting soft joints was a big concern with 15 roof arrays totaling over 2 MW. The bolted joint holding the bracket to the frame loosened chronically, causing modules to break free even in light winds. This operator gave an example of five large roof arrays totaling 2.2 MW that were losing modules even in light winds. Two attempts were made to retorque the fasteners (at a cost of $250,000 each event) before then implementing a permanent retrofit fix for $300,000.

Operators should learn to spot conditions with soft joints and not attempt to retighten. Instead, they should seek assistance from a bolted joint engineer to design a retrofit solution.

6. Flooding: Coastal and Flash Flooding

Flooding, like wind, is a damaging element very common to most severe weather events. There are differences in flooding qualities that are tied to the storm type.

For example, hurricanes and northeaster (nor'easter) storms can deliver high levels (tens of feet) of salt-laden coastal flood waters and wind-driven rain containing salt. Adding saltwater to a flood event causes additional levels of damage from corrosion to electronic components and fasteners.

Recovery from inundation with saltwater is highly expensive, likely resulting in the need to conduct a full component replacement versus a simple drying and cleaning. The switchgear is one example of a component that cannot be serviced and reused once exposed to saltwater.

Damage from flood waters range from minor to full loss of all components. Damage done by floods appear to depend on several factors:

1. Depth of water
2. Velocity of water flows through site
3. Presence of salt (saline)
4. Large debris carried by flood waters
5. Silt, mud in suspension with flood waters, and alkalinity
6. Site topology and natural contours channeling water during a flood event

Damage also depends on various design features of the solar system that determine how fragile components are to flood water.

1. Site design features anticipating flooding such as swales and drainage pathways
   A. Features used to channel water away from key components
2. Elevation of balance of system (BOS) components relative to 100- and 500-year flood events
3. Underground pull boxes and conduit designed to anticipate flood and draining plus prevention of unanticipated water flows flooding electrical equipment
4. The National Electrical Manufacturers Association (NEMA) rating of cabinets housing various components with lower ratings

Figure 40 shows a Federal Emergency Management Agency (FEMA) map of frequency of floods by county.

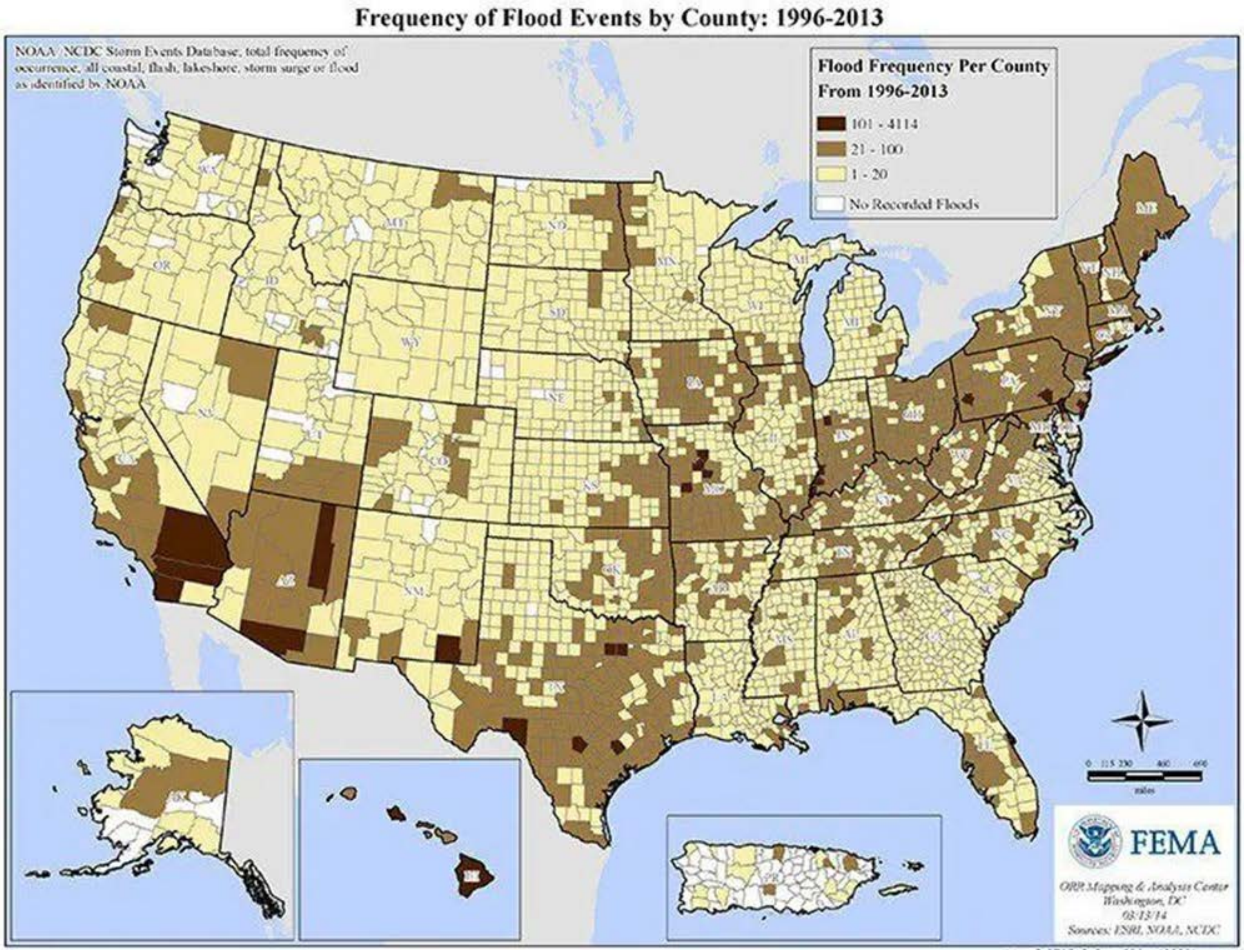


Figure 40. FEMA flood map showing frequency of flood events by county

6.1 Use of Low Cost Flood Plains Is Likely to Increase

While land acquisition in 2018 amounted to about 3.5 percent of total development costs (Fu, Feldman, and Margolis 2018) for most ground array sizes, developers will undoubtedly continue to acquire land in flood zones. Development on flood zones are generally allowed, and some local governments provide basic design guidelines (e.g., Monterey County Water Resources Agency, n.d.).

6.2 Failure Modes: Flooding and Water Inundation

Field inspections identified four types of failure modes due to flooding:

1. Flood water flows through conduit flooding into BOS electrical equipment
2. Inundation of electrical enclosures from wind driven rain
3. Poorly designed site drainage (water scour)
4. Immersion of array components from flooding

6.2.1 Failure mode 1: Water flowing through conduit, flooding balance of system electrical equipment

Field inspections of hurricane damaged ground arrays found incidences where water entered wire pull vaults and then underground conduit, resulting in flooded inverters and electrical switchgear. Underground conduit effectively can act as a drain pipe, delivering high volumes of water into BOS equipment. In one case in St. Croix, U.S. Virgin Islands, the pull vaults located in the array field were at a slightly higher elevation than the BOS equipment; the conduit was sloped toward the gear (Figure 41).

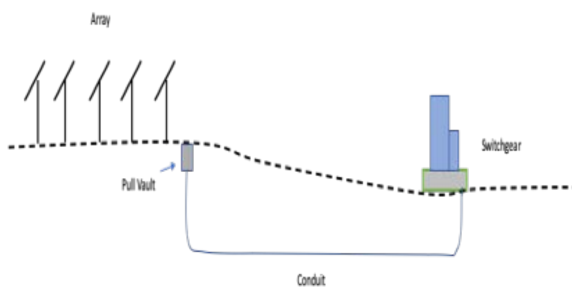


Figure 41. Elevation of BOS equipment in St. Croix array field. Source: G. Robinson, LBNL.

In the St. Croix case inspected by lab staff, they found incidents where frogs had apparently traveled with water flooding conduit into electrical cabinets (Figure 42).

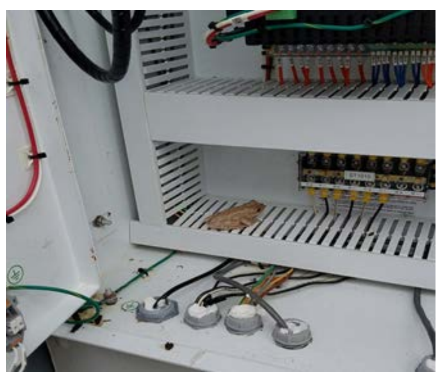


Figure 42. A frog who traveled with water flooding conduit into an electrical cabinet. Source: G. Robinson, LBNL

Conduit and electrical gear flooding can occur from standing water that accumulates during the intense and long duration downpours of a hurricane.

Obviously, coastal flooding would lead to inundated pull boxes, conduit, and electrical equipment.

Design implications

The dynamics of topology, flooding, and standing water areas need to be factored into the electrical design process in order to prevent conduit from providing a pathway for water to travel to BOS electrical equipment. Prevention features built into the wireways should also be considered.

Anticipating water flows from underground pull boxes and conduit should become part of the design process. Since wind pressure acting on the surface of standing water could force water uphill, conduit designs should anticipate water flows even if switchgear is located at a higher elevation than the array field. Building in one-way valves to allow water to drain from pull boxes, adding splice gutters, and other strategies could prevent flooding by interrupting water flows, and should moisture enter a cabinet, allow the water to drain out and not accumulate.

Site civil designs to properly manage surface water also should be utilized as a means to prevent formation of standing water ponding in large areas. Stormwater management features built into a project can handle large surges in water and prevent flooding of wireways and BOS equipment.

Operational implications
To prevent conduit and cabinetry flooding, array fields at higher (or about the same) elevation as the switchgear connected through underground pull boxes should be examined for possible retrofit. The contiguous run of conduit from the array field to the switchgear will likely need to be interrupted to prevent water from flowing to the switchgear. A splice box may need to be retrofitted into the conduit run to prevent flood water from flowing to the cabinetry housing switchgear. The volume of water that could flow through conduit is significant enough to likely overcome the flow volume of drain valves. One solution would be to install a splice box (gutter) above the elevation of the array field and route wiring through it and back to electrical equipment. The same could be done by placing a cabinet nearby to route it through.

Water buildup can occur in these electrical enclosures if they do not have adequate drainage at the bottom through a variety of means, such as installer- or manufacturer-drilled weep holes (holes to drain water) and screen-based knockout plugs.

6.2.2 Failure mode 2: Wind driven rain penetrating electrical cabinetry

Electrical switchgear with mis-specified NEMA ratings (ratings not suited to conditions) was a very commonly found condition. Many cabinets utilized a very simple sticky-backed gasketing material (Figure 43), often poorly installed. Wind-driven rain easily defeats this simple gasketing system, inundating the enclosed equipment with saltwater. The metal gauge of the cabinets was also found to be inadequate to withstand the wind forces. Some electrical cabinets were found with dented sides, or service doors either bent or missing altogether.

Figure 43. Sticky-backed gasketing material

If saltwater enters the electrical cabinets, it is doubtful that this housed equipment can be serviced and reused. The result is likely the need for full replacement.

Design implications

Electrical engineers, when specifying BOS electrical, need to request appropriately rated (NEMA 4 or better) cabinets to house gear. Nearly all manufacturers offer a variety of cabinet choices. While these cabinets are more expensive, this is a bad area to consider for value engineering.

It was noted by lab staff field inspecting solar systems in the Caribbean that cabinets that utilized multi-point door latches that compress service doors against the gasketing did very well compared to the common generic low NEMA rated cabinets. Another commonly seen successful element was a contiguous molded one-piece gasket.

Operational implications

For solar systems that are constructed with equipment cabinets not properly rated for severe weather, operators will need to devise a way to reinforce them to prevent catastrophic loss. Retrofits might include: (1) cabinet replacements/upgrades to a properly specified NEMA rating, (2) installation of a shelter to house the cabinetry that can withstand the weather forces, and (3) use of tarps, lumber, and compression straps to temporarily reinforce cabinetry through the storm.

6.2.3 Failure mode 3: Poorly designed site drainage: water velocity - soil scouring/erosion - undermining of foundations

In some instances, site civil engineering phases appear to have been skipped, perhaps as a first-cost focused savings effort. In these instances, ground arrays lack site features to manage surface water and prevent soil scouring (Figure 44). The result ranges from loss of access to array fields to mudslides to undermined foundations. Not managing site water can also lead to the flooding of underground pull boxes and conduit, as discussed above.

Figure 44. Flooded ground array

Design implications

Skipping civil engineering for ground arrays may reduce first costs, but it will lead to increases in operating period losses and potentially greatly increase the levelized cost of energy. Not only are there risks to the array field, but also to expensive environmental fines when soil migrates offsite onto neighboring properties or even worse, into nearby waterways.

Civil engineering for good stormwater management is a well-developed design field with a set of codes, standards, and practices well suited to array fields.

It is best to combine local knowledge about flooding and water flows with U.S. Geologic Service and Federal Emergency Management (FEMA) data.

Some factors that contribute to increased soil erosion and water runoff around ground mounted PV systems are:

- Compaction of soils during construction
- Removal of topsoil
- Minimal testing of soils and depth to bedrock (incomplete soil profile)
- Construction methods that remove vegetation and topsoil and backfill with gravel or other ground cover
- Long reaches of concentrated water flow that create gullies and rills

Operational implications
Existing sites can be modified by retrofitting them with stormwater management features such as swales and retention ponds. An inexpensive retrofit that would help mitigate the damage from stormwater could be the use of pollinator plants (Figure 45) that have deep root systems that absorb huge volumes of water quickly and protect against soil scouring.

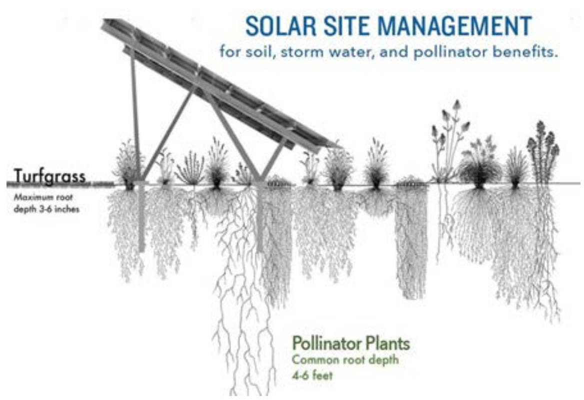


Figure 45. Pollinator planting, offering multi-benefit water management

6.2.4 Failure mode 4: Immersion of electrical components from flooding

Flooding trends indicate that the definition of a 100-year flood level is changing, with increasing depths of flooding. Array design for 100-year flood levels are likely to see those events exceeded during the operating life of a system. Figure 46 shows how the flood depths of a 100-year flood event have increased.

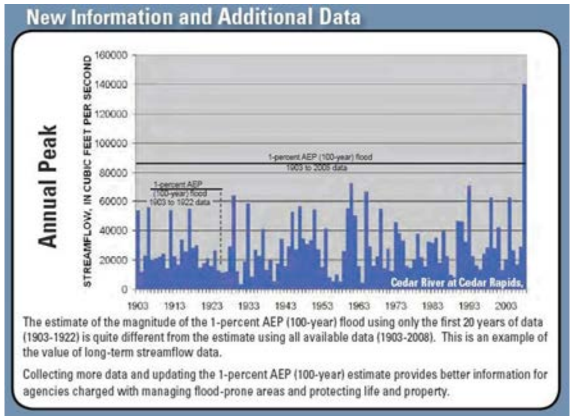
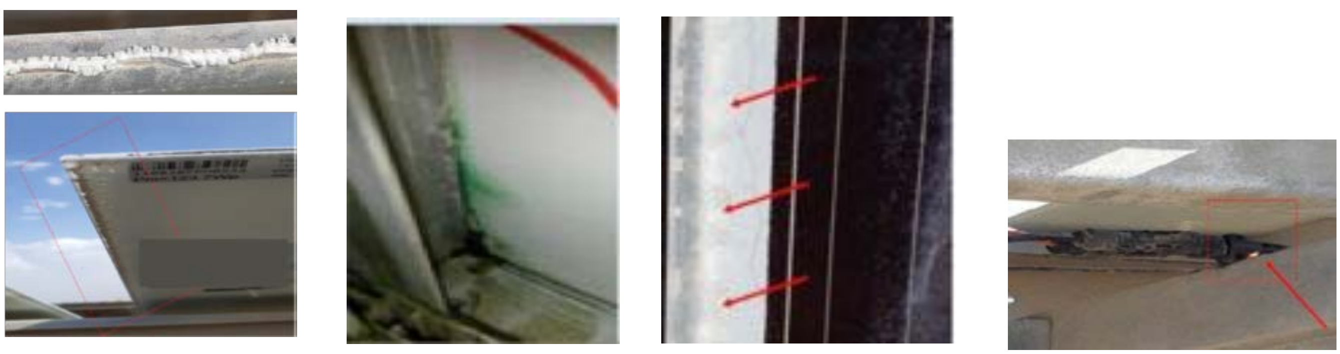


Figure 46. Increases in flood depths of a 100-year flood

Design implications

It is commonly thought that some submerged components of a solar array could survive intact and be put back in service with a simple cleaning. One of those components is the module. A November 25, 2020, *PV Magazine* presentation by Koushik Choudhury, a quality engineer with Dupont, showed the results of some field investigations of flooded modules from India.

Figure 47 shows conditions of modules after submersion, ranging from failed sealants, water ingress, and shorting MC4 connectors.



Failure of sealants | **Moisture ingress on backsheet** | **Moisture ingress on backsheet** | **MC4 Connector - Arcing**

Figure 47. Operational implications

Operational implications

Array components that are submerged will require drying, inspection, and testing before reenergizing. If salt or brackish water was involved, then the task will require extensive cleaning. Equipment inundated by saltwater will likely not be serviceable. Long term monitoring for accelerated depreciation will probably be necessary, as some conditions may not appear immediately.

Dirt buildup and corrosion inside quick connect module wire leads was seen from field inspection of arrays located in the Caribbean after hurricanes Irma and Maria. These wiring devices are rated for hose down and are considered by most designers and operators to be completely sealed to moisture and dirt ingress. Field inspections revealed that moisture and dirt both get past the quick connect O-ring seals. If inspections reveal moisture and dirt ingress on quick-connects, then disassembly, cleaning, and reconnection will be necessary.

Ensure electrical equipment that cannot be wall mounted (i.e., batteries, transformers) are installed on concrete platforms well above the flood plain.

Upgrade outdoor electrical enclosures to NEMA 4R or better. Conduct biannual inspections to determine if any issues have arisen.

6.2.5 Failure mode 5: Coastal corrosion

Design and operational implications

Marine environments with saline laden moisture (such as from coastal rains) can accelerate corrosion of various PV system components. Figure 48 shows corroded system components from a system located near the coast in the tropics. Corroded PV system components have a high probability of failure, and in particular, fasteners lose substantial strength.

Figure 48. Corroded components from rains with high salt content

7. Hurricanes

Hurricanes share weather elements with other storm events; severe wind, flooding, wind-driven rain, lightning, and tornadoes. What makes hurricanes unique among severe weather events is the damaging coastal flooding and wind driven rain containing moisture that is saline and corrosive. Severe sustained winds are unique to hurricanes but are discussed in the wind section above.

7.1 Definition

A hurricane is a tropical cyclone that is a rapidly rotating, organized system of clouds and thunderstorms that starts over tropical waters and has closed, low level circulation around a well-defined center. Once a tropical cyclone reaches sustained winds of 74 mph or higher, it is classified as a hurricane.

7.2 Seasonal Range

The yellow highlighted months significant period of hurricane activity in North America.

Jan	Feb	Mar	Apr	May	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	Dec

7.3 Average Annual Frequency

The average annual frequency for tropical regions in the United States and its territories in tropical climates is listed in Table 2. The table shows multiple strong storms (Category 3 or greater) occurring each year. A single storm can cause significant damage.

Table 2. Average Number of Hurricanes Per Year (Atlantic and Pacific Regions)

Region	Hurricanes (per year)	Category 3 or Greater (per year)
Northern Atlantic	6	2
Eastern Pacific	8	3

7.4 Geographical Range

Hurricanes originate in the North Atlantic Ocean and eastern North Pacific Ocean, as evidenced by Figure 49. Areas along the eastern seaboard and the Hawaiian Islands are particularly susceptible to hurricanes, although the effects of heavy wind, torrential rain, and flooding can be felt many miles inland.

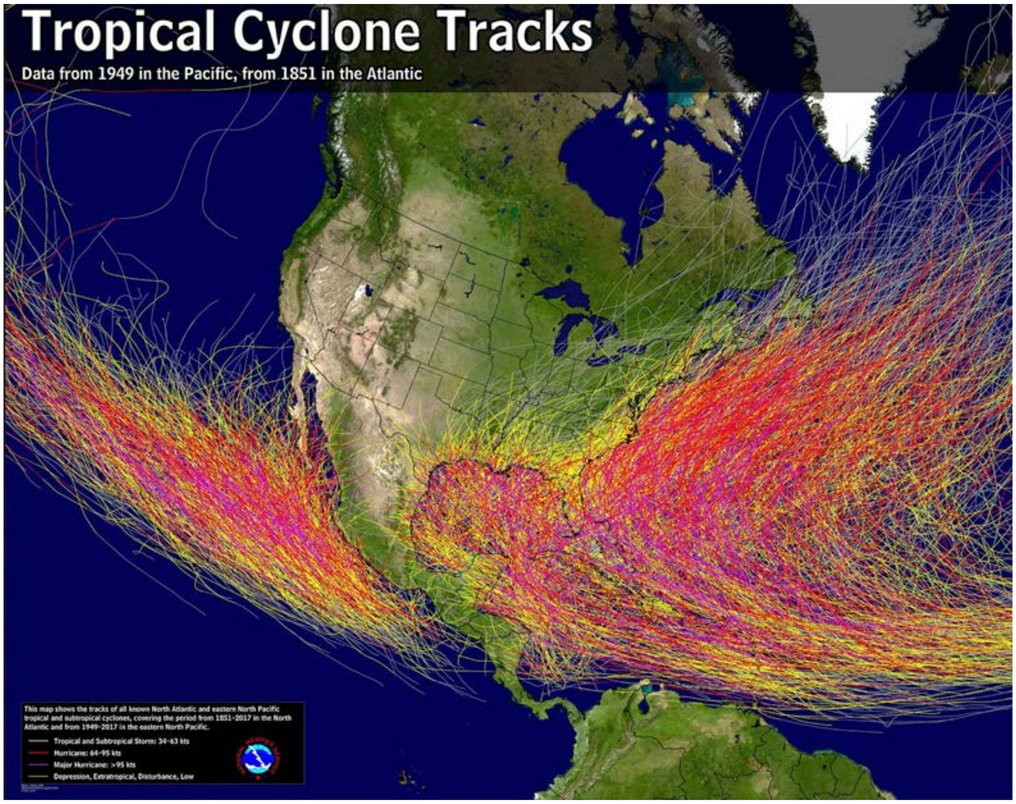


Figure 49. North American Hurricanes - Paths and Intensity. Source: nch.noaa.gov

7.5 Trends

A recent report by the National Oceanic and Atmospheric Administration (NOAA) identified the following future hurricane trends on a global scale:

- An increase in tropical cyclone intensity
- An increase in hurricane intensity (Category 4 and 5)
- An increase of 10 to 15 percent in tropical cyclone precipitation rates
- An increase of 1 to 10 percent in tropical cyclone wind speeds
- A decrease or no change in tropical cyclone frequency (Knutson et al. 2019)
- Tropical cyclone basins are expected to experience these global changes.
- The Northeast Pacific basin, including Hawaii, is projected to see an increase in tropical cyclone frequency.
- The Atlantic basin will see higher precipitation rates and wind speeds.
- Sea level rise will contribute to higher levels of coastal inundation from hurricanes in all regions.

8. Thunderstorms

8.1 Definition

According to the National Severe Storms Laboratory, a thunderstorm is a storm that is created by a cumulonimbus cloud. Although varying in severity, thunderstorms bring a variety of damaging elements such as:

- High winds
- Tornadoes
- Lightning
- Torrential rainfall
- Flash flooding
- Hail

A "severe" thunderstorm is categorized as a thunderstorm that has one of more of the following conditions: hail one inch or greater, winds gusting in excess of 58 mph, or a tornado. Damage from severe thunderstorm winds is more common than from tornadoes, and accounts for almost half of the severe weather reports in the lower 48 states.

8.2 Seasonal Range

Jan	Feb	Mar	Apr	May	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	Dec

8.3 Life Cycle and Development Stages of Thunderstorms

Thunderstorms can bring significant amounts of rainfall, heavy winds, lightning, and if severe enough, hail and tornadoes. PV system owners and operators must be aware that at the end of a thunderstorm, rainfall will decrease but lightning can still pose a threat. It is critical that system owners and operators that come out to inspect a PV system after a thunderstorm are careful to protect themselves from any after storm effects.

8.4 Wind Characteristics of Thunderstorms

Winds from severe thunderstorms come in two forms:

1. Strong wind gusts greater than 57.5 mph.
2. Straight-line downbursts, such as those seen with derecho systems (Figure 50).

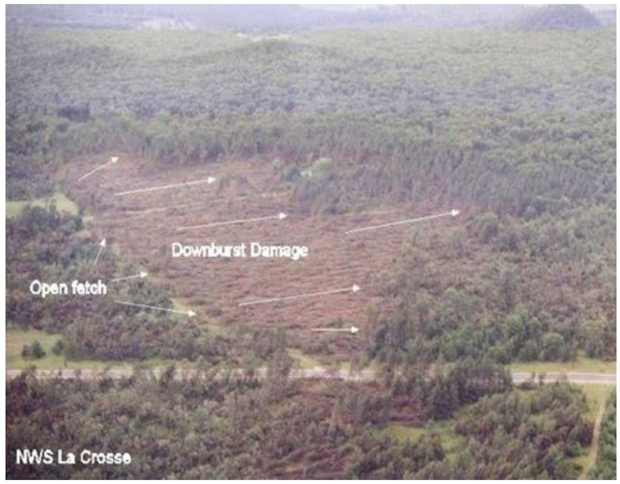


Figure 50. Derecho straight-line downburst

Three types of strong wind gusts result from a thunderstorm:

- **Straight line winds.** These are winds linked to thunderstorms that have enough strength to cause damage. Debris from straight line winds are usually blown in one direction away from the site affected by the winds.
- **Downburst.** This is stronger than average downdraft from a thunderstorm. The two types are microbursts and macrobursts, with the latter having winds similar to EF-3 tornadoes, sometimes making it difficult to determine how the damage was caused.
- **Derecho.** This is a widespread, rapidly moving windstorm that occurs simultaneously with thunderstorms and can have wind gusts exceeding 57.5 mph. In August 2020, a 700-mile wide derecho hit the midwestern United States, bringing heavy winds and rainfall, and causing significant damage to many areas. Figures 51 and 52 show a severely damaged PV system in Grand Rapids, Iowa — one of the cities hardest hit from the derecho.

Figure 51. A severely damaged PV system in Bronx, New York

Figure 52. A severely damaged PV system in Grand Rapids, Iowa

9. Hail

9.1 Definition

Hail is the results of strong updrafts in cumulonimbus clouds and is comprised of lumps of frozen precipitation (hailstones) fused together to form a larger frozen lumpy ball. Hail is not to be confused with frozen rain (sleet), which is the result of winter weather events. Sleet and frozen rain lack the size and mass necessary to cause damage to solar modules.

Really, hail events with balls large enough (severe) to cause damage to solar modules should be a concern. For a definition of what is "severe" for solar modules, the two testing standards discussed below define severe as hail balls greater than 2" in diameter.

9.2 Seasonal Range

In regions that experience significant hail events (Figure 53) the season is long, starting in late winter and extending into the fall.

Jan	Feb	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	Dec

9.3 Average Annual Frequency

In locations where hail is common, it can occur 7–9 days per year (Figure 53).

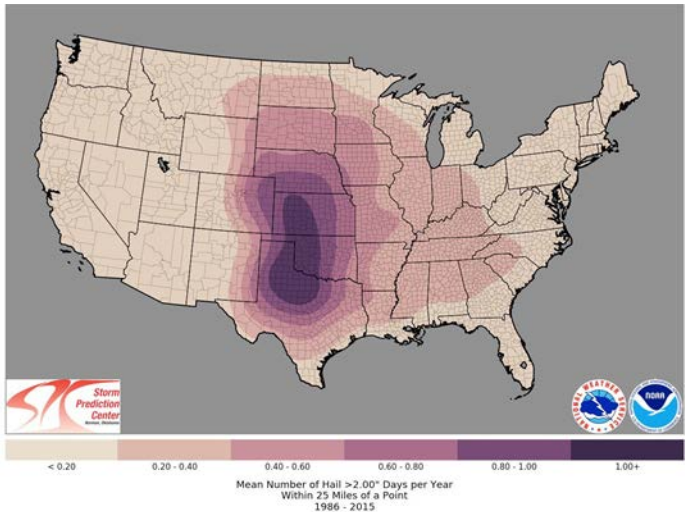


Figure 53. Mean number of days per year with hail > 2.00 inches

9.4 Geographical Range

Colorado, Wyoming, and Nebraska are known to have the most hailstorms, averaging seven to nine hail days per year in the area where the three states meet. Texas also gets a lot of hail, and hail can occur occasionally almost anywhere.

Hail has been found to fall in paths known as *hail swaths.* Hail swaths can range in size from a few acres to 10 miles wide and 100 miles long.

9.5 Trends

Research supports the anecdotal observations that the frequency and severity of hail (size and mass of hail balls) is increasing in some regions of the country. There is indication that incidents of severe events are spreading eastward as well. A study in *Nature* (Tang et al. 2019) over the years 1979 to 2017 showed an increase in days and regions with environmental conditions favorable to large hail (≤ 5 cm) formation. The study found also an increase in area and a trend showing a shift eastward, meaning more solar assets may become exposed to severe hail events.

9.6 Life-cycle of a Hail Event

Hail events are a result of severe thunderstorms. Since hail is such a prominent damaging element, it is addressed separately from the storms that cause it.

Hail is a type of precipitation that forms when raindrops are carried upward by an updraft into cold air masses and freeze. The size of hailstones grows as successive layers of water freeze. Hail will fall from the atmosphere when it becomes too heavy for the updraft to support its weight. Most hailstones are less than 1 inch in diameter but the largest hailstone in the United States fell in South Dakota in 2010, measured 25 cm (10 inches) across, and weighed 1 kg (2 lbs). There have been more than 10 storms reported with hail measuring more than 6 inches in diameter (Zdanowicz 2020). Common are severe thunderstorms that produce 2 inch diameter and greater hailstones, as seen in the NOAA Storm Prediction Center map (Figure 54).

Figure 54. Hail zones in the United States

There is uncertainty about the speed at which hail falls. This is because fall speeds are largely dependent on the following conditions:

1. Hailstone size
2. Friction between the hailstone and the surrounding air
3. Local wind conditions (vertical and horizontal)
4. Degree of melting of the hailstone

9.7 Impacts of Hail on PV System Hardware

Codes and Standards Implications

ASTM E 1038-93 “Test Method for Determining Resistance of PV Modules to Hail by Impact with Propelled Ice Balls” involves 1 inch simulated hailstones striking a module at 55 mph at the corner, edge, and middle of the module. In IEC 62215 simulated hailstones from 12.5 mm (0.5 inch) to 75 mm (3 inch) diameter are propelled from 16 to 39.5 meters per second (m/s). The UL 1703 standard drops a two-inch solid steel sphere from a height of 51 inches onto the surface of the PV module, and UL 61703 involves firing 25-millimeter (approximately one-inch) ice balls from a pneumatic cannon and measuring the resulting electrical performance degradation. Given increasing incidents of very severe hail events with large diameter hail balls, the current group of testing standards are thought to be outdated. During a November 17, 2020, *PV Magazine* Roundtable event, Daniel Chang, Vice President of Business Development of the RETC stated that of all the modules tested at his facility, none failed the existing hail tests. Given this result, RETC has developed a hail test methodology called the *hail durability test* (HDT). RETC promotes HDT as more indicative of severe hail events and a more comprehensive look at the variety of impacts that can occur to a module from hail impacts. The HDT test uses a 2 inch diameter hail ball and examines glass breakage, cell cracking, and performance degradation.

Because they are exposed to the sky, PV modules are the target of hail damage. For framed modules, damage is apparent as broken glass, and unframed modules may liberate chips and chards of glass (Figure 55). But damage may not be ascertained from visual inspection alone; the impact from hailstones might cause cracks in the underlying PV cell itself without necessarily breaking the cover glass, and this type of damage could be evaluated using IR (infrared) or EL (electroluminescent) methods.

Due to the point impact of hailstones, cracks propagate in a radial pattern from the impact site. This is more damaging than the parallel cracks that occur when bending a module because they are more likely to isolate chips from bus bars, preventing current flow.

Hail also can damage other components such as wire ties, non-metallic boxes or conduit, and other components such as instruments.

A PV module may withstand many hailstones without damage, but after one hailstone causes breakage, each successive hailstone causes further damage.

Figure 55. Unframed modules may liberate chips and shards of PV module material during a hailstorm (Photo by Andy Walker).

9.7.1 Design implications

There are a number of design implications for PV systems built in hail-prone regions. These primarily focus on tilt, orientation, thickness and type of glass, framed modules, and thin-film modules.

Tilt: PV modules in steep tilt angles have suffered less hail breakage than modules mounted in more horizontal orientations. During a *PV Magazine* Roundtable event held on November 25, 2020, Alex Roddell of Nextracker discussed the positive results from tests showing that tilt angles significantly reduced hail damage (Roddell 2020). Similarly, tracking systems may avoid some damage by driving the modules to a steep position; although hailstorms often occur during thunderstorms and high winds, which may limit this strategy. Low tilt angles are preferred for reduced inter-row shading and wind load, as well as lower rack cost, but a design might consider avoiding hail damage among the benefits of a steeper orientation.

Orientation: In many locations hail blows in from a certain direction. Since hail is associated with storms, the PV module orientation facing in the direction of the oncoming hailstorm will suffer the most severe damage. Hailstorms in the West generally move from the southwest toward the northeast, but this can vary, and large, potentially damaging hail most often falls nearly straight down. Unfortunately, south and even southwest are the best orientations for a PV array. Still, other factors being equal, a designer may prefer a southeast orientation to a southwest orientation to reduce hail damage.

Thickness and type of glass: Tempered glass used as cover sheets in PV modules may be as thick as 4 mm, but efforts to reduce cost and weight and to increase efficiency have resulted in glass as thin as 2.0 mm on some. The thinner glass used in large format and or bifacial modules cannot be tempered, and is instead heat treated strengthened, which results in a less durable glass. Thicker, strong tempered glass may reduce breakage due to hail. While PV modules that pass the hail tests of IEC61730, IEC61215, and UL1307 typically use tempered glass, manufacturing techniques prevent tempered glass in some module types.

Framed modules: Anecdotally, chips and chards of module material may be liberated from unframed glass PV modules (Figure 55) during hail breakage, whereas with some exceptions, glass of framed modules tends to stay in the frame (Figure 56). Framed modules are likely to contain materials and present less of a cleanup issue post hail damage.

Figure 56. Breakage of one large hailstone allows smaller ones to break the glass weakened by cracks, but the PV module material stays in the frame. Photo by Andy Walker

Thin-film modules: Manufacturers of some thin-film modules point out that the films are flexible and therefore do not crack in the way that crystalline cells do, and that the small dimensions of each thin-film PV cell sequester the damage. Module manufacturer First Solar claims a “hail proof” module (First Solar. n.d.).

Choosing a module for locations with severe hail risks: Since module test labs have found existing IEC test standards to be insufficient, specifiers should use tests offered by the independent labs. Two such tests are the RETC’s Hail Durability Test (HDT), and PVEL’s annual reliability scorecard, which now includes a hail test.

9.7.2 Operational implications

Inspect PV systems following a hailstorm and evaluate their condition against industry best practices and relevant technical specifications such as NFPA70, the NEC, IEEE C2 NESC, IEC 61730, UL 1703, and especially E1799-08 ASTM International “Standard Practice for Visual Inspection of Photovoltaic Modules” and IEC 61215-1 Clause 8 for major visual defects. The imperative for operations is to ensure that the system is physically and electrically safe following hail damage. With thousands of cells connected module-to-module, any module with exposed circuitry presents an electrical hazard. Physical hazards may include sharp pieces of glass, pieces of module laminate falling from carport systems, or pieces that could become airborne in high wind.

Disconnect circuits with arc- or ground-fault hazards and rope off areas with physical hazards. Perform electrical testing of the system grounding and conductor integrity per E1462 ASTM “Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules.” Record deficiencies and identify scopes of work for necessary repairs.

As much as possible, clean up broken glass from the ground and roof areas affected.

9.7.3 Operational implications: Recovery following a hailstorm

An approach to recovery following a hailstorm proceeds from the least to the most expensive, with insurance coverages and limits informing the options:

1. Assessing condition after a hail strike. Some of the nationally recognized test labs (NRTLs) active in testing modules and other components offer an assessment service using IR, EL, or UV fluorescence examinations to give owners needed insight for decision making. The assessment from a skilled imaging professional can inform system owners on minimum component replacement needs, thereby reducing the costs of recovery.
2. Option 1: If only a few modules are broken, consider replacement. Based on the low average dollar value of the insurance claims, this seems to be a very common solution, and it has been employed in thousands of systems.
3. Option 2: Remove damaged modules and consolidate good modules into a downsized array, or fewer arrays. Consider the electrical compatibility (voltage) of new module strings added to restore capacity.
4. Option 3: Remove all modules and replace them with an entirely new DC plant. Because of the labor cost of disassembly, handling, and reassembling modules, as well as contractual and liability considerations, many badly hailstorm damaged systems (more than one-third of the modules broken) are disposed of and replaced with new arrays ("totaled" in insurance parlance).

9.7.4 Case study: Fort Carson, Colorado, August 6, 2018

On August 6, 2018, a hailstorm with hailstones recorded at 1" diameter cut through Fort Carson, Colorado (Figure 57). Witnesses say they could see the "swath" in which the hail was falling, sparing PV systems outside this path. Nine PV systems were damaged by the hail. On one building 7 percent of the modules were visibly broken and another 15 percent showed hot spots on infrared images; on another building 89 percent of the modules were broken. Overall, 13 percent of the modules were visibly broken. On most of the buildings, the modules that were not visibly broken were also found to not be damaged when viewed with infrared image or I-V curve testing. The original power rating of the nine systems was 883 kilowatts (kW). Through an optimal combination of replacing broken modules and cannibalizing arrays into smaller systems, the power could be restored to 797 kW at a cost of $595,000, or $0.75/watt.

Figure 57. Hail damage to an array in Fort Carson, Colorado, caused by hailstones on the order of 2.75 cm diameter that fell on August 6, 2018.

10. Lightning

10.1 Definition

Lightning is a short duration electrostatic discharge between cloud and ground that temporarily neutralizes charge buildup. A single cloud-to-ground lightning strike is a very high voltage discharge possessing, on average, a gigajoule of energy.

10.2 Seasonal Range: North America

Regions that experience thunderstorms typically see them during the spring and summer months in the afternoon and evening hours (Insurance Information Institute, n.d.).

Jan	Feb	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sept**	**Oct**	Nov	Dec

10.3 Average Annual Frequency

The United States experiences approximately 100,000 thunderstorms every year, of which 10 percent are considered “severe thunderstorms,” meaning they have winds greater than 58 mph (National Weather Service, n.d.).

10.4 Geographical Location

Lightning occurs in every part of the United States; lightning flashes in the United States generally increase farther southeast. Florida, for example, gets more lightning flashes than any other state and averages about 59 lightning bolts per square kilometer per year.

10.5 Life Cycle of a Lightning Event

Lightning occurs most frequently during thunderstorms. A charge can build in the clouds during a thunderstorm. If a large enough charge builds up, it can neutralize through a lightning bolt between the cloud and the ground (National Severe Storms Laboratory, n.d.). A bolt can carry 300 million volts and about 30,000 amps.

10.6 Impacts of Lightning on PV System Hardware

Lightning is the main cause of PV system electrical failures (Northern Arizona Wind and Sun, n.d.).

Solar PV installations are conductive and grounded, and can cover large surface areas. As a result, they are susceptible to lightning strikes. With about 25 million lightning strikes per year in the United States (each of which is able to transmit more energy than a nuclear reactor), PV systems will inevitably be struck and sometimes damaged. Data on lightning damaged solar arrays can be seen in Section 1.1. The insurance data in Section 1.1 show widely varying insurance claims from lighting from year to year.

The likelihood of a PV system being struck by lightning depends on the actual size of the array, the surrounding structures and natural features, and the lightning flash density (Figure 58).

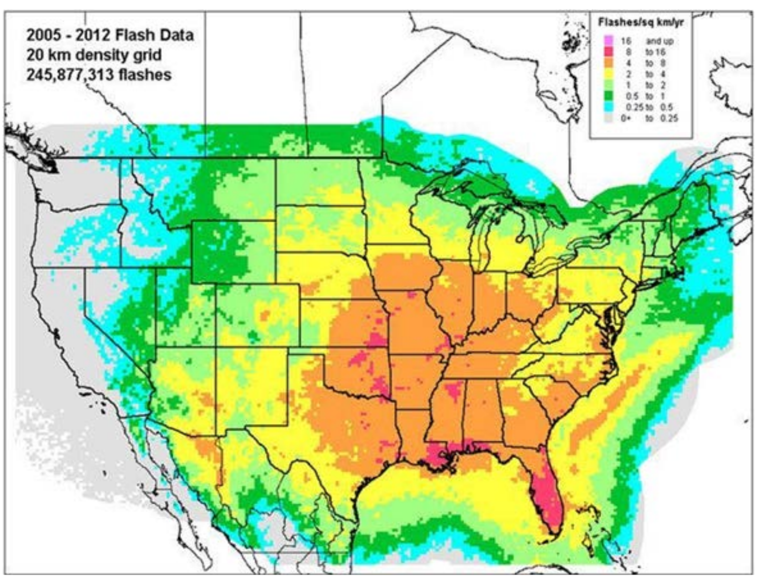


Figure 58. Lightning flash density in the continental United States. Source: Holle 2014.

Lightning can strike a PV system directly or indirectly (striking nearby and transmitting a surge through conducting materials and inducing a charge on system components).

Direct strikes can damage the modules themselves and any equipment that lightning strikes, often causing enough damage to lead to system downtime. These direct strikes can produce momentary voltages of over 75 kilovolts (kV) and can lead to explosive damage (Figure 59).

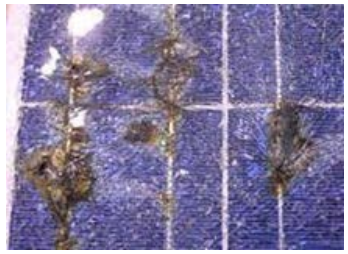


Figure 59. The result of a direct strike on a solar module. Image: Pickerel (2015).

Indirect strikes are more common. They can carry voltages of more than 25 kV and are more likely to damage system electrical components: inverters, transformers, and control circuits, for example (Bushong 2016).

10.6.1 Codes and standards implications

All components of solar PV systems are required to have a continuous ground fault current path per the National Electric Code Sections 90.3 and 690.41. This continuous grounding path will protect human safety and decrease the chance of electrical equipment damage in the event of a lightning strike on an array. A part of properly grounding a system involves soil resistivity testing and measurement.

Beyond this, lightning protection or mitigation systems are not required on PV systems and are installed at the discretion of the site developer, such as the Franklin rod shown in Figure 60 (Bushong 2016).

Figure 60. Example Franklin Rod. Image: Pickerel (2015).

10.6.2 Design implications

The decision on whether to add lightning protection beyond a continuous grounding pathway is the developer’s choice. One method to protect electrical components of an array is to use surge protection devices (SPDs) (Figure 61). These systems protect induced over-voltage to the system. They should be installed on both the AC and DC sides of the system, as well as on the input and output of the inverter, to be most effective (Bushong 2016; Pickerel 2015).

Supplement SA of UL 1449 provides the standard for surge protective devices (Pickerel 2015) and standard IEC 60364-7-712 recommends the use of surge protection systems.

Figure 61. An SPD system installed in a combiner box. Source: Zipp 2018.

Some solar developers may also wish to protect their arrays with technologies that aim to prevent lightning strikes altogether, though this is not common practice. The simplest of these is a traditional Franklin rod, which aims to prevent lightning by providing a grounded path through which charge can slowly dissipate, thus reducing the potential difference between the clouds and the earth and decreasing the likelihood of lightning. The efficacy of Franklin rods is uncertain, however, and they can face issues related to shading, cost, and appearance.

More complex lightning mitigation systems exist, including charge dissipation terminals and early stream emitter lightning air terminals (Figure 62). Both aim to prevent lightning over a large area.

Figure 62. Charge dissipation terminals and early stream emitter lightning air terminals

Figure 63 shows an early stream emitter lightning rod. This technology allows a discharge to occur between ground and cloud earlier than a single rod. This early discharge has lower potential energy and damage potential.

Figure 63. An early stream emitter lightning rod. Source: Aplicaciones Tecnológicas, n.d.

While installation of lightning protection systems on PV systems is voluntary, several resources exist, including the national fire protection association NFPA 780, Chapter 12 and the International Electrotechnical Commission (IEC-62305) standards (which have guidelines for roof mounted PV), and the National French standard NFC 17-102.

10.6.3 Operational implications

Ensure the continuous grounding path is maintained by regularly testing it. Also check that any installed mitigation equipment is functioning properly.

10.6.4 Maintenance/repair

Repair after a lightning strike involves replacing damaged parts. This can lead to system downtime or decreased production. Workers should take extra care after a lightning event that may have caused disruption to the electrical or grounding systems (Bushong 2016; Solar Power World 2016; Jim Grasty, personal communication).

Case Study: A recent example of a lightning strike
A solar array at Hill Air Force Base in Utah received extensive damage after a lightning strike and needed to be fully rebuilt. The damaged array was replaced with a 3.55 MW array that included lightning protection. Additionally, the project increased the base's resilience and is projected to save $3.2 million, which led to a 2019 Federal Energy and Water Management Award from the U.S. Department of Energy.

11. Tornado

11.1 Definition

A tornado is a narrow, violently rotating column of air that extends from the base of a thunderstorm to the ground. They are difficult to see unless they form a condensation funnel of water, dust, and debris. Tornadoes are considered to have the most violent conditions of all the atmospheric storms.

11.1.1 Resulting elements

Two main damaging elements resulting from tornadoes are discussed here: high winds and airborne debris. Wind driven rain was discussed above.

11.2 Seasonal Range

The Southern Plains region experiences the most tornadoes between May and early June, while the Northern Plains region and upper Midwest experience tornadoes between June and July. Collectively, these two regions are known as “Tornado Alley.” The Gulf Coast region, known as “Dixie Alley,” sees a consistent number of tornadoes year-round because of frequent thunderstorms, hurricanes, and other tropical storms. However, tornadoes can occur at any time of the year in the United States. More information on monthly and region-specific tornado occurrences can be found on NOAA’s U.S. Tornado Climatology webpage.

11.3 Average Annual Frequency

An average of 1,200 tornadoes strike the United States every year, and they vary in intensity. It is important to note that tornado spotting and reporting techniques have changed over the last several decades, ever since official records started being kept in 1950. This led many to believe that we do not know the actual annual average of tornadoes. Figure 64 provides a look at the average annual number of tornadoes over a 19-year span. More information from NOAA can be found on the average number of tornadoes that occur per month in the United States.

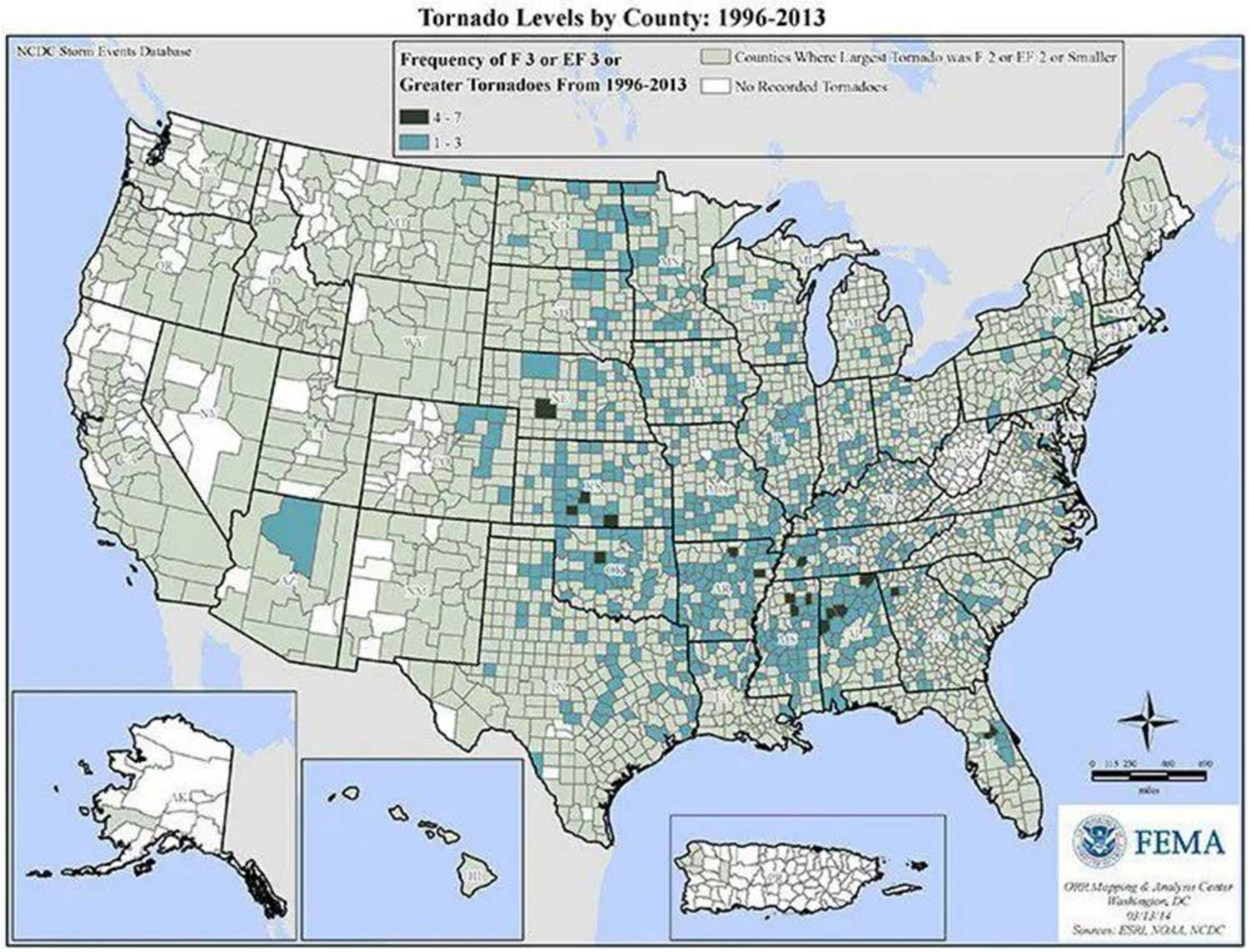


Figure 64. Tornado levels by county

Of all the tornadoes in the United States, approximately 77 percent are classified as EF-0 or EF-1, and 95 percent are below EF-3 intensity. Of the 5 percent of tornadoes that are EF-3 or higher, only 0.1 percent of those reach an EF-5 level which, as discussed earlier, sees winds in excess of 200 mph and almost total destruction.

11.4 Geographical Location

As mentioned earlier, the two regions of the United States that experience a high frequency of tornadoes compared to the rest of the country are the Gulf Coast and the Central United States. The Gulf Coast region (Dixie Alley) experiences a high number of tornadoes because of a high frequency of thunderstorms. Convective storms in rain bands of hurricanes and tropical storms can produce tornadoes (i.e., waterspouts) when they move onshore. However, tropical tornadoes are usually weaker than non-tropical tornadoes.

The other region that experiences a high frequency of tornadoes is “Tornado Alley” in the Central United States. While the boundaries of Tornado Alley can vary based on frequency, intensity, or tornadoes per unit area, Figure 65 shows the areas that are commonly included.

Figure 65. Tornado, Dixie, Hoosier, and Carolina Alleys

11.5 Trends

Similar to the changes in severe thunderstorm detection, verification, and data collection, it is difficult for experts to identify observable trends in tornadoes. Since 1954, reports from weak tornadoes (F0) have increased; however, there has been no observed change in the frequency of F1 or stronger tornadoes.

Since the late 1950s, the United States has experienced a decrease in the number of days per year when tornadoes occur. At the same time, there has been an increase in the number of days per year when more than 30 tornadoes have occurred (known as *tornado outbreaks*). Figure 66 illustrates these trends.

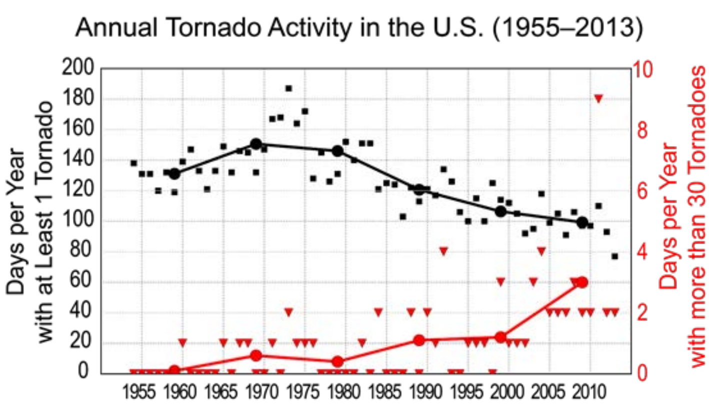


Figure 66. U.S. tornado trends since 1950

There has been no measured increase in the mean annual number of tornadoes, excluding the weakest tornadoes (EF-0 or less). Although tornadoes are observed in all months, there has been a noticeable trend of earlier calendar start dates to high tornado activity, and in general, more volatility in tornado occurrence.

11.6 Life Cycle of Tornadoes

11.6.1 Required conditions for a tornado to form

According to the National Severe Storm's Laboratory, the exact cause of a tornado is not fully understood. The most devastating tornadoes, rated at EF-3 or higher, spawn from supercells, the most destructive of all thunderstorms, but the theories on how this happens are not universally accepted.

11.6.2 Physical structure

There are a number of characteristics that tornado watchers look for when identifying a tornado's physical structure. The *condensation funnel* is composed of water droplets and must make contact with the ground when extending down from a thunderstorm in order or it to qualify as a tornado. Dust and debris are the other common components that confirm a tornado's presence to tornado watchers. The other indicators of a tornado's presence include inflow bands, beavers' tails, wall clouds, rain-free bases, and rear flank downdrafts. For more information on these, visit the website of NOAA's National Severe Storms Laboratory on tornado basics.

Detailed information on travel distance and ground time is not available. Therefore, the Enhanced Fujita Scale will be discussed to highlight how tornadoes are measured.

11.6.3 Types of tornadoes

There are two types of tornadoes: (1) a *supercell* (mesocyclone is 2 to 6 miles in diameter and much larger than the tornado within it), and (2) a *non-supercell,* where tornadoes are produced by much more localized storm systems.

11.6.4 Wind characteristics

Tornado strength is determined by the Enhanced Fujita (EF) scale, which measures the damage caused and can therefore determine wind speeds of the tornado. The EF Scale includes 28 damage indicators (i.e., building types, trees) with eight degrees of damage for each indicator, ranging from initial visible damage to total destruction. Wind speeds are estimated in three-second gusts. Table 3 shows the EF Scale, with wind speed ranges and types of damage.

Table 3. Enhanced Fujita Scale

Category	Winds (mph)	Damage
EF-0	65–85	Light
EF-1	86–110	Moderate
EF-2	111–135	Considerable
EF-3	136–165	Severe
EF-4	166–200	Devastating
EF-5	>200	Incredible

11.7 Impacts of Tornadoes on PV System Hardware

11.7.1 Design implications

Tornado damage can be grouped into two categories: (1) direct, from the funnel path, and (2) indirect, from airborne debris strikes. Tornadoes leave a very defined path (Figure 67) of destruction through a solar array, with the remainder of the array mostly undamaged.

Figure 67. Tornado path

Damage patterns with tornadoes show total loss within the funnel and partial loss within the indirect debris impact zone. Total loss within the funnel appears with even low grade tornadoes (EF-1), indicating a clear force majeure event for any tornado path through an array field. Roof and carport solar systems would likely experience total loss of the entire array.

Efforts to design a ground solar array to withstand a direct hit by the funnel would likely not yield any benefit. The general design approach should be one of "harm reduction" by reducing the likelihood of flying debris (mostly liberated modules) from measures such as through-bolting modules to mounting rails.

11.7.2 Operational implications

If an existing array suffers a direct strike from a tornado, a full audit and assessment of the solar system will need to be conducted to determine damaged, unusable components from reusable hardware.

12. Winter Storms

12.1 Definition

Any number of winter season storms produce frozen precipitation (snow, freezing rain-ice, sleet) that accumulates. Winter storms can come with our without high winds.

12.2 Seasonal range

Winter storms generally occur between November and March, although they sometimes happen outside of this seasonal range. Yellow is used to highlight active winter season.

Jan	**Feb**	**Mar**	**Apr**	**May**	June	July	Aug	Sept	Oct	**Nov**	**Dec**

12.2.1 Life cycle of a winter storm

A winter storm is an event where the main types of precipitation are snow, sleet, or freezing rain. There are many different types of winter storms, including blizzards, ice storms, lake effect storms, and snow squalls.

12.2.2 Resulting elements

Winter storms have some similarities and key differences, but overall the elements that may damage a PV system from any of them could include:

- Heavy winds, in excess of 35 mph
- Snow accumulation
- Ice accumulation
- Subfreezing temperatures
- Low visibility

12.3 Average Annual Frequency

The Northeast, Alaska, the area around Lake Superior, and mountainous regions see the most frequent winter storms overall (Figure 68).

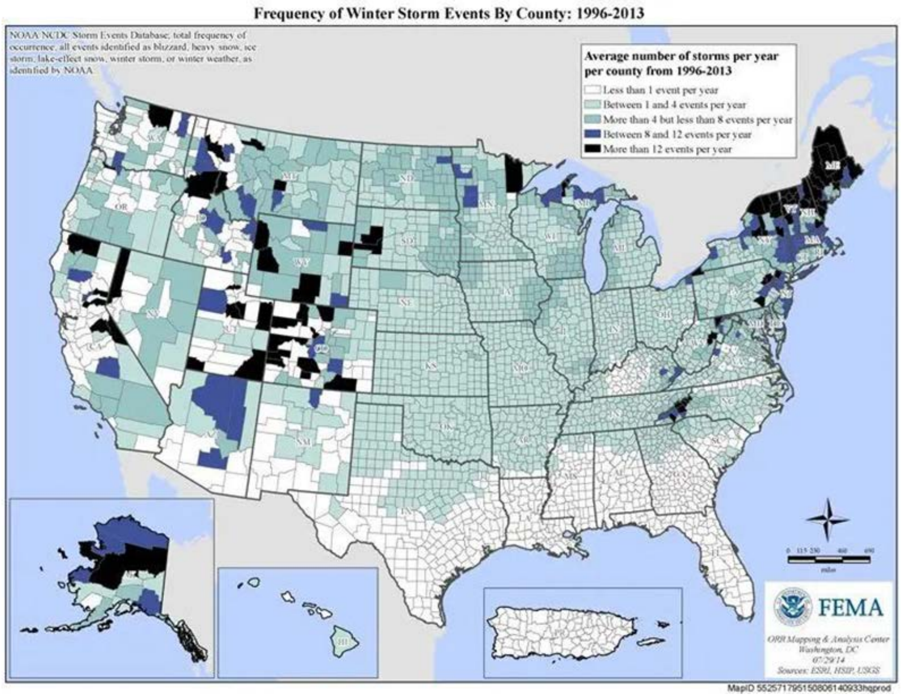


Figure 68. Frequency of winter storm events by county

12.4 Geographical Location

The variations of winter storms in the United States are based on combinations of local geography and atmospheric conditions. In the Mid-Atlantic Coast to New England Nor'easter-blizzard conditions and ice storms can lead to heavy snow. In contrast, the Gulf Coast and Southeast regions typically do not experience winter storms. The Midwest and Plains states can experience high winds during blizzards, and the Great Lakes region can see large snow accumulations from lake-effect storms and snow squalls. In the Rockies to the West Coast, moisture pulled from the Pacific Ocean rises in the mountains and drops heavy snow. Wind speeds can reach up to 100 mph, causing blizzards.

12.5 Impacts of Winter Storms on PV System Hardware

Heavy snow, cold temperatures, freeze-thaw cycles, ice, and wind from winter storms all can lead to PV system damage, as the different materials comprising a module have varying coefficients of expansion. This can lead to separation of layers, which under wind stresses is accelerated.

12.6 Design Implications

The calculation of snow loads affecting structures is covered by ASCE 7. Loading effects on a module are covered in IEC 62938:2020, which "provides a method for determining how well a framed PV module performs mechanically under the influence of inclined non-uniform snow loads."

12.6.1 Minimum loading strengths of modules

PV modules shall be tested per ASTM E1830-15 which prescribes test parameters for loading (snow and wind) of solar modules (front and back). The test also covers several other stress factors relevant to high winds such as the "twist test."

Table 4 below provides an example of modules with high front and back pressure ratings. These ratings can be used to require higher strength modules if accumulations of large amounts of ice and snow are a concern.

Table 4. Minimum Recommended Front and Back Pressure Ratings

Minimum Loading Strength of Modules		
Module Side	**Pascals (Pa)**	**Pounds per square foot (psf)**
Front Load (Push, snow) Rating	6,000	125
Back Load (Pull) Rating	5,400	113

Snow accumulation often can lead to uneven accumulation on modules, with more snow on the lower portion of the module, rather than the load being evenly distributed across the panel. This can lead to module or frame failure from less total snow accumulation than a standard test would indicate. One test, developed by TUV Rheinland, is more representative of this scenario. In this test, called the *inhomogeneous mechanical loading* (IML) test (Figures 69 and 70), weights provide uneven force across a tilted module, imparting more force on the lower side of the module (Pickerel 2016). This test is performed after 240 hours of freezing conditions to simulate winter conditions.

Figure 69. Simulating non-uniform snow/ice loading on module

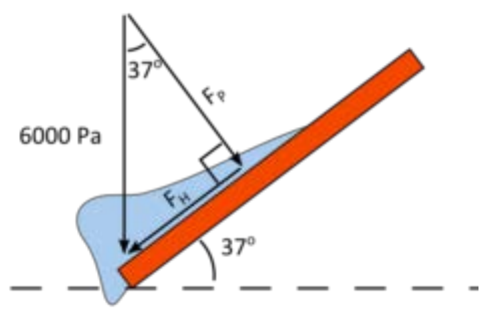


Figure 70. Force diagram on loaded module

Passing this test is voluntary for module manufacturers at this point, but it could be advantageous to require it in snowy regions.

Choosing modules with high front load ratings or modules that have passed the 6,000 Pa IML test will help limit or mitigate damage from snow loads.

Modules should be tilted in a southerly direction in all U.S. locations, with a slope of at least 5 degrees to allow for washing dirt off panels. Locations that receive significant snow should be sloped at least 15 degrees so snow slides off the panels; the steeper the slope, the better the snow will slide off (Figure 71). A space should be provided below the modules for the snow to slide off. For ground mounted arrays the space between the bottom of the module and the ground should be at least two feet (this also helps with vegetation control), or even more in areas prone to extreme snow.

Using frameless modules has advantages in snowy climates, as well. Snow can more easily slide off frameless modules (Figure 71), and there is no risk of damage to the frame (see the Mount Rainier case study below).

Figure 71. Frameless modules in the foreground and framed modules in the background: Both at a high tilt angle to allow snow to slide off. Source: DOE 2017.

Panels in roof mounted arrays should extend to near the bottom of the roof to allow for snow to slide off, but be careful of where the snow slides, since snow and ice sliding off a roof can create a personnel hazard. Panels should also extend to the top of the roof line to prevent snow from sitting on the roof above the panels, melting in the sun, and then having the water flow below the panels where the roof is cold and freezing below the panels. The ice below the panels can build up and damage the panels and mounting systems, and can push the panels off the mounting system. The image of the roof mounted PV at Mount Rainier (Figure 72) shows a nice example of PV panels extended to the top of the roof.

Figure 72. Source: Revision Energy. No date.

The stepper the panels are tilted, the less downward (compressive front) load there is on the panels if snow sits on them. Panels in northern locations such as Alaska are sometimes mounted vertically so snow does not sit on them or create snow loads (Figure 73).

Figure 73. Source: ACEP. No date.

12.6.2 Mounting systems

Specify PV panels and rail/rack systems that have a UL 1703 or UL 2703 listing (as applicable), and an ICC AC 428 evaluation report.

Three (3) rail mounting systems increase the installed strength of the panels by providing additional support and mounting locations. Panels should be mounted in portrait (with the long axis of panels pointing upward) in locations with heavy snow. Additional support of the bottom frame of the bottom modules (Figure 73) may help prevent the force of sliding snow and ice from removing the bottom frame of the modules. Mounting RailPads (Gabor et al. 2019) between the rails of the support structure and the rear side of the panel provides additional support to the back of the panel and increases the compressive strength of the panel.

Snow is more likely to pile up more on the lower sides of modules than on the upper sides. Modules mounted landscape may provide slightly more production as a result of the diode segmented layout of modules and will also resist an uneven upper-lower module load better.

12.7 Operational Implications

Snow can be removed from panels if needed with a broom or plastic shovels without metal edges. Never pound on panels to remove snow or ice since pounding can damage panels. Do not walk on panels while removing snow. For remote locations, monitoring equipment such as a camera can be used to view the array if needed.

For locations that receive lots of snow, it may be worth investigating the cost-efficacy of innovative module heating products that can melt the snow off modules. This will reduce the likelihood of damage and also increase production. These types of products are nascent and unproven, so use them with caution.

12.8 Case Study: Mount Rainier National Park

Modules can be crushed by the weight of snow. This can happen in locations that receive a large amount of heavy, wet snow, such as the Pacific Northwest in the United States. Snow and ice also can create a sliding force on tilted modules that can tear the bottom edge off of modules, which will result in module failure. An example of this can be seen in these images from Mount Rainier National Park (Figure 74).

Figure 74. Modules damaged by snow at Sunrise at Mount Rainier National Park. Photo: Aaron Bougie, NPS.

13. General Weather-Prone Failures

13.1 Failures Associated with Wiring and Wire Management

The wiring of a PV system is a critical component, as it brings the energy generated from the modules to the inverter, and thus to the consumer.

13.1.1 Failure mode 1: Improperly supported wires

The wire management components are one of the most critical parts of a PV system. In this context, wire management is considered to be the components that are used to support and protect the PV wires from the modules all the way to the inverter(s).

An effective wire management system is one of the simplest ways to mitigate the potential for dangerous electrical faults to occur, and thus reduce risk. Many PV wiring failures can occur from improper wire management due to inadequate materials and poor workmanship. It is important to highlight that severe weather can have a major impact on the effectiveness of the wire management. Weather elements like heavy winds and snow can cause loose hanging PV wires to rub against other surfaces and abrade the wire insulation, exposing the inner energized copper strands. Figure 75 shows wires that are not supported with any wire management components. Additionally, wires can degrade rapidly when exposed to sunlight if they are not rated for ultraviolet (UV) exposure.

Figure 75. Unsupported wires

Codes and standards implications

Although some parts of the National Electric Code (NEC) provide requirements on wire management, these codes leave key details unaddressed and up for interpretation by the installer. System owners and operators can benefit by having more information on how wire management components can withstand various environmental stressors.

Organizations like the NEC can leverage their status as a codes and standards-making body by requiring a wire management system account for the site's environmental stressors when selecting an effective solution in the design phase. It is critical that codes and standards for wire management are not overly prescriptive, as each site has different needs. However, the NEC can begin to steer owners and operators toward more effective wire management solutions based on weather conditions.

Design implications

The wire management components of a PV system must be an important part of the design phase. Identifying an effective solution early on in the design phase can save the owner and/or operator O&M costs, as there will not be a need to frequently replace failed components.

Environmental stressors such as wind, rain, UV exposure, and snow all can have an adverse effect on the wiring of a PV system. It is critical that background research is done to find the most effective wire management solution, as environmental stressors will vary between sites. It is also important to note that multiple wire management solutions may need to be used, as some PV systems will require more than one solution.

PV wire that is exposed directly to sunlight (UV exposure) will degrade, and the wire insulation will become brittle. Upon agitation from other weather elements like wind, snow, and rain, the brittle wire insulation can break apart, exposing the energized copper strands. All PV wires, even types that are rated to be used outdoors, must be protected from the weather elements. Figure 76 shows exterior-rated PV wires that are laying across a roof. These wires are exposed to direct sunlight as well as wind, rain, and snow. The solution in this case would most likely be to route the PV wires through conduit.

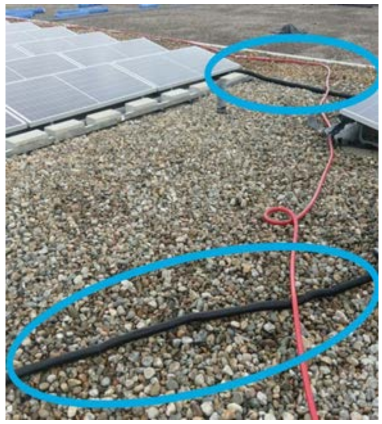


Figure 76. Exterior-rated PV wires laying across a roof

Plastic wire ties were once a commonly used component to secure PV wires to the racking assembly and modules. While considered to be a cost effective option, these plastic wire ties have become a frequent point of failure in PV systems that used them. Plastic wire ties quickly fail under high heat environments (common for rooftops) by becoming brittle and breaking. Once these plastic ties break, they cannot hold the PV wires any longer, thus allowing the wires to hang loose.

Figure 77 shows a plastic wire tie that was used to hold the PV wires has failed under the site's environmental stressors.

Figure77. Failed plastic wire tie

It is critical that best practices are followed in the installation of new wire management components. All wire management systems are susceptible to being installed improperly. Installation crews must be capable of working to secure wires safely.

Operational implications

It is a significant cost burden to owners and operators to keep entering the field to replace plastic wire ties. Frequently replacing plastic wire ties that have failed can increase overall O&M costs and reduce a project's economic viability. Figure 78 shows failed plastic wire ties under a

PV array. Since these wires are in a difficult-to-access part of the array, it would be best to replace all of the plastic wire ties at once and not in stages, regardless if they have failed or not. If plastic wire ties are present in a PV system, serious consideration should be made to replace all of them at once and install an effective solution, such as purpose built module and rail clips, metal zip ties, and conduit, where applicable.

Figure 78. Failed plastic wire ties

Ensuring that PV wires are secured and supported is an essential aspect of reducing safety risks. Wires that are exposed to wind, rain, UV exposure, and snow can degrade rapidly. Once the wire insulation becomes brittle enough, it can start to break apart and expose the energized copper strands. Damaged PV wires have the potential to create electrical faults and subsequently start fires. This type of failure, if left unattended, can cause significant damage to adjacent structures (e.g., buildings) and present a safety risk to site personnel. Systems owners and operators should ensure that all PV wiring is rated to be outdoors and supported/routed properly to avoid exposure to weather elements.

13.1.2 Failure mode 2: Corroded grounding and bonding components

All PV systems must be built with equipment grounding. The goal of a grounding system is to take all the metal components in a PV system (e.g., module frames, racking assembly, conduit) that could become energized from an electrical fault and connect them together, which is also known as *bonding.* This essentially creates one piece of metal that is connected to the grounding system. Grounding systems reduce the possibility for electrical faults to create risks like fires and shock hazards, and are considered to be a major safety component of a PV system.

Codes and standards implications

The NEC requires that all electrically conductive materials in a PV system be bonded and connected to the grounding system in order to prevent damage from electrical faults. During the design and installation phases, the installer should always follow the manufacturer's instructions for grounding and bonding components. The installer should also follow what is required in the NEC handbook and any requirements from the local authority having jurisdiction

(AHJ). However, factors like environmental conditions, thermal cycling, and dissimilar metals are integral to the longevity of the grounding and bonding components.

Design implications

Corroded grounding and bonding components will hinder the grounding system's ability to prevent electrical faults from causing damage. There are many factors that must be considered in the design phase for the PV system's grounding and bonding components.

Important factors are the site's environmental conditions and the weather elements that will affect the PV system.

System owners and operators must conduct background research to make sure the components used in the grounding and bonding can withstand the site's environmental conditions. Marine environments (e.g., coastal areas) can create conditions for certain components to corrode, as seen in Figure 79. It is also critical that these components are rated for outdoor use, as those rated for indoor use only will quickly degrade and compromise the grounding system's functionality.

Figure 79. Corroded PV components

Another factor that must be considered is the expansion and contraction of metal components from thermal cycling. Different materials (e.g., steel, aluminum, copper) may have different thermal expansion rates. Over time, thermal movement can cause the connection between these components to loosen. While proper installation is critical, thermal cycling can cause any grounding system to fail (Smalley 2015).

Another factor that must be considered during the design phase is the interactions of dissimilar metals. In a PV system, there will be varying metals between the modules, racking assembly, and grounding components. Dissimilar metals, when combined with moisture, will cause corrosion to the components, which can prevent the grounding system from negating the effects of electrical faults (Smalley 2015).

Operational implications

Choosing the right grounding and bonding components during the design phase can have a significant impact on the site's operations. If these components are chosen without any consideration for the factors above, corrosion will most likely occur. Replacing these corroded components can come at a significant cost burden to system owners and operators. This is because a PV system may contain hundreds of grounding and bonding components, many of them in hard-to-access areas underneath an array.

It is critical to determine the root cause of corrosion if it is found on a grounding or bonding component. Depending on the reason, it may be necessary to replace all of the grounding and bonding components to prevent further corrosion, and also to prevent corroded components from being replaced in a piecemeal fashion. The grounding system is a critical part of a PV system to protect adjacent structures and site personnel from fire and shock hazards caused by electrical faults.

14. References

ACEP. No date. Bifacial Solar Photovoltaic Panel Performance at High Latitudes. http://acep.uaf.edu/facilities/solar-photovoltaic-test-site.aspx.

Aplicaciones Tecnológicas. n.d. 32 percent of damages in photovoltaic plants are caused by lightning. Lightning & Earthing Smart Solutions. https://lightningprotection-at3w.com/company/news/32-percent-of-damages-in-photovoltaic-plants-are-caused-by-lightning/s33c445.

Andrews, R. W., A. Pollard, and J. M. Pearce. 2013. "The effects of snowfall on solar photovoltaic performance." *Solar Energy* (92); 84–97.

Burgess, C., and J. Goodman. 2018. "Solar Under Storm: Select Best Practices for Resilient Ground-Mount PV Systems with Hurricane Exposure." https://rmi.org/solar-under-storm-designing-hurricane-resilient-pv-systems.

Bushong, Stephen. 2016. " Three steps to protect a solar farm from lightning strikes." *Solar Power World.* https://www.solarpowerworldonline.com/2016/08/three-steps-protect-solar-farm-lightning-strikes/.

Cain, J. H., D. Banks, and C. P. Petersen. 2015. Wind Loads on Utility Scale Solar PV Power Plants. Structural Engineers Association of California (SEAOC). 2015 SEAOC Convention Proceedings.

DOE (U.S. Department of Energy). 2017. Let it Snow: How Solar Panels Can Thrive in Winter Weather. Office of Energy Efficiency & Renewable Energy. January 5. https://www.energy.gov/eere/articles/let-it-snow-how-solar-panels-can-thrive-winter-weather.

Elsworth, James, and Otto Van Geet. 2020. "Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience." June. https://www.nrel.gov/docs/fy20osti/75804.pdf.

FEMA. 2018. "Rooftop Solar Panel Attachment: Design, Installation, and Maintenance: Hurricanes Irma and Maria in the U.S. Virgin Islands." https://www.fema.gov/sites/default/files/2020-07/mat-report_hurricane-irma-maria_virgin-islands.pdf.

FEMP (Federal Energy Management Program). 2021. GSA Guide to Existing Storm Vulnerabilities.

Fu, R., Feldman, D., and R. Margolis. 2018. U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018. National Renewable Energy Laboratory. NREL/TP-6A20-72399. https://www.nrel.gov/docs/fy19osti/72399.pdf.

First Solar. n.d. "Highest Quality Solar Panels." First Solar website. https://firstsolarteam.com/highest-quality-solar-panels/.

Gabor, A., R. Janoch, A. Anselmo, J. Lincoln, E. Schneller, H. Seigneur, D. Harwood, M. Rowell less (2019), Materials Science 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)

GCube Insurance. 2016. "Extreme Weather Losses Increase Global Solar Claims Severity." https://www.gcube-insurance.com/news/extreme-weather-losses-increase-global-solar-claims-severity/

Ghazi, S., and K. Ip. 2014. "The effect of weather conditions on the efficiency of PV panels in

the southeast of UK." *Renewable energy* (69); 50–59.
Grasty, Jim. 2020. Personal communication (phone call). Alltec.
Gupta, V., M. Sharma, R. Pachauri, and K. D. Babu. 2019. "Impact of hailstorm on the performance of PV module: A review." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 1–22.
Heidari, N., J. Gwamuri, T. Townsend, and J. M. Pearce. (2015). "Impact of snow and ground interference on photovoltaic electric system performance." *IEEE Journal of Photovoltaics* 5(6): 1680–1685.
Holle, Roland. 2014. "Diurnal Variations of NLDN-Reported Cloud-to-Ground Lightning in the United States." *Monthly Weather Review* 142(3). https://www.researchgate.net/publication/262982019_Diurnal_Variations_of_NLDN-Reported_Cloud-to-Ground_Lightning_in_the_United_States.
Insurance Information Institute. n.d. Facts + Statistics: Lightning NOAA. Lightning Flash Rate. Science on a Sphere. https://sos.noaa.gov/datasets/lightning-flash-rate/.
: Jackson, N., and T. Gunda. 2021. "Evaluation of Extreme Weather Impacts on Utility-scale Photovoltaic Plant Performance." *Applied Energy* 302: November 15 https://www.researchgate.net/profile/Nicole-Jackson-3/publication/353944206_Evaluation_of_extreme_weather_impacts_on_utility-scale_photovoltaic_plant_performance_in_the_United_States/links/613ec461e4419c5e6ec9c826/Evaluation-of-extreme-weather-impacts-on-utility-scale-photovoltaic-plant-performance-in-the-United-States.pdf
Jordan, D. C., and S. R. Kurtz. 2014. "Reliability and Geographic Trends of 50,000 Photovoltaic Systems in the USA (No. NREL/CP-5J00-62801)." National Renewable Energy Lab. Golden, Colorado (United States). https://www.nrel.gov/docs/fy14osti/62801.pdf.
Karin, T., C. B. Jones, and A. Jain. 2019. "Photovoltaic Degradation Climate Zones." In 46th IEEE Photovoltaic Specialist Conference (PVSC). IEEE. Chicago, Illinois. 0687–0694. https://pvtools.lbl.gov/pv-climate-stressors.
Knutson, T., S. J. Camargo, J. C. Chan, K. Emanuel, C. Ho, J. Kossin,. . . and L. Wu. 2019. "Tropical Cyclone and Climate Change Assessment: Part 1: Detection and Attribution." *Bulletin of the American Meteorological Society* (10: 100); 1987–2007). doi:https://doi.org/10.1175/BAMS-D-18-0189.1.
Monterey County Water Resources Agency. n.d. Monterey County Guidelines for Solar Array Projects located in the FEMA 100-year floodplain.
National Severe Storms Laboratory. n.d. "Severe Weather 101." https://www.nssl.noaa.gov/education/svrwx101/lightning/.
National Weather Service. n.d. How Powerful Is Lightning? https://www.weather.gov/safety/lightning-power#:~:text=Weather.gov%20%3E%20Safety%20%3E%20How,120%20Volts%20and%2015%20Amps.
Northern Arizona Wind and Sun. Solar Lightning and Lightning Protection. https://www.solar-electric.com/learning-center/solar-system-lightning-protection.html/.
Pickerel, K. 2015. Lightning protection for solar panels protects your investment. Solar Power World Online. https://www.solarpowerworldonline.com/2015/03/lightning-protection-for-solar-panels-protects-your-investment/.

Pickerel, K. 2016. “What are the mechanical loading tests for solar panels?” *PV Magazine* July 5.

Pickerel, K. 2018. “How the solar industry is responding to the increasing intensity of natural disasters.” https://www.solarpowerworldonline.com/2018/01/solar-industry-responding-increasing-intensity-natural-disasters/

Revision Energy. n.d. Do solar panels even work in the winter? https://www.revisionenergy.com/why-go-solar/solar-works-in-winter/.

Roddell, Alex. 2020. Quality Roundtable event July 21, 2020*. Restoring Utility PV After Extreme Weather Damage. PV Magazine.* https://www.youtube.com/watch?v=M49HQhBy5Fs.

Santhakumari, M., and N. Sagar. 2019. “A review of the environmental factors degrading the performance of silicon wafer-based photovoltaic modules: Failure detection methods and essential mitigation techniques.” *Renewable and Sustainable Energy Reviews* (110): 83–100.

SEAOC (Structural Engineers Association of California). 2017. Wind Design for Solar Arrays PV2-2017. https://www.seaoc.org/news/374059/SEAOC-Wind-Design-for-Solar-Arrays-PV2-2017-is-now-available.htm.

Smalley, J. 2015. “What is the process of grounding and bonding a solar PV array?” https://www.solarpowerworldonline.com/2015/08/what-is-the-process-of-grounding-and-bonding-a-solar-pv-array/.

Solar Power World. 2016. The threat of lightning on solar farms. Contractors Corner Podcast. August 11. https://www.owltail.com/podcast/0PMsO-Solar-Power-World.

Strata Solar. 2019. “Force Majeure & Energy Modeling: 1 Hurricane, 81 PV Plants Down.” In Solar Risk Assessment: 2019. Quantitative Insights from the Industry Experts. https://now.solar/2020/06/29/solar-risk-assessment-2019-quantitative-insights-from-the-industry-experts/

Verisk Claim Data 2020 https://www.nrel.gov/docs/fy21osti/78588.pdf

Zdanowicz, Christina. 2020. “Hailstone the size of a football in Argentina may have smashed a world record.” CNN. May 2. https://www.cnn.com/2020/05/02/weather/gargantuan-hailstones-record-scn-trnd/index.html. Accessed August 14, 2020.

Zipp, Kathie. 2018. Lightning and overvoltages: Why solar systems need surge protection. October 9. https://www.solarpowerworldonline.com/2018/10/lightning-and-overvoltages-why-solar-systems-need-surge-protection/.

Appendix: List of Articles Discussing Severe Weather Events

Greentech Media

Hawaii's Solar Industry Calls Tropical Storm Lane a 'Wake-Up Call'
https://www.greentechmedia.com/articles/read/solar-industry-in-hawaii-calls-tropical-stor m-lane-a-wake-up-call.

- Tropical Storm Lane
- Hawaii's solar industry avoided serious damage, no reported damage or incidents from installers or developers
- Rainfall, tropical cyclone, flooding, winds

Clean Energy Players Weather Through Florence
https://www.greentechmedia.com/articles/read/clean-energy-players-weather-hurricane-florence

- Hurricane Florence
- Historic amounts of rain, flooding
- Duke Energy avoided damage and remotely reconnected to 40 solar sites
- No reports on damage in the utility sector, minimal damage in the residential sector

Solar Partnership Grapples with Extreme Weather Damage Worsened by Climate Change
https://www.greentechmedia.com/articles/read/solar-inspection-partnership-grapples-with-extreme-weather-damage-worsened

- Hurricane Florence, most North Carolina solar operators said modules went unharmed (visible damage)
- Partnership between PVEL and Heliolytics to conduct post-storm module damage assessments
- Hurricanes, hail, tornadoes, 100–500 year floods

Can the Electricity Industry Seize Its Resilience Moment?
https://www.greentechmedia.com/articles/read/can-the-energy-industry-seize-its-resilienc e-moment.

- Hurricane Florence, "slate of natural disasters" (list of hurricanes)
- Wade Schauer (Wood MacKenzie) provides anecdotal evidence of PV systems in New England damaged by feet of snow; Duke Energy reported most of its solar came online quickly (one experienced damage, and three experienced substation interconnection issues).
- Mentions the FEMA and Rocky Mountain Institute (RMI) documents about retrofitting, installing, and maintaining PV systems to be storm-resistant

How to Install Solar PV Systems That Will Hold Up in Hurricanes
https://www.greentechmedia.com/squared/the-lead/how-to-build-resilient-solar-pv-for-a-world-undergoing-climate-change

- Hurricane Maria, Puerto Rico, extreme weather, RMI and FEMA reports

- Quantify storm damage, improve installation practices
- 180 mph winds destroyed PV systems while other systems fared well.

Puerto Rico's Latest Challenge: Utility Curtailment of Wind and Solar Farms
https://www.greentechmedia.com/articles/read/puerto-rico-prepa-curtailment-of-wind-and- solar

- Chris Shugart (senior VP of wind developer Pattern Energy) …several utility scale solar plants and distributed rooftop solar installations…had little damage after the devastating storm."

America Is Getting Wetter and Hotter, Impacting Solar Performance Around the Country
https://www.greentechmedia.com/articles/read/america-is-getting-wetter-and-hotter-impac ting-solar-performance

- Warm, wet conditions affected PV performance in the United States in Q2.
- Higher than average temperatures in the regions across the United States, intense rainfall, clouds, hail

Renewable Energy World

Branson's Virgin Group Buys Storm-Damaged Caribbean Solar Farm
https://www.renewableenergyworld.com/2018/08/08/bransons-virgin-group-buys-stormdamaged-caribbean-solar-farm/

- BMR Energy bought 4-MW solar farm in St. Croix after it had sustained damage after Hurricane Maria in 2017.

Florence Update: One GW of Solar Capacity Went Offline after Historic Storm
https://www.renewableenergyworld.com/2018/09/20/florence-update-one-gw-of-solar-capacity-went-offline-after-historic-storm/

- Duke Energy 1 GW of solar capacity was not available to Duke; 100 MW was taken offline or tripped off during storm causing a greater outage.
- Hurricane Florence

Duke Energy Says Solar Assets at Risk of Flood Damage from Hurricane Florence
https://www.renewableenergyworld.com/2018/09/13/duke-energy-says-solar-assets-at-ris k-of-flood-damage-from-hurricane-florence/

- Hurricane Florence, damaging winds, flooding, hurricanes, Hurricane Matthew
- Pre-Hurricane Florence, CEO of Duke not concerned with wind, no issues reported

Getting Serious about Solar for Disaster Response and Recovery
https://www.renewableenergyworld.com/2017/10/27/getting-serious-about-solar-for-disast er-response-and-recovery/

- Hurricanes Maria and Irma
- Solar as resilient energy solution post storms
- Hurricane-prone, 150 mph winds (Category 4 hurricane), strong and/or additional anchors for racking assembly

Solar's Remarkable Survival in the Most Extreme Weather
https://www.renewableenergyworld.com/2017/10/12/solar-s-remarkable-survival-in-the-most-extreme-weather/

- Physical impact of storms on solar PV, strong winds, category 3–5 hurricanes, debris damage, flooding, torrential rainfall, extreme weather events
- "Recent history has shown that solar is quite resilient in the face of extreme weather."

Haitian Solar PV Weathers Hurricane Irma
https://www.renewableenergyworld.com/2017/09/13/haitian-solar-pv-weathers-hurricane-irma/

- Hurricane Irma
- Sigora Haiti (micro-utility company) reported no damage to their PV systems.
- Flying debris, damaging winds

Climate Change and Solar Solutions: A Hurricane Sandy (Ongoing) Experience
https://www.renewableenergyworld.com/2012/11/14/climate-change-and-solar-solutions-a-hurricane-sandy-ongoing-experience/

- Interview with residential PV system owner after Hurricane Sandy
- Modules survived, inverters higher than flood level, no damage

The Question Day 32: What is the Most Difficult Issue Facing the Solar Industry?
https://www.renewableenergyworld.com/2012/11/15/the-question-day-1-what-is-the-most-difficult-issue-facing-the-solar-industry/

- Weather-related damage to PV

Rise in severe weather from climate change threatens grid, according to Accenture research
https://www.renewableenergyworld.com/2020/05/21/rise-in-severe-weather-from-climate-change-threatens-grid-according-to-accenture-research/

- Utilities expect extreme weather (heavy winds, flooding, and winter ice/snowstorms) to have significantly damaging effects on grid infrastructure.

Solar Power World

Mounting a solar system to survive a hurricane
https://www.solarpowerworldonline.com/2020/09/mounting-a-solar-system-to-survive-a-hurricane/

- Challenge of installing PV systems to withstand 100+ mph winds, susceptible to annual superstorms, better installation practices, ballasted systems should have mechanical attachments to the roof, ASCE 7-16
- Wind pressure load ratings, uplift, negative pressure (snow)
- Module frame connections failed

DEPCOM Power, Nextracker and Solar Support host virtual event on utility solar recovery after natural disasters
https://www.solarpowerworldonline.com/2020/07/depcom-power-nextracker-solar-support-

virtual-event-utility-solar-operations-maintenance/

- Webinar, extreme weather restoration, recovery, natural disasters

Solar Support enlists partner companies for solar site restoration program
https://www.solarpowerworldonline.com/2020/06/solar-support-enlists-partner-companies- for-solar-site-restoration-program/

- Extreme weather restoration and recovery, hurricane, natural disasters

Emergency O&M: How to restore utility-scale solar projects after extreme weather damage
https://www.solarpowerworldonline.com/2020/05/emergency-operations-maintenance-sol ar-projects-extreme-weather/

- Severe weather events, natural disasters, recovery process for a storm damaged PV system

Renewable Guard Insurance Brokers introduces new hail policy for solar developers
https://www.solarpowerworldonline.com/2020/04/renewable-guard-insurance-brokers-introduces-new-hail-policy-for-solar-developers/

- Insurance companies, new parametric for a hail insurance program for solar project developers

PVEL, Heliolytics launch new Incident Response service to help solar owners address natural disasters
https://www.solarpowerworldonline.com/2019/09/pvel-heliolytics-launch-new-incident-response-service-to-help-solar-owners-address-natural-disasters/

- Partnership for Incident Response service, natural disasters, storm recovery, microcracking of cells, hot spots

Lightning and overvoltages: Why solar systems need surge protection
https://www.solarpowerworldonline.com/2018/10/lightning-and-overvoltages-why-solar-sy stems-need-surge-protection/

- Lightning, damage, power surges

Solect Energy offers tips to solar system owners after string of severe storms in Northeast
https://www.solarpowerworldonline.com/2018/03/select-energy-offers-tips-to-solar-system -owners-after-string-of-severe-storms-in-northeast/

- Severe storms, Northeast, snow, storm, damaged

GCube says needs to invest time and resources to increase its tolerance to risk
https://www.solarpowerworldonline.com/2016/09/gcube-says-needs-invest-time-resource s-increase-tolerance-risk/

- Losses from extreme weather conditions, unforeseen risk, natural catastrophes, financial impacts, failure prevention methods, weather most common causes of claims, hail

Aerial site inspections can pinpoint problem areas during solar O&M
https://www.solarpowerworldonline.com/2018/02/aerial-site-inspections-can-pinpoint-probl em-areas-solar-om/

- Inspections by drones, insurance claims, extreme weather damage, IR imaging, O&M, repairs, regular site assessments, benchmarking, preexisting defects

How the solar industry is responding to the increasing intensity of natural disasters
https://www.solarpowerworldonline.com/2018/01/solar-industry-responding-increasing-intensity-natural-disasters/

- Weather patterns, lifetimes and performance, natural disasters, GCube report on insurance claims, wildfires, hurricanes, tornadoes, Puerto Rico, hailstorms, blizzards, floods

Small-scale EPC replaces 17,920 panels at two-year-old solar farm
https://www.solarpowerworldonline.com/2017/07/small-scale-epc-replaces-17920-panels- two-year-old-solar-farm/

- Solar farm in Texas destroyed by hail, replaced all 17,920 modules

Vaisala insists U.S. solar asset managers account for extreme weather impacts
https://www.solarpowerworldonline.com/2017/03/vaisala-insists-u-s-solar-asset-managers-account-extreme-weather-impacts/

- Effects on PV performance in United States from extreme weather

Are your solar projects ready for El Niño flooding?
https://www.solarpowerworldonline.com/2016/01/are-you-prepared-for-el-nino-flooding/

- El Niño, flooding, stormwater management, ground mounted PV systems

Hurricane Sandy Recovery, Solar Restoration Efforts
https://www.solarpowerworldonline.com/2012/11/hurricane-sandy-recovery-solar-restorati on-efforts/

- Hurricane Sandy, inverter damage, restoration

PV Magazine

Solar survives the storms in Puerto Rico
https://pv-magazine-usa.com/2017/11/07/solar-survives-the-storms-in-puerto-rico/

- Hurricanes Irma and Maria, Puerto Rico, damage, roof mounted PV systems, ballasted versus mechanically attached versus hybrid systems

How to install solar power strong enough for a hurricane
https://pv-magazine-usa.com/2018/08/24/a-how-to-solar-power-strong-enough-for-a-hurri cane/

- 2017 hurricane season, RMI report – Solar Under Storm I, failed systems (clamps, racking, under-torqued bolts)

In case of hurricane, apply Enphase, tighten bolts and mind your wind codes!
https://pv-magazine-usa.com/2018/11/29/in-case-of-hurricane-apply-enphase-and-mind-y our-wind-codes/

- FEMA recommendations for rooftop PV systems, hurricanes, Caribbean

When disaster strikes
https://pv-magazine-usa.com/2019/08/14/when-disaster-strikes/

- Preparation and recovery, hurricanes, O&M teams

Floating PV array catches fire after typhoon
https://www.pv-magazine.com/2019/09/09/japans-largest-floating-pv-plant-catches-fire-after-typhoon-faxai-impact/

PVEL and Heliolytics team up for solar disaster investigation
https://pv-magazine-usa.com/2019/09/26/pvel-heliolytics-team-up-for-solar-disaster-investigation/

- PVEL and Heliolytics, post-storm inspections, fires, tornadoes, earthquakes, hurricanes, damaging winds, microcracks

The weekend read: We need to talk about wind resilience
https://www.pv-magazine.com/2019/11/09/the-weekend-read-we-need-to-talk-about-wind-resilience/

- Single axis trackers, wind damage, aeroelastic effects, site conditions, evolving technology, standards

Long read: What broke at Oakey
https://www.pv-magazine-australia.com/2019/12/07/long-read-what-broke-at-oakey/

- Single axis tracking system, significant wind damage

How to make rooftop PV resilient in hurricane regions
https://www.pv-magazine.com/2020/02/20/how-to-make-rooftop-pv-resilient-in-hurricane-regions/

- RMI Report – Solar Under Storm II, rooftop installation best practices, failure characteristics, Caribbean islands

Floating PV systems are storm-resistant
https://www.pv-magazine.com/2020/11/06/floating-pv-systems-are-storm-resistant/

- Severe storms, wind speeds, system durability

Virtual Roundtable Resiliency in the Wake of Change
https://www.pv-magazine.com/2020/11/19/pv-magazine-tackles-extreme-weather-resilien cy-

the-future-of-storage-and-more-in-virtual-roundtables-usa/

- Hail, wind, hurricanes, wildfires, O&M

Extreme weather is causing solar insurance premiums to explode
https://pv-magazine-usa.com/2020/12/14/extreme-weather-is-causing-solar-insurance-premiums-to-explode/?utm_source=pv+magazine+USA&utm_campaign=05adc81512-RSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_80e0d17bb8-05adc81512-15963 4110

- Extreme weather events, hurricanes, hailstorms, wildfires