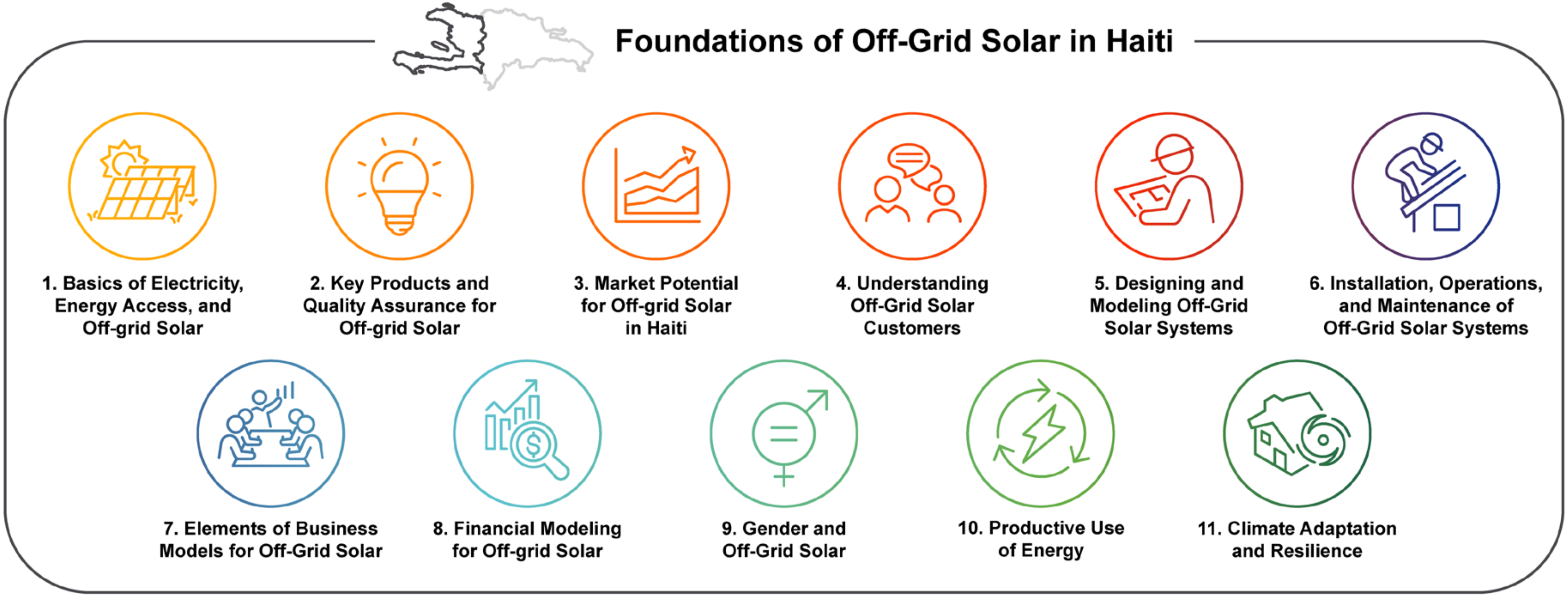
6. Installation, Operations, and Maintenance of Off-Grid Solar Systems

Foundations of Off-Grid Solar in Haiti

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Overview



Foundations of Off-Grid Solar in Haiti
1. Basics of Electricity, Energy Access, and Off-grid Solar
2. Key Products and Quality Assurance for Off-grid Solar
3. Market Potential for Off-grid Solar in Haiti
4. Understanding Off-Grid Solar Customers
5. Designing and Modeling Off-Grid Solar Systems
6. Installation, Operations, and Maintenance of Off-Grid Solar Systems
7. Elements of Business Models for Off-Grid Solar
8. Financial Modeling for Off-grid Solar
9. Gender and Off-Grid Solar
10. Productive Use of Energy
11. Climate Adaptation and Resilience

Overview

The objectives of this module are to provide an overview and key resources/tools for understanding:

- How are off-grid systems configured? (Go to Section)
- How are off-grid systems installed? (Go to Section)
- What are additional installation considerations for hurricane areas? (Go to Section)
- How are off-grid solar systems operated and maintained? (Go to Section)

Disclaimer

The below slides provide a high-level overview of concepts and approaches for installation and maintenance of photovoltaic (PV) systems, but they do not constitute formal training or certification for the installation, operation, and maintenance of PV systems. **Installation, operations, and maintenance should only be completed by trained professionals.**

How are off-grid systems configured?

AC- vs. DC-coupled Systems

Electric current flows in two ways as an **alternating current (AC)** or **direct current (DC).** The main difference between AC and DC lies in the direction in which the electrons flow. In DC, the electrons flow steadily in a single direction. In AC, electrons keep switching directions, going forward and then backwards.

For Off-Grid Solar, the difference between DC- and AC-coupled systems is how the battery bank is charged in the system:

- **DC-coupled** systems charge the battery bank with DC power directly from the PV array.
- **AC-coupled** systems convert DC power from the PV array to AC power, then convert this AC power back to DC power to charge the batteries.
- Hybrid systems include multiple generation sources (e.g., a solar and back-up generator could be either DC-coupled, AC-coupled, or both).

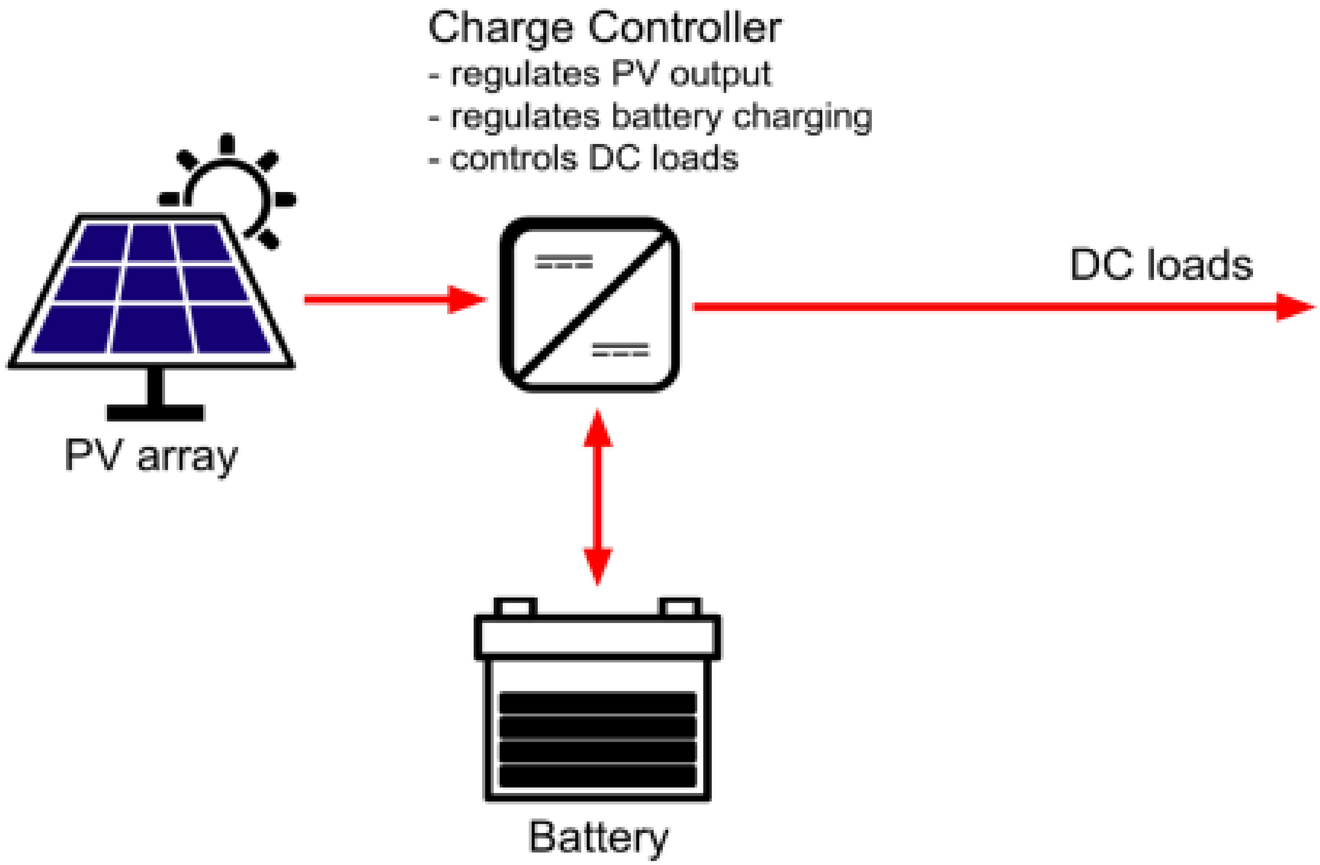
Source: Lighting Africa Requirements and Guidelines for Installation of Off-grid Solar Systems for Public Facilities

Advantages and Disadvantages of AC / DC

System Type	Advantages	Disadvantages
DC - Coupled	• More efficient battery charging • Fewer inverters • Closed-loop communications and dynamic control of charge/discharge of batteries	• **PV and battery need to be in the same location** • No potential inverter redundancy between energy sources – if the inverter fails, the site is no longer provided with AC power • More difficult future expansion – if the site requires a larger battery bank in the future, the inverter may need to be upgraded • Higher wiring costs
AC - Coupled	• **PV and Battery can be in separate locations** • May be more efficient for large daytime AC loads • Inverter redundancy between energy sources • Easier future expansion • Lower wiring costs	• Less efficient battery charging • More inverters – inverter(s) are needed to convert PV power from DC to AC and inverter(s) are also needed to convert battery power from DC to AC • Open-loop communication – system may not recover from a low battery state of charge if there is no backup generator

Source: Lighting Africa Requirements and Guidelines for Installation of Off-grid Solar Systems for Public Facilities

Common Off-Grid Solar (OGS) Configurations – DC-coupled only DC loads



Advantages: simple, no inverter required, lots of DC appliances available.

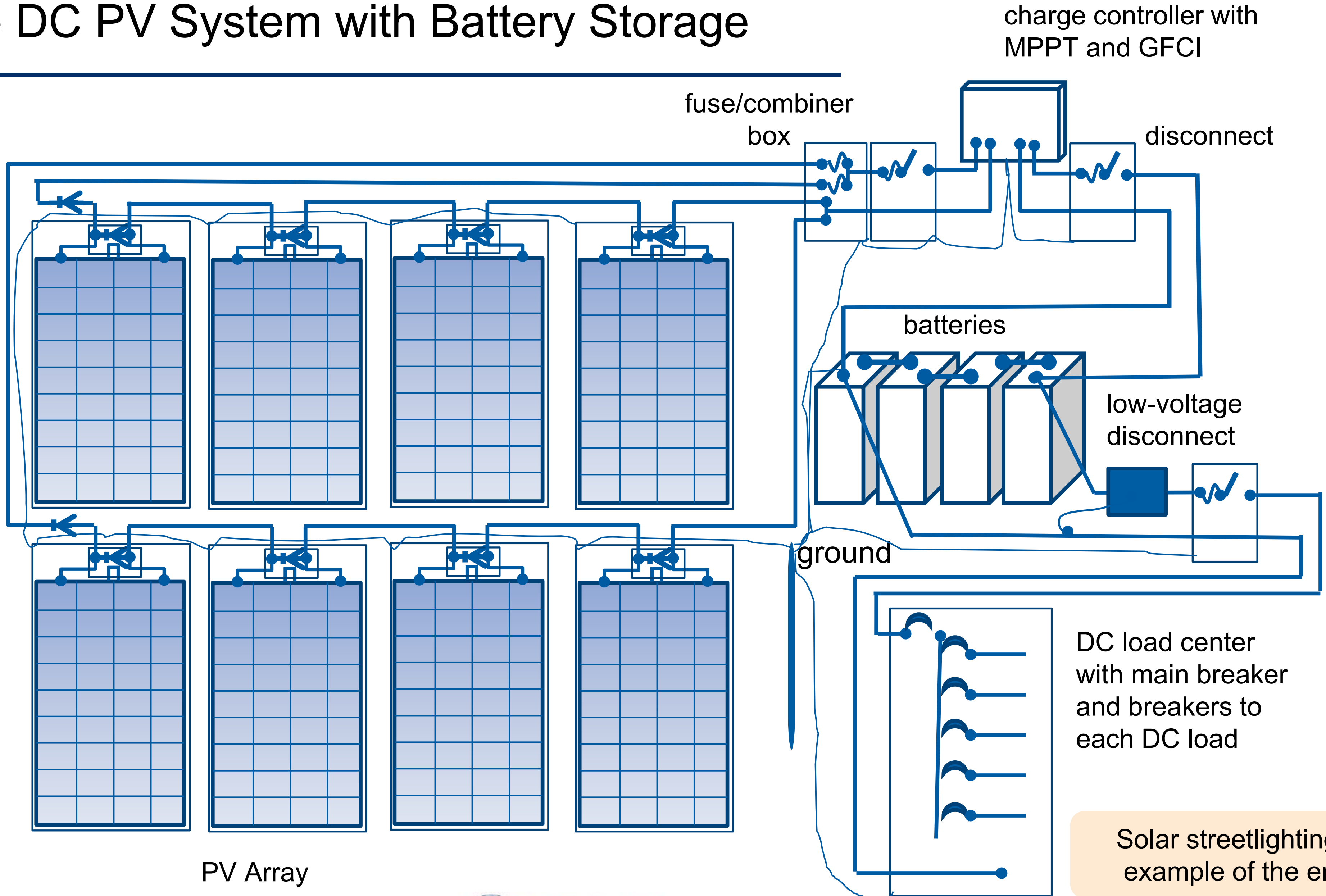
Disadvantages: cannot power AC loads.

Appropriate applications: site with only DC loads and no anticipated future AC loads; typical systems are smaller than 1 kW. An example in Haiti is solar streetlighting.

Other less common configurations can be seen in the Lighting Africa report below.

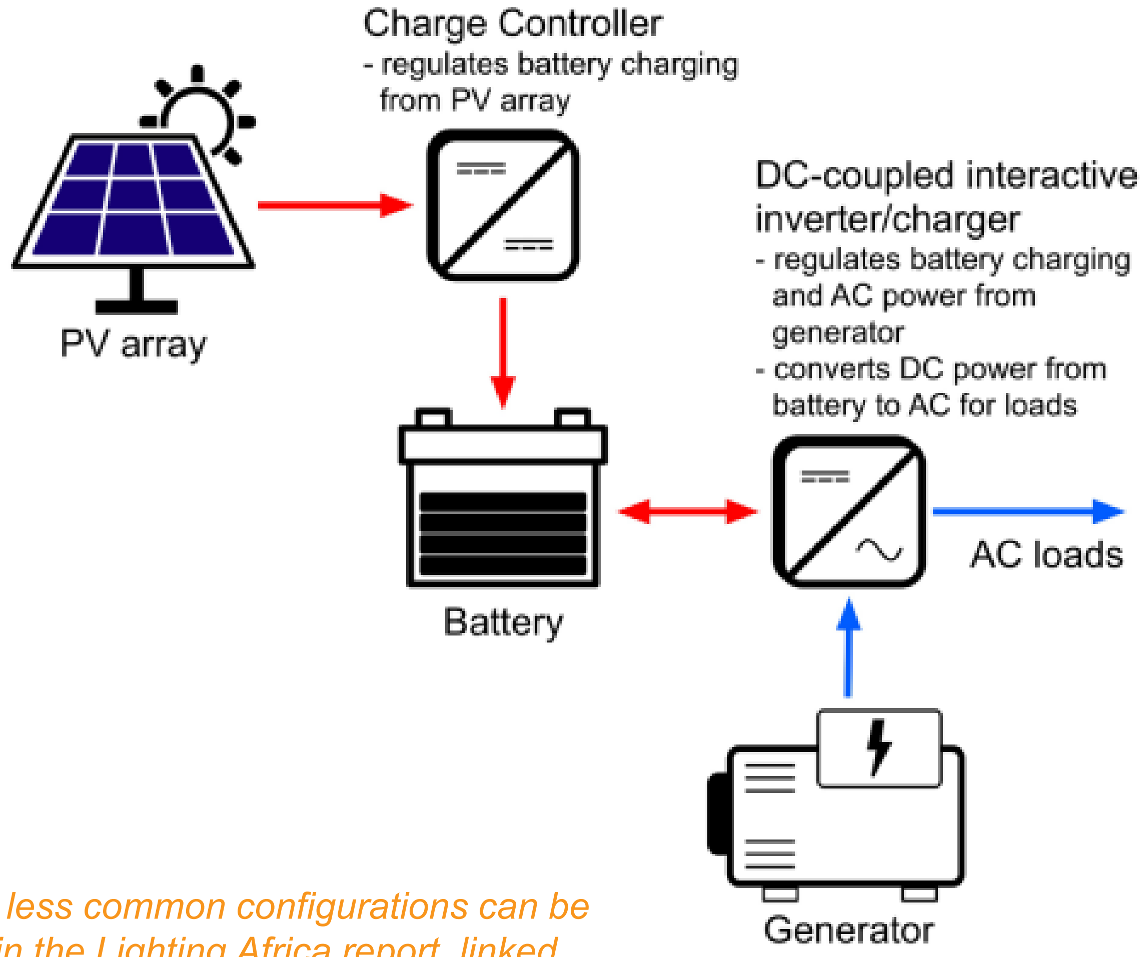
Source: Lighting Africa Requirements and Guidelines for Installation of Off-grid Solar Systems for Public Facilities

Simple DC PV System with Battery Storage



Solar streetlighting can be an example of the end DC load

Common OGS Configurations – DC-coupled, AC/DC Inputs, Integrated Inverter



Advantages: more efficient use of battery power, no PV inverters, generator provides on-demand power.

Disadvantages: less efficient for daytime loads.

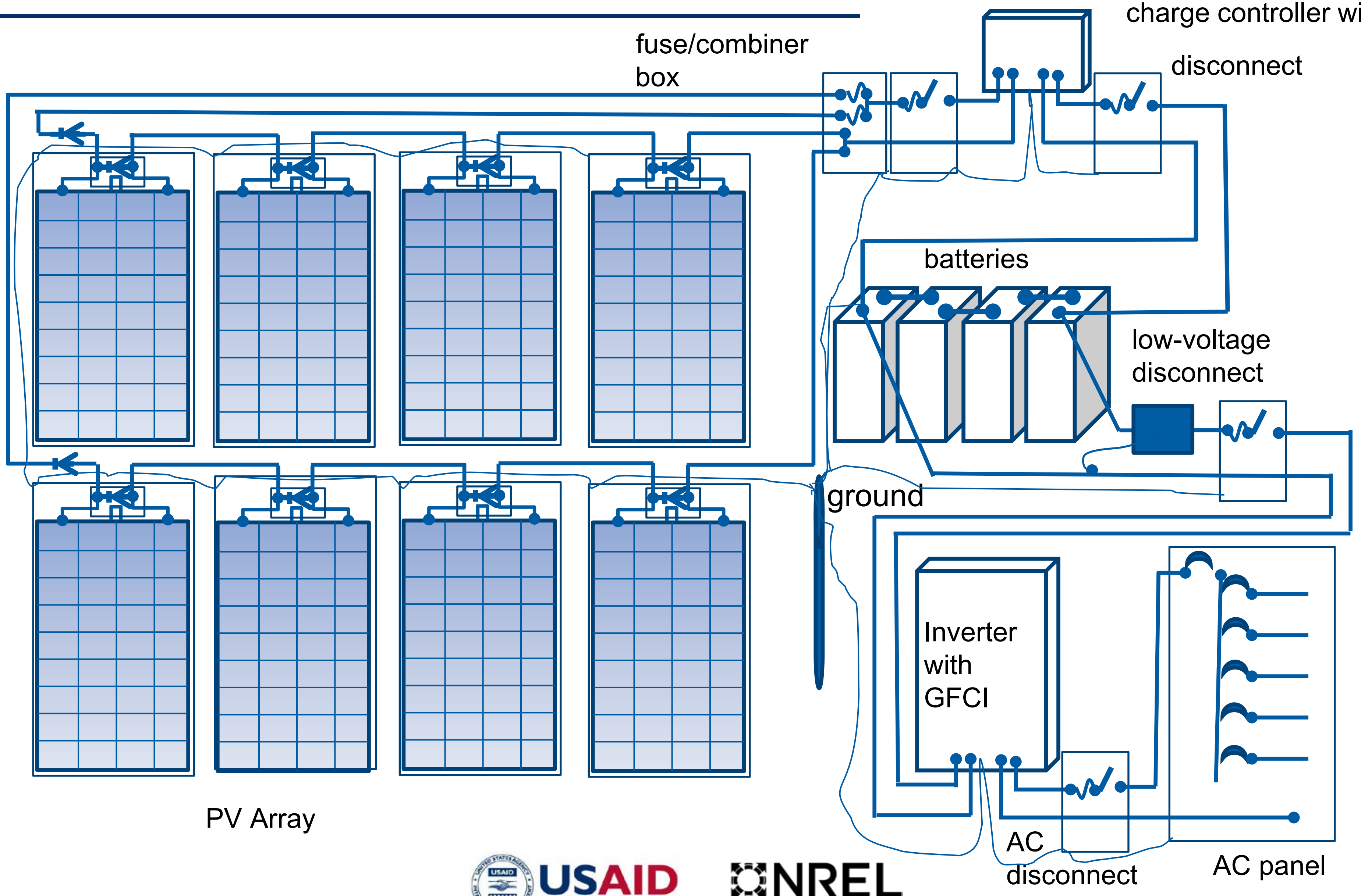
Appropriate applications: site that cannot be powered with PV/battery alone.

Other less common configurations can be seen in the Lighting Africa report, linked below.

Source: [Lighting Africa Requirements and Guidelines for Installation of Off-grid Solar Systems for Public Facilities]

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Alternating Current (AC) PV System with Inverter



How are solar systems installed?

General PV Installation Stages

Verify System Design

Key tasks include:

- Verifying client needs and expectations
- Reviewing site survey and characteristics
- Confirm system sizing
- Review energy storage design
- Confirm string sizing calculations
- Review component selection
- Review wiring and conduit sizing
- Review overcurrent protection
- Review fastener selection
- Review plans

Manage the Project

Key tasks include:

- Construction meetings
- Permits and approvals
- Manage project labor
- Manage project equipment
- Implement site specific safety plan

Install Electrical Components

Key tasks include:

- Mitigating electrical hazards
- Install grounding systems
- Install conduits
- Install electrical components
- Install circuit conductors
- Install system instrumentation
- Install battery components

Install Mechanical Components

Key tasks include:

- Install equipment foundation
- Install mounting rack
- Install PV modules

Complete Installation

Key tasks include:

- System testing
- System commissioning
- System documentation
- Customer orientation

Off-grid solar installation, particularly for solar kits, will likely follow different and slightly simplified processes, but generally this flow is appropriate. Each of these stages is detailed in the comprehensive NABCEP Guide.

Source: NABCEP PV Installation Professional Resource Guide

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Key Components of Off-Grid Solar

PV Modules

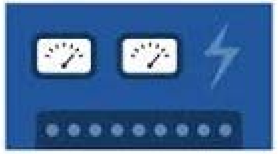
Converts the sun’s irradiation to usable electricity.

Racking / Mounting

Secures the PV module in place either on the ground or on a rooftop.

Charge Controller

Regulates how the PV modules charge the batteries to ensure safety and optimal health of the batteries.



Battery

Stores electricity produced by solar panels.

Electricity to appliances and users

Inverter

Converts DC electricity, which is what a solar panel/battery generates, to AC electricity, which is what appliances use.

Disclaimer

The images below highlight best practices and examples of installation, components and configurations for distributed solar systems. In Haiti, particularly in less formal solar installations, these practices may differ, but this section illustrates good practice for the design and installation of distributed solar systems in line with international codes. The material also focuses on large systems, but solar home systems and solar kits will follow similar principles, but their installations will also usually include clips and other manufacturer-specific instructions.

Types of PV Mounting

Roof mounts: attached or ballasted

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

Photo Orlando Utilities Commission images.NREL.gov #18715

Currently in Haiti, mounting for solar projects can tend to be one-off solutions designed for individual projects, but as the sector becomes more formalized, more specialized and standardized mounting will become the norm.

Ground mounts: tracking or fixed

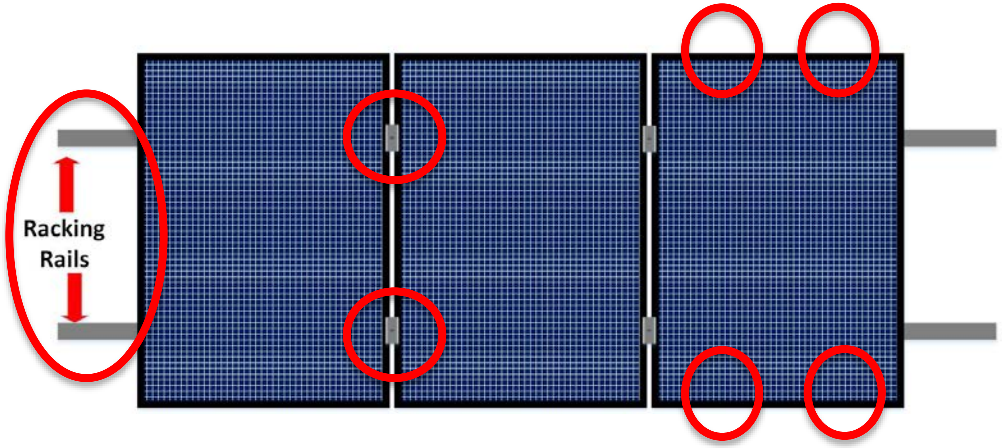
Photo by Andy Walker

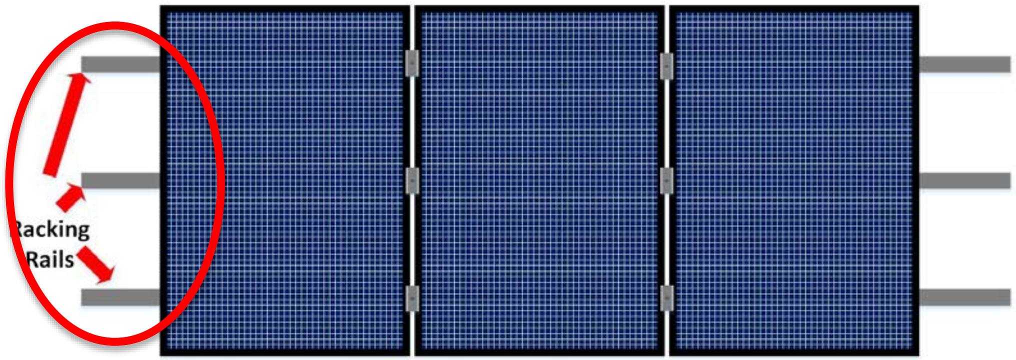
Images.nrel.gov 56760r, NREL

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Weather Factors - Wind Loading

- Gaining full strength rating of a module depends on how it is mounted
  - Type of fasteners used (e.g., top-down clamps, through bolting)
  - Quantity of fasteners
  - Location of fasteners
    - Fasteners placed on the long side produce greater strength
  - Number of mounting rails





Clamps versus "through-bolts" connected to rack rail

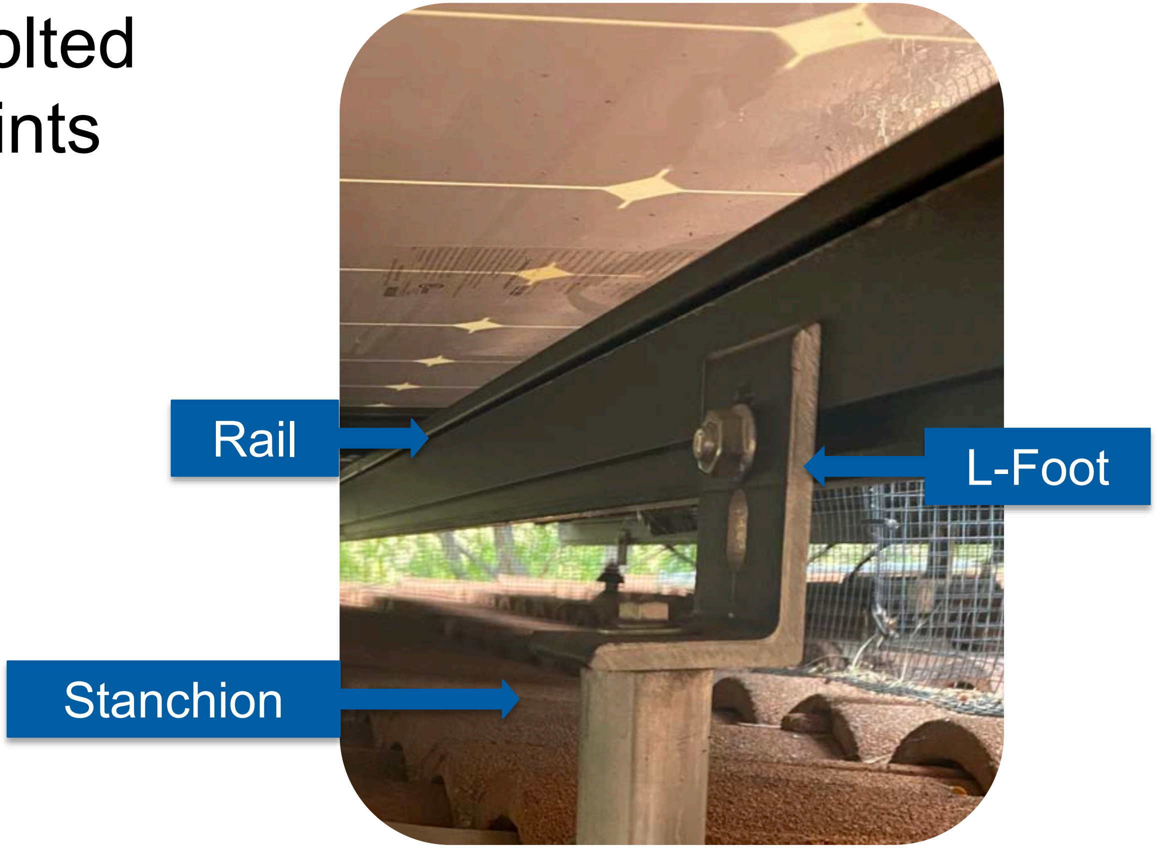
Clamps

Through-bolt

Photos by Andy Walker, NREL

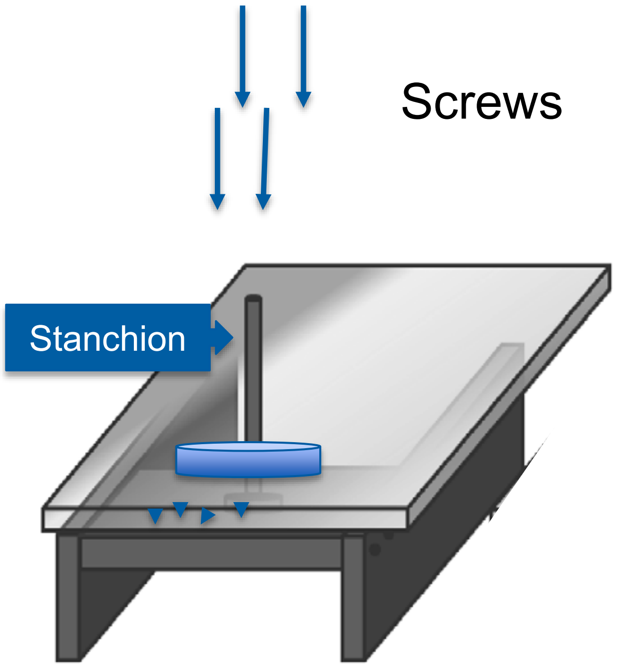
Rail-to-Stanchion Connection

- L-foot
- Bolted joints



Photos by Andy Walker, NREL

Stanchion-to-Roof Connection and Flashing



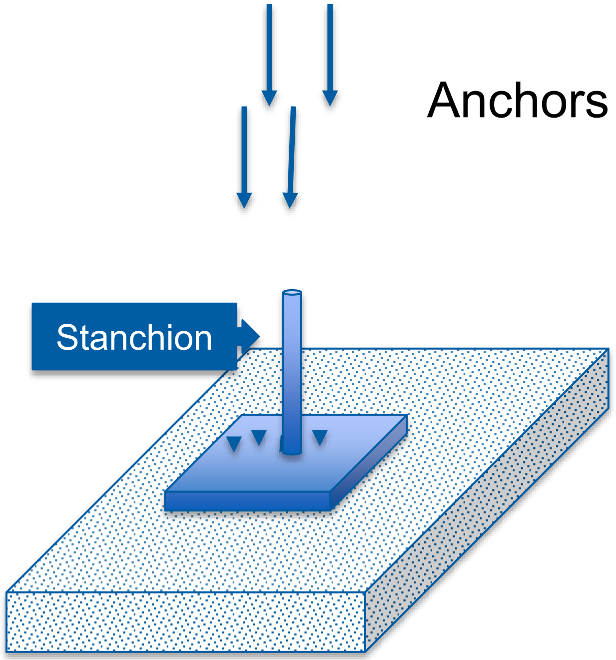
Blocking between rafters

Flashing for shingle

Flashing for tile roof

Photos by Andy Walker, NREL

Concrete/Asphalt Roof Stanchion

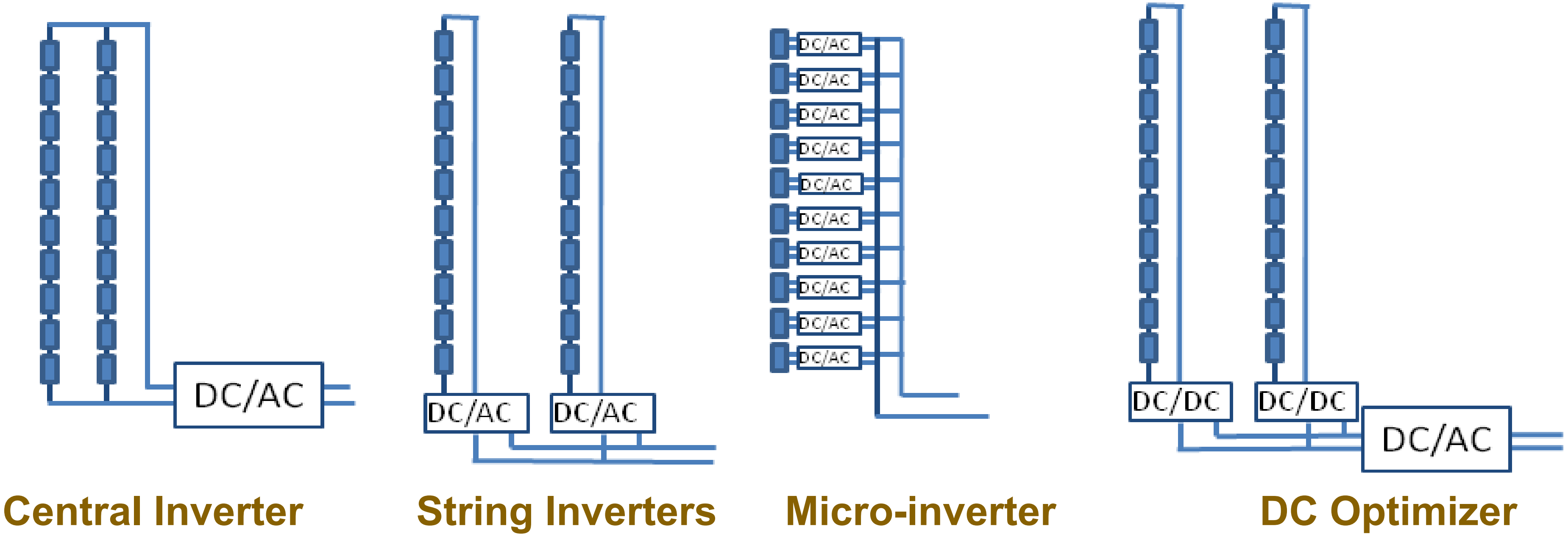


Stanchion is attached to a roof deck or roof structure under insulation; mated to roof membrane with elevated water seal; cone shaped flashing; and sealant to roof membrane.

Photo by Andy Walker, NREL

Photos by Andy Walker, NREL

Different Inverter Arrangements



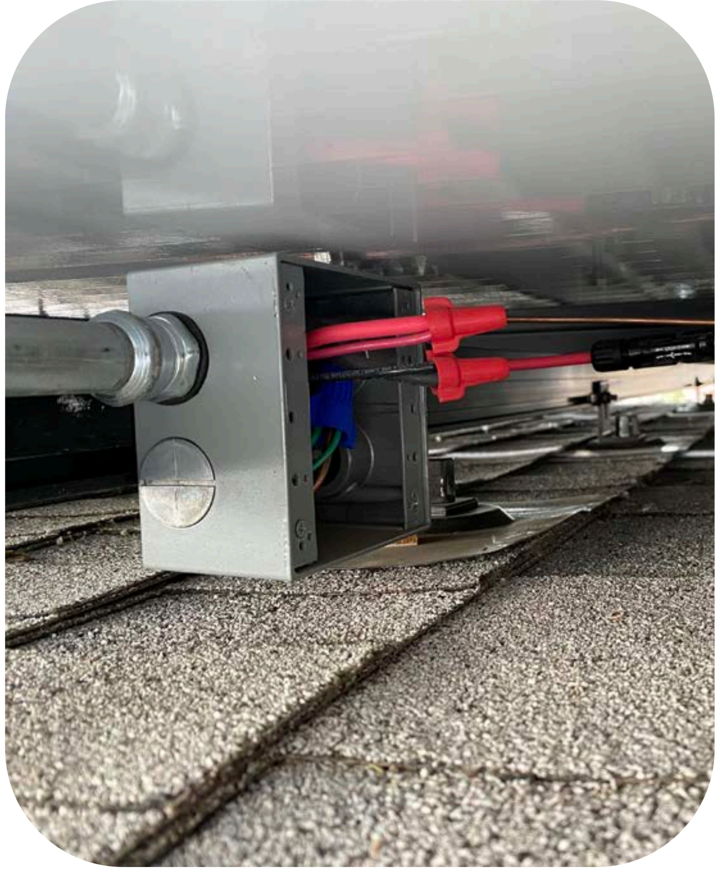
Micro- and String Inverters

- More expensive than central inverter
- Reduces production losses
- Provides rapid shutdown near array
- Provides detailed data
- More conventional AC wiring

Figure by Andy Walker, NREL

String Inverter Installation

MC connectors between PV modules.



Transition from PV wire to wire in conduit to inverter.

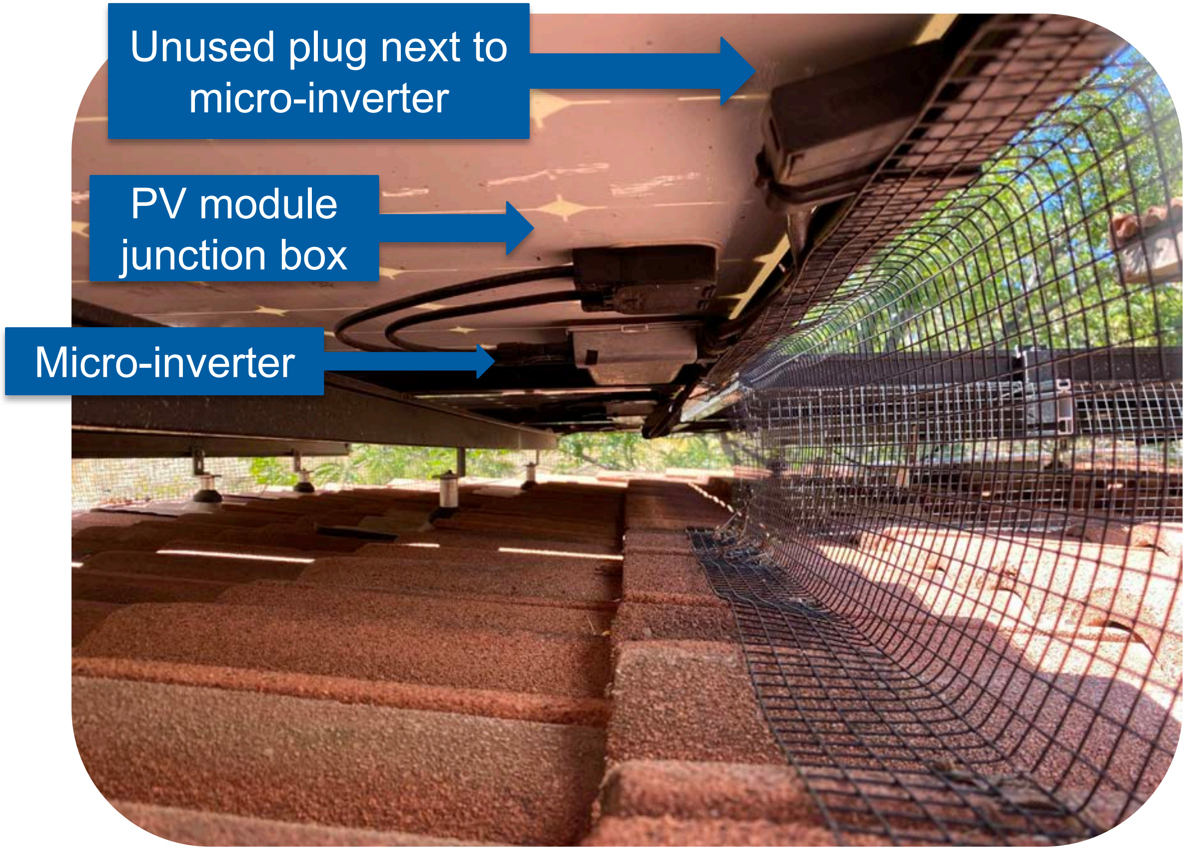
Inverter with DC and AC disconnect and wiring to building panel.

Photos by Andy Walker, NREL

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Micro-inverter Installation

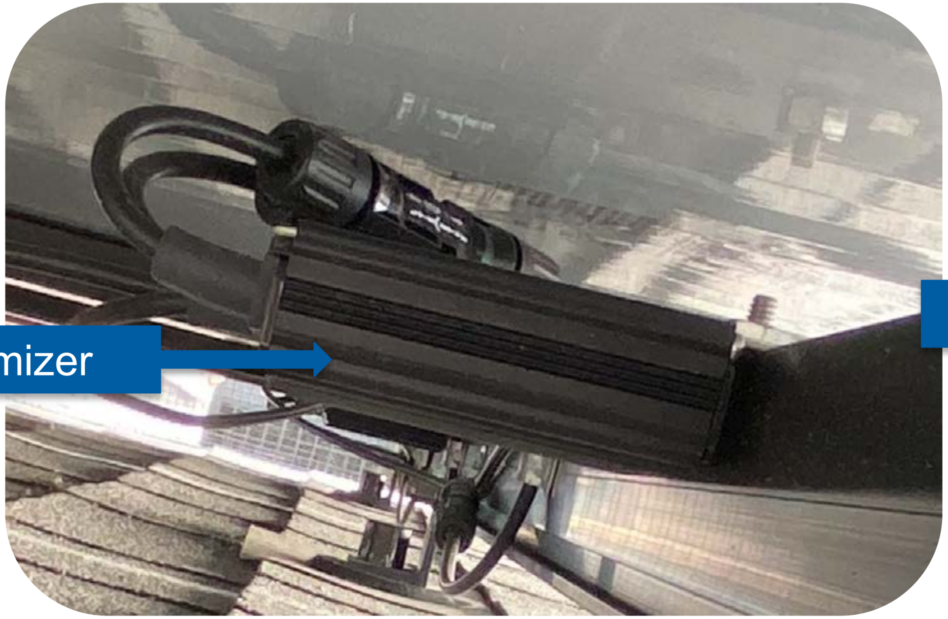


- PV module leads to micro-inverter
- Plug to next micro-inverter (not used)
- Plug terminal at end of line

Photos by Andy Walker, NREL

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

DC Optimizer Inverter Installation



- DC optimizer on each PV module
- Fastened to rack rail

- Inverter with wi-fi antenna and disconnect

Photos by Andy Walker, NREL

USAID FROM THE AMERICAN PEOPLE   NREL Transforming ENERGY

Wire Sizing

There are three important criteria for selecting wire size

- Current (Ampacity)
- Voltage
- Minimum size required by required physical strength or by codes and standards

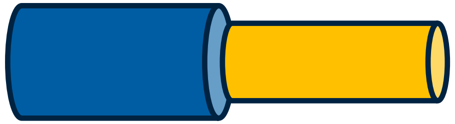
Ampacity

- Current carrying (amps) ability of a wire
- Larger wire = more capacity
- Using wire with low ampacity that carries a large current will overheat the wire
- Overheating means wasted energy and inefficiency, and can result in melted insulation, a short circuit, or fire

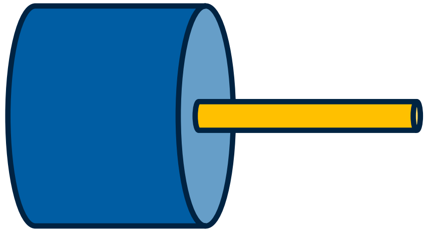
Voltage Rating

- Maximum voltage of a wire (600V, 1000V or 1500V)
- Thicker insulation = more the voltage rating

Power = Current * Voltage



High Current:
More conductor



High Voltage:
More plastic insulation

Wire Management

Wire ties to rack

To conduit

Cable trays

Direct bury

Photos by Andy Walker, NREL

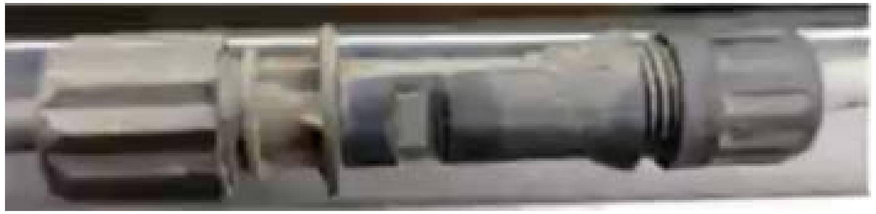
USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

PV Connectors

Many failures in PV systems are from the connectors

- Mismatched or improperly attached PV connectors
- Module string to inverter connectors are often “field made”
  - Hot-spot risk
- Connectors should only be paired with connectors from the same manufacturer—**DO NOT CROSS-MATE CONNECTORS UNLESS SPECIFICALLY DESCRIBED IN INSTRUCTIONS FROM THE MANUFACTURER!**



Photos by Matt Piantedosi

Source: Clean Energy Associates (2021), Understanding PV Fire Risk: Is Your Commercial Rooftop Safe?

USAID FROM THE AMERICAN PEOPLE NREL Transforming ENERGY

Disconnects

- Each piece of equipment in a PV system, such as inverter, batteries, and charge controllers, must be able to disconnect from all sources of power
- Disconnects should:
  - Be switches or circuit breakers
  - Be accessible and labeled
  - Not have any exposed live parts
  - Indicate whether they are on or off (closed or open)
  - Be rated for the nominal system voltage and available current

Disconnect switch

Earthing / Grounding

An earthing system or grounding system connects specific parts of an electric power system with the ground, typically the Earth, for safety and functional purposes.

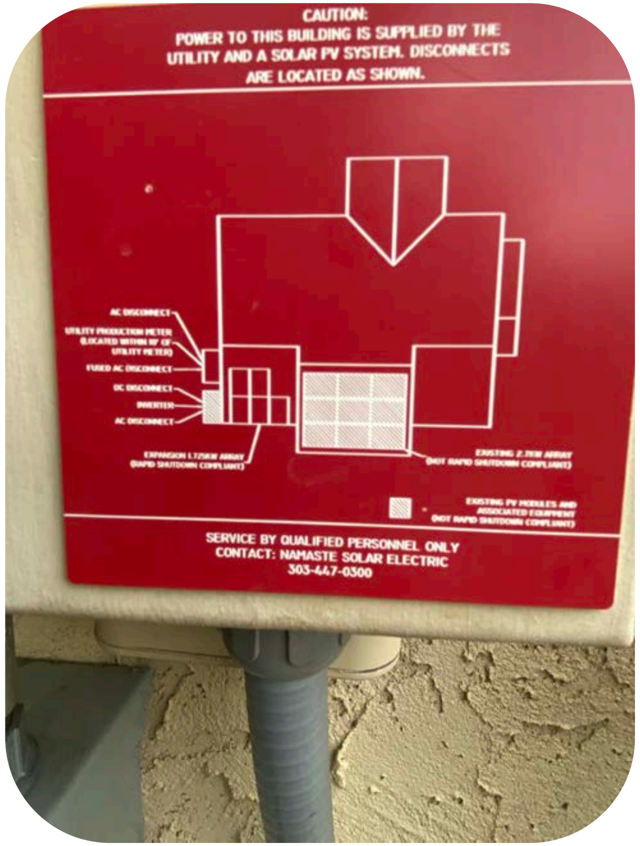
Equipment grounding

- In this case, Earth is connected to the noncurrent-carrying part, or the chassis (the external body of the equipment)
- Used to protect personnel from shocks caused by a ground fault and is required in all PV systems

System grounding

- In this case, Earth is connected to the current-carrying parts by taking one conductor from a two-wire system and connecting it to the ground
- Used to protect equipment

Warning Labels and Instructions



Observe all code and program requirements regarding location and spacing of warning labels.

Photos by Andy Walker, NREL

USAID FROM THE AMERICAN PEOPLE
NREL Transforming ENERGY

Commissioning Checklist

Commissioning checklists will vary by company, location, and project type, but a high-level example of a commissioning checklist is as follows:

- Measured Voltage of all PV strings
- Polarity of all PV strings
- Sufficiency of wire management (e.g. conductors do not touch the roof)
- Inverter or inverter/charger settings and set points, if applicable, e.g. battery charger settings based on battery manufacturer recommendations
- Charge controller set points, if applicable
- Battery bank voltage versus inverter voltage reading
- Assessment of roof and wall penetration waterproofing, if applicable
- System is free of earth faults (i.e. no non-earthed conductor has continuity with Earth)
- No faults (short circuits) between independent conductors (e.g. positive and negative PV conductors)
- Load shedding, if present, is functional, and critical loads remain operational when noncritical loads are disabled
- Remote monitoring interface, if applicable, is functional
- Remote monitoring system is outputting the correct GPS coordinates or project location, if applicable
- PV modules, racking systems, and metallic conduit are bonded
- All other metal equipment is bonded
- Neutral return path is present, if applicable
- No galvanically dissimilar metals are in contact with each other
- Disconnects are functional
- All loads (lamps, fans, water pumps, etc.) are functional
- All outlets are functional
- DC outlets, if present, are significantly different from the AC outlets to prevent connecting incorrect appliances
- Load limiters, if present, are functional and operate at the correct current or power set point
- All live parts of system are adequately insulated. This section of the commissioning report should include the results of the following (if conducted):
- Insulation resistance testing
- Thermal imaging pictures of PV modules, if possible

Source: Lighting Africa Requirements and Guidelines for Installation of Off-grid Solar Systems for Public Facilities

Selected IEC Standards (other standards also apply)

Standards for rural electrification

IEC/TS 62257-1, Recs for small renewable energy and hybrid systems for rural electrification - Part 1: General introduction to rural electrification.

IEC/TS 62257-2, Recs for small renewable energy and hybrid systems for rural electrification - Part 2: From requirements to a range of electrification systems.

IEC/TS 62257-3, Recs for small renewable energy and hybrid systems for rural electrification - Part 3: Project development and management.

IEC/TS 62257-4, Recs for small renewable energy and hybrid systems for rural electrification - Part 4: System selection and design.

IEC/TS 62257-5, Recs for small renewable energy and hybrid systems for rural electrification - Part 5: Protection against electrical hazards.

IEC/TS 62257-6, Recs for small renewable energy and hybrid systems for rural electrification - Part 6: Acceptance, operation, maintenance and replacement.

IEC/TS 62257-7, Recs for small renewable energy and hybrid systems for rural electrification - Part 7: Generators.

IEC/TS 62257-7-1, Recs for small renewable energy and hybrid systems for rural electrification - Part 7-1: Generators - Photovoltaic arrays.

IEC/TS 62257-7-3, Recs for small renewable energy and hybrid systems for rural electrification - Part 7-3: Generator set - ….

IEC/TS 62257-8-1, Recs for small renewable energy and hybrid systems for rural electrification - Part 8-1: Selection of batteries ,,,

IEC/TS 62257-9-1, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-1: Micropower systems.

IEC/TS 62257-9-2, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-2: Microgrids.

IEC/TS 62257-9-3, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-3: Integrated system - User interface.

IEC/TS 62257-9-4, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-4: Integrated system - User installation.

IEC/TS 62257-9-5, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-5: Integrated system - Selection of portable PV ...

IEC/TS 62257-9-6, Recs for small renewable energy and hybrid systems for rural electrification - Part 9-6: Integrated system - Selection of Photovoltaic Individual Electrification Systems (PV-IES).

IEC/TS 62257-12-1, Recs for small renewable energy and hybrid systems for rural electrification - Part 12-1: Selection of self-ballasted lamps (CFL) for rural electrification systems and Recs for household lighting equipment.

Source: PV Resources

Selected IEC Standards (continued)

Standards for off-grid PV systems

IEC 62509, Battery charge controllers for photovoltaic systems - Performance and functioning.
IEC 61194, Characteristic parameters of stand-alone photovoltaic (PV) systems.
IEC 61702, Rating of direct coupled photovoltaic (PV) pumping systems.
IEC/PAS 62111, Specifications for the use of renewable energies in rural decentralised electrification.
IEEE Std 1526, IEEE Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems.

Standards for PV Array

IEC 62548-1:2023 design requirements for photovoltaic (PV) arrays including DC array wiring, electrical protection devices, switching and earthing provisions

Standards for charge controllers

IEC 62509, Battery charge controllers for photovoltaic systems - Performance and functioning.
IEC 62093, Balance-of-system components for photovoltaic systems - Design qualification natural environments.

Standards for batteries

IEC 61427, Secondary cells and batteries for solar photovoltaic energy systems - General requirements and methods of test.
IEC 60896-11, Stationary lead-acid batteries - Part 11: Vented types - General requirements and methods of tests.
IEC 60896-21, Stationary lead-acid batteries - Part 21: Valve regulated types - Methods of test.
IEC 60896-22, Stationary lead-acid batteries - Part 22: Valve regulated types - Requirements.
IEC 62259, Secondary cells and batteries containing alkaline or other non-acid electrolytes - Nickel-cadmium prismatic secondary single cells with partial gas recombination.
IEC 60623, Secondary cells and batteries containing alkaline or other non-acid electrolytes - Vented nickel-cadmium prismatic rechargeable single cells.
IEC 62675, Secondary cells and batteries containing alkaline or other non-acid electrolytes - Sealed nickel-metal hydride prismatic rechargeable single cells.
IEEE Std. 937, Recommended practice for installation and maintenance of lead-acid batteries for PV systems.
IEEE Std. 1013, Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems.
IEEE Std. 1361, Recommended practice for determining performance characteristics and suitability of batteries in PV systems.

Source: PV Resources

Additional Resources for PV Installation

NABCEP PV Guide

Grid Alternatives Construction Safety Manual

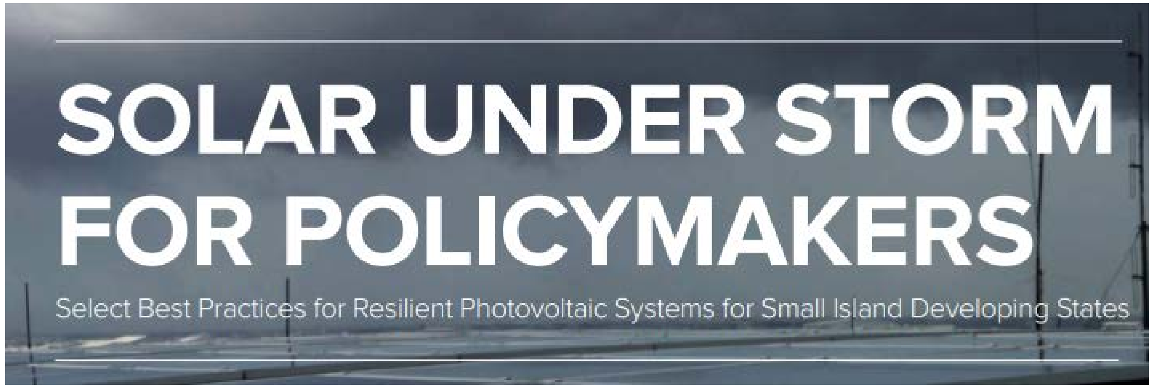
SAPC Best Practices in PV System Installation

What are additional installation considerations for hurricane areas?

Rocky Mountain Institute (RMI) - Solar Under the Storm

RMI has analyzed root causes of PV system failures from hurricanes in the Caribbean in the 2017 season. **Some key specifications for improved resiliency include**:

- Using high-load PV modules (5,400 Pa)
- Requiring a structural engineering review and wind-tunnel report review
- Specifying a bolt hardware locking solution and bolt quality control process
- Specifying through bolting of modules as opposed to top-down or T clamps
- Requiring structural engineer review of lateral loads
- Not using self-tapping screws
- Specifying dual post pier foundations



Source: RMI Solar Under the Storm

Similarities Across Surviving and Failed Systems

No system can be 100% resistant to the impacts of hurricanes, but there are similarities between failed systems and surviving systems which can inform how to design systems to be more resilient

Similarities of Failed Systems	Similarities of Surviving Systems
Top-down or T-clamp cascading failure of module retention	Appropriate use/reliance on ballast and mechanical attachments
Lack of vibration-resistant connections	Sufficient structural connection strength
Corner of the array overturned due to incorrect design for wind	Through-bolted module retention or four top-down clips per module
Insufficient structural connection strength	Structural calculations on record
Roof attachment connection failure	Owner's engineer with QA/QC program
System struck by debris/impact damage, especially from liberated (dislodged) modules	Vibration-resistant module bolted connections
Failure of the structural integrity of the roof membrane	
PV module design pressure too low for environment	

Key challenge for Haiti → Failure of the structural integrity of the roof membrane

Source: RMI Solar Under the Storm

USAID FROM THE AMERICAN PEOPLE NREL Transforming ENERGY

Hurricane Design for Solar PV – Do’s and Don’ts

Do’s

- ✓ Choose reliable module fasteners (#1 point of structural failure)
  - ✓ Directly bolt modules to racking if possible
  - ✓ If using clamps, choose clamps with larger grip area on the module and rack that cannot easily rotate out of the racking rail.
  - ✓ Use locking hardware
  - ✓ More attachment points can help
  - ✓ Check that fasteners are tight annually
- ✓ Select modules rated for high wind loads (>5000 Pa uplift pressure)
- ✓ Use a low tilt angles (as low as possible that will allow water to runoff)
- ✓ Anchor all systems to roofs
- ✓ Racking structure should provide support laterally and longitudinally. Additional cross-bracing is recommended
- ✓ Use 316-grade stainless steel to resist corrosion in marine environments.
- ✓ All electrical enclosures should be NEMA 4X rated and fully watertight
- ✓ Use an experienced PV installer with NABCEP-certified employees
- ✓ Design systems to ASCE 7-22 (without wind tunnel exemptions). Additionally, require design in accordance with SEAOC PV 2-17.

Dont’s

- X Install PV tracker systems
- X Use large format modules
- X Self-install if inexperienced
- X Use plastic wire ties
- X Take an installer’s word that a system is designed to withstand hurricanes. Ask for proof and consult with engineers.

Note: The codes listed here represent U.S. best practices, but they are still relevant to Haiti.

Note: The codes listed here represent US best practices that are still relevant to Haiti

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Wind Pressures and Forces on Solar Panels

Hurricane Category	Wind Speed (m/s)	Maximum Pressure (Pa)	Safety Factor	Minimum Solar Panel Load Rating Needed (Pa)	Max Force on Solar Panel Tilted at 19° (N)	Max Force on Solar Panel Tilted at 5° (N)
Category 1	33-42	1082	1.5	1623	704	189
Category 2	43-49	1473	1.5	2209	959	257
Category 3	50-58	2063	1.5	3095	1343	360
Category 4	59-70	3005	1.5	4508	1957	524
Category 5	>70	4968	1.5	7452	3235	866

- Solar Panels are typically rated to withstand at least 2400 Pa of uplift pressure
- The best panels for wind loading are rated up to ~5400 Pa
- Additional mounting points can increase this rating further
- Modules must be mounted according to manufacturer specifications to meet these load ratings

- Lower tilt angles will lead to much lower forces on panels
- The power production lost at these lower tilt angles is insignificant (~3%)

Estimates provided for a typical 2m x 1m rooftop solar panel; 90 m/s used for Category 5 calculations

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Strength of Mounting Structures

The typical strength of the various mounting structures that may be involved in the installation of a solar system vary from ~35 ksi to 80 ksi.

- Recent industry trend is to use A1011 High-Strength Low-Alloy Steel with Improved Formability (HSLAS-F) Grade 80, which has a minimum yield strength of 80 ksi.
- Stronger steel doesn't necessarily mean a stronger structure, as designers who use stronger steel, typically use less steel and wider gaps between supports. **Best practice: design for a stiff structure regardless of the strength of the steel.**
- Use front and rear post supports for ground-mounted systems.
- Decrease distance between foundation supports to increase system stiffness.

ASTM A1011 HSLAS-F Grade 80

Checklist for Pre-Storm Preventative Actions

Category	Ground-mounted	Roof-mounted
Site: Debris	❑ Clear site of all debris, material, and equipment no longer in use, if possible; otherwise, tie down. ❑ Tie down or anchor HVAC and other in-use equipment. ❑ Cut back vegetation or tree branches that could cause damage to the system.	❑ Clear site of all debris, material, and equipment no longer in use, if possible; otherwise, tie down. ❑ Tie down or anchor HVAC and other in-use equipment. ❑ Cut back vegetation or tree branches that could cause damage to the system. ❑ Clear roof drains of any debris and install a roof drain cover, if possible.
Site: Flooding	❑ Ensure flood control and drainage systems are functioning and clear of debris	❑ Ensure flood control and drainage systems are functioning and clear of debris. ❑ Ensure any roof penetrations are watertight and apply outdoor-rated sealant, if possible.
Mechanical : Module	❑ Check module framing to ensure structural integrity. ❑ Check module for damage ❑ Take photos to capture state of array before event	❑ Check module framing to ensure structural integrity. ❑ Check module for damage ❑ Take photos to capture state of array before event
Mechanical : Fasteners	❑ Perform a tightness check on the fasteners in the system and tighten, if possible. ❑ Check for any missing or corroded fasteners and replace, if possible.	❑ Perform a tightness check on the fasteners in the system and tighten, if possible. ❑ Check for any missing or corroded fasteners and replace, if possible
Mechanical : Racking	❑ Check all hardware for corrosion, missing or damaged parts, and replace, if possible. ❑ Remove any debris ❑ Perform a tightness check on the racking hardware and tighten, if possible	❑ Check all hardware for corrosion, missing or damaged parts, and replace, if possible. ❑ Remove any debris. ❑ Perform a tightness check on the racking hardware and tighten, if possible.

Source: NREL Preparing PV Systems for Storms

Checklist for Pre-Storm Preventative Actions (cont.)

Category	Ground-mounted	Roof-mounted
Electrical: Connectors, Wiring, and Supports	❑ Before conducting any electrical adjustments or modifications, ensure all system AC/DC disconnects, fuses, switches, and circuit breakers are in the open position. ❑ Check J-box is securely attached to the module and is intact. ❑ Check that PV cable connections are connected securely, free of corrosion, and not damaged ❑ Ensure all cable ties are in place, holding cable securely to the module frames and racking Replace damaged or worn materials with UV-resistant ties and wire clips/clamps (preferably metal) on modules and rails, if possible. ❑ Check all system wiring for exposed conductors. ❑ Inspect other cable connections for secure contact and corrosion. ❑ If using conduit, check conduit to ensure it is not damaged and is continuous. ❑ If using conduit, check conduit supports and secure conduit ❑ Check enclosures for integrity, corrosion, and watertightness. This includes combiner boxes, inverter boxes, and enclosures. ❑ Perform a tightness check on the structural mounting hardware for the enclosures and tighten, if possible. ❑ Check electrical connections in enclosures for corrosion, damaged or burns, including all bolted power connectors.* ❑ Check grounding system for tightness of connections and visual continuity of system.*	❑ Before conducting any electrical adjustments or modifications, ensure all system AC/DC disconnects, fuses, switches, and circuit breakers are in the open position. ❑ Check J-box is securely attached to the module and is intact.* ❑ Check that PV cable connections are connected securely, free of corrosion, and not damaged ❑ Ensure all cable ties are in place, holding cable securely to the module frames and racking. Replace damaged or worn materials with UV-resistant ties and wire clips/clamps (preferably metal) on modules and rails, if possible. ❑ Check all system wiring for exposed conductors .* ❑ Inspect other cable connections for secure contact and corrosion.* ❑ If using conduit, check conduit to ensure it is not damaged and is continuous.* ❑ If using conduit, check conduit supports and secure conduit ❑ Check enclosures for integrity, corrosion, and watertightness. This includes combiner boxes, inverter boxes, and enclosures.* ❑ Perform a tightness check on the structural mounting hardware for the enclosures and tighten, if possible. ❑ Check electrical connections in enclosures for corrosion, damaged or burned connections, including all bolted power connectors.* ❑ Check grounding system for tightness of connections and visual continuity of system.*

Source: NREL Preparing PV Systems for Storms

Checklist for Pre-Storm Preventative Actions (cont.)

Category	Ground-mounted	Roof-mounted
Electrical: Waterproofing	❑ Check gasketing, conduit fittings, and seals on penetrations in electrical enclosures to prevent wind-driven rain; tighten and/or apply outdoor-rated sealant if possible. ❑ Ensure access panels to equipment are closed and latched, if possible.	❑ Check gasketing, conduit fittings, and seals on penetrations in electrical enclosures to prevent wind-driven rain; tighten and/or apply outdoor rated sealant, if possible. ❑ Ensure access panels to equipment are closed and latched, if possible.
Final Steps	❑ During the storm, it is recommended that the system be powered down and turn all disconnects into the “open” position.*	❑ During the storm, it is recommended that the system be powered down and turn all disconnects into the “open” position.*

**This checklist is for more formal distributed solar systems, but in general provides considerations that are relevant for any off-grid systems as well

Source: NREL Preparing PV Systems for Storms

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Checklist Examples

The diagram to the right highlights key examples of elements to check when preparing PV systems for storms. These are also relevant for general operations and maintenance as well.

Source: [NREL Preparing PV Systems for Storms]

How are off-grid solar systems operated and maintained?

Why is O&M Important?

PV systems tend to require very little maintenance compared to other types of electric generators, but effective O&M can help to:

- Increase efficiency and energy delivery (kWh/kW)
- Decrease downtime
- Extend system lifetime
- Reduce cost of O&M ($/kW/year)
- Ensure safety and reduce risk
- Enhance appearance and image
- Reinforce confidence in the long-term performance and revenue capacity of an asset to attract lower-cost financing

Note: PV system O&M is often required as part of financing and warranty

Source: NREL Best Practices for O&M of Solar Systems

O&M Contracts

Typical O&M contract format

- List of preventative (scheduled) maintenance items based on “Fixed Cost”
  - Periodic inspection, Vegetation control, etc.
- Corrective maintenance (unscheduled repair after failure) based on "Cost Plus" where labor costs and equipment markup are negotiated in O&M Contract.
  - Inverter replacement, broken modules, wind damage, etc.

- System owners are likely to seek a “performance contract,” where specified performance is guaranteed
  - Important to understand Key Performance Indicators (KPIs) and how they are defined in the contract
    - **Performance Ratio:** measured generation (kWh) / model generation (kWh) (IEC 61724)
    - **Availability:** fraction of time system is operational (IEC 63019)
    - **Annual production**; weather adjusted

Source: NREL Best Practices for O&M of Solar Systems

Preventative Maintenance

Preventive maintenance maximizes system output, prevents more expensive failures from occurring, and maximizes the life of a PV and energy storage system. The goal is to manage the optimum balance between cost of scheduled maintenance, yield, and cash flow through the life of the system.

A checklist and timeline for preventative maintenance tasks can be found on page 107 of the Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition Report including:

- Array cleaning
- Vegetation management
- Corrosion inspection
- Disconnect inspections
- Grounding and cable inspections
- Performance testing
- Visual inspections

Source: NREL Best Practices for O&M of Solar Systems

Corrective Maintenance

Required maintenance to repair damage or replace failed components. Balance needs to be struck between urgency of repair, lost revenue, and risks for further system impacts. For example, faults or conditions that introduce a safety problem should be addressed as soon as possible, even if the recovered revenue is small, but smaller corrective tasks can be combined with preventative schedules.

A checklist and timeline for corrective maintenance tasks can be found on page 116 of the Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition Report including:

- Replacing fuses and connectors
- Repairing faults
- Rerouting conduits
- Replacing wiring
- Reinstalling software
- Replace batteries
- Replace racking

Source: NREL Best Practices for O&M of Solar Systems

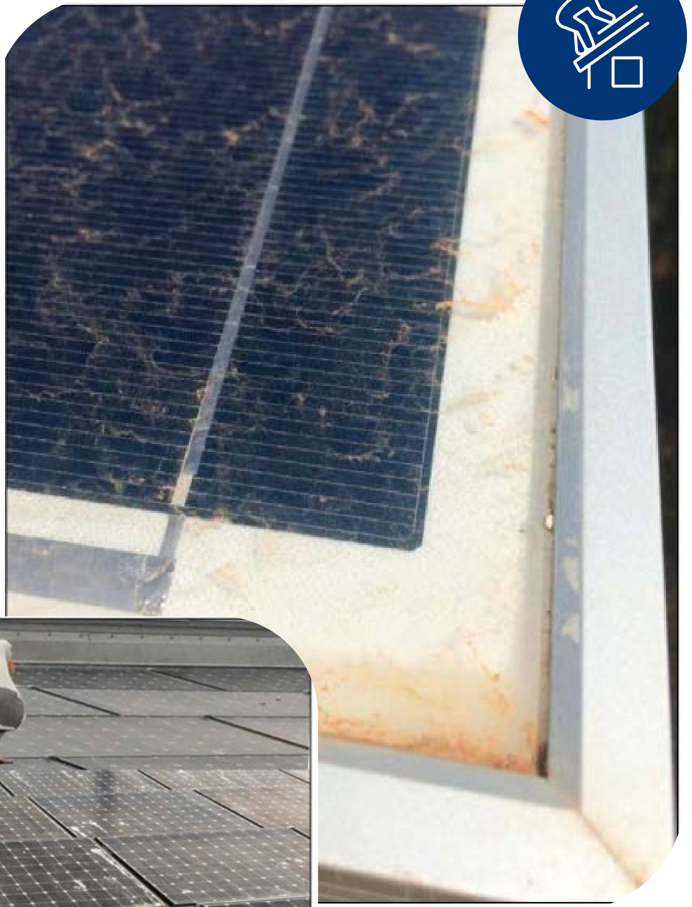
Cleaning

- Soiling of PV panels can reduce energy output – **upwards of 6% losses per year**
- Cleaning may be defined at regular intervals (E.g. monthly) or based on conditions (e.g. based on performance of cells)

Some common sources of soiling include:

- Agricultural dust
- Construction dust
- Pollen
- Bird nests and droppings
- Diesel soot
- Industrial sources

Most manufacturers include PV cleaning instructions, but generally will include plain water and mild soap avoiding hard brushes and abrasives



Source: NREL Best Practices for O&M of Solar Systems

Vegetation Control

International Fire Code (IFC) 2018 1204.1

- A clear, brush-free area of 10 feet shall be required for ground-mounted photovoltaic arrays as a fire-protection measure
- Vegetation can shade PV modules
- Roots can affect foundations
- Vegetation can attract pests and increase bird droppings.
- Deny vegetation access to nutrients, sunlight and water.

- **Livestock, particularly sheep** have been employed for vegetation control and there are increasingly "agrivoltaics" installations which couple solar land with more controlled agriculture growth

Source: NREL Best Practices for O&M of Solar Systems

Photos by Andy Walker, NREL

O&M Considerations for PV Mounting

Roof – Mounted	Ground – Mounted
Ballasted: accumulating leaves and debris; leaks under ballast pans; movement of items on roof **Attached:** leaks around stanchion flashings **Roof system:** membrane, cover-board, insulation, air and vapor barriers, and the roof deck **Complexity:** more complex roofs = more expensive repairs **Slope or Pitch:** higher slope/pitch on roof = more expensive repairs **Condition:** roof/decking damage **Scale:** size of roof affects per-unit cost **Type of roof:** different roofs require different maintenance	**Vegetation management:** mowing, trimming, tree removal, etc. **Snow removal:** on array, access roads and alleys, between tracker rows **Cleaning:** dirt, dust, pollen, etc. **Initial design:** clearance from ground, racking space, vegetation growth on adjacent properties **Ground cover:** gravel can be problematic **Erosion:** can endanger stability of PV rack **Movement**: can damage rack and conduit **Bird populations:** require frequent cleaning

Source: NREL Best Practices for O&M of Solar Systems

USAID FROM THE AMERICAN PEOPLE   NREL Transforming ENERGY

Spare Parts

- A critical factor for successful operations and maintenance of solar systems is keeping an inventory of spare parts readily accessible for repairs.
- The list of spare parts will vary depending on the type of solar solution and location, but generally include electrical components (e.g. batteries, inverters, panels, wiring, etc.), balance of systems , connections (e.g. ports, plugs, connections, contactors, switches, etc.), as well as consumables (e.g. screws, fuses, filters, nuts, and bolts) – see next slide

A general equation for spare parts:

$$n = N * R^{P} / (1 - P)$$

n	N	R	P
Number of replacement parts to keep in inventory	Total number of parts (of a specific component) in the system	Desired reliability (0-1)	Probability a part will fail

Source: NREL Best Practices for O&M of Solar Systems

USAID FROM THE AMERICAN PEOPLE

NREL Transforming ENERGY

Spare Parts

- **Frequently replaced parts**
  - Rack fasteners (nuts and bolts); PV module clamps
  - Wire ties, PV connector plugs, wiring harnesses, length of damaged wire
  - Fuses, fuse holders, breakers, disconnect switches
  - Inverter air filter
  - Enclosure gaskets, door fasteners
- **Common Replacement parts**
  - Micro-inverters or string inverters; components of central inverter (data acquisition card, control card, driver cards, IGBT matrix, capacitors)
  - AC contactors, DC contactors, reclosers
  - Sensors and data acquisition and communications components (broken or simply obsolete)
  - Tracking rack parts (actuator motor, bearings)
- **Rarely replaced parts**
  - Rack foundation and stationary rack parts
  - Transformer

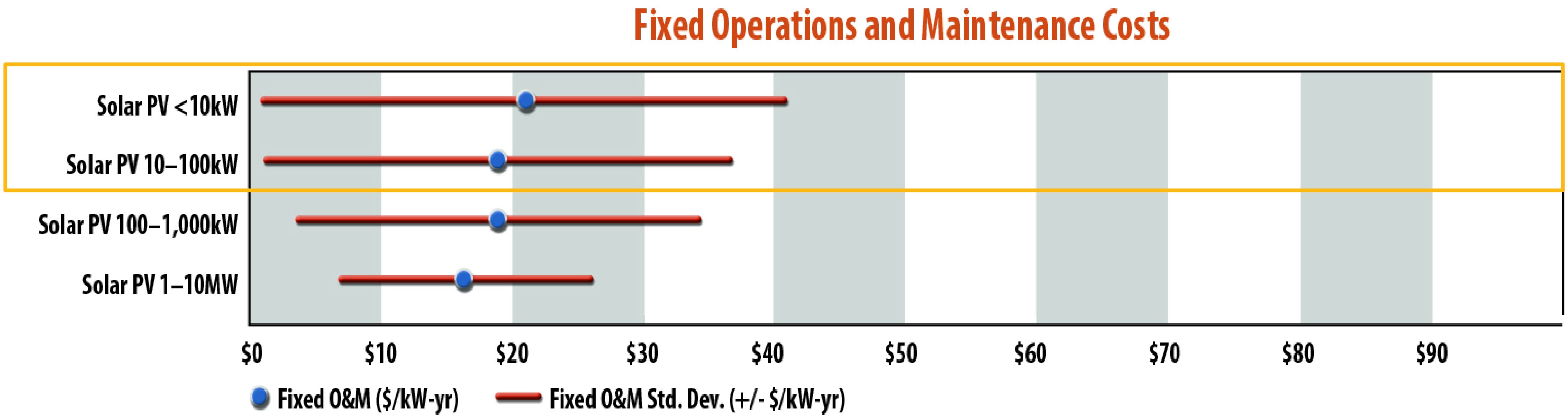
Warranty Management

- Follow instructions *carefully* to not **void warranty** – small deviations such as handling of packaging can result in a voided warranty
- Document data to **prove that a module is underperforming**
- Plan for **labor to remove, ship, and re-install** an underperforming module
- Try to get a warranty for the manufacturer to "**repair or replace" rather than "supplement**"
- Consider an **Insurance Policy** that provides that warranty claims will still be processed in the event of the liquidation, receivership, or closure of a dealer

Source: NREL Best Practices for O&M of Solar Systems

General Cost Ranges for O&M for Solar

The below table shows conservative estimates for O&M costs (USD) for solar installations of different sizes



Source: NREL Best Practices for O&M of Solar Systems

Thank you

USAID
FROM THE AMERICAN PEOPLE

NREL
Transforming ENERGY

This work was authored, in part, by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the United States Agency for International Development (USAID) under Contract No. IAG-19-2120. The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof, including USAID. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL/PR-7A40-89249