U.S. DEPARTMENT OF ENERGY

Solar PV O&M - (CAS) and (CAIS) User Group

Gerald Robinson – FEMP

FEMP Federal Energy Management Program

FEMP's Distributed Energy Program Training Team

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Overview

Agenda	
I.	FEMP Background
II.	Inspection Plan & Preparation
III.	Inspections
IV.	Latent Vulnerabilities – Corrective Actions
V.	O&M Scope & Implementation
VI.	Challenging Circumstances
VII.	Repowering or Replacement
VIII.	FEMP PV Performance Program
IX.	FEMP Resources and Q&A

Learning Objectives

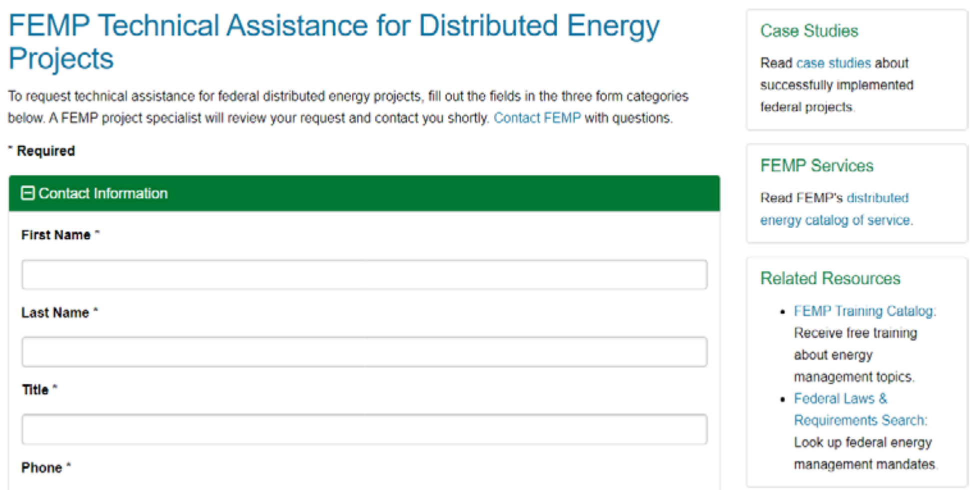
- Importance of inspections in an effective O&M plan
- How to develop an inspection program
- Understand major sections of O&M Scope and how to budget and implement
- Understand when to repair, repower or replace
- Working with FEMP to achieve your management objectives

Contact Information

FEMP's Distributed Energy Team Main Points of Contact	Expertise
Nichole Liebov – FEMP AAAS STPF / 240-702-3509 / nichole.liebov@ee.doe.gov	FEMP Program Manager for Onsite CFE
Andy Walker – NREL Senior Research Fellow / 303-384-7531 / andy.walker@nrel.gov	All aspects of O&M program development + PV Performance
Jal Desai – NREL Researcher/ 303-275-3636 / jal.desai@nrel.gov	PV Performance
James Elsworth – NREL Resilience Engineer / 303-275-4242 / james.elsworth@nrel.gov	Training for self-performing O&M
Gerald Robinson – LBNL Program Manager / 510-486-5769 / gtrobinson@lbl.gov	Repair recovery strategies, O&M Procurement

Ask for Project Assistance

- Request help with your project today!
- Fill out a quick and easy application through the FEMP portal

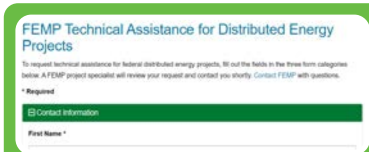


Link to the FEMP Distributed Energy Portal

FEMP Solar PV O&M Support Tools & Initiatives

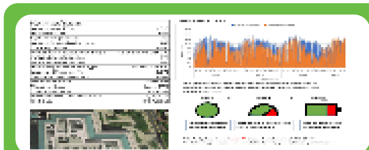
Navigate to all FEMP Solar PV O&M resources

https://www.energy.gov/eere/femp/optimizing-solar-photovoltaic-performance-longevity



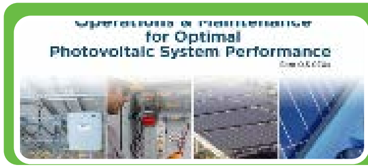
FEMP's Distributed Energy Technical Request Portal

https://www7.eere.energy.gov/femp/assistance/



Solar PV Performance Initiative

- Is your system operating within bounds?
- Provide valuable baseline for moving ahead with O&M programs



Training

- Operations & Maintenance for Optimal Photovoltaic System Performance
- O&M Best Practices for Small-Scale PV Systems

Solar PV O&M Procurement Templates

Finance

Energy Savings Performance Contracting (ESPC) ENABLE:
https://www.wbdg.org/continuing-education/femp-courses/fempodw036

https://www.energy.gov/eere/femp/optimizing-solar-photovoltaic-performance-longevity

Best Practices Guide Version 3

Best Practices for Operations & Maintenance of PV & Energy Storage Systems; 3rd Edition

https://www.nrel.gov/docs/fy19osti/73822.pdf

Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition

National Renewable Energy Laboratory,
Sandia National Laboratory, SunSpec Alliance,
and the SunShot National Laboratory Multiyear Partnership (SuNLaMP) PV O&M Best Practices Working Group

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-7A40-73822
December 2018

Why Care About PV O&M?

- ✓ Increase efficiency and energy delivery (kWh/kW)
- ✓ Decrease downtime (hours/year)
- ✓ Extend system lifetime (25–40 years)
- ✓ Reduce cost of O&M ($/kW/year)
- ✓ Ensure safety and reduce risk
- ✓ Enhance appearance and image
- ✓ Often required in financing and warranty
- ✓ Address critical latent issues before they lead to cascading failures

PV requires very little maintenance compared to other types of electric generators, but an effective O&M Program is needed to achieve all of these benefits.

Solar PV Inspection & Maintenance is Unique

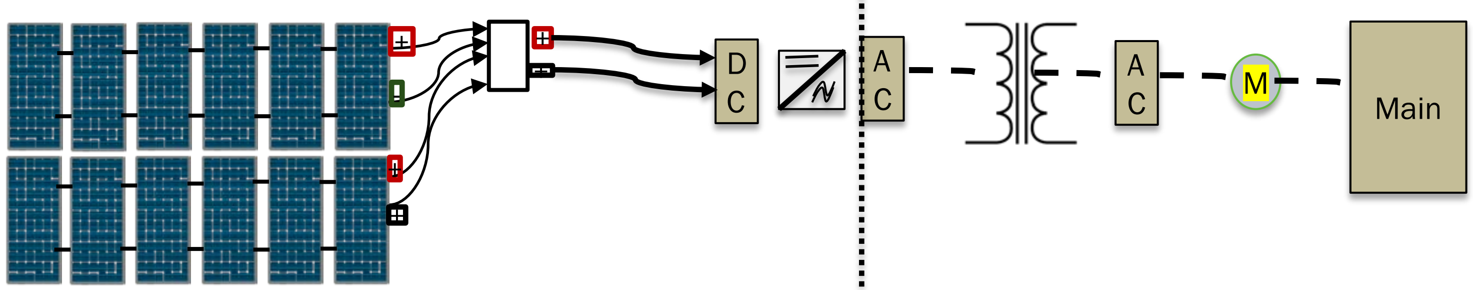
- **Solar PV system technologies can be highly reliable should they be engineered, installed and maintained well.**
- **However, the industry lacks the hallmarks of other matured industries (e.g. buildings) underpinned by well developed codes and standards with testing protocols.**
  - Structural
  - Mechanical
  - Electrical
  - Civil

PV System Owner's Guide to Identifying, Assessing, and Addressing Weather Vulnerabilities, Risks, and Impacts
(https://www.energy.gov/sites/default/files/2021-09/pv-system-owners-guide-to-weather-vulnerabilities.pdf)

Focus on Presentation – Mostly on DC Side

DC String Wiring

AC Wiring



<u>Solar Specific Electrical Standards</u>

1. NEC 690
2. NFPA 70
3. IEC 62446-2020*
4. Guidance documents
5. Code Gaps

*Used in new construction commissioning – need to know which tests to use in existing systems.

<u>Traditional Electrical Preventative Maintenance</u>

1. NFPA 70B
2. IEEE 3007.1-3007.3
3. NETA MTS

Solar Specific Software Tools - Heliovolta

- Developed under a DOE/SETO Grant
- Software is available for free use by federal agencies
- Clouded system with resident software on a tablet or phone

ABOUT SOLARGRADE

The cloud-based platform for smarter, faster renewable energy fieldwork.

SolarGrade empowers teams to operate safe, reliable, and high-performing renewable assets — **at scale, on time, and on budget.**

- Be 30% more efficient in the field
- Increase production with more uptime
- Prevent safety events by standardizing QA/QC practices
- Elevate asset management with better data

SolarGrade was made by renewable experts to meet the needs of field technicians and asset managers.

Implement Proactive Asset Care
Generate fleet-wide analytics and portfolio-level task lists to centralize O&M work in one calendar.

Know Where Issues Are
SolarGrade leverages mobile devices' built-in geolocation capabilities to track issue location.

Streamline Data Collection
Standardize field data collection steps to move quickly and accurately in the field.

Achieve Consistency
Leverage industry-leading SolarGrade QA/QC and O&M frameworks or create your own.

Work Simultaneously at Sites
Split up tasks while following consistent workflows.

Easily Update As-Builts
Upload and geolocate project as-builts on-site and make mark-ups on mobile, even offline.

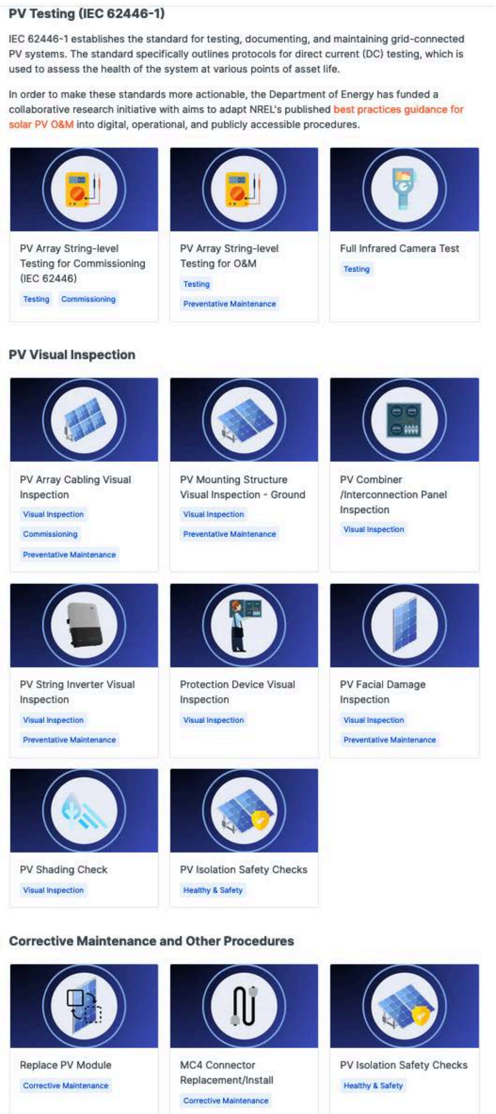
KEY FEATURES

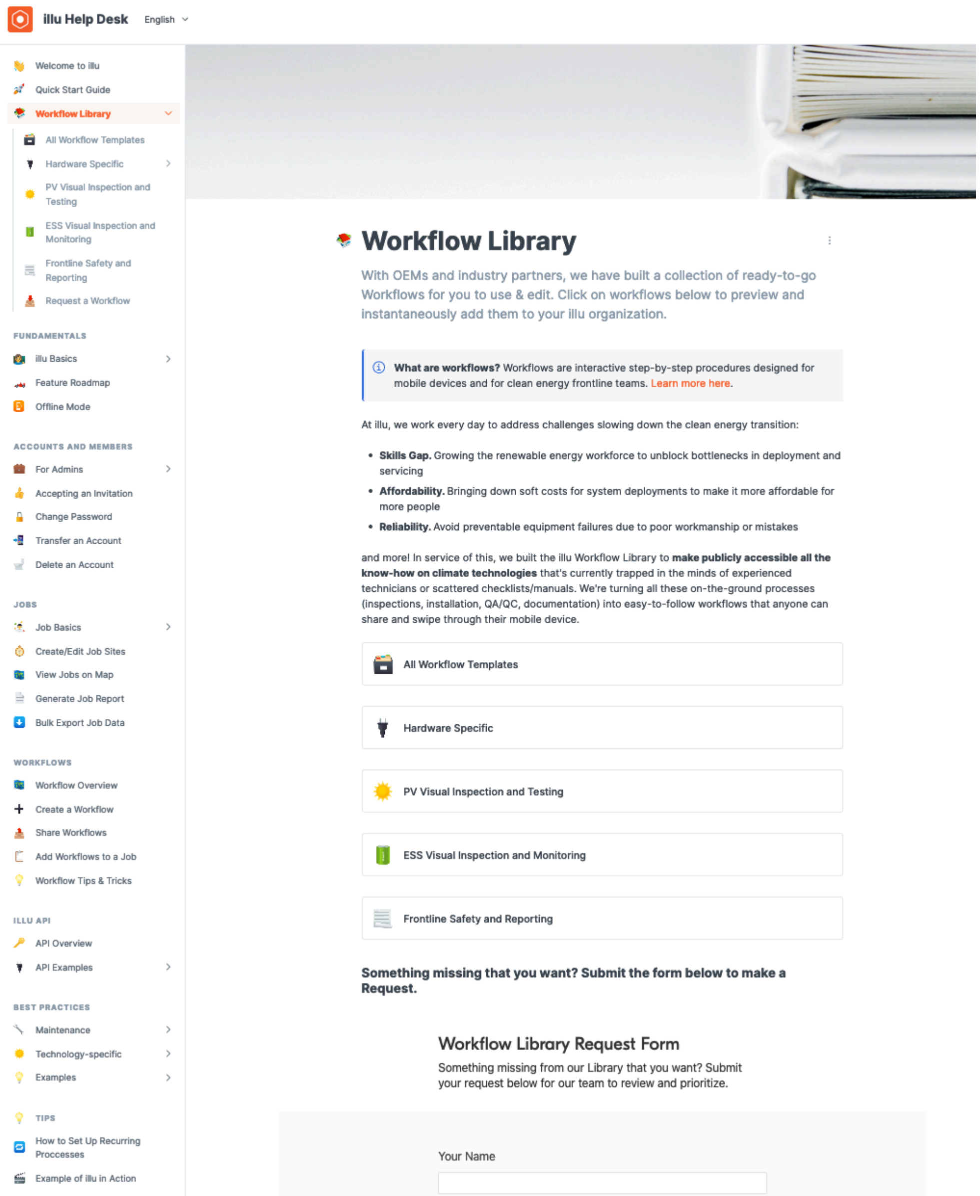
- Georeferenced issue tagging
- Photo capture and editing
- Pre-built, pre-loaded inspection protocols (customizable)
- Pre-written, pre-loaded issue descriptions (editable)
- Integrated as-builts with mark-up tools
- Automated reporting
- Automated punchlists

Start Your Free Trial
Sign up at solargrade.io/

SOLARGRADE
BY HELIOVOLTA

Solar Specific Software Tools – Illu.WORKS





Training Needed – Hands On Testing/Diagnosis

- **Need for Training**
  - Solar PV is different enough, electrically, structurally and mechanically
  - Experience with Solar PV DC source circuits troubleshooting and diagnosis
- **Solar Energy International**
  - https://www.solarenergy.org/courses/solar-training-pv-systems-tools-and-techniques-for-operation-and-maintenance-lab-week-grid-direct/
  - https://www.nabcep.org/

Solar PV Inspection Plan

PV O&M by System Type: Different Mounting Arrangements

Roof mounts: attached or ballasted

Photo by Mercury Solar Solution images.NREL.gov #18062

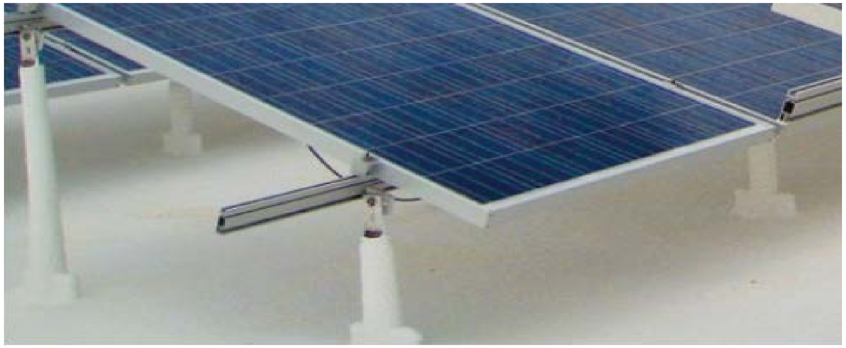


Photo Orlando Utilities Commission images.NREL.gov #18715

Ground mounts: tracking or fixed

Photo by Andy Walker, NREL

Photo by Andy Walker

Planning & Training – Inspection

- **As-built drawings & equipment manuals**
  - Check that drawings match what is installed
    - Include beam types, metal gauge, joint details and fasteners
    - Wire gauge and types
    - Component manufactures and model numbers
- **Training**
  - Training needed with DC systems and PPE
  - How to measure for performance, grounding, faults, conductor integrity
- **Training resources**
  - **O&M Best Practices for Small-Scale PV Systems (https://www.wbdg.org/continuing-education/femp-courses/fempfts27)**
  - Solar Energy International (SEI) (https://www.solarenergy.org/)
  - FEMP Resources on O&M topics (https://www.energy.gov/femp/optimizing-solar-photovoltaic-performance-longevity)
- **Creating a plan**
  - Start with Best Practices – 3rd Edition
    https://www.nrel.gov/docs/fy19osti/73822.pdf

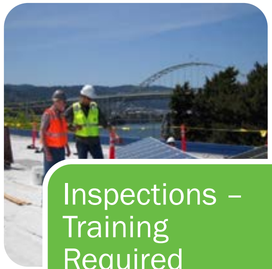
Inspections

Inspections

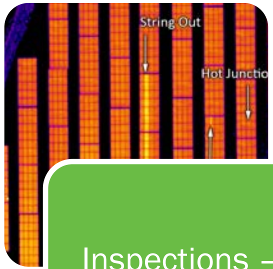
- General Rule – 20% effort yields 80% results
- Start with visual inspections leading to more invasive measures as needed

Planning
- Plan
- Documentation
- Tools
- Software

Visual Inspections
- Structural
- Mechanical
- Electrical
- Environmental



Inspections – Training Required
- Performance
- Electrical
- Metering
- Structural



Inspections – Professional Imaging

Inspections – Visual

1. **Site Conditions:**
   1. Ground or Canopy Mounted Arrays
      - ✓ Weed growth
      - ✓ Signs of soil loss from floods
      - ✓ High dust/dirt sources
   2. Roof
      - ✓ Rack dislodged
      - ✓ Weed growth
      - ✓ Leafy debris buildup
      - ✓ Roof drain clogs
      - ✓ Animal nesting or damage
      - ✓ Animal soiling
   3. General Organization of Site

Photo by
Gerald Robinson, LBNL

Photo by
Gerald Robinson, LBNL

Photo by
Gerald Robinson, LBNL

Photo by
Solar Builder Magazine

Photo by
Gerald Robinson, LBNL

Photos by Gerald Robinson, LBNL

Inspections – Visual

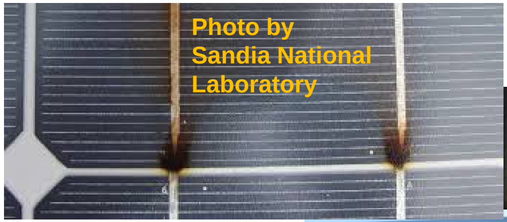
- **Mechanical – Fasteners**
  - Push/pull on modules – loose?
    - Modules loose on rack
  - Loose or missing fasteners
  - Damaged; bent, sheared
  - Wrong fasteners for critical applications
    - Self tapping sheet metal screws
    - Clamping fasteners - rack assembly
    - ”Nylok” for vibration resistance
    - Helical split washers

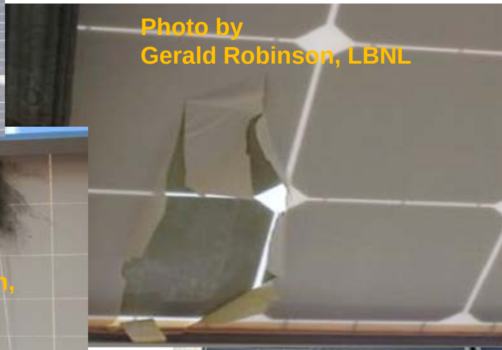
Critical Fasteners – Loss Results in Cascading Failures

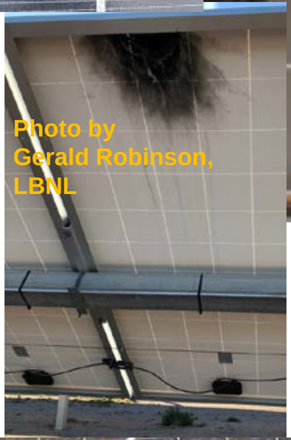
Photo by
Gerald Robinson, LBNL

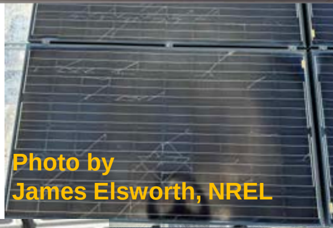
Inspections – Visual

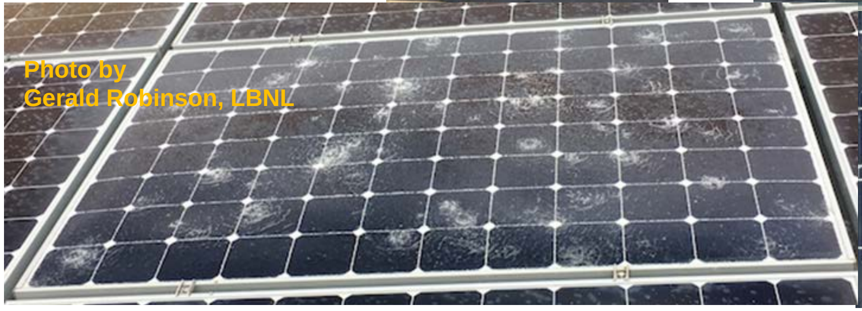
1. **Module condition:**
    1. Obvious module degradation
        1. Cracked glass
        2. Delamination
        3. Discoloration
        4. Backsheet cracking
        5. Snail trails
        6. Diode failure
    2. In most cases modules must be replaced

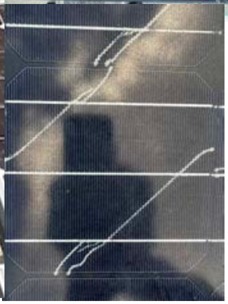






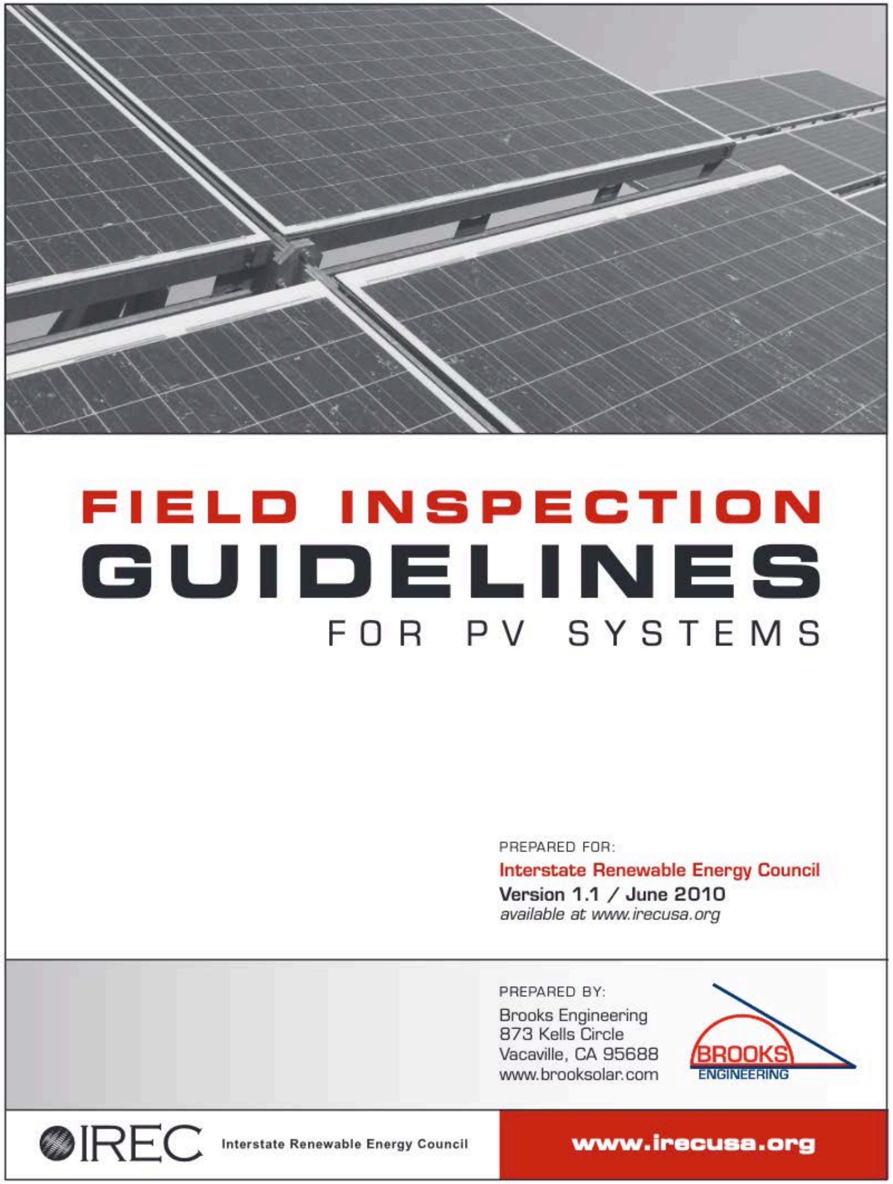






TIP: Require replacement modules meet – PVEL or RETC standards

Inspections – DC Wire Management



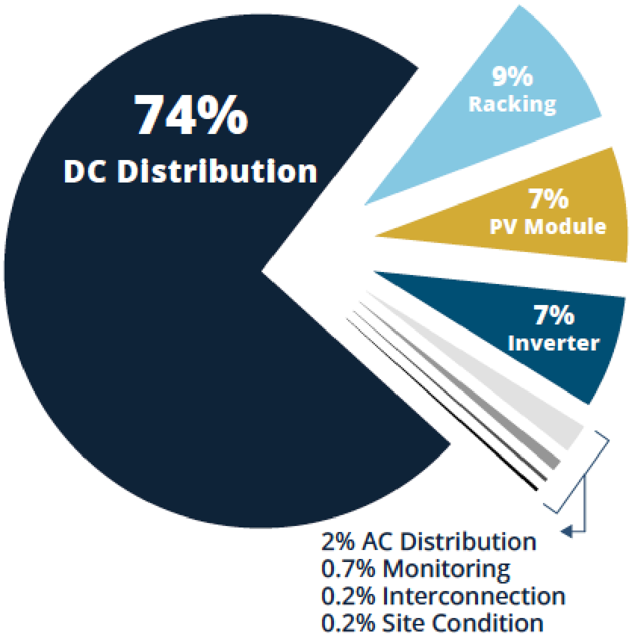
Inspections – What other inspectors have found

DC Distribution System is Currently the Most Critical Inspection Topic

Heliovolta "The SolarGrade Health Report" 1st Edition - https://solargrade.io/heliovolta/

74% of all issues were located in the **DC Distribution** section of PV systems.

SHARE OF ISSUES BY PV SYSTEM SECTION



Inverters often appear to cause PV system problems: they are usually the primary source of energy yield data and error messages when PV systems trip and shut down.

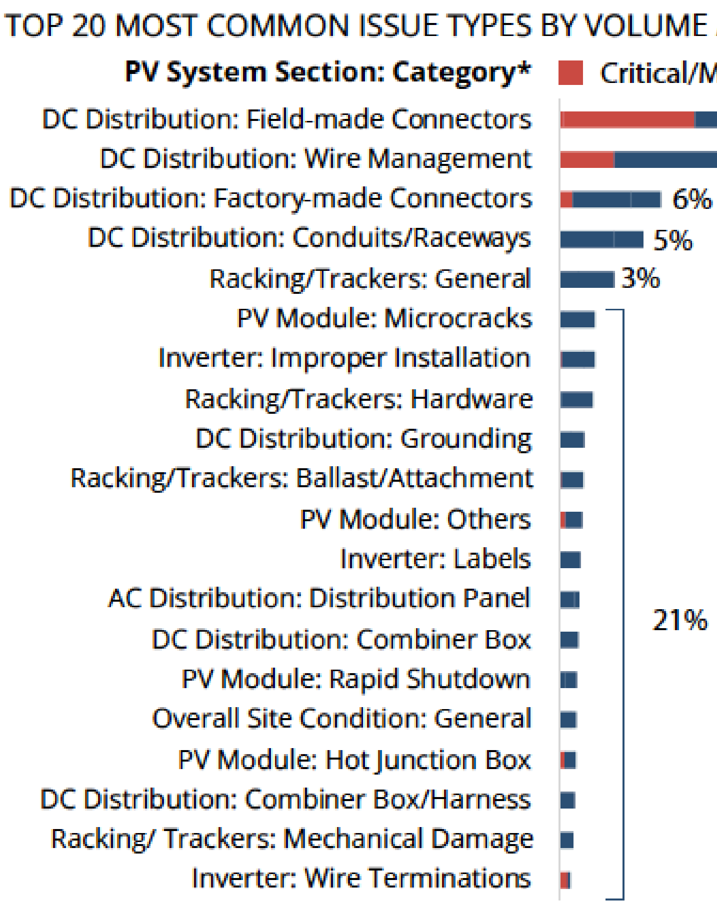
Yet, on-the-ground data reveals that inverters are rarely the root cause of downtime. In most cases, inverters trip because they detect underlying issues located within the DC Distribution section.

WHAT YOU SHOULD KNOW

DC Distribution issues are more likely to present safety risks than issues in any other section of the system.

Inspections – What other inspectors have found

59% of all issues are related to **field-made connectors and wire management** in DC Distribution.



This chart shows the 20 most frequently observed issue types, or categories. They make up 94% of all observed issues.

Connectors and wire management top the list. PV systems contain more wires and connectors than any other piece of equipment, so these categories are expected to have higher quantities of issues.

*Y-axis labels specify issue sections (or locations) and categories (or types). SolarGrade's automated interactive and PDF reports use this structure.

Heliovolta "The SolarGrade Health Report" 1st Edition - https://solargrade.io/heliovolta/

Inspections – Visual

1. **DC String Wiring**
    1. MC4 Connectors
        1. Mis-mating
        2. Signs of heat damage – melting
        3. Examine with IR camera
        4. Mark each for replacement

Photos by FLIR

Photo by Heliovolta

Photo by Kevin Watson, LBNL

Inspections – Visual Only

1. **DC String Wiring**
    1. Improper support/securing
        1. Embrittled nylon wire ties
        2. Broken wire ties
    2. Non-rated wire
    3. Wrong gauge
    4. Excessive lengths
    5. Turn radius
    6. Contact with combustibles

Photos by Gerald Robinson, LBNL

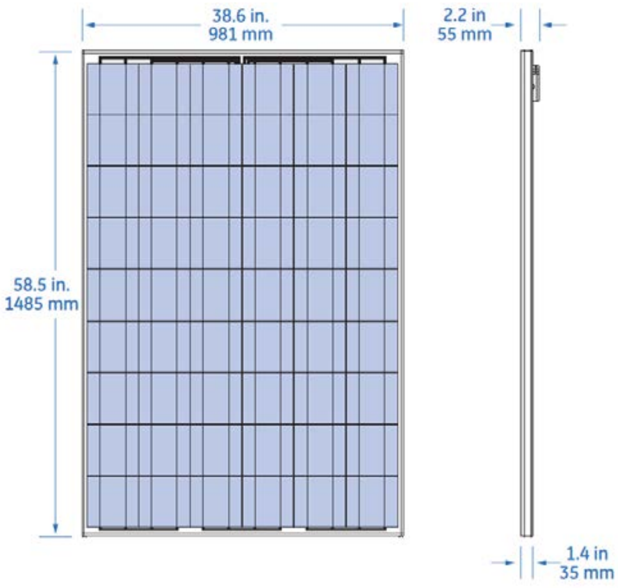
Inspections Requiring Training + PPE

Inspections - PV Performance In Field

1. **Simple, static in-field test to determine performance**
    1. True performance over time is the only way to measure, however a snapshot can provide clues.
2. **String-level testing (requires training and PPE)**
    1. If using IEC 62446 – only use Imp and Vmp
3. **Individual module testing (requires training and PPE)**
    1. Used only after clamp on DC meter confirms no current on the connected string

Great Lakes Science Center Example

PTC Rating (W) Watts 173.1

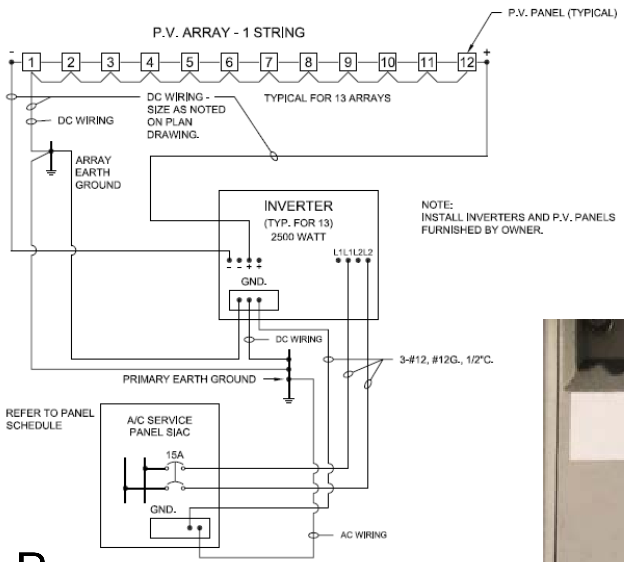


Typical Performance Characteristics

Peak Power (Wp) STC Rating	Watts	200
Max. Power Voltage (Vmp)	Volts	27.1
Max. Power Current (Imp)	Amps	7.4
Open Circuit Voltage (Voc)	Volts	34
Short Circuit Current (Isc)	Amps	7.8
Short Circuit Temp. Coefficient	mA/°C	5.6
Open Circuit Voltage Coefficient	V/°C	-0.12
Max. Power Temp. Coefficient δ	%/°C	-0.5
Max. Series Fuse	Amps	15
Normal Operating Cell Temperature [NOCT]	deg. C	45

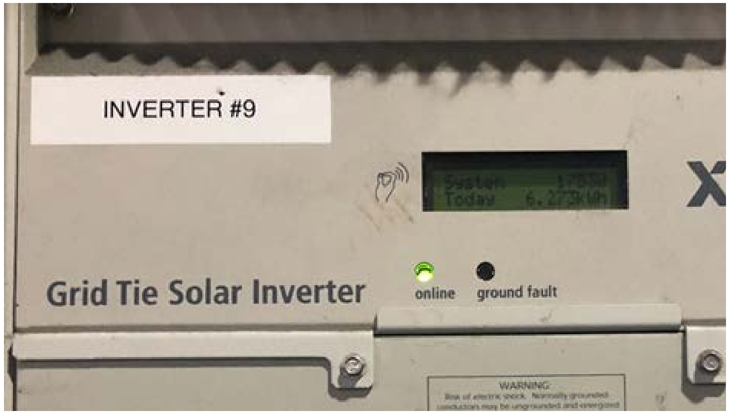
PTC Ratings for Modules:
https://solarequipment.energy.ca.gov/Home/PVModuleList

P_{PTC} and P_{out}



P_{PTC}
= 12 modules * 173.1 W/module
= 2077 W

P_{out}
From inverter
In this photo = 1753 W



Solar Measurement

Gref = 1000 W/m2 (full sun)
Measure sunlight perpendicular to the rays

Performance Ratio (PR)

η_{BOS} = balance-of-system efficiency; **say η_{BOS} = 0.90** for example
degr = an age degradation factor that is 1.0 initially but degrades at o.6 to 1.0%/year
After 10 years say degr = 0.94
δ = temperature coefficient of power (1/°C), which is usually on the order of 0.004 1/°C
In our case it is 0.005 1/C

$$\frac{1}{\left\{\eta_{BOS} * degr * \left(1 - \delta(T_{ambient} - 20C)\right)\right\}}$$

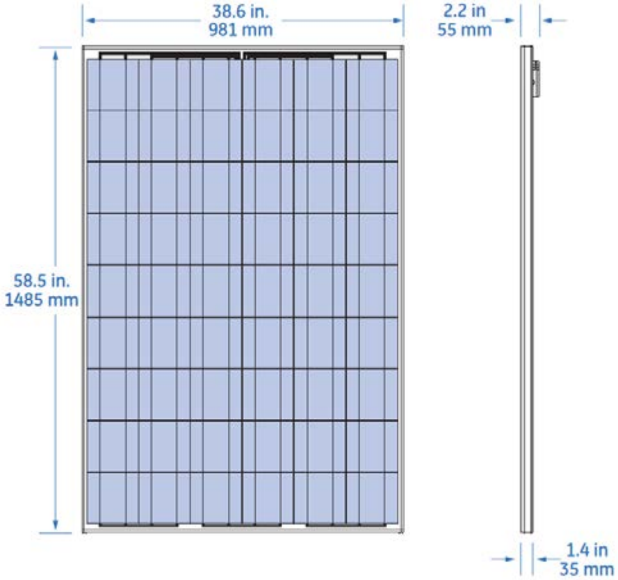
= 1/(____ * ____* (1-0.005(____C – 20C))

=_____

PR = (_______ W)/(2077 W) * (1000 W/m2)/(______W/m2)* 1.22

Inverter Number #____ PR =_________

Great Lakes Science Center Example



PTC Rating (W)	Watts	173.1

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Short Circuit Current (Isc)	Amps	7.8
Short Circuit Temp. Coefficient	mA/°C	5.6
Open Circuit Voltage Coefficient	V/°C	-0.12
Max. Power Temp. Coefficient δ	%/°C	-0.5
Max. Series Fuse	Amps	15
Normal Operating Cell Temperature [NOCT]	deg. C	45

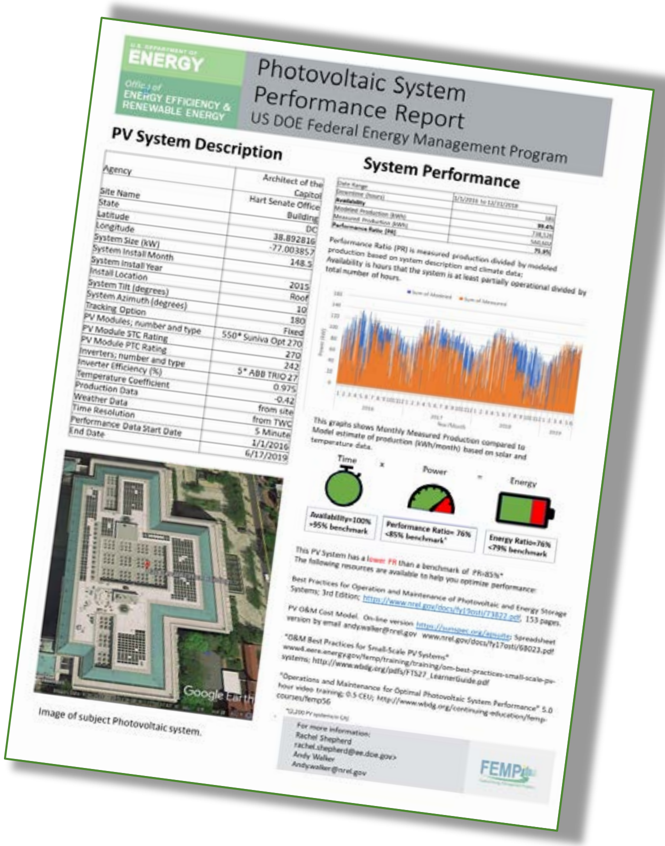
PTC Ratings for Modules:
https://solarequipment.energy.ca.gov/Home/PVModuleList

Inspections - PV Performance – String Level

1. **Simple steps to string level Imp test**
   1. Number of modules on string*Imp rating of one module = total Imp for string calculated.
   2. Measure amps at combiner box or at string inverter.
   3. Measure irradiance parallel to module surface in field and divide by 1,000 W/M^2 = available solar resource as a percentage.
   4. Multiply calculated string Imp*available solar resources = Imp for string adjusted for irradiance levels.
   5. Compare the measured against the calculated Imp adjusted for irradiance levels. If measured is >=15% then further electrical testing is needed to find cause.
      1. Rule out module degradation.

FEMP PV System Performance Assessment

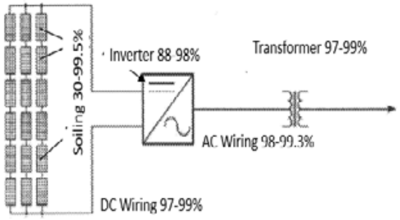
- **Information from Site**
  - System description
  - Production data (time series)
- **Information from NREL Analysis**
  - Solar resource data
  - Temperature data
  - Performance model (SAM)
- **Results**
  - **Availability** (% uptime)
  - **Performance Ratio** (measured/modeled production when available)
  - **Energy Ratio** (measured/modeled energy)
- **Goals**
  - For sites: Identify performance potential and provide resources
  - For FEMP: Inform future feasibility studies; informative discussions with site staff



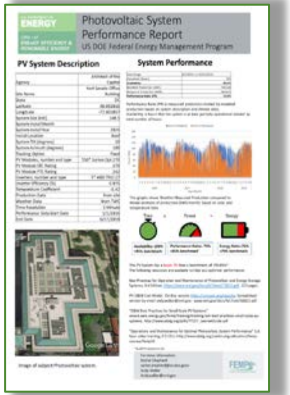
Performance Evaluation

Production Meter

Record of Measured Production



System Description



Performance Evaluation

SAM

Modeled Production

Satellite Sensors

Solar Radiation Data
Temperature Data

Mickey Leland Case Study

- Demonstrates the impact of the analysis and monitoring
- PV production data indicated an anomalous dip in production around August 2018, which was attributed to a problem with an inverter. General Services Administration staff worked with their O&M contractor to identify the specific issue. After the repair was completed in August 2019, PV production returned to expected levels—as shown by the improved system performance metrics.

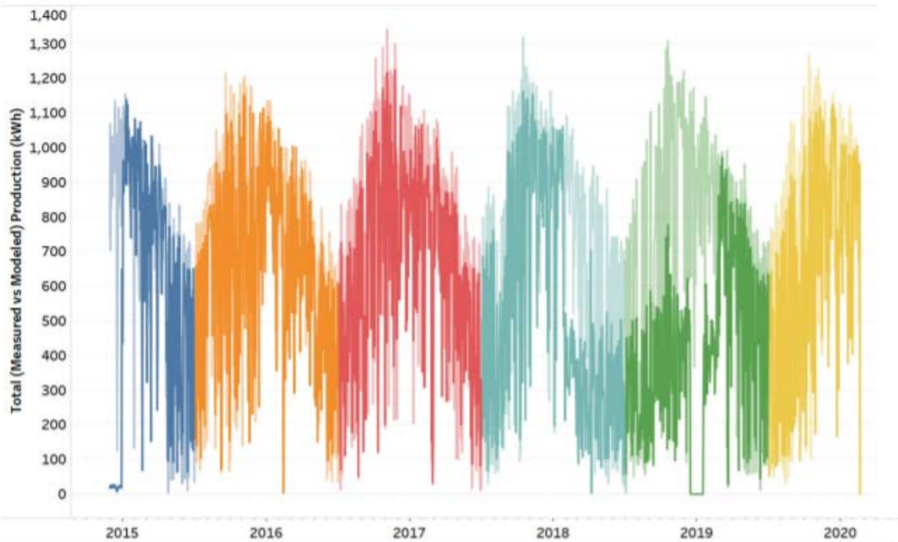


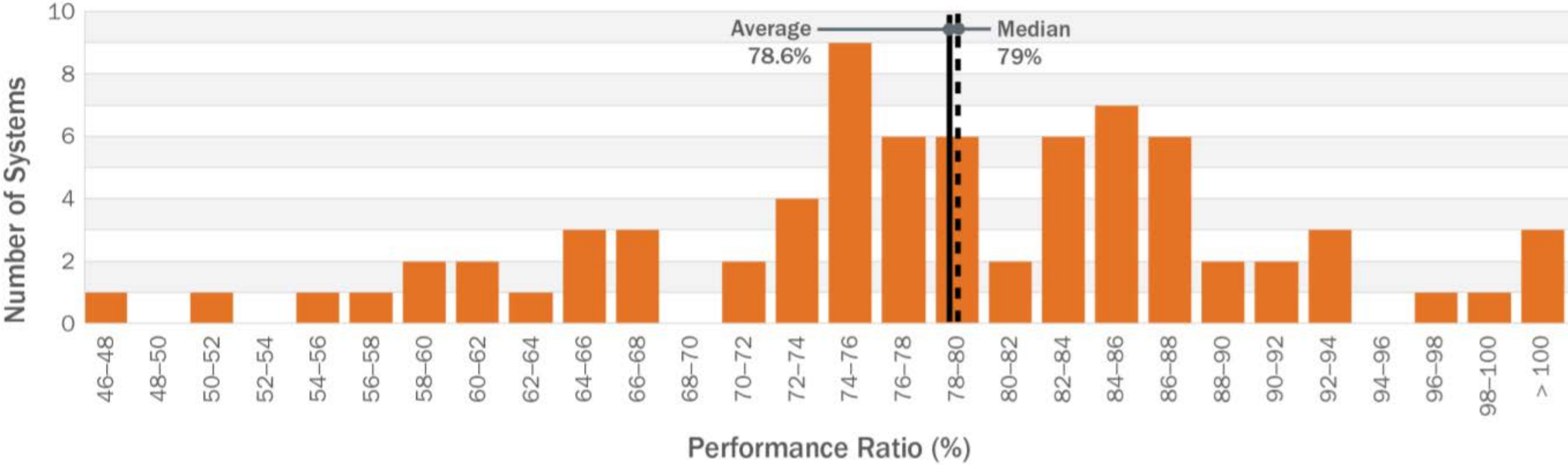
Figure 2. System performance at the Mickey Leland site. This graph shows the total daily measured production (darker shade) compared to total daily modeled estimate (lighter shade) across 5 years and 2 months of production (kWh).

Table 1. Annual PV Performance Metrics for the Mickey Leland Site

	2015 (June–December)	2016	2017	2018	2019	2020 (January–August)	Total
Availability	85%	98%	98%	97%	89%	97%	94%
Performance Ratio	99%	91%	91%	78%	66%	91%	85%
Energy Ratio	81%	90%	90%	77%	58%	89%	80%

https://www.energy.gov/sites/default/files/2021-10/mickey-leland-federal-building-fact-sheet.pdf

FEMP PV Performance Assessment: Performance Ratio



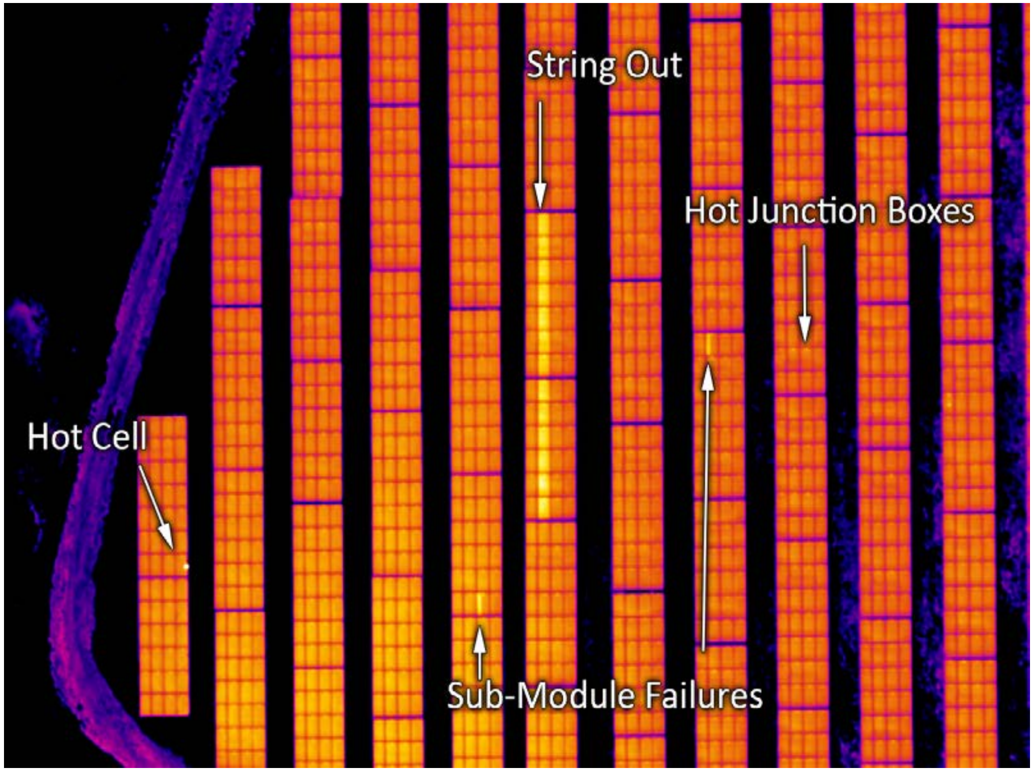
	Minimum	Average	Median	Maximum	Standard Deviation
Performance	46.0%	78.6%	79.0%	101.0%	11.7%

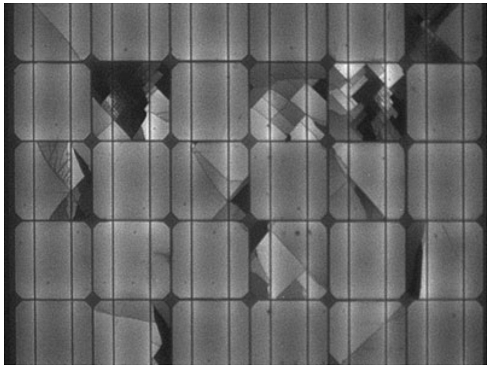
Inspections – Drone or Aircraft

Large systems, mass module concerns:

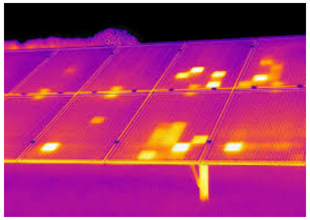
- Common methods
  - IR
  - Electroluminescence (EL)
  - UV - Florescence

- Drone or aircraft with equipment having software to process images and provide real information
- High accuracy in identifying issues affecting performance.



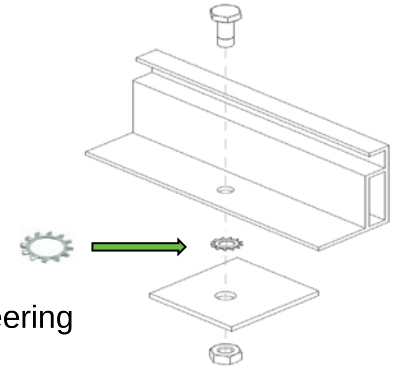


Photos by NREL



Equipment Bonding Conductor – Module Fastener Stack

- Equipment bonding loss due to corrosion, galvanic action is serious issue.
- Field inspection of loosened joint show evidence of serious corrosion and probable electrical resistance.
- Using fastener stack as bonding pathway is problematic and needs to be checked for resistance.
- These joints will loosen chronically



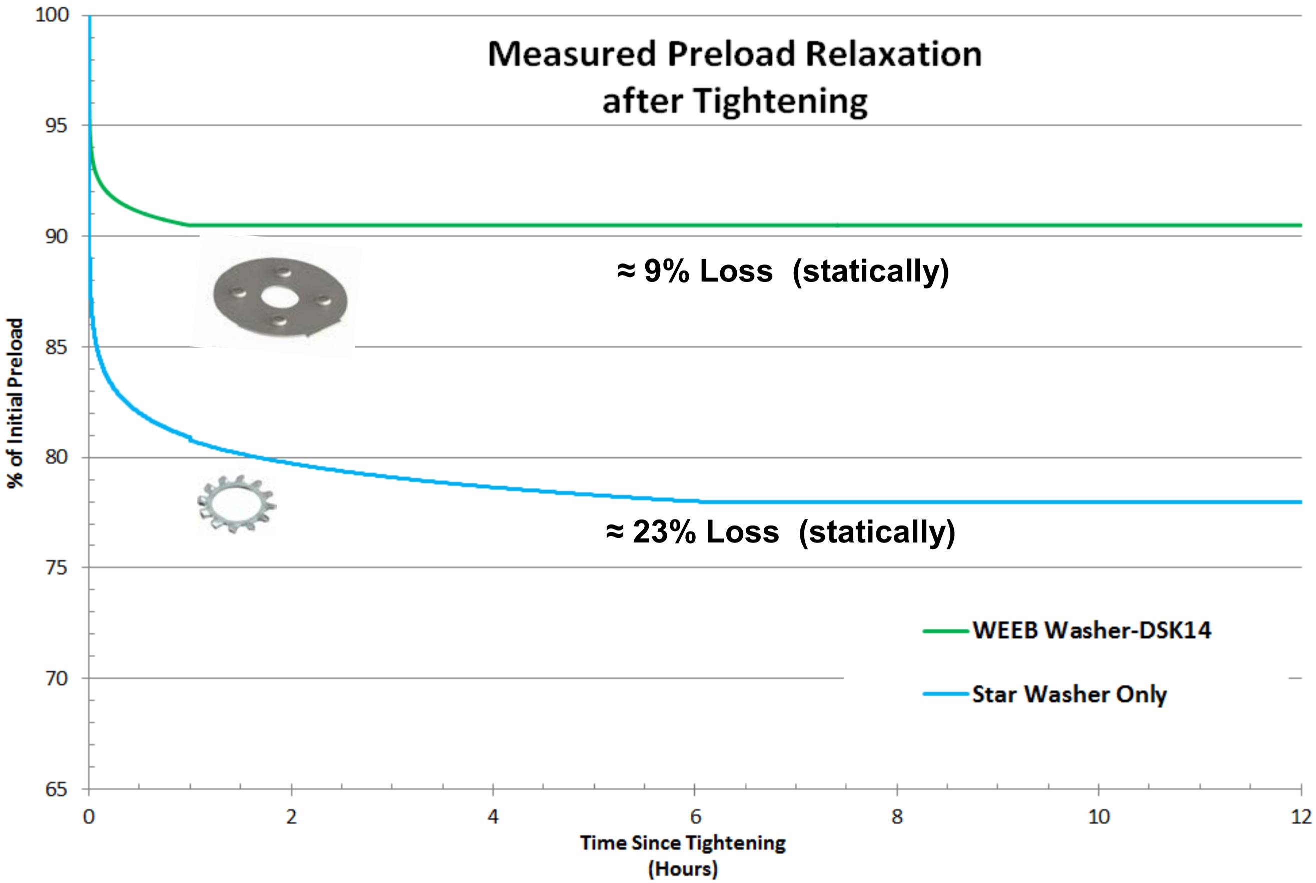
Images by Matrix Engineering

Code/Standard	Applicability
UL 467	Describes how to create grounding and bonding pathways between non-current carrying components e.g. modules, racking systems, equipment.
UL 2703	Solar PV specific and covers topics related to both bonding and fasteners.
NEC 250	Lists required equipment, location of grounding connections, methods and capacities of devices.

Useful Reference Materials
1. https://ases.org/wp-content/uploads/2021/11/Corrosion-in-Solar-PV-Grounding-and-Bonding-.pdf
2. https://hubbellcdn.com/brochure/WIL_WEEB_Washer_Guide_Washer_Theory_BRO.pdf

Equipment Bonding Conductor – Module Fastener Stack

Ongoing - Experimental Work



Inspections – Special Circumstances Rack movement

High deflection, low resonate frequencies and lateral movement:

- Unanticipated strong compound forces on fasteners
- Modules will fatigue and fail
- Cascading failure effects
- Requires some re-engineering after root causes are understood

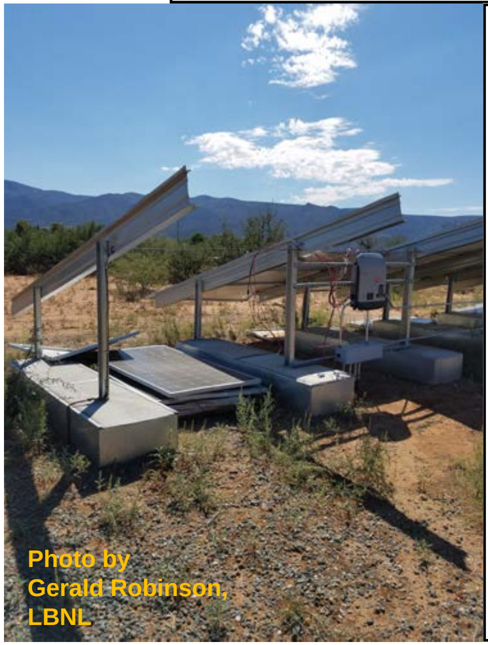
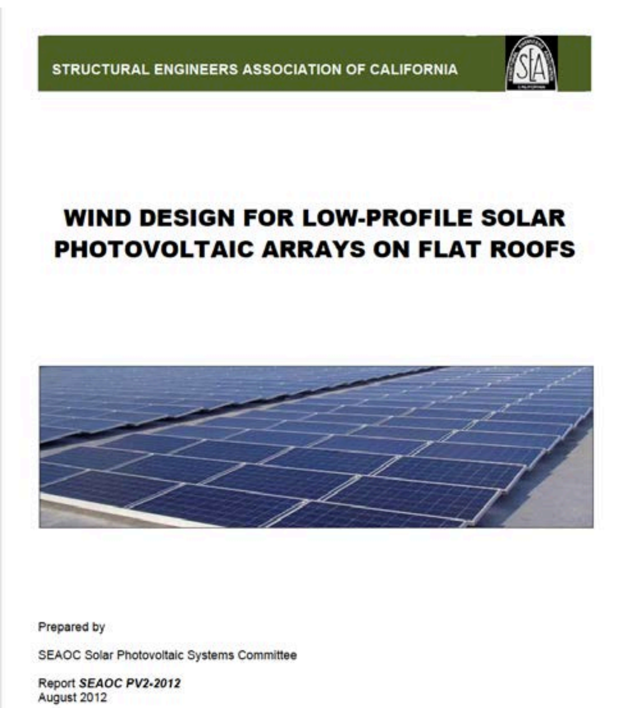


Photo by Gerald Robinson, LBNL

Inspections – Special Circumstances Flat Roof

1. Entrapment of array and roof system.
2. Fully ballasted vulnerable to wind events.



STRUCTURAL ENGINEERS ASSOCIATION OF CALIFORNIA

WIND DESIGN FOR LOW-PROFILE SOLAR PHOTOVOLTAIC ARRAYS ON FLAT ROOFS

Prepared by

SEAOC Solar Photovoltaic Systems Committee

Report *SEAOC PV2-2012*
August 2012

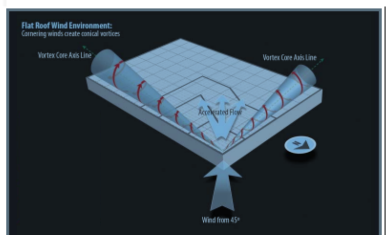


Figure 3: Corner vortices on a roof top (Figure courtesy Cermak Peterka Petersen)

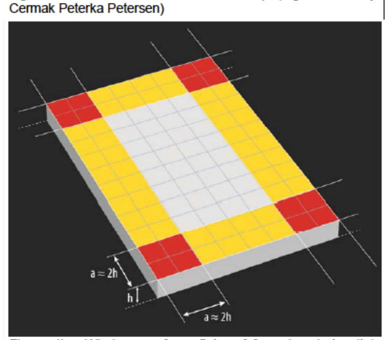
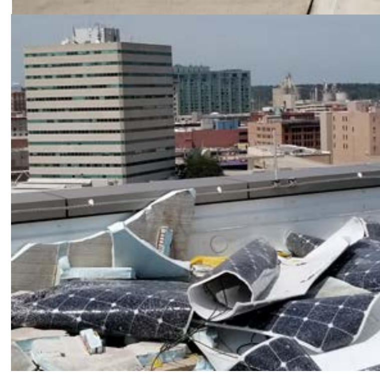


Figure 4b: Wind zones for a flat roof for solar photovoltaic array wind loading (Diagram courtesy Cermak Peterka Petersen)



O&M Implementation

Contract versus Self-Perform O&M

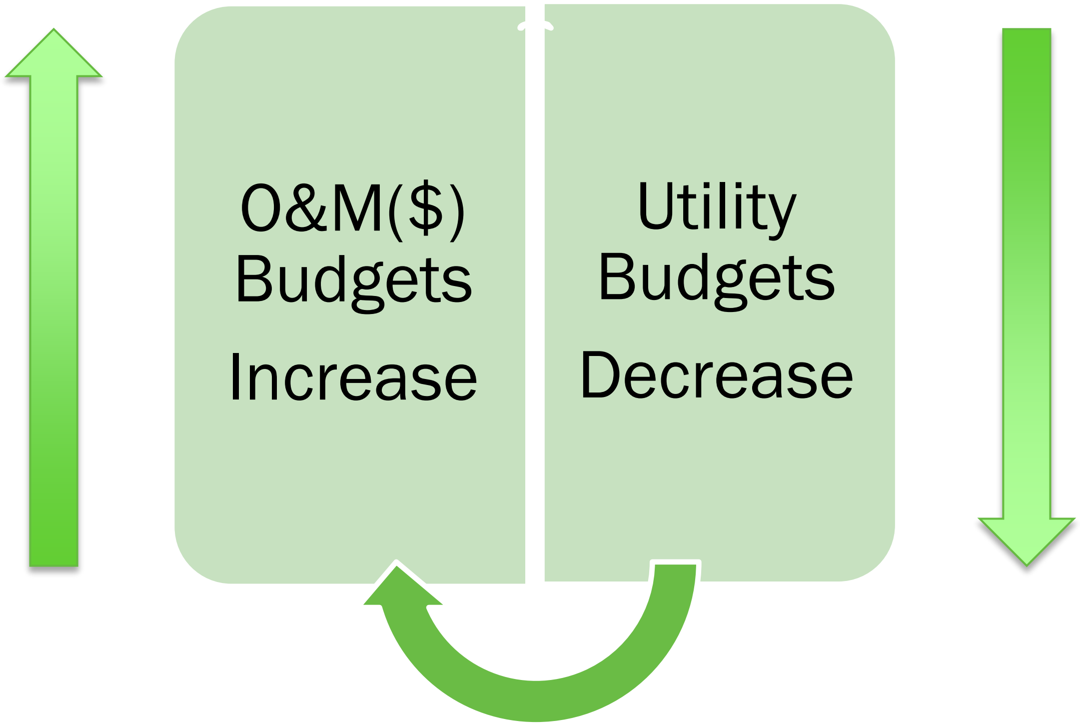
	Pros	Cons
Self-Perform	1. Full control over the service delivery 2. Fast response times	1. Often lack staff capacity and skill 2. Difficult to administrate warranty claims 3. Staff changes
O&M Service Firm	1. Have specialized staff, skills and tools 2. Labor, vehicle and other expenses are tax deductible expenses 3. Contractor can maintain continuity through agency staff changes	1. Contracts are hard to solicit for and monitor consistently

Procurement Vehicles - Contracted

Procurement Vehicle	Description	FEMP Resource
"Full & Open"	Traditional contracting method requiring development of a whole RFP and contract package	Operations and Maintenance (O&M) Request for Proposal Template for Government-Owned Solar Photovoltaic (PV) Systems - https://www.energy.gov/femp/articles/operations-and-maintenance-om-request-proposal-template-government-owned-solar
GSA Supply Schedule	Issue simple scope of work document with simple selection of contractor	Scope of work document "Performance Work Statement (PWS)"
Site Operating Agreements (e.g. BOSS)	Add simple scope language existing contract	FEMP to issue template language in FY24
Performance Approach	Utilize ESPC contract authority for O&M contracting	FEMP looking for demonstration site
ESPC/UESC	Add long-term O&M requirements to ESPC/UESC	

O&M Budget Considerations – Color of Money

- O&M Budgets Increase & Utility Budgets Decrease
- Made complicated by headquarters level budgeting



Reducing Cost and Improving Performance

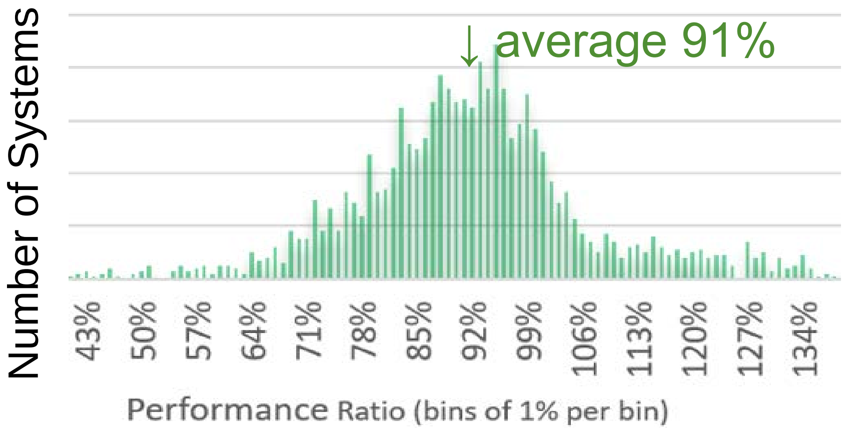
PV O&M Costs vary widely, but reported between $10 and $20/kW/year

At $15/kW/year, O&M adds about $0.01/kWh to cost of energy

Performance Ratio = actual production/expected production

5% performance loss adds about $0.005 to the cost of energy

Performance can be improved with comprehensive O&M (overall average increase from 91% to 95%



Optimal (100%)

- Quality assurance system in the planning and construction phases
- Comprehensive asset management
- Good preventative O&M
- Good corrective O&M

Good (50–75%)

- Comprehensive asset management
- Good preventative O&M
- Good corrective O&M

Under-Performing (lowest 25%)

- Little or no preventative O&M
- Some corrective O&M
- Can be increased from 83% to 94%

Average (25–50%)

- Some preventative O&M
- Good corrective O&M
- Can be increased from 89% to 94%

Performance data from 2,200 PV system in oSPARC

PV O&M Cost Model Inputs

Inputs

General Inputs		
Analysis Period (Project Life)	25	years (40 max)
Discount Rate	7.00%	% per annum
Inflation Rate	2.00%	% per annum
Desired Confidence that Reserve Covers Cost	0.92	
Working Hours/year	2,080	

System Inputs		
Name of System	Ground Mount Tracking	
Location	Denver, CO	
System Size (kWp DC)	10,000.0	
Energy Yield Year 1 (kWh/kWp/year)	1,400.0	
System Installed Cost	$3,000,000	
Module Efficiency	16.0%	
Module Power (W STC)	305	
Array Area (m2)	62500	
Number of Modules	32787	
Module Type/ Degradation	Mono-crystal silicon: 0.36%/year	
Degradation Rate per year	0.0036	
Modules per String	14	
Number of Strings	2342	
Strings per Combiner Box	15	
Number of Combiner Boxes	157	
Combiner boxes per DC disconnect	1	
Number of DC Disconnects	157	
Inverter Type	Central Inverter	
Inverter Replacement Cost/ Wp	$0.190	
Number of Inverters	10.0	
Inverter Capacity (kWp)	1,000.0	
Number of Transformers	10.0	
Inverter Warranty (years)	10.0	
PV Module Product Warranty (years)	10.0	
Other equipment (EPC) Warranty (years)	1.0	
Purchased monitoring contract (years)	0.0	Enter '0' if not applicable

Market Sector	Utility (1 MW)
Mounting Location	Ground Mount
Roof Slope	Sloped, 4:12
Type of Roofing Material	Composite Shingle
Mounting Type	Attached
Inspection technique	Arial
Array Area per Roof Attachment (m2)	2.0
Number of Roof Attachments	31250
Ground Coverage Ratio (GCR)	33%
Site Area (acres)	52.6
Modules/Row	200
Total Rows:	164
Tracking or Fixed	1-axis Tracking
Rows per Tracked Block:(ignore untracked)	16
Total Tracking Blocks:(ignore untracked)	10.2
Foundations per row: (ignore rooftop)	10

Environmental Conditions	
Indicate "1" if condition applies to project, "0" if not applicable	
Snow	0
Pollen	1
Bird Populations	0
Sand/Dust	0
Humid	*Not yet implemented*
Hot	*Not yet implemented*
High Wind	*Not yet implemented*
Hail	*Not yet implemented*
Salt Air	*Not yet implemented*
Diesel Soot	*Not yet implemented*
Industrial Emissions	*Not yet implemented*
Construction Site Nearby	*Not yet implemented*
High Insolation	*Not yet implemented*

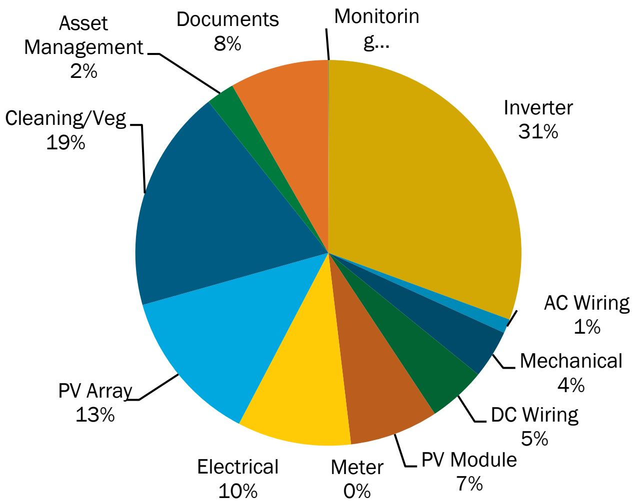
Inverter Types - Replacement Costs

Inverter Types	20 Year Replacement Cost ($/W)
String Inverter	$0.30
DC Optimizer	$0.02 - 0.06
Central Inverter	$0.19
Microinverter	$0.51

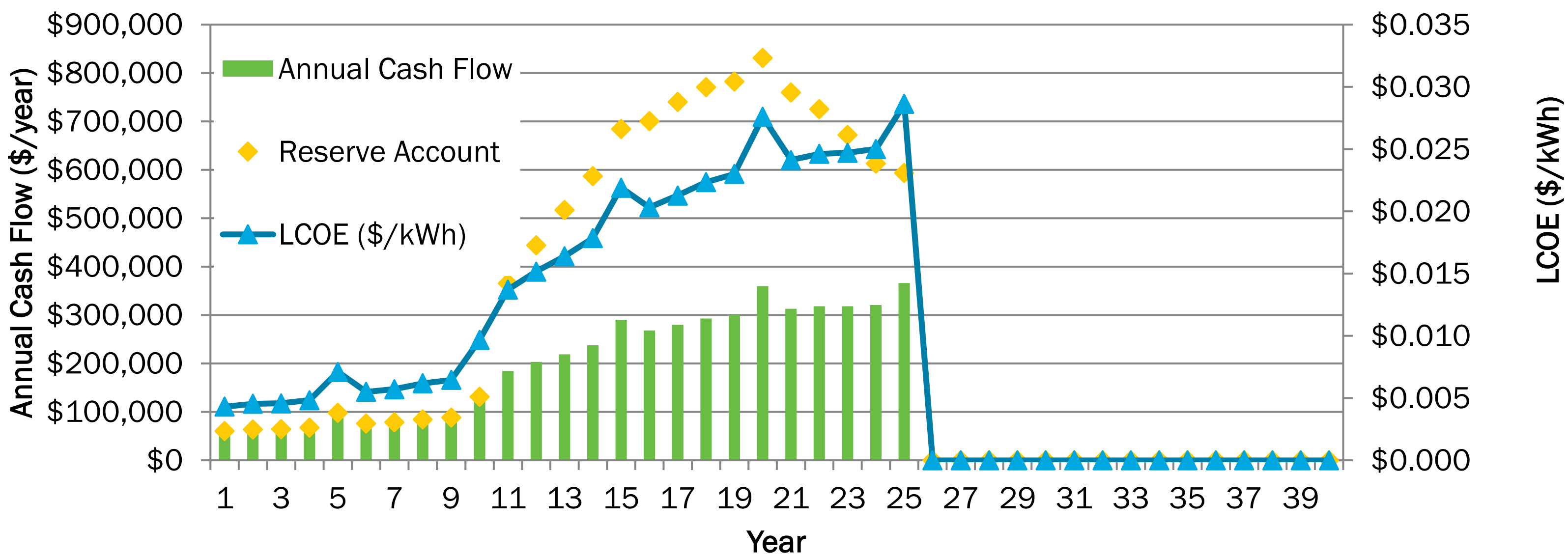
Q4 2015/Q1 2016 April 29, 2016. David Feldman NREL Daniel Boff DOE; Robert Margolis NREL

PV O&M Cost Model Results

Results on 100 kW Rooftop PV System	
Annualized O&M Costs ($/year)	$126,471
Annualized Unit O&M Costs ($/kW/year)	$12.65
Maximum Reserve Account (year 20)	$831,685
Net Present Value O&M Costs (project life)	$1,800,124
Net present value (project life) per rated power	$0.180
NPV Annual O&M Cost per kWh	$0.011



High LCOE in Late Performance Period



- Warranties have expired
- Inflation has raised parts and labor prices
- The Weibull failure distributions show high failure rates in later years
- On a per kWh basis, performance had degraded (0.5%/year)

O&M Activities

- **Administration**
  - Billing; accounting
  - Hiring subcontractors
  - Enforcement of warranties
  - Management of budget and reserves
- **Monitoring**
  - Metering for performance and safety
  - Alarms
  - Diagnostics
- **Preventive Maintenance**
  - Scheduled and planned
  - Expenditure is budgeted
- **Unforeseen Maintenance (repair)**
  - Unplanned or condition-based
  - Possible expenditure is kept in reserve or line-of-credit
  - Must be timely and effective

Inspection of a 67-kW PV system at Mesa Verde National Park. Photo by Andy Walker, NREL

O&M Plan Details

- **Administration**
  - –Billing; accounting
  - –Hiring subcontractors
  - –Enforcement of warranties
  - –Management of budget and reserves
- **Operations**
  - –Controls
  - –Utility interaction
- **Preventive Maintenance**
  - –Scheduled and planned
  - –Expenditure is budgeted
- **Monitoring**
  - –Metering for revenue
  - –Alarms
  - –Diagnostics
- **Unforeseen Maintenance (repair)**
  - –Unplanned or condition-based
  - –Possible expenditure is kept in reserve or line-of-credit
  - –Must be timely and effective

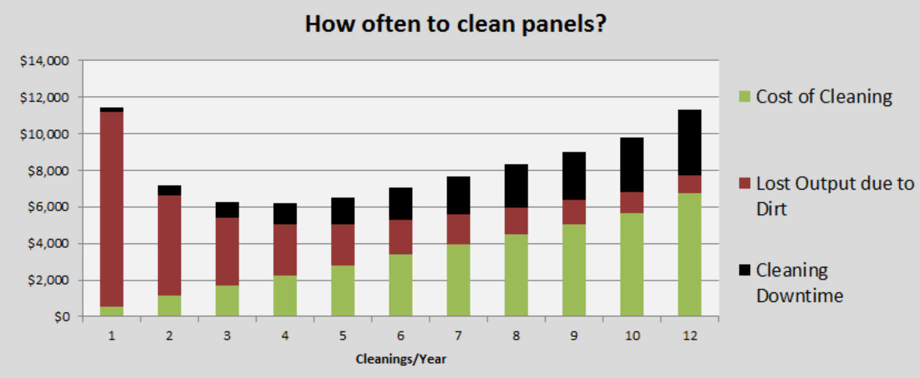
PV O&M Manual

Table of Contents

1. Contact information
2. System descriptions
3. Performance estimates and shade studies
4. Training plans
5. Chronological O&M log
6. Operational indicators, error messages
7. Manufacturer's preventive maintenance
8. Responding to alerts and re-acceptance
9. Troubleshooting guide
10. Criteria for repair or replacement
11. Equipment lists
12. Inventory of spare parts
13. Operator manuals
14. Warranties
15. Commissioning, inspection, work order, repair reports
16. Contracts
17. O&M budget

Cleaning Solar PV – Much Debated

- Most rely on rain to keep the array clean; no cleaning regimen
- Dirty modules run hot = loss of life
- Cleaning improves output by 6% [SMUD] or 7.4%
  about 0.05% reduction in output per day due to dirt
- Depends on local sources of dirt
  (e.g., diesel soot, dust, construction, agriculture, industrial pollution)
- Depends on dust corrosiveness
- Optimize cost of cleaning versus improvement in performance (see example below)
- Adapt cleaning schedule to rain,
  pollen season, bird season, etc.
- Clean PV modules with plain water
  or mild dishwashing detergent
  Do not use brushes, any types
  of solvents, abrasives, or harsh detergents
- Cleaning robots are available for
  large systems



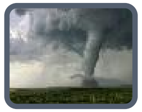
Inverter Topology & Inspection + O&M Scope

Central Inverter

- Must follow manufacturer's instructions on O&M to not void warranties
- Involves much more DC wiring, which might require more repair vs. AC wiring
- Electricians need extensive PPE when working on the system
- Disconnects can be more costly
- Monitoring is less complicated vs. micro/string inverters
- Numerous subsystem repairs are supported vs. replacing the whole unit in micro/string inverters
- Fans, filters and screens
- Gasket condition
- Corrosion of cabinet
- Screen – indicating faults and power, energy

Hurricanes/Typhoons

- Eastern Seaboard, FL, TX, NC, SC, Guam, American Samoa



Tornadoes

- TX, OK, KS, NE, CO, SD

Earthquakes

- AK, CA, NV, HI, WA, WY, ID, MT, OR

Hail

- TX, AZ, CO, WY

Flooding

- FL, LA

Wildfires

- Western States

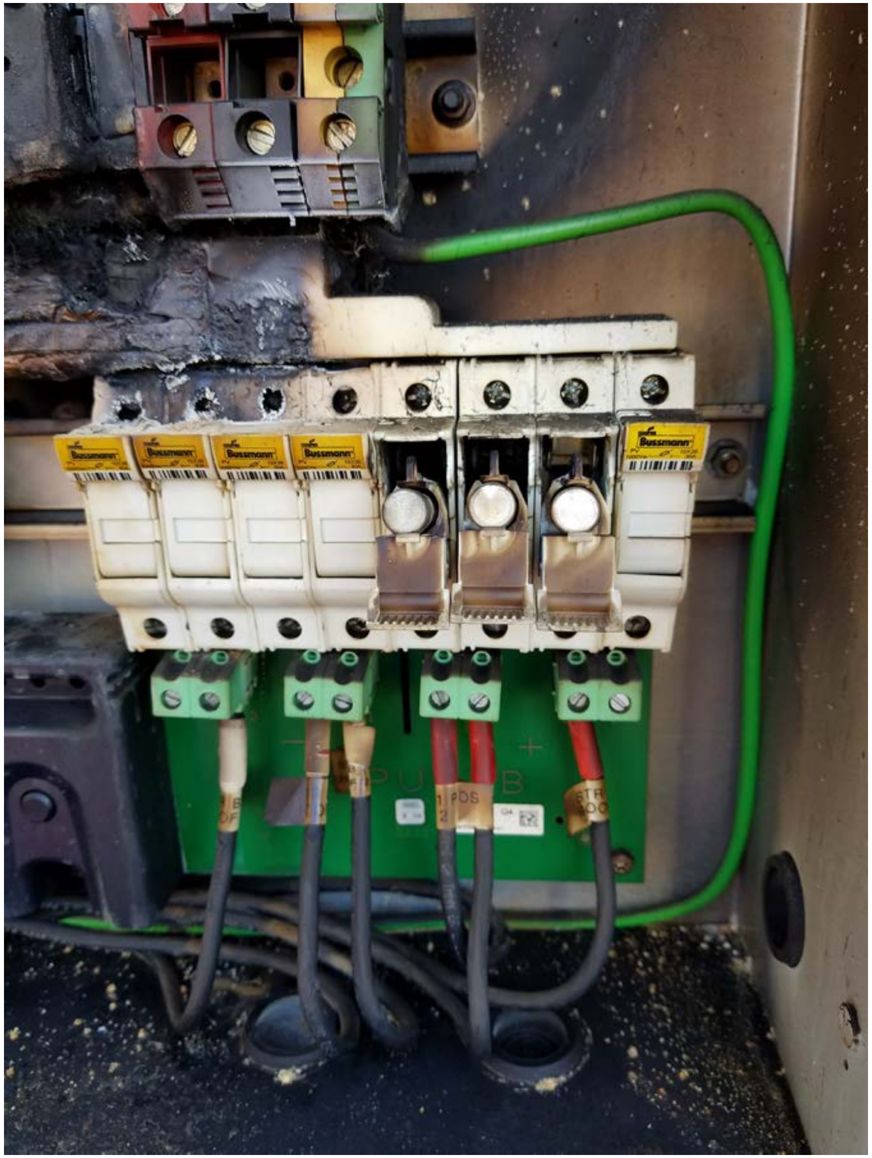
Photos of hurricane, hail and flooding by Andy Walker, NREL
Photos of Tornado, earthquake, wildfire from Powerpoint Stock Images

Before The Storm Event Hits

Measure	Action(s)
Power it all down!	✓ Turn all disconnects into “open” position ✓ Use qualified and trained personnel only
Prepare site	✓ Remove debris and loose material from in and around array or lash down ✓ Remove trees and branches at risk of falling on array
Check fasteners and bolted joints	✓ Implement formal torque audit and take actions to tighten fasteners based on outcome ✓ Replace any missing fasteners
Electrical equipment and conduit	✓ Inspect gasketing in cabinets and make sure all equipment doors are closed with compression latches tight
General	✓ Replace or backup plastic wire ties with metal versions or clips and or other means for securing string wiring

O&M: Key Role in Preventing Storm Damage

- ✓ Prep an array prior to storm arrival
- ✓ Identify and correct construction defects
- ✓ Bring array back online quickly without causing severe unintended damage to electrical system

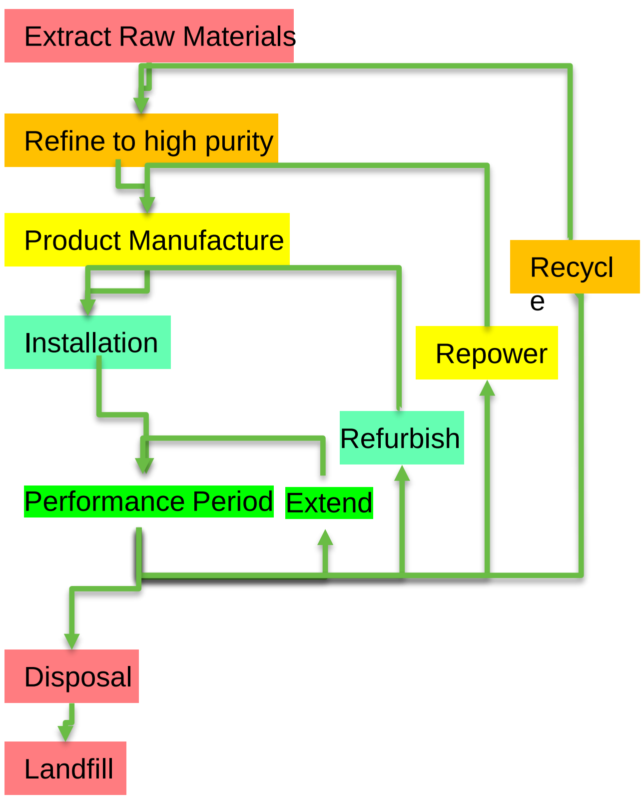


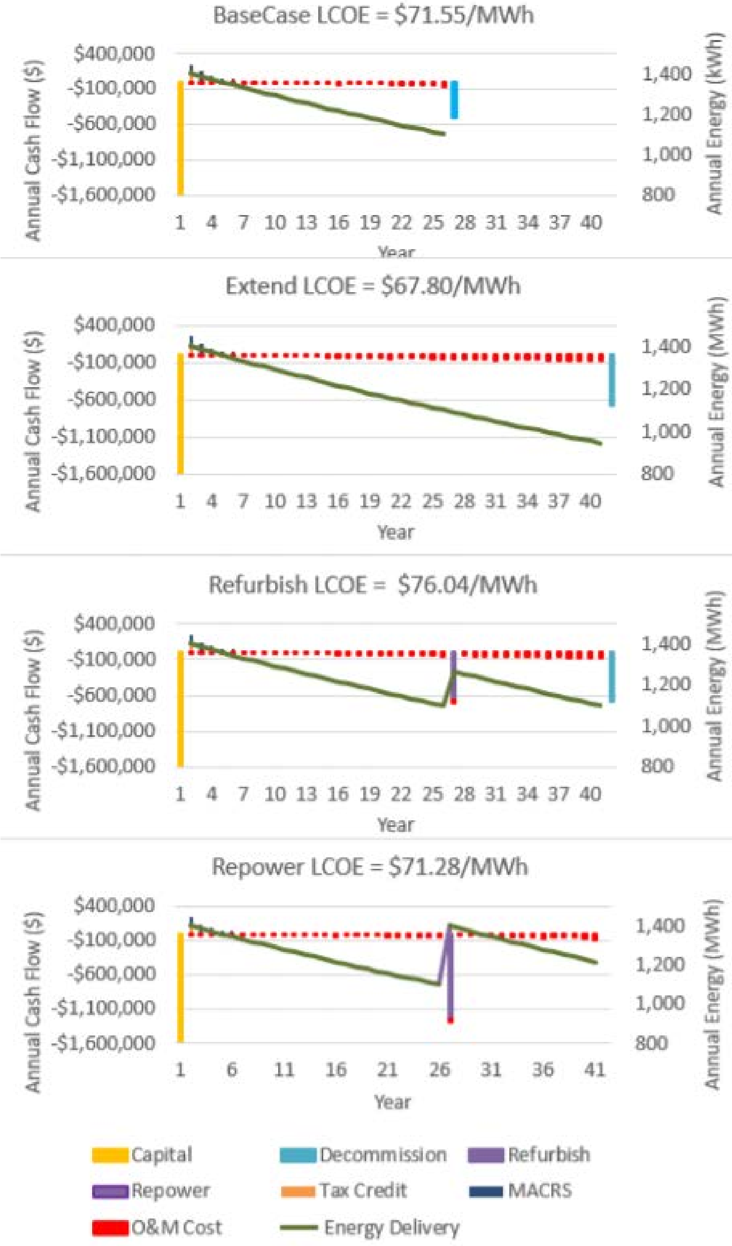
After The Storm Event

Measure	Action(s)
Test before you power up!	✓ Each component of electrical system must be tested for faults, compromised wire insulation and loose lugs ✓ Megger test all wiring if possible ✓ Don't forget transformer – test for damage to windings ✓ All cabinets dried out first and if inundated with salt, cleaned by a licensed electrician ✓ Over current protection devices and disconnects may need to be serviced professionally ✓ Drain any standing water from conduit ✓ Don't forget to test power feed to meters and weathers stations
Manage array damage	✓ Remove trees and branches at risk of falling on array
Check fasteners and bolted joints	✓ Implement formal torque audit and take actions to tighten fasteners based on outcome ✓ Replace any missing fasteners
Electrical equipment and conduit	✓ Inspect gasketing in cabinets and make sure all equipment doors are closed with compression latches tight
General	✓ Replace or backup plastic wire ties with metal versions or clips and or other means for securing string wiring

Best Practices at the End of Performance Period

Decommission
Extend Performance Period
Refurbish
“RE-Power”
Recycle





Photos from Images.NREL.gov 48004, 21769, 60066 (Dennis Schroeder), 5292 (David Parsons)

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Question & Answers

Reference Slides

Wire Sizing

- Ampacity Requirements (safety): 1.25*1.25* amp
- Refer to section 300 of NEC
- Wire Length for 2% Voltage Drop in 12 V

Amps	#14	#12	#10	#8	#6	#4	#2	#1/0	#2/0	#4/0
1	45	70	115	180	290	456	720	.	.	.
2	22.5	35	57.5	90	145	228	360	580	720	1060
4	10	17.5	27.5	45	72.5	114	180	290	360	580
6	7.5	12	17.5	30	47.5	75	120	193	243	380
8	5.5	8.5	11.5	22.5	35.5	57	90	145	180	290
10	4.5	7	11.5	18	28.5	45.5	72.5	115	145	230
15	3	4.5	7	12	19	30	48	76.5	96	150
20	2	3.5	5.5	9	14.5	22.5	36	57.5	72.5	116
25	1.8	2.8	4.5	7	11.5	18	29	46	58	92
30	1.5	2.4	3.5	6	9.5	15	24	38.5	48.5	77
40	.	.	2.8	4.5	7	11.5	18	29	36	56
50	.	.	2.3	3.6	5.5	9	14.5	23	29	46
100	.	.	.	.	2.9	4.6	7.2	11.5	14.5	23
150	.	.	.	.	.	.	4.8	7.7	9.7	15
200	.	.	.	.	.	.	3.6	5.8	7.3	11

- Conduit: conductor fills 40% of cross sectional area

Wire Selection

Use only 90C (not 60 or 75C) temperature rating

Type	*Temp. °C/°F*	*Moist*	*Condui Req.*	*Sunlight Res.*
PV	**90/194**	**Wet**	**No**	**Yes**
THHN	90/194	Damp	Yes	No
THWN	75/167	Wet	Yes	No
THWN	90/194	Dry	Yes	No
THWN-2	90/194	Wet	Yes	No
THW	75/16	Wet	Yes	No
THW-2	90/194	Wet	Yes	No
RHW	75/167	Wet	Yes	No
RHW-2	**90/194**	**Wet**	**Yes**	**No**
RHH	90/194	Damp	Yes	No
USE	75/167	Wet	No	Yes
USE-2	**90/194**	**Wet**	**No**	**Yes**
UF	60/140	Wet	No	Marked
SE	75/167	Wet	No	Yes

- PV special wire for PV systems
- T Thermoplastic insulation
- H 75°C (Note: lack of "H" indicates 60°C)
- HH 90°C
- N Nylon jacket
- W Moisture resistant
- R Rubber insulation
- U Underground use
- USE Underground Service Entrance *
- UF Underground Feeder *
- SE Service Entrance *
- -2 90°C and wet

Recent Products and Presentations

FEMP Trainings:
“Operations and Maintenance for Optimal Photovoltaic System Performance,”
https://www4.eere.energy.gov/femp/training/.

“O&M Best Practices for Small-Scale PV Systems”
https://www4.eere.energy.gov/femp/training/training/om-best-practices-small-scale-pv-systems

Best Practices in PV O&M. https://www.nrel.gov/docs/fy17osti/67553.pdf
The guide describes how to plan and deliver a cost-effective O&M program including dependencies on system type and condition and how to estimate cost and reserve account requirements. Scopes of work and model contract language are included in appendices.

O&M Cost Model. PV O&M Cost Model is available at http://apsuite.sunspec.org/ the Cost Model User Guide [https://sunspec.org/wp-content/uploads/2016/03/SunSpecPVOMCostModelUserManual-Beta.pdf] that details the methods, assumptions, and calculations behind the on-line annual cost and reserve account calculations.
Open Solar Performance And Reliability Clearinghouse (oSPARC)
http://sunspec.org/sunspec-osparc/

Sandia PV ROM (Reliability, Operations & Maintenance) Database http://energy.sandia.gov/tag/pvrom/
Reference for alpha and beta in Weibull

PV Performance: Standards Organizations

- **UL - Underwriters Laboratories.**
  >Safety Certification, Insurance industry

- **NFPA - National Fire Protection Association.**
  >National Electric Code; Fire Safety Testing

- ASTM - American Society for Testing and Materials.
  >Performance Testing

- IEC - International Electrotechnical Commission.
  >Compliance and Performance Testing

- **IEEE - Institute of Electrical and Electronic Engineers.**
  >Performance Testing

- TUV Rheinland - European.
  >Safety Certification

- CE - European Conformity.
  >Performance Certification

- **CSPC – Consumer Product Safety Commission.**
  >Safety certification.

IEC PV Standards

Technical Committee 82 develops standards for PV. Some of the most relevant include:

IEC 1194 Characteristic Parameters of Stand-Alone PV Systems

IEC 1721 Resistance to Impact

IEC 1727 Characteristics of the PV Utility Interface

IEC 1829 On-site Measurement of i-v Characteristics of Crystalline Silicon PV Arrays

IEC 16904 Photovoltaic Devices: measurement of i-v curve; measurement and reference requirements; and many other requirements related to the characterization of PV cells and modules.

IEC 61215 Crystalline Silicon Terrestrial Photovoltaic (PV) Modules- Design Qualification and Type Approval (2005).

IEC 61646 Thin Film Terrestrial Photovoltaic (PV) Modules- Design Qualification and Type Approval (2008)

IEC 61853 Photovoltaic Module Performance Testing and Energy Rating (2010)

IEC 61730 PV Module Safety Qualification (2004)

IEC 62124 Photovoltaic Stand-Alone Systems- Design Verification (2004)

IEC 61727 Photovoltaic Systems- Characteristics of Utility Interface (2004)

IEC 61683 PV Systems- Power Conditioners-Procedure for Measuring Efficiency (2011)

IEC 62109 Safety of Power Converters for Use in Photovoltaic Power Systems

IEC 62446 Grid Connected Photovoltaic Systems- Minimum Requirements for System Documentation, Commissioning Tests, and Inspections (2009); working on Part II Operations and Maintenance

IEC 62548 Installation and Safety Requirements for Photovoltaic Generators (2011)

Standards Related to PV O&M

- IEC 62446-1, Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 1: Grid connected systems - Documentation, commissioning tests and inspection
- IEC 62446-2, Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 2: Grid connected systems - Maintenance of PV systems
- IEC 62446-3, Photovoltaic (PV) systems - Requirements for testing, documentation and maintenance - Part 3: Photovoltaic modules and plants - Outdoor infrared thermography
- IEC 62548, *Photovoltaic (PV) arrays – Design requirements*
- EC 61724-1:2017
- Photovoltaic system performance - Part 1: Monitoring
- IEC 61724-2 Ed. 1.0, Photovoltaic system performance - Part 2: Capacity evaluation method
- IEC 61724-3 Ed. 1.0 Photovoltaic system performance - Part 3: Energy evaluation method
- IEC TS 61836 Ed. 3, Solar photovoltaic energy systems - Terms, definitions and symbols
- IEC TS 63109 - Information Model for Availability
- NFPA 70E, Standard for Electrical Safety in the Workplace, documents electrical safety work practices enforced in the U.S

IEEE PV Standards

- IEEE 519 Recommended Practices and Requirements for Harmonic Control in Electric Power Systems
- IEEE 927 Recommended Practices for Installation and Maintenance of Lead Acid Batteries for PV Systems
- P929 Recommended Practice for Utility Interface of Photovoltaic (PV) Systems
- IEEE 1145 Installation and Maintenance of Nickel Cadmium Batteries for PV Systems
- IEEE 1262 Recommended Practice for PV Module Qualification PV Module Performance and Reliability
- IEEE 1374 Guide for Terrestrial PV Power System Safety
- IEEE1547 Standard for Interconnecting Distributed Resources with Electric Power Systems
  - display “Utility-Interactive” on the listing label
  - frequency and voltage limits, power quality, non-islanding inverter testing
  - 1547a allows low frequency ride through, low voltage ride through, and non-unity power factor
- IEEE1526 Recommended Practice for Testing the Performance of Stand Alone Photovoltaic Systems
- IEEE2030 Guide for Smart Grid Interoperability of Energy Technology and Information Technology operation with Electric Power Systems and End-use Applications and Loads

Underwriters Laboratory (UL)

- Standards for Electrical Equipment Safety relates mainly to manufacturers.
- The National Electric Code requires that almost any piece of equipment used in a PV system is "listed" by a nationally recognized testing laboratory, such as UL (http://www.ul.com) and most jurisdictions in the US will not issue an electric permit unless all the components are so listed, including not only PV modules and inverters but wire, breakers, and all other components. UL ratings for common components of PV systems include:
- UL1703 Standard for Safety for Flat Plate Photovoltaic Modules and Panels
- UL1741 Inverters, Converters, Controllers and Interconnect System Equipment for Use with Distributed Energy Resources
- UL2703 Rack Mounting Systems and Clamping Devices for Flat Plate Photovoltaic Modules

ASTM Standards related to PV

- E927-10 Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing
- E1026-08 Standard Test Methods for Electrical Performance of Non-concentrator Terrestrial Photovoltaic Modules and Arrays…
- E1038-10 Standard Test Methods for Determining Resistance of Photovoltaic Modules to Hail…
- E1171-09 Standard Methods for Photovoltaic Modules in Cyclic Temperature and Humidity Environments
- E1462-00(2006) Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules
- E1799-08 Standard Practice for Visual Inspection of PV Modules
- E1830-09 Standard Test Methods for Mechanical Integrity PV Modules
- ASTM is also working on standards for installation of PV on rooftops; performance, weathering and aging; and accelerated life testing of PV modules, all of which will be useful when completed.

National Fire Protection Association (NFPA)

National Electrical Code (NEC)

Electrical Power System Installation

relates to electrical trade and industry experts.

NEC Article 300: Wiring Methods and Materials

NEC Article 480: Storage Batteries

NEC Article 690: Article 690: Solar Photovoltaic Systems

- requires listing for utility interface inverters by “Nationally Recognized Testing Laboratory (NRTL)” such as:
  - Underwriters Laboratory (UL)
  - Edison Testing Laboratories (ETL)
  - Factory Mutual Research (FM)

NEC Article 705: Interconnected Electrical Power Production Sources

NEC Article 720: Circuits and Equipment Operating at Less Than 50V

Check out http://www.nmsu.edu/~tdi/codes&.htm

Publications addressing PV O&M

Topic /Paper Title	Link
*Model of Operation and Maintenance Costs for Photovoltaic Systems**	https://www.nrel.gov/docs/fy20osti/74840.pdf.
*Performance of Photovoltaic Systems Recorded by Open Solar Performance and Reliability Clearinghouse (oSPARC)**	https://www.nrel.gov/docs/fy19osti/75162.pdf.
Best Practices in Operation and Maintenance of PV Systems, 3rd Ed.*	https://www.nrel.gov/docs/fy19osti/73822.pdf
Severe Weather Factors for Existing Asset Owners	Final review and approval at LBNL
Insurance in the Operation of Photovoltaic Plants	https://www.nrel.gov/docs/fy21osti/78588.pdf
Best Practices at the End of the Photovoltaic System Performance Period	https://www.nrel.gov/docs/fy21osti/78678.pdf
PV Fleet Performance Data Initiative: Performance Index-Based Analysis	https://www.nrel.gov/docs/fy21osti/78720.pdf
Cybersecurity in Photovoltaic Plant Operations	https://www.nrel.gov/docs/fy21osti/78755.pdf

Component Specifications

PV Component Codes and Standards and Their Voltage Limits

Applicable Area	Geography	Code	Current Voltage Limitation	Expected Future Changes
Modules	International	IEC 61215, IEC 61646, IEC 61730-1, IEC 61730-2	1,500 Vdc	Global Harmonization with UL
	North America	UL 1703	1,500 Vdc	Adjusted mid-2015
	Japan	JIS C 8990:2009, JIS C 8991:2011, JIS C 8992-1:2010, JIS C 8992-2:2010, JIS Q 8901:2012	1,000 Vdc	-
Junction Boxes	International	IEC 62790	1,500 Vdc	-
	International	TUV 2 Pfg 1798 (US), TUV EN 50548 (International)	1,500 Vdc	-
	North America	UL 1703; UL 746C	1,500 Vdc	Adjusted mid-2015 for 1,500 Vdc
Connectors	International	IEC 62852	1,500 Vdc	-
	Europe	EN 50521	1,500 Vdc	-
	North America	UL 6703, UL 6703a, UL 1703, UL 1977, UL 746C	1,500 Vdc	Adjusted mid-2015 for 1,500 Vdc
Cabling	International	IEC 60228	1,500 Vdc	-
	International	TÜV 2Pfg1990/05.12 (International), TUV 2PfG 1169/08.2007 (expiring in 2017)	Enables 1,500 Vdc cabling	-
	Europe	EN 50618 (will replace TUV standards above – enable 1,500 V)	1,500 Vdc	-
	North America	UL 4703	2,000 Vdc	-
	Japan	JCS 4517:2013	1,500 Vdc	-
Wiring Harnesses	North America	UL 9703	None	-
Fuses and Disconnects	International	IEC 60269-6	1,500 Vdc	-
	North America	UL 98, UL 98 B	1,500 Vdc	-
Combiner Boxes	International	IEC 60947-3	1,500 Vdc	-
	North America	UL 1741	No voltage limits, though testing specifics only for 1,000 Vdc	2016-2017 Global Harmonization
Inverters	International	IEC 62109-1, IEC 62109-2	2,000 Vdc	-
	North America	IEEE 1547, IEEE 1547.1	-	-
	North America	UL 62109-1, UL 62109-2	2,000 Vdc	-
	North America	UL 1741	No voltage limits, though testing specifics only for 1,000 Vdc	2016 harmonization with IEC
	Japan	JEAC 9701:2012	1,000 Vdc	-
System Standards and Codes	International	IEC 60364-7-712, IEC 61727	1,500 Vdc	-
	United States	NEC 2011, NEC 2014, NEC 2017 (in development)	Limits rooftop voltage to 1,000 Vdc for commercial, 600 Vdc residential, no utility specification	Update in 2017
	United States	NESC	No voltage limits, UL often still required for utility projects	-
	Japan	JIS C 0364-7-712:2008	1,000 Vdc, though 1,500 Vdc systems are not prohibited	-

Resources: End of Performance Period

- End of PV Performance Period / Repowering PV https://www.nrel.gov/docs/fy21osti/78678.pdf
- NSF 457, 2019 - Sustainability Leadership Standard for Photovoltaic Modules and Photovoltaic Inverters https://global.ihs.com/doc_detail.cfm?document_name=NSF%20457&item_s_key=00745029
- Best Practices in Operation and Maintenance of PV Systems https://www.nrel.gov/docs/fy19osti/73822.pdf
- Insurance Hazard Data related to Photovoltaic Systems https://www.nrel.gov/docs/fy21osti/78588.pdf
- PV Fleet Performance Data Initiative: Performance Index-Based Analysis https://www.nrel.gov/docs/fy21osti/78720.pdf
- Cybersecurity in Photovoltaic Plant Operations https://www.nrel.gov/docs/fy21osti/78755.pdf
- "PV ROM (Reliability, Operations & Maintenance) Database" Sandia National Laboratories http://energy.sandia.gov/tag/pvrom/ Reference for alpha and beta in Weibull failure distributions
- FEMP Severe Weather Fact Sheet https://www.energy.gov/eere/femp/downloads/solar-photovoltaic-systems-hurricanes-and-other-severe-weather
- Solar Under Storm: Designing Hurricane-Resilient PV Systems https://www.rmi.org/solar-under-storm-designing-hurricane-resilient-pv-systems/
- Operations and Maintenance for Optimal Photovoltaic System Performance On-Demand Training https://www4.eere.energy.gov/femp/training/
- O&M Best Practices for Small-Scale PV Systems On-Demand Training https://www4.eere.energy.gov/femp/training/training/om-best-practices-small-scale-pv-systems

Resources: Preventing & Recovering from Damage

- *PV System Owner's Guide to Identifying, Assessing, and Addressing Weather Vulnerabilities, Risks, and Impacts* (https://www.energy.gov/sites/default/files/2021-09/pv-system-owners-guide-to-weather-vulnerabilities.pdf)
- Solar Photovoltaic Systems in Hurricanes and Other Severe Weather, Shepherd and Robinson 2018. https://www.energy.gov/sites/prod/files/2018/08/f55/pv_severe_weather.pdf
- FEMP Energy Savings Performance Contract/Energy Sales Agreements ,Energy Savings Performance Contract Energy Sales Agreement Toolkit
- Solar Photovoltaics in Severe Weather: Cost Considerations for Storm Hardening PV Systems for Resilience. Elsworth and Van Geet 2020. https://www.nrel.gov/docs/fy20osti/75804.pdf
- National Renewable Energy Laboratory, Sandia National Laboratory, SunSpec Alliance, and the SunShot National Laboratory Multiyear Partnership (SuNLaMP) PV O&M Best Practices Working Group. 2018. Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-73822. https://www.nrel.gov/docs/fy19osti/73822.pdf.
- Schwab, Amy, Andy Walker, and Jal Desai. 2020. Insurance in the Operation of Photovoltaic Plants. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78588. https://www.nrel.gov/docs/fy21osti/78588.pdf
- Curtis, Taylor, Garvin Heath, Andy Walker, Jal Desai, Edward Settle, and Cesasr Barbosa. 2021. Best Practices at the End of the Photovoltaic System Performance Period. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5D00-78678. https://www.nrel.gov/docs/fy21osti/78678.pdf
- Solar Under Storm 1, 2, and 3. https://rmi.org/solar-under-storm-designing-hurricane-resilient-pv-systems/
- FEMA MAT Report https://www.fema.gov/sites/default/files/2020-07/mat-report_hurricane-irma-maria_virgin-islands.pdf
- National Center for Disaster Preparedness. U.S Natural Hazards Index. Earth Institute, Columbia University. https://ncdp.columbia.edu/library/mapsmapping-projects/us-natural-hazards-index/
- FEMA. Risk Mapping, Assessment and Planning (Risk MAP) https://www.fema.gov/flood-maps/tools-resources/risk-map?web=1&wdLOR=c629CEADE-012F-439D-8468-214B9D70CA18
- USGS. 2018 Long-term National Seismic Hazard Map. https://www.usgs.gov/media/images/2018-long-term-national-seismic-hazard-map
- USAA. Hail Risk. https://www.usaa.com/inet/wc/adv_advice-home-hailriskmap-ig