

SCTE • ISBE[®]

S T A N D A R D S

Energy Management Subcommittee

SCTE STANDARD

SCTE 246 2018

**Best Practices in Photovoltaic System Operations and
Maintenance for Cable System Operator**

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1. Introduction

1.1. Executive Summary

This document provides recommended best practices for photovoltaic system operations and maintenance. This guide may not include all operations and maintenance routines or scenarios, but provides general guidance for safety practices, management, operations, and preventative maintenance of PV systems.

Solar Photo Voltaic (PV) power generation systems in cable facilities are becoming more prevalent. There are several factors impacting the deployment of these PV systems including, high cost of electricity, reduced reliability of the electrical grid, national, state and utility incentives, carbon reduction and sustainability goals. Solar PV is operational during daylight hours for base, intermediate or peak load power generation replacing kW/MW normally supplied by the local utility.

PV power generation systems are typically deployed to reduce the amount of power consumed that is generated from burning fossil fuels and increase the amount of power consumed by renewable energy sources. Most PV systems can reduce grid dependency with the addition of energy storage and provide relief for the electrical grid during high consumption periods. When electrical grids are under the most strain due to high consumption is also the time period the solar systems are operating at peak output.

Key components of PV Systems include:

- Roof or ground mounted Direct Current (DC) power generating photo-voltaic panels
- Direct Current (DC) to Alternating Current (AC) inverters
- Electrical distribution systems
- Kilowatt hour (kWh) and current (amperes) metering and monitoring
- Electrical distribution system disconnects and breakers

Roof mounted PV systems are the most deployed systems at cable facilities. Ground mounted systems utilize valuable ground space and, in most locations, facility ground space is limited. Utilization of reclaimed ground space, such as decommissioned satellite dish space, is an option for deploying ground mounted systems.

PV systems require periodic, scheduled maintenance to maintain reliability and operational efficiency. One of the most important areas of an O&M program is safety. Only qualified and trained personnel or contractors should be permitted to service or maintain PV systems. The most dangerous parts of a solar electric system is the electricity generated by the PV system. Personal protective equipment for arc-flash protection, lock-out/tag-out procedures, and rooftop safety are required when working around PV systems. Keeping contractors and/or employees as safe as possible by preparing them for prevention of hazards and fall risks associated with PV systems.

1.2. Scope

The scope of the operational practice covers grid tied and grid independent solar photovoltaic systems deployed in cable operator's infrastructure.

1.3. Benefits

Solar PV systems are expected to have a 20 plus year lifecycle and maintaining the deployment can help optimize performance. Conditions such as soiling should be addressed according to this operational

practice to both support energy production and reliability. Where the system is deployed as part of power availability strategy, following the outlined operational practice should help ensure the quoted power output is produced during time of critical need.

1.4. Intended Audience

Solar PV system owners and facility managers should familiarize themselves with this operational practice.

1.5. Areas for Further Investigation or to be Added in Future Versions

At the time of publication, no areas of further investigation has been discussed.

2. Normative References

The following documents contain provisions, which, through reference in this text, constitute provisions of this document. At the time of Subcommittee approval, the editions indicated were valid. All documents are subject to revision; and while parties to any agreement based on this document are encouraged to investigate the possibility of applying the most recent editions of the documents listed below, they are reminded that newer editions of those documents might not be compatible with the referenced version.

2.1. SCTE References

- No normative references are applicable.

2.2. Standards from Other Organizations

- No normative references are applicable.

2.3. Published Materials

- No normative references are applicable.

3. Informative References

The following documents might provide valuable information to the reader but are not required when complying with this document.

3.1. SCTE References

- No informative references are applicable.

3.2. Standards from Other Organizations

- No informative references are applicable.

3.3. Published Materials

- National Renewable Energy Laboratories, Best Practices in Photovoltaic System Operations and Maintenance 2nd Edition,
<https://www.nrel.gov/docs/fy17osti/67553.pdf>

- National Institute of Building Sciences – Web-based Training, Operations and Maintenance for Optimal Photovoltaic System Performance,
<https://www.wbdg.org/continuing-education/femp-courses/femp56>
- PV System Installation Best Practices Guide,
<http://www.nrel.gov/docs/fy15osti/63234.pdf>
- SAPC standard contracts for commercial and residential offtake
https://financere.nrel.gov/finance/content/solar-securitization-and-solar-access-public-capital-sapc-working-group#standard_contracts

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<i>deprecated</i>	Use is permissible for legacy purposes only. Deprecated features may be removed from future versions of this document. Implementations should avoid use of deprecated features.

5. Abbreviations and Definitions

5.1. Abbreviations

AC	alternating current
AMI	advanced metering infrastructure
AMR	automated meter reading
ASCE	American Society of Civil Engineers
ANSI	American National Standards Institute
ASNT	American Society of Non-destructive Testing
ASTM	American Society for Testing and Materials
C	Celsius
CAD	computer-aided design
CT	current transformer
DAS	data acquisition system
DC	direct current
DOE	U.S. Department of Energy

EAM	enterprise asset management
EISA	Energy Independence and Security Act
EPC	engineering, procurement, and construction
EPDM	ethylene propylene diene monomer
EPRI	Electric Power Research Institute
ERP	enterprise resource planning
ESCO	Energy Services Company
EVA	ethylene vinyl acetate
FEMP	Federal Energy Management Program
FERC	Federal Energy Regulatory Commission
GHI	Global Horizontal Irradiance
GO	generator owner
GOP	generator operator
GSU	generator step-up
IBTS	Institute for Building Technology and Safety
IEC	International Electrotechnical Commission
IECRE	International Electromechanical Commission Renewable Energy
IEEE	Institute of Electrical and Electronics Engineers
IGBT	insulated-gate bipolar transistor
IP	Internet Protocol
IRR	internal rate of return
ISBE	International Society of Broadband Experts
IT	information technology
IV	current-voltage
KPI	key performance indicator
kVAR	Kilovolt-amperes reactive, thousand Volt-ampere reactive, a unit of reactive power
kW	Kilowatt
kWh	Kilowatt Hour
LCOE	levelized cost of energy
LLC	Limited Liability Corporation
m ²	meter square
ms	millisecond
MFS	maximum foreseeable loss
MLPE	module level power electronics
MPPT	maximum power-point tracking
MW	megawatt
NABCEP	North American Board of Certified Energy Practitioners
NCU	Network Control Unit
NEMA	National Electrical Manufacturers Association
NERC	North American Electric Reliability Corporation
NFPA	National Fire Protection Association
NLE	Normal Loss Expected
NREL	National Renewable Energy Laboratory
O&M	operations & maintenance
OMC	outside management control
OSHA	Occupational Health and Safety Administration
PML	probable maximum loss
POA	plane of array

PPA	power purchase agreement
PPE	personal protective equipment
PR	performance ratio
PV	photovoltaics
PVC	polyvinyl chloride
RCRA	Resource Conservation and Recovery Act
REC	Renewable Energy Certificate
RMS	root mean square
ROI	return on investment
SAM	System Advisor Model
SAPC	Solar Access to Public Capital
SBS	styrene butadiene styrene
SCTE	Society of Cable Telecommunications Engineers
SDO	standards developing organization
SREC	Solar Renewable Energy Credits
STC	standard test conditions
TCIR	total case incident rate
TPO	thermoplastic polyolefin
UAV	unmanned aerial vehicle

5.2. Definitions

Asset owner	Entity that holds title to the PV system or portfolio of systems and may be an individual, a corporation, or most commonly a special-purpose corporation, such as a Limited Liability Corporation (LLC), formed just to implement and operate the PV project.
Asset management	Systematic process of planning, operating, maintaining, upgrading, and replacing or disposing of assets effectively with minimum risk and at the expected levels of service over the assets' life-cycles. It therefore contains all of the services that would fall under O&M, but also includes business services operations, such as billings and collections from power purchase agreement (PPA)- and lease-based systems (DOE, 1999). Asset Management involves: planning and budgeting for O&M; administration; billing; accounting; tax preparation and filing; hiring subcontractors; enforcement of warranties; management of budget and reserves; insurance policies; renewable energy certificate (REC) certification and trading; performance reporting; plant supervision; quality control; as-built plant documentation; ongoing environmental compliance; and compliance with any other regulatory or utility requirements.
PV Operations	
Administration of operations	Ensures effective implementation and control of O&M services including curation of as-built drawings, equipment inventories, owners and operating manuals, and warranties. Curation involves not only keeping an archive but selecting what to keep, pursuing missing documents, preserving documents, keeping them up to date, and finally, archiving documents. Administration includes keeping records of performance and O&M measures, preparing scopes of work and selection criteria for service providers, contracting with suppliers and

	service providers, paying invoices, preparing budget, and securing funding and contingency plans for O&M services. Administration includes compliance with regulations by the government or authorities having jurisdiction, as well as mandatory guidelines issued by utilities.
Conducting operations	Ensures efficient, safe, and reliable process operations including making decisions about maintenance actions based on cost/benefit analysis. This includes serving as a point of contact for personnel regarding operation of the PV system; coordinating with others regarding system operation; power and energy forecasts; scheduling maintenance operations; spare parts inventory (either in-stock on-site or in suppliers' consignment stock); and inspecting work and approving invoices. Meanwhile, operations include any day-to-day operation of the system to maximize power delivery; performance assessment and trends; operation of grid interface; manage curtailments; or adjust settings such as power factor or other ancillary services.
Directions for the performance of work	Specifies the rules and provisions to ensure that maintenance is performed safely and efficiently, including the formalization and enforcement of: safety policy (including training for DC and AC safety, rooftop safety, minimum staffing requirements, arc flash, and lock-out tag-out); work hours; site access, laydown areas, and parking; and any other stipulations under which work is performed. This includes confirming and enforcing qualifications of service providers, as well as compliance with any environmental or facility-level policies regarding the handling of controlled materials (e.g., solvents, weed killer, insecticide).
Monitoring	System analysis of resulting data to remain informed on system status; metering for revenue; alarms; diagnostics; and security monitoring. Includes comparing results of system monitoring to benchmark expectation and providing reports to facility stakeholders. This includes periodically preparing reports as required by O&M contract or as required by the system owner including reports of plant performance; key performance indicators; problems and alarms, and maintenance services performed. Site security is performed both locally and with remote monitoring (cameras, intruder alarms) to protect against theft and vandalism.
O&M	Operations and maintenance for solar PV systems should include proper care and tasks required to meet OEM warranties and optimization of system performance over the course of the system lifetime.
PV Operator knowledge, protocols, documentation	Ensures that PV operator knowledge, training, and performance will support safe and reliable PV plant operation. Information such as electrical drawings, part specifications, manuals, performance information, and records must be deliberately maintained and properly filed/catalogued.
PV Maintenance	
Administration of maintenance	This overlaps with "Administration of Operations" and ensures effective implementation, control, and documentation of maintenance services and results. Administration includes: establishing budgets and securing funds for preventive maintenance; establishing reserves or

	lines of credit for corrective maintenance: planning services to avoid conflict with system operation or operations at the customer site; correspondence with customers, selection and contracting with service suppliers and equipment manufacturers; record keeping, enforcement of warranties; providing feedback to designers of new systems; and reporting on system performance and the efficacy of the O&M program.
Preventive maintenance	Scheduling and frequency of preventive maintenance is set by the operations function and is influenced by a number of factors, such as equipment type, environmental conditions at the site (e.g., marine, snow, pollen, humidity, dust, wildlife), and warranty terms. Scheduled maintenance is often carried out at intervals to conform to the manufacturer's' recommendations as required by the equipment warranties.
Corrective maintenance	Required to repair damage or replace failed components. It is possible to perform some corrective maintenance such as inverter resets or communications resets remotely. Also, less urgent corrective maintenance tasks can be combined with scheduled, preventive maintenance tasks.
Condition-based maintenance	Condition-based maintenance is the practice of using real-time information from data loggers to schedule preventive measures such as cleaning, or to head off corrective maintenance problems by anticipating failures or catching them early. Because the measures triggered by condition are the same as preventive and corrective measures, they are not listed separately. Rather, condition-based maintenance affects when these measures occur, with the promise of lowering the frequency of preventive measures and reducing the impacts and costs of corrective measures.
End-of-performance period disposition	Specifying the options for the parties in an offtake contract (such as a PPA) at the end of the performance period, or at the end of the projected life of a host-owned system, the alternatives are the following: to continue the performance contract for an extended term, including continued O&M; purchase of the system by the site or others (often at "fair market value"), involving a new O&M provider; or removal of the system and restoration of the site.
Guarantees	Response time guarantee; availability guarantee; performance ratio guarantee; and energy production guarantee

6. Typical PV Installation Applications

Photovoltaic systems can be installed in most cable facility types and some network distribution applications including:

- Data Centers
- Head Ends and Hubs
- Call Centers
- Field Force Offices
- Administrative Facilities
- Power Supplies



Figure 1 - Solar PV installed at Headend

7. O&M and the Financing of PV Assets

An effective O&M program enhances the likelihood that a system will perform at or above its projected production rate and cost over time. Therefore, it reinforces confidence in the long-term performance and revenue capacity of an asset. Historically, O&M practices and approaches have not been standardized, and instead, they were implemented in various proprietary methods. This approach can increase the cost to projects and portfolios, as well as raise the perception of risk from investors. Specific recommendations from the PV O&M Working Group to reduce variations in O&M practices include:

- Define performance metrics uniformly. A system characterized by a guarantee to deliver 1,000 MWh/year would be difficult to compare and bundle with another that has a guarantee to be operational 90% of the time. Investors need performance metrics and evaluation methods to be the same across a bundle of assets.
- Refer to specified standards. Practices and delivery of O&M services also differ, and investors need to know that an existing system has been maintained according to standard definitions and criteria.
- Make cost estimates uniform and predictable. Differences in types of systems and also geographic location and climate conditions can confound securitization. Investors want to know how much it will cost to perform required O&M and secure the performance of the investment. Cost estimates must be uniform and predictable so that they can be bundled, yet they should reflect the factors that cause O&M costs to vary from site to site.

Many investors are more interested in reducing risk than maximizing internal rate of return (IRR). Investors would prefer 5% IRR with 100% certainty over 10% IRR with 50% certainty, even though the two are of statistically equivalent value. Investors will make an investment decision based on mitigating performance risk with effective O&M, and then the financing rates are determined mainly through competition from other banks. Standardization of O&M practices will facilitate investor analyses of risk factors and can reduce due diligence time and costs. Risk reduced by effective O&M will enable banks to qualify more projects, and that will eventually increase competition and reduce borrowing costs.

Although PV systems may have different origins, they can be pooled together in portfolios—and thus, be financed more efficiently—if they adhere to clear, industry-accepted business and technical guidelines regarding O&M. Industry groups important to this effort include the Institute for Building Technology and Safety (IBTS), the SunSpec Alliance, and the North American Board of Certified Energy Practitioners (NABCEP). National and international standards-developing organizations (SDOs) important to this effort include the American National Standards Institute (ANSI), the Institute of

Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), and ASTM International (formerly known as the American Society for Testing and Materials [ASTM]).

Two SDOs—the ASTM and the IEC—are coordinating directly with NREL and Sandia National Laboratories to develop O&M standards, with drafts being made available to working group members. These standards are primarily technical in nature and focus on life-cycle management, design for O&M guidelines, and detailed maintenance processes and procedures.

Representatives from ASTM and IEC were involved in developing these best practices. This document is offered as what is referred to in the standards-making process as “research,” to be considered as the IEC and ASTM committees develop the language of the standards. The IECRE, which is the Renewable Energy IEC system for certification to standards, will receive this PV O&M Guide for consideration of recommendations. It will serve as input to PV industry certification and compliance approaches and practices.

8. Scope and Prerequisites for a Successful O&M Program

8.1. Scope of PV O&M Guide

This document is targeted at fleets of third-party-owned, grid-connected PV systems of the following size classes: residential rooftop (typically less than 10 kW); commercial and industrial rooftops and shade structures (10 kW to 1,000 kW); and ground-mounted systems (often greater than 1,000 kW).

Services covered in the guide include: asset management; monitoring; operations; preventive maintenance; corrective or condition-based maintenance (repair); and end of performance period (disposition).

The guide addresses dependencies due to system type such as: micro-, string-, or central inverter; ground versus roof mounted; attached versus ballasted mount; and tracking versus fixed mount. The guide also addresses dependencies based on site conditions including: sources of soiling; bird populations; snow; pollen; and high temperatures.

The guide provides information on the delivery of O&M services including qualifications of service providers, contractual relations, and performance guarantees related to O&M.

8.2. Prerequisites for a Successful O&M Program

Borrowing from classroom grades, where “A” is best, it is possible to bring a PV system earning a “D” grade up to a “C” or “B” with effective O&M. But it is not possible to earn an “A” unless O&M was a consideration in the design of a system. Also, O&M might not be able to save a failing system if the problems are intrinsic to the design or products used. O&M issues should be considered in design, engineering, and construction in order to:

- Select low- or no-maintenance alternatives when available
- Make use of network-connected inverters for remote testing, software configurations and/or updates, and remote resets
- Provide required access to and clearance around equipment for maintenance (EPRI 2010)
- Enable third-party inspection and commissioning of original EPC installations to spot operation problems before acceptance (EPRI 2010)
- Conform to the evaluation and quality-assurance protocol detailed in the SAPC PV System Installation Best Practices Guide (applicable to residential systems only)

- Apply IEC 62446: Grid Connected Photovoltaic Systems-Minimum Requirements for System Documentation, Commissioning Tests, and Inspections

(2009, http://webstore.iec.ch/Webstore/webstore.nsf/ArtNum_PK/42990!opendocument&pre view=1), which requires documentation of the system, array testing, and whole-system performance test¹ (applicable to commercial, industrial, and utility-scale systems).

Commissioning is the link between the engineering, procurement, and construction (EPC) contractor and the operator. In addition to the above-mentioned safeguards, commissioning is now recommended to be a two-part process: the first part is done when the system starts operation, and the second is performed after one year of operation. Full acceptance of the system comes after the second step. Third-party verification of a plant can also help ensure that best practices are applied throughout the life-cycle of a plant. Such verification could include: concept; site selection; design; equipment selections; installation; commissioning; final commissioning; PV system performance reporting; annual certification; certification for transfer of ownership or for refinancing; O&M practices; and/or end-of-performance-period.

9. Dependencies on PV System Type, Site, and Environmental Condition

It is useful to consider how O&M requirements and attendant costs depend on the type of system and components, some details of the site, and climate and other environmental conditions such as agricultural area versus urban setting.

9.1. Electrical System

If micro-inverters are not used, the PV system will have both alternating current (AC) and direct current (DC) components. The DC system determines system power capacity and energy production, whereas the inverter and the AC system has the greatest impact on system reliability. There can be several single points of failure in the AC system—for example, the central inverter, or the generator step-up (GSU) transformer. Central-inverter considerations are discussed in the next section.

O&M measures and cost depend on the wire management system employed. O&M will be minimal for conductors in conduit or lay-in trays, which are designed as an integral part of the rack and wiring system. Maintenance must be provided to ensure that the wire management system continues to protect the wires from physical damage. O&M problems will be exacerbated if:

- Wires, plastic wire-ties, or grommets/bushings are exposed to sunlight. Even products listed for direct UV exposure will show degradation over the long life of a PV system and require eventual replacement.
- Allowable movement or rubbing against modules, rack parts, or other wires due to wind or thermal expansion/contraction will require more frequent inspection, testing, and replacement. Movement of ballasted rack systems on a roof can cause damage to conduit or wires, and even ground mounted parts can experience movement over a long period of time. A design that accommodates such movement and thermal expansion/contraction will require less corrective maintenance.
- Wire ties that pinch wires too tightly will eventually deform the insulation. Faults may occur anywhere that wires are held tightly between metal parts.

¹ Other commissioning guides are also available.

- Wires that are pulled too tight or that do not have strain relief will require more frequent maintenance. Wires exposed where the weight of accumulated ice, or where module leads do not come in the right length for the installation, will required frequent testing and repair.
- Exposure to animals, such as squirrels, will require measures to deny access of the animals to the wiring and to repair any sections where the insulation has been chewed.
- Large bundles of wires may not allow wires at the center of the bundle to cool as they would in open air, leading to early degradation of the insulation and potential fault.
- Direct bury of conductors versus placing in conduit: Direct bury of conductors is a lower first cost than installing conduit and pulling conductors. Failure risk of direct-bury conductors is usually low, and failures are typically caused by chewing rodents. Proper compaction of the soil is best-practice for reducing this problem. However, if the direct-bury conductor does fail, the conductor must be dug up to find and fix the problem. This can be very expensive: not only does the conductor need to be dug up, but there is likely other buried infrastructure in the vicinity, making the dig-up process very slow. Direct bury is chosen in many cases, driven by capital-cost considerations.



Figure 2 - Maintenance of Wire Management Systems

Figure 2 above depicts maintenance of wire management systems depend on plastic wire-ties and grommets which can break or pinch wires (left), exposure to sunlight, wind and weight of ice (center), and access by chewing rodents (right). (photos by Andy Walker)

GSU transformers are common in utility-scale PV plants, and the failure risk has been low historically. In the past, transformers were overbuilt and have a reputation for being very reliable. However, as design engineers now have access to computer-aided design (CAD) tools, they are able to meet requirements without overdesigning. If the GSU does fail, it can idle the plant for months. GSUs are very expensive and have a very long lead time. Also, they are large and heavy, and the logistics associated with delivery are complicated. Delivery of GSUs may include a crane and require special permits for transport on roads and interstates.²

The risk of GSU transformer failure may be mitigated during the design phase by dividing the plant into multiple arrays, each with its own GSU transformer. It is critical to follow the manufacturer's recommendations for a preventive maintenance program. It may also be possible to work with local

² Accessed August 2016 <http://community.energycentral.com/community/t-d/managing-risk-transformer-failures>

utilities to pool resources for better access to replacement units. At the minimum, the responsible party should have a fully formed reaction plan in place.

9.2. Central, String, DC Optimized, or Micro-Inverter Configuration

Operation and maintenance depends on the topology of the inverter system: micro-inverters on each module, string inverters on series strings of modules, DC-optimized inverters that combine elements of both topologies, or larger central inverters. The cost per watt of capacity is much higher for a micro-inverter and string inverter than it is for a central inverter. The different types of inverters have different failure and replacement profiles and different effects on production.

Table 1 - Cost of Micro, String, DC-Optimized, and Central Inverter Replacement [Q4 2015/Q1 2016 April 29, 2016. David Feldman NREL, Daniel Boff DOE; Robert Margolis NREL]

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

Inverter reliability continues to increase, with 10-year warranties now commonly available and 20-year extended warranties/service plans also gaining prevalence. However, a sound O&M plan should account for inverter failure because it is one of the most frequent causes of PV system performance loss (EPRI 2010). The best preventive maintenance for the inverters would be to perform the manufacturer's required maintenance—to include, but not limited to, re-torquing current-carrying conductor fasteners (screw lugs on terminal blocks), and thermal imaging of sand-cleaning air filters. Inverter air filters will take in grass and dust during mowing, high winds, or dusty conditions, and the O&M plan should establish a timeframe when the grass-cutting is done and schedule a preventive filters swap/cleaning to follow such dusty conditions. A technician will be dispatched faster to service a central inverter (see Appendix C for corrective maintenance choices for both string and central inverters), whereas failures of micro-inverters, and to a lesser extent string inverters, can be delayed until a scheduled visit because their impact on the performance of a large plant is marginal.

Additional steps include the following:

- Decide whether the inverter is to be replaced or repaired based on inverter size, type, manufacturer's ability and availability for timely repairs, and associated costs. Replacement is preferred over repair when spare-parts availability and lead time trigger an upgrade. But upgrading may lead to other concerns such as not being able to get the correct replacement size, footprint, and electrical conduit and wiring configuration. Include remote monitoring to confirm the inverter status, reset the inverter, and remotely diagnose problems.
- In remote locations, it is advisable to stock component replacements onsite, especially for equipment commonly in need of repair, such as driver boards if the manufacturer support or warranty is not available. Replacement micro-inverters and power optimizers should also be stored onsite.

Central Inverter

Central inverters involve much more DC wiring to deliver the PV energy from a very large distributed array to the location of the central inverters. Electricians working on energized DC circuits (combiner box and array) must don personal protective equipment as required per NFPA 70E and OSHA Standards (including but not limited to arc-rated clothing, insulation gloves, faceshield, and other personal protective equipment [PPE] as required for the level of voltage and arc-flash potential being worked on). The gloves with liners and leather protectors are sometimes unwieldy, so complex tasks are difficult and tasks take longer to perform. The cost of a technician that has training and PPE to work on live DC circuits is in one case \$128/hour versus \$70/hour for a journeyman electrician who could maintain ordinary AC circuits. Other items such as disconnects are also more expensive in DC version than AC version. An arc fault is more persistent in DC wiring than in AC wiring. The additional DC wiring of a central-inverter configuration might require more repair than the corresponding AC wiring of a micro-inverter or string-inverter configuration. Large central inverters become a single point of failure—if the inverter is down, either intentionally for maintenance or unintentionally, the entire associated electrical production is lost, not just a portion. Monitoring using only a few central inverters is less complicated than multiple micro- and string inverters, and it involves less energy consumption by the monitoring system itself. Advanced features such as non-unity power factor (sourcing kVAR), curtailment of output power, low-voltage ride-through, and low-frequency ride-through are easier to implement in central inverters, and such controls will add more to the “per watt” cost of micro- and string inverters. For central inverters, numerous subsystem repairs to the inverter are supported (control cards, driver cards, components such as an insulated-gate bipolar transistor (IGBT) matrix and capacitors), assuming that each is repaired independently, in contrast to micro- and string inverters, which requires replacement of the entire unit.

String Inverters, Micro-Inverters, and DC-Optimized Inverters

Micro-inverters and string inverters shut down automatically as required by IEEE 1547 upon loss of AC connection, and only the strings of modules connected to the string inverter remain energized. The wiring from the string inverters to the central AC switchgear becomes de-energized, which is the important advantage of string inverters with an impact on O&M costs, since it is simpler and less expensive to work on de-energized, conventional, AC wiring than it is to work on energized DC wiring. Micro- and string inverters avoid the need for an additional control circuit and hardware required for rapid shut-down (NEC 690.12) and avoids the need for arc-flash protection when working on the connecting AC wiring. Power optimizers work similar to micro-inverters but shut down the DC power coming from the power optimizers to the inverters. Each power optimizer will output only 1 V, meaning that the string connecting the modules to the inverter is also de-energized. Regarding corrective maintenance, manufacturers of string inverters vary, but can take up to about one month to send in new warranty inverters for replacement. The customer should go to the site and take a photo of the dead string inverter and then call the company to ship the replacement materials authorization (RMA), which is a long process when compared to replacing failed components of a central inverter with spares on-hand. However, replacement of string inverters is quick and easier than repair of central inverters and can be accomplished by an electrician rather than an inverter specialist. Annual production can be improved over that of a central inverter by keeping string inverters in stock for replacement, and to rotate this stock as inverters fail—an approach that is not feasible for central inverters.

With string inverters, fewer arrays are impacted with one inverter failure. Even though it is unlikely that all the string inverters will be down at the same time, there is a corresponding probability that, at any given time, at least some string inverters will be down and in need of service or replacement (called “whack-a-mole” by service providers). Micro-inverter manufacturers have developed a sophisticated data platform that maps location and can monitor performance, and also pushes out software upgrades on a

module-by-module level—much more detailed information than data from a central inverter. Power optimizers also offer the ability to see module-level data through mapping of module locations and, in many cases, can remotely offer the same troubleshooting capabilities of onsite current-voltage (I-V) sweeps. The selection of string inverters assumes replacement or swap as the most common corrective action, rather than replacing failed parts as in a central inverter.

9.3. Roof Maintenance Related to PV System

O&M measures related to the roof for rooftop systems include finding and fixing roof leaks and any maintenance related to the rack attachments or effects of ballast on the roof. Rather than only the roof membrane, a “roof system” includes membrane, cover-board, insulation, air and vapor barriers, and the roof deck. O&M considerations provide preventative maintenance for the roof and avoid damage to any of these roof-system components as the PV system is being serviced. Roofs under warranty require annual preventive roof maintenance to maintain the roof warranty. It is a best practice for the PV O&M provider to meet with the roof maintenance provider to make sure both teams understand their roles and responsibilities and respect the needs of the other. Failure to provide for maintenance of a roof system may result in roof-system failure, thereby necessitating PV system removal for roof repair/replacement, which is bad for the prospects of the PV system. By meeting, the roof maintenance provider can share particular areas of concern with the PV O&M team, and vice versa. This kind of collaboration can minimize contentious finger-pointing when problems arise. Scope and cost of maintenance for rooftop systems are affected by several factors, discussed below.

Complexity: It costs more to perform repairs on a roof with a complex layout, such as multiple sections or multiple ridges in different orientations.

Slope or Pitch: It is more difficult, requires more safety equipment and training, and costs more to perform repairs on a steep roof than a low-slope roof. Slopes greater than 34:12 pitch (vertical to horizontal, about 18 degrees, some companies use 14 degrees as the low-slope/steep slope criterion) require a higher standard for fall protection (29 CFR 1926.500)—warning lines alone are not allowed, guardrails must have toeboards, etc.—and contractors charge more for pitches above 7:12 because of the difficulty, special equipment required, and because the company pays higher insurance costs. See OSHA 1926.501(b)(10) for low-slope roof requirements and 1926.501(b)(11) for steep roofs. A ballasted, rather than attached, system may be used on flat and low-slope roofs, but not sloped roofs.

Condition: Prior to proceeding with installing a PV system the roof condition should be evaluated, structural analysis should be performed to verify roof structure can support the additional live and wind loads and If the roof and decking is damaged, any repairs or replacement costs will be additional scope and cost. This could occur if a water leak has damaged the underlying roof deck. Often, water damage is not noticed until after the roofer has removed shingles and looked at the deck.

Scale: The size of the roof—and more specifically, the areas under the PV system and requiring maintenance associated with the solar energy system—affects the per-unit cost. With a high cost of mobilizing equipment and labor to the site, leaks in small roof areas (e.g., residential) will be very expensive to fix on a per-square-foot basis. Roofers talk in units of “squares” and one square equals 100 sf.

Type of Roof: The costs per-square-foot for different roof types can vary drastically based on country, size, site access, location, and labor markets. Membrane flat-roof applications include fully adhered thermoplastic polyolefin (TPO) membrane roof, ethylene propylene diene monomer (EPDM), or polyvinyl chloride (PVC). For ballasted systems, there is a sacrificial slip sheet between the bottom of the ballast pan and the roof membrane.

The links below provide estimated roof repair costs based on various criteria (http://welcome.homeadvisor.com/costguide_roofing and <http://www.homeadvisor.com/cost/roofing/repair-a-roof>.)

The use of manufacturer-specific materials are required for the flashing to PVC, TPO, and other membrane-type roofs. The flashing must bond chemically with the field membrane, and all materials and adhesives must be compatible. Bituminous and modified bitumen roofs use cone-shaped metal flashings, and the skirt of the flashing is sealed with a torch-down bitumen capsheet, with an EPDM collar sealing the flashing to the post.

Overburden Waiver: An overburden waiver, often required to maintain a roof warranty, agrees to remove the PV system should the roofing company need access to do any roof work. If required, the cost of removing and re-installing a PV array area is high and also entails lost production.

Roof Warranty: Determine if roof currently has an active warranty. Roofing contractors often guarantee the work they do, which is often between 5 and 10 years for their workmanship. This will typically cover leakage or total failure, but not wear-and-tear or damage associated with the PV system. Some roofing manufacturers offer 25-year warranties, but those typically apply to commercial projects and require certain installation procedures. PV systems can be installed on many different types of roof. However, installation of a PV system can increase a roof's potential for leaks and damage due to increased rooftop foot traffic and additional attachments to and through the roof membrane. So measures need to be taken to continue a warranty and ensure long-term performance of the roof under the PV system. The following scope of work is recommended for the roofing company having the warranty or service contract on the roof, or failing that, then another roofing company certified by the roof manufacturer:

- Provide forms to fill out or procedures to follow and information required to officially notify roofing company and manufacturer of roof problems related to a PV system and plan for repairs.
- Review the repair plan to ensure that it is appropriate for the existing type of roof, compatibility of materials, stresses, expansion/contraction, membrane puncture, insulation compression, and recommended repair/replace practices. Identify the conditions required to maintain the roof warranty or recommendations for the quality of the installation, such as thickness and material properties of slip-sheets, and also including selection of cleaning agents and any other future O&M impacts.
- Inspect the condition of the roof prior to repair work. Provide details of any repairs or reinforcement required.
- Inspect the final condition of the roof upon completion and acceptance of the repairs. To reduce the potential for leaks and to provide a more durable platform under all types of PV systems, the roof manufacturer will specify requirements and recommendations. For ballasted rack PV systems, this would include a sacrificial layer (membrane) of minimum thickness under the feet of the ballasted rack system (Figure 2); walkway system comprising a walkway pad or pavers around the blocks of the PV arrays; requirements to remove PV components to investigate a leak or make a repair; requirements that the system be rendered safe (de-energized) for roof work, and other requirements considered necessary by the roofing company or roof material manufacturer. New flashings or other alterations to the roof must follow all technical standards and details provided by the manufacturer.



Figure 3 - Slip Sheet

Figure 3 depicts installation of a run slip sheet continuously under rack members to avoid direct contact with roof membrane. In this photo, direct contact of the rack is prevented that could cut into the roof surface (SCTE Headquarters).

Snow and Ice Removal: Snow is rarely removed from PV systems because it is not cost effective and damage may occur to the PV modules and wiring. Snow may slide off of arrays tilted more than, say, 30 degrees, but will remain on lower tilts until it melts. If snow is not removed, annual production is reduced by about 3% on average and up to 15% in very snowy climates (e.g., Truckee, CA). However, it is sometimes necessary to remove snow to avoid limits on roof weight loading. For light snow, a turbofan or brushes and squeegees may do less damage than shovels and rakes, but extreme care is required to avoid damage. Snow is sometimes removed from the roof or ground in front of the array to provide clearance for snow to slide off of the PV array. Cost for snow removal varies depending on roof height, roof slope, number of panels, depth of snow, etc.

Removal of Ice Dams: Ice dams should be removed to allow the roof to drain properly. Snow over the ice dam can be removed with a rake or shovel and the ice dam can be removed using chemical ice melters or a de-icing cable. Extreme care must be taken not to damage the roof membrane, the PV modules, or connecting wiring.

Removal of Debris: Debris that has collected such as leaves should be removed to allow water drainage and to prevent material for vegetation growth and nesting on the roof. Cost for removal of debris is often included in the estimated cleaning cost, but is a cost in addition to cleaning the surface of the PV modules themselves.

9.4. Ballasted or Attached Rack

PV arrays may be attached to the roof deck or structure or they may be ballasted, which means held in place by added weight. Ballasted systems can only be used with flat or low-slope roofs (as specified by supplier, but not more than 5 degrees; 1:12 pitch). To reduce wind loads, ballasted systems can only be used if solar collectors are at a low tilt angle—usually a 10-degree tilt and limited to no more than 20 degrees (one dual-orientation ballasted system has a south-facing panel tilt angle of 25 degrees, and north-facing of 15 degrees). Such a low tilt angle is a minor penalty on annual energy delivery depending on latitude, but allows more kW per square foot of roof area and delivers more in summer, when utility rates are higher.

Roofing Material: Maintenance of a ballasted PV system is affected by the type of roofing material. Coal tar pitch, styrene-butadiene-styrene (SBS) modified bitumen, or other soft materials may be damaged by

the pressure of a ballasted system, although suppliers of those roofs have introduced products and methods to accommodate ballasted PV. Fully adhered TPO membrane roof, ethylene propylene diene monomer (EPDM) or PVC-type roofs are protected by a slip sheet of material between the ballast foot and the roof membrane.

Compressible Insulation: Maintenance issues may arise on roofs that have compressible insulation and some measure may be needed to avoid membrane damage and ponding of water. Ponding of water in depressions under the added weight of a ballasted PV system can deform and stretch the membrane, accumulate dirt, and increase abrasion—in turn, requiring more maintenance to avoid leaks in the membrane. To avoid this, in design, the insulation should be polyisocyanurate (polyiso) board stock as base layer, with a more rigid backer-board to serve as an underlayment for the membrane, such as 15.8-mm (5/8-in.) gypsum cover board; otherwise, special protective layers may be required to avoid compression of insulation and membrane damage.

Wear on Roof Membrane: The manufacturer will specify requirements including the thickness of slip-sheets between the ballast feet and the roof membrane. Even with this sacrificial layer, or where the layer is not present, movement causes wear of the membrane, and maintenance will be required to maintain the integrity of the membrane. Two best practices are recommended: 1) a continuous slip-sheet roll running underneath the entire racking rail (as compared to individual slip-sheets placed individually under contact points; and 2) during O&M, make sure these slip-sheets are still in place under racking contact points. The slip-sheets can sometimes work themselves loose over time.

Roof Deflection: Typically, an attached system will add less than 3 pounds per square foot of solar collector area, whereas a ballasted systems will add 3 to 8 pounds per square foot depending on the tilt angle and wind loading. The weight of ballast materials varies from the edges to the middle of the racking system, depending on the load to be resisted; so ballast weight is not necessarily distributed uniformly across the array. Edges of structures have greater wind loads than the center of the roof; thus, it has more ballast weight. The added weight of a ballasted system can cause deck deflection, resulting in increased ponding of water. In that case, there may be measures to improve drainage.

Wind Damage: To use a ballasted rack solution, advanced wind-loading evaluations have to be performed above the general requirements of ASCE-07. Wind loading is usually the determining consideration on whether a ballasted system is feasible (i.e., in areas susceptible to high wind, the ballast weight required could be excessive and so an anchored system would be better). Product-specific design can aid in the placement of a ballasted arrays to avoid strong wind areas.

Extreme Snow Loads and Ballasted Racks: Snow loads are a variable load consideration common to both attached and ballasted systems. Extremely heavy snow loads may exceed the rating (often 240kg/m² or 50 lbs/ft²) for low-slope ballasted rack hardware, and may cause damage to the rack and modules.

Maintenance of Proper Roof Drainage: The position of PV rack and ballast materials must be arranged so that they do not disrupt drainage or result in accumulation of small debris. Ballasted racks have many obstructions (numerous ballast feet laid on the roof) unlike attached systems, which sit up taller on stanchions. Thus, ballasted racks take more effort to keep the roof clear of debris and ensure that these obstructions do not impede drainage.

Migration of Connections on Roof: Unattached, ballasted components can move over time. The design should accommodate this movement in the conduit to the stationary interconnection. But eventually, cumulative movement will require a revision to the conduit to avoid stresses. For large commercial rooftop PV systems this may occur every 5 years.

9.5. Ground-Mount

Ground mount avoids the roof maintenance issues listed above but introduces ground maintenance issues, including:

- Vegetation management (mowing, trimming, tree removal, herbicides), which are often estimated as a cost per acre of site area.
- Snow removal can involve removal from the array itself, clearing of access roads and alleys, and removal where snow accumulates as it slides off an array. If snow is removed from the array, care should be taken to ensure that the modules are not mechanically damaged by the removal techniques. In the case of single-axis trackers, significant damage can occur if snow is not cleared from between tracker rows, because the modules can come into contact with snow banks when the tracking mechanism is at its extreme east or west positions.
- Cleaning requirements increase for ground-mounted arrays because they are closer to the source of airborne dirt and pollen.

Just as equipment O&M issues should be considered in the design phase, the long-term maintenance of the ground cover and drainage should be considered in the design, civil engineering, and construction phases of ground-mounted systems to reduce O&M risks and costs. In climates with high rainfall, for example, grass-cutting and vegetation control costs can equal or exceed equipment O&M costs (Brehaut 2015) (Huff 2013).

9.5.1. Design

Initial design considerations that can significantly impact O&M costs for ground-mounted systems include ensuring that panels are mounted with sufficient and relatively uniform clearance from the ground; racking is spaced widely enough to allow access for efficiently sized mowing; and cleaning equipment and to protect panels from damage from such equipment (EPRI 2010) (Brehaut 2015). During site selection, it is important to consider vegetation growing on adjacent properties. Consider how tall the trees will be in twenty years, and will this cause shading of the system.

In an informal survey and series of interviews conducted by NREL with more than 30 members of the PV industry, several respondents cited significant problems with panels mounted too close to the ground to allow access under the panels by an arm of a mower, causing significant costs for more labor-intensive vegetation management approaches.

Initial design considerations also include establishing proper drainage to avoid or accommodate flooding and to control erosion which can undermine equipment pads and racking. Several NREL survey respondents cited increasingly unpredictable and extreme weather conditions that impacted operations and pointed to the need to design not for historical, but more extreme climatic conditions.

9.5.2. Ground Cover

Upfront investment in developing ground-cover solutions tailored to each site's climate and soil conditions and establishing such solutions in the initial year or two of operation can ensure longer-term viability and lower the risks of shading, erosion, and excessive weed and vegetation abatement costs during the operations phase (Hernandez 2014).

Applying gravel as a ground cover was widely identified by NREL survey respondents as expensive and problematic because it creates uneven work surfaces, changes runoff coefficients, and does not provide a long-term weed abatement solution. Gravel applications were described as requiring either regular

application of herbicides, which can be restricted by local regulations, or mechanical weed control, which can kick up rocks and damage modules.

In general, NREL survey respondents saw low-growth, vegetative ground cover as ideal for ongoing maintenance, although many cited challenges in re-establishing vegetation following construction. Successful solutions included:

- Replanting with low-growth species selected by a horticulturalist or other expert based on site soil and climate conditions, including bent grass, white clover, and buffalo grass combined with blue grama (ESCO Associates Inc., publication pending)
- Replanting with pollinator-friendly or other habitat-supporting ground cover in coordination with local agricultural extension services or other partners.
- Preserving existing, sometimes native, vegetation through minimizing grading, which can reduce weed infestations.

Some survey respondents, as well as an NREL study of revegetation applications at a utility-scale PV site in Colorado, report greater success with broadcasting seeds and raking them into the soil, or drill seeding, than with hydro-seeding to reestablish vegetative cover in more arid areas. (ESCO Associates Inc. publication pending)

9.5.3. Vegetation Management

Chemical vegetation abatement may be more efficient and at times less costly, particularly in arid areas. However, several NREL industry survey respondents cited problems with soil stabilization after herbicides eliminated vegetation; the added risk to, and safety requirements of, those handling the chemicals; and, most often, local or state regulations that restrict herbicide use. In addition, chemical vegetation abatement can conflict with public expectations of environmental stewardship from the solar industry.

In arid areas, mowing may be unnecessary with proper soil stabilization. For areas where mowing is required, there is the added risk of projectiles damaging modules.

Some companies in Germany and a growing number of utility-scale PV systems in North Carolina and Hawaii are working with local ranchers and farmers to use sheep grazing for vegetation management (Figure 3). Goats are not a good option because they jump up onto the array, and cattle are large powerful animals that damage the array by scratching against it. Those with experience in this area report greater success when forage needs are taken into consideration in the design phase and determining the re-seeding mix. Grazing considerations can include slightly higher ground clearance and conduit to protect wiring (Huff 2013).



Figure 4 - Animal use for Vegetation Control

Figure 4 depicts sheep aiding in vegetation control around ground mount PV systems. Note, goats or cattle is not recommended. (photo by Eliza Hotchkiss)

9.5.4. Erosion Control

Grading prior to PV system construction exposes soil that is extremely susceptible to runoff and erosion due to rainfall. Civil engineers may design for “sheet flow” of storm water. But, in fact, once a small rill starts to form it collects more water and grows into a large gully. The rill and gully erosion that occurs under such conditions can endanger the stability of the PV rack foundations and fences, expose buried conductors, and damage access roads and inverter pads. Thus, a best practice is to design specific pathways for storm-water runoff that include check- dams throughout the site that feed into channels lined with rock (rip rap) and that have the channels terminate in splash pads and integrated into the site storm-water management system, such as a retaining basin. Runoff and erosion can be reduced by stabilizing the aggregates at the soil surface with soil conditioners. Such soil conditioners are polymers that are sprayed on the dry soil surface before the rainy season. There are several types of polymer soil conditioners, but they all have a high molecular weight and complicated molecular shapes that bond with soil and act as a cementing material that stabilizes the soil against the force of raindrops, as well as preventing pores in the soil from clogging with clay. The type and amount of polymer applied depends on the soil type and conditions at the site. Reapplication is required if treated soil is disturbed or the appearance of rills shows the need for reapplication. Once the long-term ground cover (described above) is established, reapplication of the polymer should not be necessary.



Figure 5 - Drainage and Storm-Water Run-Off

Figure 5 depicts poor drainage and storm-water run-off management from a system where it was not accounted for during the PV array is installation. This condition requires diligence in design and construction of storm-water management systems (photo by Andy Walker).

9.6. Tracking Mounts

The complexity of tracking systems requires much more maintenance, not only on the load-bearing moving parts of the array, but also, for the associated system for actuators and controls. Additional considerations for tracking systems include:

- **Electrical:** Check electrical connections and enclosure for tracking motor/controller; check grounding braids for wear.
- **Controls:** Inspect and calibrate anemometer, replace cup-wheel; inspect inclinometer; inspect limit switch; replace tracking-controller power-supply fan filter; inspect/test tracking controller.
- **Rack and Actuator:** Check drive-shaft torque and visually inspect gearbox lubrication; inspect module table; grease screw jack; inspect screw jack; lubricate slew-gear; check slew-gear torque and inspect wear; grease universal-joint (zerk fitting); inspect universal joint; lubricate tracker-mounting bearings/gimbals; repair/replace tracker drive shaft; replace hydraulic cylinder; replace tracker drive bearing; replace tracker motor controller; replace tracker mount bearing; replace/upgrade tracker control software.



Figure 6 - Tracking Mechanisms and Controls

Figure 6 highlights installation that looks to improve annual energy delivery, especially in summer, tracking mechanisms and controls require regular maintenance to be effective (photo by Andy Walker).

9.7. Environmental Conditions

Many environmental conditions can affect O&M, and many are outside human control. Soiling can be addressed by the O&M contractor through cleaning, and possibly during the site-selection process. That is to say, if two potential sites are being evaluated, and the only difference is that one has a source of soiling and the other does not, choose the site with no soiling problem. Other environmental conditions can affect O&M, but are outside human control. Examples include:

- Humidity (this may be addressed by installing dehumidifiers in shelters that contain sensitive equipment)
- Hot climate
- High wind
- Hail
- Salt air
- High insolation.

9.7.1. Cleaning

Soiling reduces the energy output of the PV array, and can lead to localized hot-spot failures if the soiling is uneven. Efforts should be taken to reduce uneven soiling, for example from bird droppings. Care must be taken with array cleaning to avoid damaging the components. Follow the PV module manufacturer's recommendations with any array cleaning. Clean PV modules with plain demineralized water with mild detergent recommended by the manufacturer. An economical method is with a bucket of water, strip cleaner and squeegee (often on opposite sides of the same tool), using overlapping vertical strokes in the