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STANDARDS

Energy Management Subcommittee

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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

4. Compliance Notation

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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
m2	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 warrantees 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 test[1] (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- torqueing 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 lobor 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 if 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). Goads 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 same way window glass is cleaned on commercial buildings. Do not use high-pressure water, brushes, or any types of solvents, abrasives, or harsh detergents. Robotic Cleaning systems are available for large systems, and many of these require that the design of the system accommodate the movement of the robotic cleaning system.

Cleaning may be on a defined interval or "condition based," and the impact of soiling can be measured by instruments to trigger a cleaning (for example a sensor with and without a shutter of soiled glass). In either case the benefits of cleaning may be hard to calculate. For example, an instrument may indicate that the array is dirty, which would trigger a cleaning, but there may be a heavy rain the next day which would clean the array for free. In the case of uniform soiling, a local, site-specific cost-benefit analysis should be performed to determine whether routine cleaning of the array is warranted. The frequency determined may be seasonal, depending on local rainfall and dust characteristics. Optimal cleaning interval is affected by several parameters:

- Cost of cleaning: usually a fixed fee to mobilize a cleaning crew and then a per-unit-area cost for labor and materials ($/m2)
- The rate at which soil accumulates on the array, expressed as a power loss in %/day, %/month, or %/year.
- The capacity factor for the location: the better the solar resource is the higher the reward for cleaning
- The value of the delivered power ($/kWh): the higher the value of the power the higher the reward for cleaning
- PV module efficiency: the lower the efficiency the more area (m2) of array needs to be cleaned for the same benefit.

It is tempting to combine these parameters to calculate a cleaning interval that justifies the cleaning expense. However, due to the fact that dirt begins to accumulate again as soon as a system is cleaned and due to the effects of rain, a simulation is required to account for time- series effects. Using such a simulation, Naeem (2014) found that for a system in Mesa Arizona with an annual soiling loss of 1.91%, a single annual cleaning would reduce the loss to 1.52%/year (-20%), two annual cleanings to 1.32%/year (-31%), and three annual cleanings to 1.20%/year (-37%). Including the effect of soil accumulation and rain in an hourly simulation can also take into account that the effect of soiling changes throughout the day, with losses due to soiling in the morning and evening about twice that in the middle of the day due to high incident angle (the shadow cast by each dirt particle grows longer with increasing incident angle).

Most rely on rain to keep the array clean; no cleaning regimen is employed. Heavy rains result in a nearly complete cleaning effect, whereas light rains clean much less effectively and can even increase soiling if dust then sticks to sparse water droplets. Mohammad Hussain Naeem (2014) did a comprehensive study based on empirical data for both soiling rates and cleaning costs and concluded that cleaning is not cost-effective for neither residential, commercial, nor utility-scale plants. He found that cleaning costs varied from large systems to single residential systems, and water consumptions was around 1 liter/m2 of system area.

However, where special conditions (listed below) occur, cleaning will be required on a schedule that depends on the source and nature of the soiling. Annual soiling losses are reported in a range from 4.3% to 7.5%, with many studies confirming losses around 6%/year. However, annual values are confounded by the rain cycle and it is more helpful to look at how soil accumulates daily, in-between heavy rains. Studies report about 0.05% reduction in output per day due to soiling. Naeem (2014) provides a good analysis of cleaning and survey of the literature and reports daily soiling rates of 0.061%/day and a range from 0.057% to -0.085%/day from his own experiments. He recounts another study of 186 systems reporting 0.051%/day and another reporting a range of 0.04% to 0.07%/day. In an area with heavy agricultural activity 0.36%/day is reported, and contrasted to a rate of 0.01%/day in a desert area void of agricultural, construction, or industrial activity. Large bird populations may result in losses accumulating as high as 0.5%/day and dust storms in places like India have reported losses accumulating at around 1.5%/day.

Soiling and resulting cleaning regimen depend on local sources of dirt. A sample swabbed from the PV module surface can be taken to an analytical laboratory to ascertain its origin. Some sources of soiling may be eliminated or reduced at the source (birds, factories, construction sites), whereas others will be corrected only by cleaning. Sources of soiling that may indicate the need for prevention or a cleaning regimen include:

- Agricultural dust: cleaning can be scheduled following plowing. In parts of the world without active soil conservation, persistent dust can require frequent cleaning.
- Construction dust: cleaning can be scheduled after completion of nearby construction. Encourage construction manager to implement dust suppression.
- Pollen: schedule cleaning after end of pollen season.
- Bird Populations: Reduce open cracks between panels where birds can build nests; use plastic bird slides to change flat surfaces to steep-sloped surfaces; use bird netting to seal areas under the panels down to the roof completely around the array; install bird spikes along the top edge of the array to prevent roosting; use plastic owl or falcon with swivel head to scare off birds; Schedule rooftop services and removal of nests according to nesting season timing. Birds are creatures of habit and their behavior can be changed over time to avoid your roof.
- Diesel Soot: present in cities and concentrations such as bus depot and may require frequent cleaning.
- Industrial Sources: Processes such as cooking or manufacturing can be sources of array soiling. This can be identified by testing samples of the dirt. As an example, a filter added to a fryer can reduce oil in kitchen exhaust air.

Figure 7 - Module Soiling

Figure 8 - Bird Populations

Figure 7 captures module soiling that can often be traced to a source, such as construction-site dust shown here resulting in about 5% loss. (photo by Andy Walker)

Figure 8 clearly illustrates bird populations as a source of soiling. (photo by Andy Walker)

9.7.2. Snow Removal

Design of array can increase or decrease snow accumulation (Figure 7). Clearance between the bottom of the array and the ground or roof avoids wind-driven drifts and allows snow to slide off. Snow generally slides off steep arrays (for example, 30 degree tilt), but does not slide off low-sloped arrays (<20 degree tilt). Snow removal is generally not recommended because it damages the modules, but it is sometimes required to reduce snow weight on a roof or to remove ice dams. Snow removal is by powerful turbo-fan, not shovel or other mechanical means. Snow removal to provide access (roads, walkways) is generally required.

Figure 9 - Snow

Snow is shown in Figure 9 where an environmental condition that both reduces performance and complicates provision of O&M services is shown (photo by Andy Walker).

9.8. Site Access

Utility-scale sites frequently have access roads through the array. These are installed during civil construction to facilitate array construction services. Because these sites can be several acres, driving access is needed. Roads must also accommodate emergency vehicles such as fire trucks. The roads may also be built to accommodate cranes, and crane access may be needed during O&M services. Roads are placed in natural breaks, such as the end of several strings, or the end of an array tracking mechanism. To ensure an accessible site, these roads must be maintained periodically.3

Site security is another issue to consider. If the site is in a rural area, perhaps a fence and locks on the enclosures and shelters is all that is needed. In a more populated area, cameras or occasional visits by a security guard may be warranted.

9.9. System and Site Considerations Checklist

	Is Site Owned or Leased – Leased sites most likely will require owner approval prior to installation.
	What are the near term plans for the site – are there discussions on possibly selling the site or moving out?
	Was O&M a consideration in system design? Are the interests of EPC and O&M provider aligned?
	Are conductors buried or placed in conduit? If direct-bury, is ground compacted to deter chewing rodents?

	Preventative maintenance schedule for inverters followed? Is repair or replacement criteria for inverter based on availability, size, type, and cost? Do inverters have remote monitoring and control?
	Is system compliant with roof warranty? Is there an overburden waiver defining responsibilities for each party? Is a system in place for notifying the roofing company if roof problems arise related to a PV system?
	Does conduit design account for movement in rooftop ballasted systems?
	Are climate, extreme weather events, ecological conditions, and environmental regulations accounted for and budgeted into the O&M plan?
	Does civil engineering design adequately provide for road access, drainage, and security? Does panel spacing allow for vehicle access between rows?
	Do panel cleaning methods follow manufacturer recommendations and cleaning schedule account for local conditions? Has a cost-benefit analysis been run to determine if regular cleaning is cost-justified?
	Is the plant required to meet North American Electricity Reliability Corporation (NERC) compliance for utility-scale plants?

10. System Performance and O&M Plans

The PV O&M plan should be considered within the context of the performance period required for a residential or commercial PV system to generate a sufficient return on investment (ROI).

The PV O&M life-cycle begins with planning and system design. The life cycle ends with provision for decommissioning or disposal of the system. The asset life (about 25 years) is considered the performance period even though ownership may change multiple times during that period.

The cost of the monitoring program can range from minimal (e.g., checking the total electricity generated as reported by the inverter once per year) to high in high-accuracy monitoring equipment that is watched daily for signs of problems or needed cleaning. As discussed below and in the appendices, the monitoring program is chosen to align with the expected increased revenue because it would depend on the size of the system and the logistical details.

A system owner is likely to seek a performance contract where a specified performance indicator, such as MWh/year energy delivery, is guaranteed. Indicators that account for changes in weather, force majeure, and anticipated degradation are recommended (such as the performance ratio as described in Appendix A).

The scope of work for the performance contract is called a Performance Work Statement, with “performance” being quantified by indicators such as energy delivery or availability. Appendix E includes an example Performance Work Statement based on the key performance indicator of 80% of system nameplate rating and corrected for balance-of-system efficiency and conditions.

10.1. Planning for PV System Performance

Many performance indicators have been proposed: select a type of key performance indicator that minimizes cost, but ensures optimal system performance under varying conditions.

Consideration of performance indicators includes how they should be used, when they are or are not accurate, benefits of each, and pitfalls of using them for the wrong application. PV system performance is based on how much time is lost when a system is not available and on the performance of the system when it is available. A system may have an availability of 95%, but a performance index of 100%. The stakeholders will have a much better assessment of the system if they measure performance based on both metrics—down-time and energy delivery.

Performance indicators are also important in the monitoring and guarantee sections of this guide.

Performance Indicators

Examples of key performance indicators (KPIs) include the following:

1. "Availability" (or "uptime") refers to the percentage of time that a condition is met— usually that a component or system is operating. In contrast, IEC 61724 states that "energy availability" is a metric of energy throughput capability that quantifies the expected energy when the system is operating relative to the total expected energy, rather than the percent of time that a plant is available, which is the more traditional use of the term "availability." When defining availability as a contract term, it is important to distinguish events that are "outside management control" (OMC). Operators should not be penalized for events that are OMC. Availability standards under development strive to remove from the calculation the lost energy production during the time of an OMC event.
   However, there are many modified forms of defined availability, the details of which can be segmented and which should be explicitly documented.
    a. Is the availability affected by the grid interaction (grid down, power reduction, or planned shutdowns to avoid grid instabilities) or by the plant itself (shutdowns for planned O&M downtime due to malfunction)? IECRE's implementation of IEC 61724-3 suggests also reporting the energy availability with external causes identified and OMC events excluded.
    b. The energy availability may be reported for the complete system or for "blocks" within systems. For example, a 2-MW plant may consist of four 500-kW "blocks" and one may be down while the other three continue to operate. The energy availability may be reported either for the subsystems or for the entire system. Block availability is more appropriate than whole-system availability whenever the unaffected parts of a system can continue to operate unimpeded.
    c. Availability can also be specific to the components or subsystems within a system. For example, there may be a KPI for one service provider to maintain a given availability for the tracking system and a separate KPI for another provider regarding uptime of the inverter. See Klise and Balfour (2015) for more detail. When availability is applied at the component level, it may make more sense to use the time-based availability, reporting, for example, the fraction of days per year that the component was available rather than attempting to identify the energy availability associated with that specific component.
    d. An availability spec is currently being drafted by IEC that further breaks down unavailability into various categories. Some categories may be planned categories such as maintenance; others may be unplanned such as equipment failure, or unplanned, but force majeure, such as weather or grid outage.

2. "Energy Availability": Because the availability of a PV system during times of darkness is not of much relevance to functionality, it is useful to define "energy availability," which effectively provides an energy-weighted version of the time-derived availability metric. For a PV system IEC 61724-3 states that Energy availability is a metric of energy throughput capability that quantifies the expected energy when the system is operating relative to the total expected energy. The energy availability may be expressed as a percentage or a fraction. The system is viewed to be operating when the inverter(s) is peak-power tracking and feeding energy into the grid. If a system has multiple inverters and only a fraction of the inverters are functioning, then the calculation of the "operating" expected energy is calculated only for the inverters that are operating. If a system has string-level monitoring, then the "operating" expected energy may be calculated to reflect only the operating strings. Measurement of the energy availability requires knowledge of the weather data in addition to knowledge of when the inverters are operating; it is described in more detail in IEC 61724.
3. "Energy Performance Index": The performance index is defined by IEC 61724-3 and may be used to complement the energy availability metric. The performance index compares the energy that was produced by the plant with the energy that was expected for the plant based on the measured weather and irradiance, and a performance model agreed to by the stakeholder. The performance index may be defined to stand alone or to complement the energy availability metric by using the options:
    a. "All-in energy performance index" is the ratio of the total electricity produced divided by the electricity that was expected including all hours and seasons of the year.
    b. "In-service energy performance index" is the same ratio, but excluding the electrical energy that was expected when the system was not operating. The in- service performance index is useful toward quantifying how well the plant functions when it is functioning and is best used to complement the energy availability metric.
4. "Energy Delivery" refers to the measured MWh/year energy delivery; Adjusted Energy Guarantee is discussed in IEC 61724 and NREL report Analysis of Photovoltaic System Energy Performance Evaluation Method
5. "Specific Performance" refers to energy delivery divided by plant rated capacity, in units of kWh/kW/year. This is also referred to as "Array Output Energy" in IEC 61724.
6. "Performance Ratio" as described in IEC 61724-1 or ASTM E2848 – 13 Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance. The latest version of IEC 61724-1 defines several ways to calculate various types of performance ratio. Variable definitions of performance ratio can prevent direct comparisons in some cases. The "standard" definition of performance ratio does not include a temperature correction. Recommendations are provided in the NREL report Weather-Corrected Performance Ratio on how to avoid the variability of performance ratio with weather conditions. Appendix A presents an example of such a description of how performance ratio is applied.
7. "Power Performance Index": Measurement of the power performance index is described in IEC 61724-2 and is similar to the energy performance index except that it reflects the power output rather than the energy output. A performance ratio (PR) is not as relevant as a performance index. A PR of 0.8 may be fine for some locations, but not for others. PR will usually be higher in the winter and lower in the summer. In contrast, a more consistent metric is the performance index, which compares the measured power or energy to the expected power or energy—where expected power or energy is based on measured weather and irradiance, and a performance model agreed to by the stakeholders. Ideally, both the power performance index and the energy performance index are close to unity. Thus, the performance indices are more likely to deliver consistent metrics across times of the year, geographic locations, and times of weather anomalies.
8. Capacity Test, or "Short-term Performance Test": The power delivered by the inverter (kW) is compared to the power of the PV system as calculated as a function of environmental conditions by the following equation:

$$P_{solar} = P_{STC}\left\{\frac{(\eta_{BOS} * degr)}{\left(\frac{1000W}{m^2}\right)} I_c \left(1 - \delta\left(\left(T_{ambient} + \frac{(NOCT - 20C)}{\left(\frac{800W}{m^2}\right)} I_c\right) - 25C\right)\right)\right\}$$

Where:

Psolar = predicted average power output in kW of the solar system, averaged over the duration of the test

PSTC = rated size in kW, nameplate capacity; STC refers to Standard Test Conditions

ηBOS = balance-of-system efficiency; typically = 0.77 to 0.84 (NREL, 2011), but stipulated based on published inverter efficiency and other system details

degr = an age degradation factor that is 1.0 initially but degrades at 0.5 % per year

Ic = measured solar insolation in plane of array (W/m2), averaged over the duration of the test

δ = temperature coefficient of power (1/°C), which is usually on the order of 0.004 1/°C for silicon PV modules and may be less for other technologies

Tambient = ambient temperature (°C), averaged over the duration of the test

NOCT = nominal operating cell temperature, which is a number found in the manufacturer's literature and is often around 47°C

The ratio of measured average power to predicted average power is the performance index based on the short-term performance test. Notice that this is a "spot check" on instantaneous power performance and does not include availability (or down-time) in the metric.

O&M managers should consider how to allocate risk associated with inaccuracy of the calculation of PR or error in the implementation of the evaluation method. For example, dirt on a pyranometer will exaggerate PR. Thus, exclusions such as clipping (high AC/DC ratio), force majeure, specific representations made by the O&M provider, and underlying solar resource considerations should be specified in calculations and the evaluation method. Note that a dirty irradiance sensor may be a maintenance issue, but clipping may be a model issue, and it is useful to distinguish between the two issues. The maintenance of instrumentation is very important.

Current PV system performance standards development suggests that a model should be used in the calculation, and such a model may include simulation of issues such as clipping. An example of such a performance model is the System Advisor Model (SAM) program by NREL (https://sam.nrel.gov/), although there are many acceptable models available.

10.2. The PV O&M Plan

The PV O&M plan prepared by the owner, EPC firm, and/or the developer and accepted by the asset manager is the only long-term operations plan for a PV system. The motivations of the

EPC and the long-term operator may be different and they may clash—the EPC is more concerned with getting through the installation warranty period, but the operator is more interested in protecting the value of the system and his or her contractual agreements for many years. The O&M manager retains in the plan archive all the initial planning, warranty, design, and other system specification documents, and also revises the plan as the system is constructed, maintained, and modified over time. The O&M plan provides the specific measures to achieve the level of performance specified by the KPIs in the Performance Work Statement.

An O&M plan can accommodate different system configuration by including all the descriptions and measures for systems and adding the terms "if applicable"—for example, "lubricate tracking ring gear, if applicable." However, the scope of work and cost estimate for suppliers should itemize the measures to be performed based on system details affecting maintenance, such as the number and types of different inverters, fixed rack vs. tracker, rooftop vs. ground mount, transformer vs. transformer-less system, and others. A documented PV system O&M plan for a system or fleet of systems should include the following (depending on system size, complexity, and investment):

Table 2 - O&M Plan Checklist

	List of responsible-party contact information including site owner and offtaker of power, utility, local jurisdiction, local landowner, as well as emergency numbers.
	System documentation including as-built drawings, specifications, site plans, photo records, special safety considerations, electrical single-line diagrams, schematics, drawings, installed components' "cut sheets" and warranties (including warranties from system installer), performance estimates, insolation/shade studies (including a description of nominal conditions to make it easier to see malfunctions or deviations), operation manuals associated with any of the equipment (including emergency shut-down and normal operating procedures), and contracts for preventive maintenance, service, and other operations documents, including contacts for each, and specified response times and availability
	Uphold manufacturers' preventative-maintenance measures to preserve warranties and to optimize system energy delivery, and the schedule for each. Includes details such as cost and current supplier of each preventive-maintenance measure and special instructions such as hours that work is to be performed, access to site, and locations where vehicles may be parked and equipment staged.
	Descriptions of operational indicators, meters, and error messages; description of any physical monitoring setup and procedures by which performance data are to be archived and reported; and procedures by which data are regularly examined for system diagnostics and analytics.
	Keep an inventory of spare parts onsite, or easily accessed by maintenance crew, and implement a process for determining when other spare parts need to be ordered based on component failure history.

	Clearly define availability and performance metrics, and events outside of management control.
	Implement focused training program for all O&M staff on processes relevant to each worker, and the equipment they may be working on.
	Implement chronological O&M log: work order and task tracking to include initial commission report, inspection reports, and ongoing O&M history.
	Established procedure for responding to alerts from monitoring diagnostics, error messages, or complaints from the building owner. Provider should also compile a troubleshooting guide for common problems.
	List of all equipment with make, model, and serial numbers and map of placement in system (to spot trends in manufacturing defects); for each piece, a supplier of replacement part (vendor) should be listed.
	Criteria to decide whether to repair or replace a component. Criteria to decide whether to “cannibalize” a string of modules to source replacement modules or to order new parts.
	Establish procedures for re-acceptance testing following a repair.
	Budget for O&M program including costs for monitoring and diagnostics, preventive maintenance, corrective maintenance, and minimum exposure (line of credit) if replacement of inverter or more expensive corrective maintenance is needed.

10.3. Use of O&M Plan

Following construction and commissioning, the O&M plan is the only surviving operational plan that contains the complete history of the plant in its archive. Therefore, it is critical to ensure that the O&M plan is well-documented and safely archived.

- Ensure, by establishing a well-organized directory, that a well-documented and maintained O&M plan is available for each system in the fleet, along with a preventive maintenance schedule.
- Maintain a tracking log for customer-driven alerts for corrective maintenance and any measures taken on a system. Up-to-date document service histories for each installation should also be included.
- Maintain the O&M plan in an online mobile work-order management system (there are dozens). Use such a ticketing system to record work.
- Include decommissioning in the PV O&M plan and/or asset management.

O&M Plan for Residential/Small Commercial PV Systems

The residential and small commercial O&M focus is on fleet performance goals rather than individual systems; meeting performance warranties of individual systems to meet customer satisfaction goals should be balanced against cost and cash-flow optimization. These PV systems are typically simple, small, and geographically spread out over different metropolitan areas and states. The aim of the operations team is to minimize “truck rolls” and efficiently schedule any needed work. Use the SAPC PV System Installation Best Practices Guide, which includes requirements for design guidelines, system inspections, and system documentation.

Table 3 - O&M Plan Considerations for Residential and Small Commercial

	System should be installed according to SAPC PV System Installation Best Practices Guide [http://www.nrel.gov/docs/fy15osti/63234.pdf]
	Small commercial and residential onsite inspections are the responsibility of the contract off-taker (small commercial) or homeowner (residential). Often the small size precludes the use of automated monitoring (although developments, such as microinverter or power optimizer communications, are making automated and remote monitoring more feasible).
	Any inspection of fleets of small systems is usually on a representative sample rather than every system.
	Performance guarantees should consider typical amounts of malfunction (e.g., one string fuse) and soiling to ensure insignificant corrections can be deferred, and module cleaning and snow removal (by turbofan) is not provided. Treat extreme soiling situations as corrective maintenance.
	Provide a manual to the homeowner with contact information and description of operational indicators and procedures he/she can do, including clear documentation that states the customer is responsible for maintaining original insolation/shade study results by completing routine bush and shrub trimming.

O&M Plan for Larger Commercial and Industrial PV Systems

O&M focus for commercial and industrial PV is more on the performance of individual systems rather than fleets and meeting performance warranties. The investment and revenue of large systems justifies more detailed monitoring for anomalies in performance and increased communications and sensors to trigger condition-based or corrective maintenance services and alerts. Module cleaning, snow removal (for access and in front of modules, only from modules themselves in unusual circumstances where required, such as excessive weight of snow), tree trimming, etc., should be included in the O&M plan and schedule of services and based on the plant environment (e.g., dusty) and financial and performance goals. The PV O&M cost tool supports modeling of different regimes (see Appendix B). One of two reference modules could be cleaned to compare and evaluate the effect of cleaning; this information could be used to trigger a cleaning based on cost.

Key considerations for an O&M plan for systems larger than 500 kW:

Table 4 - O&M Plan Considerations for Commercial and Industrial

	Automated monitoring with diagnostics to push error alerts triggering corrective maintenance?
	Continually analyze performance information to optimize condition-based O&M, such as cleaning, and long-term issues such as reliability trends?
	Provide offtaker with manuals containing contact information and descriptions of their participation and responsibilities, self-inspection of the system, and what conditions necessitate the O&M provider to be notified of problems?
	Provide offtaker with a shelter onsite for workers to meet and look at plans if size warrants

10.4. Document Management and Record Keeping

Documentation is essential to O&M services, and important records include: the physical condition of a PV plant, current contracts for services, insurance policies, tax records, proof of ownership, and compliance with regulations; warranties and the terms to keep warranties in effect; records of past changes to the system; and records of past corrective maintenance services and the results of each. Before undertaking any maintenance service, the service provider must know what equipment was installed initially and any changes that have been made since. If not available, such records should be created (complete set of as-built drawings) at the cost of the asset owner. Some problems are difficult to diagnose and solve, so records of what has been attempted previously are often essential for eventually correcting the problem. Good record keeping of work orders and trouble tickets is required to ensure that each issue is ultimately resolved.

A document management system provides proper storage, access control, change control, and back-up for essential data. A log should be kept of who has accessed the documents, who has taken them out if possible, and what modifications were made, if any. Version control should be implemented so that people can see what document is currently in effect and can look at the history of the document. Documents to be managed in a structured document management system include:

Table 5 - Document Management Checklist

	Maintain list of responsible party contact information including site owner and offtaker of power, utility, local jurisdiction, local landowner, as well as emergency numbers.
	Maintain list of all equipment with make, model, and serial numbers and map of placement in system.
	Maintain all documents produced by the EPC, including As-built drawings (plant location, property boundaries, plant layout, electrical diagram), specifications, product datasheets, and wiring diagrams
	Maintain operating manuals for inverters and other equipment.

	Maintain documentation of health and safety issues and rules.
	Maintain reports from commissioning, re-commissioning, and inspections.
	Maintain past and current contracts with all service providers and suppliers' name, start and end dates, scope of work, contract value and pricing, performance indicators and guarantees, contract clauses).
	Maintain preventative maintenance and inspection records (proof that preventive maintenance required to keep warranties in effect has been completed), as well as corrective maintenance event logs (alarms (with date); status (problem flagged, cause identified; pending, action taken, confirmed that problem is solved); corrective action taken and date; who did the work with contact information).
	Maintain an inventory of spare parts: stock count and location; names and part numbers; date purchased.
	Maintain all warranty documentation: warranty documents; claims made (affected equipment, claim description, occurrence date, correspondence with manufacturer/supplier).
	Document environmental (weather) conditions: meteorological data (insolation in plane of array; temperature, other such as wind speed).
	Document production data: AC active and reactive power at point of interconnection; power consumption of auxiliary systems and "house power"; power at other subsystems such as DC power into inverter, and other measurements as available.

10.5. PV Plant Operations

PV systems are often thought of as passive systems without as much "operations" as a conventional fossil-fuel engine. However, operations programs that consisted largely of

delivering solar power whenever it was available are becoming obsolete. PV system operations is a growing field because increasing PV penetration into the larger utility system, and an emerging market for ancillary services (e.g., dispatch of storage, sourcing reactive power, curtailment of output) require more system interaction on an ongoing basis. Plant operations include forecasting of output; scheduling maintenance operations; spare parts inventory (either in stock on site or in supplier's consignment stock); and inspecting work and approving invoices.

Meanwhile, operations include any day-to-day operation of the system to maximize power delivery; assess performance and trends; operate grid interface; manage curtailments, or adjust settings such as power factor.

10.5.1. Forecasting PV Plant Output

Plant operations include forecasts of power and energy delivery hours and days in advance. Suppliers of PV monitoring systems often also supply forecasts; or other forecasting services based on proprietary or publicly available weather forecasts, satellite data, and statistical methods are also available. In addition to these weather-based forecasts, the operator should impose any scheduled outages or maintenance services that affect the forecasted plant energy delivery. Forecasts are important for two applications:

- Allow PV systems to participate in markets that require advance (e.g., “day-ahead”) contracts to provide power. Such contracts come with an associated level of reliability and financial penalty for non-performance, so an accurate forecast is essential to participate in such day- ahead markets.
- Allow for unit commitment and dispatch of conventional resources (e.g., diesel generator), which is essential in a microgrid application or for a remote system (such as on an Island out in the sea) and is desirable in mainland grid-integration efforts.

Metrics associated with forecasting systems include:

- Forecast horizon: How far in advance the system predicts PV plant energy delivery. Some provide a two-week forecast, but the second week appears to be the astronomical (sun position) forecast, and only the first week appears to incorporates site-specific weather forecast.
- Time resolution: When using conventional weather forecasting techniques, hourly is considered state of the art. To get higher time resolution may require on-site sky observations. Image processing instruments to project cloud movement have been invented and demonstrated, but are not yet in commercial use. Likewise, models to predict cloud formation based on thermodynamics and transport phenomenon in the atmosphere are in their infancy.
- Update frequency: How often is the forecast updated? For example, one vendor updates its forecast every four hours.
- Accuracy: Accuracy of the forecast can be proven out over time by taking the root mean square (RMS) error of the production forecast compared to actual plant output, and considering other factors such as if parts of the plant are dirty or out of service for maintenance.

10.5.2. Inventory of Spare Parts

The O&M service provider is usually responsible for stocking spare parts, but the asset owner may also participate in spare-parts ownership and storage. Parties should agree on “bailment,” which is liability if the parts are stolen or damaged in storage, and the party providing storage should have insurance to mitigate such risk. Storage should provide for security (theft, vandalism), storage conditions (temperature, humidity, moisture), and organization (e.g., first in- first out, do not mix new and returned parts).

As part of the O&M manual and system documentation, the EPC contractor should have provided a spare-parts list with makes and model numbers, as well as recommended sources of such parts. Frequently used parts are called “consumables” and should always be stocked (e.g., fuses, filters, nuts and bolts). The number of other spare parts in inventory depends on several factors: the reaction time required by the O&M contract; the allowable downtime; contractual commitments; and potential for liquidated damages. The higher the desired (or contractually required) availability for a plant, the more spare parts will have to be kept in inventory.

As discussed in more detail below regarding cost estimate for reserve account, the number of replacement parts to keep in inventory, n, depends on the total number of parts (of that component) in the system, N; the probability that a part will fail in a given year, P; and the desired reliability R, according to the relationship n = N * R^P / (1 - P). The cost of maintaining this amount of inventory must be weighed against the time delay in obtaining parts not in inventory and the consequences of down time. Experience with this equation indicates that it is prohibitively expensive to stock parts to maintain a desired reliability of greater than 0.95 or so. Experience in operating the plant (which parts fail, which failures result in lost production) will help fine-tune the inventory of spare parts.

Strategies to reduce the cost of maintaining an inventory of spare parts include:

- Regional clusters of systems surrounding a warehouse to share stock and reduce travel time; share spares for long-lead-time items such as inverters and transformers among multiple projects in a portfolio.
- Standardizing on certain makes and models to reduce diversity in stock.
- Arrangements with suppliers to guarantee availability or consignment stock with manufacturer.

10.5.3. Compliance with Regulatory Requirements

Large PV power plants (greater than 20 MW at the utility interconnection) that provide power into the bulk power system must comply with standards related to reliability and adequacy promulgated by authorities such as the North American Electric Reliability Corporation and Federal Energy Regulatory Commission (FERC). This requires that an operator trains and certifies personnel and demonstrates compliance with multiple requirements specified in standards. NERC and FERC regulations require that the operator establish and maintain a listing on the NERC compliance registry as a generator owner (GO) and generator operator (GOP) and provide and document such things as: cybersecurity and critical infrastructure protection; emergency preparedness plans; reactive power and voltage control; services during and after disturbances; active power control; harmonics; facility interconnection studies; and communications (voice and data link) between plants and grid operators. PV plant operations increase quite a bit, and impose additional maintenance requirements, if the plant operator is registered by NERC as a GOP. Most of the services and associated costs are associated with the systems and security that comes regarding the documentation process. There is also a risk of incurring costs associated with not meeting the FERC/NERC requirements.

Table 6 - Operations Checklist

	Is system performance monitored and recorded? Are trends in performance examined continuously or regularly?
	Does the monitoring supplier provide forecasting? At what horizon, time resolution, update frequency, and accuracy?
	Are corrective maintenance response times specified in the contract?
	Is module degradation rate specified?
	Are all service contracts and insurance policies kept up to date?
	Are all required operating permits, compliance documents, and licenses kept up to date?

10.6. Preventive/Scheduled Maintenance

Preventive maintenance maximizes system output, prevents more expensive failures from occurring, and maximizes the life of a PV system. Preventive maintenance must be balanced by financial cost to the project. Therefore, the goal is to manage the optimum balance between cost of scheduled maintenance, yield, and cash flow through the life of the system. Preventive maintenance protocols depend on system size, design, complexity, and environment. A comprehensive list of these protocols is supported by the PV O&M cost model included in Appendix B.

10.7. Corrective Maintenance

Lost revenue accrues while a system is down or when output is reduced. Repairs should be delayed only if there is an opportunity to do the repair more efficiently in the near future.

Response time for alerts or corrective action for the O&M function should be specified as part of the contract, but typically will be 10 days or less for non-safety-related corrective maintenance service. For small residential systems, a fleet operator may make repairs only when enough work has accumulated to justify a truck roll to the area, or at the next regularly scheduled preventive/inspection of a site. Appendix C contains service descriptions for corrective maintenance selections available in the PV O&M cost model. This cost model (described in Section 12) provides an estimated prediction of the corrective maintenance costs from year to year, but it is impossible to accurately predict when and where failures will specifically occur.

The model has the ability to use fault and failure probabilities of specific components, if known. Additional considerations include the following:

- The O&M plan should include how to perform corrective maintenance quickly in response to field failures, including how funds may be used from a reserve or line of credit.
- Response time and urgency of repair specified in the O&M plan should balance the cost of a “truck roll” with lost revenue. Consider system size, geographic location, spare-parts inventory, other scheduled maintenance, fleet performance requirements, and cost of response.
- Faults or conditions that introduce a safety problem should be addressed as soon as possible, even if the recovered revenue is small.

10.8. Enforcement of Warranties

There is a distinction between “product warranties” and “performance warranties.” Product warranties cover materials and workmanship, and protect a purchaser against failures due to manufacturing defects (Figure 8 and Figure 9). Most solar panel manufacturers provide product warranties of 10–12 years, although some are as short as 5 years and one extends for 25 years. The performance warranty guarantees a certain power output that declines over time because the manufacturer knows that there will be some natural degradation in the performance, usually ending up at 80% of the initial rating after 25 years. PV modules are unique in that they carry very long-term performance warranties of 20 or 25 years (very few types of electrical equipment have such long warranties). The schedule of the decline in anticipated power output has an impact on the value of the warranty, with manufacturers offering a linear decline in the guaranteed output claiming that they provide a benefit over those that reduce the guaranteed performance in a stair-step fashion. In the past, inverter warranties were only for a 1-year term; but starting initially with European manufacturers, a 10-year warranty is now more the norm, with some offering the longer term only along with a 10-year service contract. The EPC contractor may offer a shorter-term warranty (e.g., 1-year, 2-year) on the entire plant including civil works such as storm-water management.

Figure 10 - Failure in Materials and Workmanship

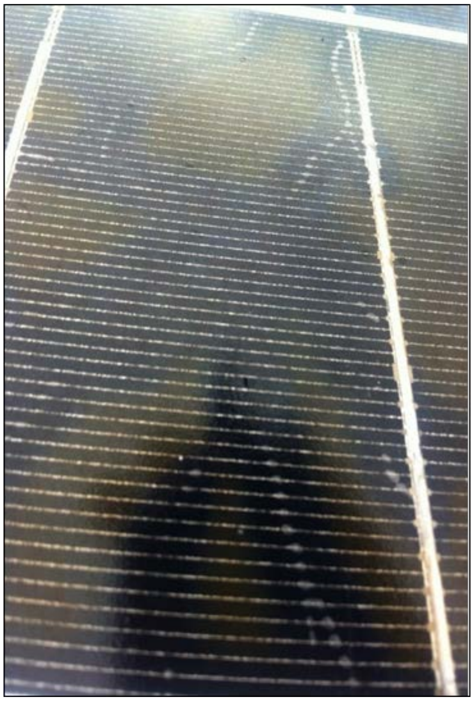


Figure 11 - Cracks in Cells Caused By Flexure of the Panel at the Factory

Figure 10 demonstrates failure in materials and workmanship, such as encapsulant of this module and are often covered by “product warranty” (photo by Andy Walker).

Figure 11 depicts snail trails in encapsulant and are attributed to cracks in cells caused by flexure of the panel at the factory, shipping, or installation. The module would be covered by the “performance warranty" only if the cracks isolate fragments of the cell and reduce the output over time (photo by Andy Walker).

Many financiers do not have faith in manufacturer's warranties for the following reasons:

- A warranty may be voided by mishandling or not observing instructions or conditions of the warranty. For example, storing modules improperly on site, such that the packaging is destroyed by rain, may void a warranty (Figure 10). Failure to provide adequate ventilation may void an inverter warranty.
- Even reputable PV manufacturers with quality products have gone out of business.
- It is difficult to prove that a module is underperforming, and it might require an expensive standardized test of each module.
- The manufacturer's warranty might cover replacement, but not labor to remove, ship, and re-install an underperforming module. In marketing literature and proposals, the dealer may offer to cover these labor costs, but such language rarely makes it into the final contract because small local dealers are not in the position to incur such costs.
- The warranty often gives the manufacturer the option to "repair, replace, or supplement," with "supplement" meaning to provide modules to make up the difference in lost power. For example, if a system has 100 modules that are underperforming by 5%, the guarantor could satisfy that by providing five additional modules to make up for the lost power, rather than replacing the 100 modules. But increasing the plant size by five modules to restore guaranteed power might not be possible due to lack of rack space or electrical infrastructure. Also, expanding the system "nameplate" capacity would generally trigger a new interconnect agreement and permitting, even though it would generate no more than the initial amount of power.
- Manufacturers often have the option of paying a cash-value equivalent to the lost capacity of underperforming modules; but as the price of modules declines, this might be less than originally paid for the modules. Given the complications described above, this option is often preferred by system owners unless there is a required level of performance that must be maintained.

Figure 12 - Proper Handeling of Boxed Producted

Figure 12 captures the proper handling of boxed and shipped modules awaiting installation at the SCTE office in Exton Pennsylvania.

Financiers take warranties into account in their financial prospectus only when offered by larger, more reputable, or more diversified companies with a sound credit rating. To hedge risk, warranty insurance is available from insurance companies, but adding the cost of such insurance to a project reduces the ROI or may make a competitive bid too high to get the contract. The cost of such insurance is lower for portfolios than for individual projects because risk is mitigated by a diverse collection of manufacturers—if one manufacturer goes out of business, it would affect only part of the portfolio (Cook, Borger, Bishop, 2016).

10.9. PV Module Degradation Rate

When comparing measured performance to predicted performance, it is important to consider the expected degradation in PV module output over time in the prediction. Prior to 2000, degradation rates exhibited considerable variability; but now, these rates are more uniform among types and manufactures and are often on the order of 0.5% per year (Jordan and Kurtz 2012). However, module degradation rates are only part of the story. As modules degrade, they do so at varying rates. This causes an induced circuit-level mismatch loss that should also be modeled. Some module-level power electronics (MLPE) solutions have the advantage of minimizing this added mismatch loss.

This is not to be confused with the failure rate of modules. PV module failures are rare, with a reported failure rate of 0.025%/year to 0.1%/year (Dhere 2005), depending on the source.

Measured and predicted performance can be compared using a module degradation value given by the manufacturer. If no value is available, one can assume a default value of 0.5% per year for new crystalline silicon products.

Degradation is calculated based on the age of the system at the time of evaluation. But for life- cycle cost analysis, a degradation factor of 0.94 provides an estimate of the degradation levelized over a 25-year lifetime with a 5% discount rate.

Module type does not have a large effect on raw O&M costs per year, but it has a tremendous effect on cost of O&M per kWh delivered—especially late in the performance period when production is markedly decreased, failure rates are higher in the aged equipment, and inflation has increased the per-unit O&M costs. The impact of O&M costs on levelized cost of energy (LCOE) is much less with PV modules that have lower degradation rates.

Table 7 - Representative PV module degradation rates (Photovoltaic Degradation Rates—An Analytical Review, D.C. Jordan and S.R. Kurtz, http://www.nrel.gov/docs/fy12osti/51664.pdf)

PV Module Type	Degradation Rate per Year (%/year)
Amorphous silicon (a-Si)	0.87
Monocrystalline silicon (sc-Si)	0.36
Multicrystalline silicon (mc-Si)	0.64
Cadmium telluride (CdTe)	0.40

Copper indium gallium diselenide (CIGS)	0.96
Concentrator	1.00

10.10. Example Work Statements

A contract to implement an O&M plan or part of an O&M plan should include a complete list of obligations under the contract. Examples of commercial-system work statements are detailed in Appendix E; the statements contain a maintenance "Schedule of Services" typically found as an addendum to an O&M contract comprising a fixed contract fee, with provision for an added time-and-materials cost adder for non-warranty corrective maintenance. Schedules are included for commercial rooftop and ground-mount systems.

10.11. End-of-Performance Period

The economic prospectus for a PV project contemplates an initial investment followed by a long performance period. Life-cycle cost standards specify a maximum of 25 years for electrical equipment (10CFR436), but there is evidence that PV systems could last longer and some industry guidance suggests a 40-year analysis period (EISA 2007). Asset owners and managers will have several options at the end of the performance period depending on the contractual commitments to the landowner and regulatory requirements of the authority having jurisdiction. These options include:

- Refurbishing the system and extending its life (say from 25 years to 40 years)
- Extending the term of the performance contract or power purchase agreement
- Selling the system at fair market value
- Removing the system and restoring the site to an earlier condition or other use.

The rate at which PV systems are being installed today will be equal to the rate of system disposition in 25 years or so. Relevant U.S. law here is codified under the U.S. Resource Conservation and Recovery Act (RCRA) governing non-hazardous waste (Subtitle D) and hazardous waste (Subtitle C). These laws assign responsibility to the generator of waste, although some PV manufacturers also practice extended producer responsibility

(e.g., http://www.firstsolar.com/en/Technologies-and-Capabilities/Recycling-Services). Today's manufacturer may in 25 years become a recycler, or rather, a re-processor of PV modules and other components. Components should be designed for recyclability and to control toxic materials. Current best practices are to minimize hazardous materials and/or design for recyclability and control of such materials (IRENA 2016).

Such foresight in recyclability and management of substances may affect the eventual cost and benefits of end-of-life PV waste management. During project permitting, decommissioning plans may include site-restoration requirements and financial mechanisms to deal with recycling or proper disposal of waste. Such planning would likely consider the value of recovered copper, aluminum, and steel, which can be substantial.

Demonstration projects at SolarWorld and commercial-scale recycling operations at First Solar have shown that 84% to 90% by weight of a PV module can be recycled (Larsen 2009).

If a system will transfer ownership, it is important to consider how warranties will be handled. It is often the case that manufacturers or EPCs will not honor the warranty if the original purchaser no longer owns the equipment. However, many manufacturers have a process for transferring the warranty to the new owner. Such a process typically consists of paperwork, a small fee, and a finalization period (usually 30 days) after the equipment sale. This service must be planned along with the rest of the ownership transfer process.

11. O&M Provider Qualifications and Responsibilities

PV O&M personnel, service category, scope of work, salary, and qualifications for the following roles are detailed in Appendix D: administrator/management; designer; cleaner; tree trimmer; pest control; roofing; structural engineer; mechanic; master electrician; journeyman electrician; network/information technology (IT); inspection; inverter specialist; PV module/array specialist; and utilities locator. These roles are defined in the PV O&M cost model for work calculations, but can be customized by the user for different pay rates, roles, and local work conditions and context.

11.1. Qualifications of Plant Operators

Solar plant operators require monitored data to analyze and identify the root cause of performance issues observed by the operator. It is critical to identify root cause of failure to reduce maintenance costs when dispatching service providers.

There are two ways to identity root causes of failures and performance problems:

- Qualified personnel who understand the specific plant design, with the necessary experience to identify anomalies (i.e., NERC certified operators, experienced in power plant operations/generation, remote monitoring, remote data analysis) and/or,
- A software and/or asset management system infrastructure that is able to define the specific plant hierarchy that can then automatically identify anomalies, conduct root-cause analysis, and suggest remedies long before the need to dispatch a service provider.

11.2. Qualifications of Service Providers

Every service provider—from the person that mows the grass to the master electrician—requires some sort of qualifications. Examples are listed in Appendix D for most types of service providers. Most electricians work on AC building systems, and most electricians are unfamiliar and untrained to deal with DC-based PV systems. PV-specific qualifications may include:

These electrical qualifications are essential, but each O&M service category has required qualifications. For example, certifications to apply herbicides and insecticides may be required for those removing weeds and infestations, as listed in Appendix D for each job category.

Table 8 - Service Provider Qualification Checklist

	Licensed electrical contractor
	NABCEP PV Installer certified and/or UL PV System Installation certified
	Experience with and on power generation systems
	Experience with medium-voltage, DC electrical systems
	Experience and working knowledge of NFPA 70E

	Familiarity with sections of the National Electric Code specific to PV (section 690/691)
	ASNT certified for planning and conducting thermal imaging (American Society for Non-destructive Testing)
	Internal equipment calibration and tracking program
	Meet NERC compliance for utility-scale systems
	Audited financial statements available
	Bank and/or supplier references, and access to letters of credit, surety bonds, etc., and credit rating
	Track record of performance?

11.3. Financial Solvency

Contractors should provide documentation that communicates the financial solvency of the O&M service provider. The purpose of references is to determine if the contractor is in financial distress. Financial distress of the installation contractor or O&M service provider could have a negative impact on the level of system quality and the timeliness and quality of delivered O&M services.

These references should be made available to financing sources upon request. Sample documentation includes:

- Audited financial statements
- Bank references (DUNS, Data Universal Number System)
- Supplier references
- Bond ability/bank letter of credit
- Credit rating matrix
- Track record.

11.4. Health and Safety

The asset owner is ultimately responsible for safety related to a PV system, and must meet that responsibility through the specific requirements of O&M service contracts and mitigate risk through accident and liability insurance. In the U.S., the Occupational Health and Safety Administration (OSHA, www.osha.gov) promulgates regulations related to workplace safety. Health and safety issues include all of those involved in construction or electrical maintenance work, vegetation control, plus some that are specific to PV systems. Roof fall protection, electrocution, arc-flash protection, lock-out-tag-out, and dehydration and heat stress are of special importance to workers providing maintenance of PV systems. It is important to recognize that health and safety issues are relevant to all personnel and work locations, even office workers (ergonomics, safe work environment). All workers must have at least basic training in safety and at least an orientation to hazards specific to each system.

O&M services are usually done by small teams of workers, and it is cost-prohibitive to have a dedicated health and safety professional with each team for each site visit. As a result, the O&M contractor depends on a strong safety culture, along with well-trained workers. Health and safety is usually considered an indirect cost, and it falls into the overhead cost category. It consists mainly of training, inspection, and auditing functions, with typical services that may include:

- Periodic inspection of personal protective equipment
- “Ride-alongs” to watch workers perform their jobs, capitalizing on teachable moments
- Site inspections to ensure that measures such as dead fronts on electrical panels and other guards are in place.

Because PV systems only produce power from sunrise to sunset, O&M teams have a plant shutdown every night. Many O&M contractors do their work at night, only working on de- energized systems. Although nighttime work introduces its own risks, these are lower than risks present when equipment is energized. Working at night assumes that problems have been identified with certainty and that the work being done is likely to solve the problem.4

Personal protective equipment is required for all jobs depending on the hazards. It is important to understand that providing the equipment is not enough—the user of the equipment has to be trained and in most cases certified in its use, and the condition of the equipment has to be continuously assessed and the equipment replaced if need be. PPE often encountered in PV system maintenance includes the following (which is not all-inclusive and depends on particular circumstances):

- General: Most sites will require at all times a helmet, safety glasses, safety vest, and work boots (steel-toed preferred).
- Lock-out–tag-out: Locks and tags specifically suited to the types of switches and breakers in the system, and the procedure of locking out circuits so that someone unaware does not energize a circuit that someone else is working on.
- Fall protection: Working at elevated heights requires fall protection, which may include personal fall arrest systems and guardrails around openings and edges of roofs.
- Arc-flash protection: Face shield, helmet, gloves, and apron suited for the amount of arc- flash energy that is calculated based on details of the circuit being worked on.

Table 9 - Health and Safety Checklist

	Meet with “first responders” such as fire marshal, local fire department, first-aid providers, and police to familiarize them with access and shutoffs, and make them aware of the plant purpose and location.
	Control access to site and brief visitors and workers on safety procedures.
	Identify hazards unique to the site and system, and plan work to reduce risks associated with these and all hazards.
	Use a company health and safety manual, which establishes appropriate rules and procedures concerning reporting of health and safety problems, injuries, unsafe conditions, risk assessment, and first aid and emergency response. Verify that this satisfies all laws and regulations regarding workplace safety. The manual should provide a complete list of personnel training requirements and certifications.
	Designate a health and safety coordinator or point of contact for questions or complaints.
	Have an entity with the authority to periodically inspect and stop work to verify that safety measures are in place and observed.

	Ensure that all site personnel are equipped with complete personal protective equipment for the task, including fall protection from roofs and arc-flash protection for working on live circuits. Ensure that all personnel have met the training and certification requirements of NFPA 70E for being a qualified worker.
	Verify that areas with hazards have clear and evident signage identifying the hazard to authorized or unauthorized visitors, and that visitors are kept away from hazards by enclosures and barriers.
	Site supervisor (if applicable) should have a minimum of an OSHA 30 certification; all site personnel should have an OSHA 10 certification.
	Maintain an OSHA TCIR of 5.00 or less or similar rate based on a substantially equivalent, accepted measure used to report workplace injuries.

11.5. Insurance

O&M program best practices can have a positive impact on reducing insurance losses, thus reducing premiums paid for insurance. An insurance engineer and underwriter should be engaged to evaluate a facility (or the design for a yet-built system), including the O&M program, to quantify loss potential and estimate insurance coverage and costs. This review also provides a better understanding of risks that might impact the performance of a PV plant. Insurance products that may be of interest to the owner (which are different than coverages that an O&M provider should have at a minimum) are outlined by EPRI (2015).

Liability and risks should be mitigated through contracts that clearly articulate the insurance requirements to O&M service providers. Concepts related to insurance include:

- Normal Loss Expected (NLE), which determines the dollar amount of the deductible for an item that can be expected to occur, such as inverter replacement, without an insurance claim.
- Probable Maximum Loss (PML), which determines the premium paid on a portfolio over time. As far as insurance premiums are concerned, rate * total insurable value (reported value of physical assets + annual business income) is offered as a cost benchmark (David Walter, Senior Engineer, Renewable Energy, The Hartford Steam Boiler Inspection and Insurance Company, 6/7/2016).
- Maximum Foreseeable Loss (MFS), which sets dollar limits on coverage and represents the worst-case loss scenario.

Confirm that the contracting company maintains current and appropriate business insurances.

Table 10 - Insurance Checklist

	Property insurance: coverage commensurate with value of buildings, equipment, or improvements to a property
	General liability: required value per occurrence, required value aggregate; covers negligence claims, settlements, and legal costs. Review your corporate requirements.
	Inland marine insurance: insures against loss of equipment not on the property premises

	Workmen's compensation: Required amount each accident, each employee, policy limit. Review your corporate requirements.
	Professional liability insurance: insures against errors and omissions often required by board of directors
	Commercial vehicle insurance: insurance for owned and rented vehicles; or personal vehicles used on company business
	Warranty insurance: equipment warranty issued by manufacturer but backed up by an insurance company in the event that the manufacturer company goes out of business
	Commercial general liability insurance: in a form or forms covering all installations undertaken by installer and all subcontractors, written on an occurrence basis, including coverage for products and completed operations, independent contractors, premises and operations, personal injury, broad form property damage, and blanket contractual liability, in an amount at required by internal corporate or business unit policy.
	Business interruption insurance covers lost revenue due to downtime caused by covered event.
	Specific projects due to their complexity or risk exposure may necessitate additional or supplemental insurance for this project. Check with your Corporate Insurance or Risk Management Group for review and guidance.
	Insurance Claims: Insurance claims are made by the asset owner or a representative of the owner such as asset manager or O&M service provider. The procedure for making claims described in the insurance policy should be followed to the letter, keeping copies of all submittals and correspondence with the insurance company. The insurance company (claims adjuster) will need to be provided access to the site to assess damage and to collect information needed to process the claim. Value of claims may not reach your companies deductible – check with your Corporate Insurance or Risk Management Group.

11.6. Redundancy in Service Providers

Investor confidence is increased if a “hot back-up” service provider is available. This second service provider would be paid a fee to be available and to have the capability (products and training) to perform O&M on the system if a current O&M service provider fails to perform. This second company could be hired to perform capacity and energy tests and provide a check on the decisions of the current O&M service provider.

12. System Monitoring

The three main areas of best practices for system monitoring are the following: data presentation, quality of monitoring equipment, and transparency of measurement protocols and procedures.

The approach to monitoring and associated cost depends on the revenue associated with the performance of the asset. IEC 61724 classifies monitoring systems (A, B, C); the O&M related to monitoring depends on the system class.

Data are valuable, and it should be established who owns the monitoring data and who will have access to the data for what purpose. Data analysis is a powerful tool for understanding PV system performance, but it is fundamentally limited by the quality of sensors and models being used, in addition to the condition of the array.

The objective of monitoring is to provide enough information to accomplish an “energy balance” accounting for the amount of solar resource available, and the losses in each energy conversion process up to delivery at the point of interconnection. Advanced operation of a PV plant such as modulating output or power factor can confound the drawing of conclusions from monitored data. A monitoring system should account for clipping of output due to high DC-to-AC ratio, interconnect limits, and called-for curtailment or any other reason.

12.1. DC Array Inspection

Because of the inherent inaccuracies of data monitoring alone, it is common to implement a secondary check of the DC array to detect string- and module-level faults through periodic inspection and testing (Figure 11). The two main methodologies used for these inspections are manual electrical testing and aerial thermal-imaging inspections.

12.2. Manual Electrical Testing

Manual electrical testing such as open-circuit voltage, operating current, or field I-V curve tracing is used as a method to detect faults in the DC system that the monitoring system is not able to detect. The accuracy of testing equipment is limited by the combined accuracy of irradiance, temperature, and electrical sensors, and in the case of I-V tracing, it is limited to around 5% for standard field units. This testing reveals only defects that are currently causing significant module failure, and it will not detect hot-spot defects that are not currently causing significant electrical degradation of the module. However, these signatures can be important for understanding underlying module-quality issues, in addition to allowing early detection of possible fire risks.

Figure 13 - Cracked or Peeling Backsheet

Cracked or peeling backsheet is captured in Figure 13. This leads to water infiltration and ribbon corrosion. (photo by Andy Walker)

Manual testing is performed over several days or weeks to test a large array, and the meteorological conditions will vary over this time, making it difficult to spot relative differences in the array and requiring significant documentation to ensure that measurements are comparable. Because this testing must be performed inside the isolated combiner while the system is operational, arc-flash PPE is required for all testing—which can limit the speed of effective inspections, and can pose a potential safety risk to operators. It should be noted that for some combiner topologies, the arc-flash hazard may be too high according to NFPA 70E, and electrical testing on live circuits in the combiner box may not be possible or may require portions of the array to be de-energized prior to measurement. Manual inspection and testing requires that inverter wiring enclosures, re-combiner boxes, combiner boxes, and eventually module junction boxes be opened to access the circuits; it is important to note that these must be properly re-sealed (gasket, screw-torque) to maintain the original NEMA rating for the type of enclosure (Figure 13).

Figure 14 -Failed Junction Box

Figure 14 highlights the importance of manual inspection and testing by opening NEMA-rated enclosures. The integrity of any enclosure seal must be restored after opening to avoid moisture damage as in this module junction box (photo by Andy Walker).

12.3. Aerial Thermal Imaging

Aerial thermal imaging inspections refer to the collection and processing of image data collected by aerial sensors with the goal of detecting string, module, and sub-module faults in the array. By detecting thermal variations between modules, any critical defect that is causing a reduction in module efficiency can be detected, in addition to the proactive detection of hot spots and potential fire risks (Figure 14). These inspections can be performed instead of manual electrical testing as part of an annual preventative maintenance, and can also be used for system commissioning and end-of-warranty inspections, and infrared inspection of AC substation.

Aerial thermal imaging can be performed using manned survey aircraft or unmanned aerial vehicles (UAVs). The quality of the assessment depends largely on the imaging and post- processing systems that are used. These systems should have the following characteristics:

- Thermal detector sensitivity of <0.02°C and frame integration time of <2 ms
- Thermal wavelength imager ground resolution of 19 cm/pixel or better; visible wavelength imager ground resolution of 3 cm/pixel or better
- Irradiance at a minimum of 600 W/m^2 with an irradiance deviation of <100 W/m^2 and a temperature deviation of <5 °C during inspections
- The resulting imagery should be processed by a validated processing routine to correctly identify module defects and their specific location in the field. These defects should be identified to the module level, and labelling should be provided to allow field technicians to quickly identify and remediate module-level issues. When properly applied, remote imaging inspections can proactively detect the following classes of array faults:
    - Module faults: Hot spots, diode failures, full module failures, junction-box heating, cracked modules, ethylene vinyl acetate (EVA) fogging, yellowing, antireflective coating degradation, acute soiling (bird droppings, debris, vegetation), and other module-level defects
    - String and system faults: Fuse failures, inverter failures, module-connector failures, reverse-polarity wiring, major maximum power-point tracking (MPPT) faults
    - Racking and balance of system: Major racking shifts, systemic shading, major erosion.
- The use of proper post-processing tools is critical to accurately detect and classify module faults. Post-processing tools should be validated against ground data, allowing a properly validated tool to identify the exact location and probable cause of all thermal faults in an array.
- For inspections without validated post-processing routines, it is important to note that many of the problems described above cannot be diagnosed with aerial inspections. The inspection simply points out symptoms and the rough location of the problem. Further troubleshooting on the ground is required.[3]
- Alternatively, if the system is metered at the string level, and robust data analytics or data review is in place, then module faults that are affecting string output can be identified with a robust remote monitoring system. However, cell-level hot spots generally will not significantly affect module performance and cannot be detected by data analytics alone.

[3] EUCI Workshop 2016

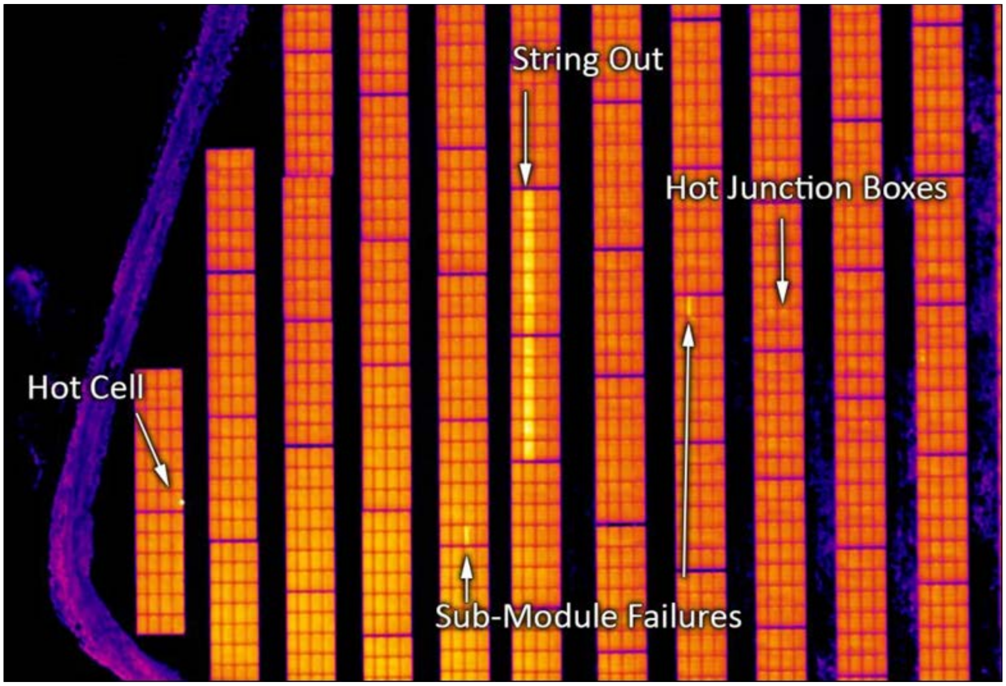


Figure 15 - High-resolution infrared aerial imaging

Figure 15 shows high-resolution infrared aerial imaging that can identify failed strings, modules, and cells within modules (by Rob Andrews, courtesy of Heliolytics Inc.).

12.4. Data Presentation

Good reporting is essential to obtain value from monitoring data. In the field of PV plant operations, operations quality is determined by 1) the ratio of the amount of energy harvested to the potential amount of energy available for a particular plant and 2) plant equipment availability over time. Given this definition, keeping the plant up and running at its peak operating point requires accurate performance measurements, the ability to easily pinpoint issues, and prompt cost-effective repair of defects. Active plant monitoring is essential, and the quality of the monitoring system itself is fundamental to the overall quality of the plant.

Reports should include the following information:

- Site name, location, size of PV plant, other reference information
- Insolation (on-site or satellite data, plane of array, kWh/m2); temperature (ambient, module)
- Real power and energy delivery (kW, kWh)
- Peak power delivery (kW)
- Other advanced meter data such as reactive power (kVAR)
- Estimate of power that should have been produced and performance ratio
- Time-based availability; energy-based availability
- Inverter efficiency, balance-of-system efficiency
- Measurement of soiling, if any. Additional considerations:
- An Internet-accessible portal should be available at any time with:
    - Downloadable raw data, and
    - Charts and tables to interpret data (dashboard or user interface configured to specific user).

- Daily feeds of previous day, month-to-date, and year-to-date production values should be developed and stored.
- Data should include insolation in the plane of the array; energy delivery (kWh); performance ratio (kWh delivered/kWh expected); and specific yield (kWh/kW), as well as any alarms or other performance indicators. Alarms should convey all the information in the alarm format of the manufacturer, so that operators can act on the error message.
- Data format should be compatible with standards (“open platform,” IEC 61724 and SunSpec Alliance) for aggregation into larger data platforms. Data format should be clearly documented.
- O&M plans should be built to notify actionable personnel on critical production or safety issues as soon as possible, and within 5 days for issues that affect production but not safety, depending on what the anomaly is and considering lost revenue and safety issues. Fire alarms and intrusion detection alarms should be pushed out immediately to on-call personnel.
- Complete loss of production and non-communication should be reported on a daily basis (immediate reporting of such issues is reportedly a source of false alarms).
- Systems producing lower-than-forecasted energy correlated to local weather/insolation conditions should be reported on a weekly or monthly basis. Using intervals smaller than a week increases the possibility of false positives and usually does not provide business value.
- Reliable data back-up and storage should be provided. Best practice is for dataloggers to store 6 months of data and to back up data to cloud storage. A reliable method to “back- haul” the data is required. Most connect to the internet via DSL, but be aware that many site owners will not allow the solar monitoring system to use the site network. This may require a separate Internet connection and often requires cellular or satellite back-haul of the data to an operations center or user website.

12.5. Quality of Monitoring Equipment

Use open standards for information and data communication throughout the plant, fleet, and enterprise. Ensure that the monitoring system addresses the following:

- Transparency of measurement protocols and procedures (see Section 10.4)
- Ability to audit measurement protocols and procedures
- Ability to maintain hardware and software by a variety of service providers, including calibration and servicing requirements
- Ability of systems to share information with stakeholders
- Ability to ensure “operational continuity” (backup and restore)
- Support of third-party access for custom application development
- Security of software and applications
- The entire monitoring system should be on an uninterruptible power supply.

In this document, we do not pick a standard to be used to calculate and report system performance. But there should be an effort to at least collect and maintain data that can be used to report PV system performance as specified in the most common standards for the industry, regardless of how it is reported by any operator or for any plant. This procedure will allow system performance to be reported according to any of these standards if the need arises.

12.6. Instrumentation

Requirements vary depending on the performance measurement model used, the required accuracy, and other considerations—and not just whether the system size is above or below a certain system size. For instance, a fleet of 5,000 residential systems may rely on satellite and local weather data. A fleet of 50- to

100-kW commercial systems may have requirements to accurately measure irradiance, module temperature, and weather at each site. We describe recommended guidelines, but the requirements should actually be based on an accuracy level required by the subject system or fleet of systems.

It is important to understand that for any system there exists an underlying uncertainty in the calculation of system performance from measured data. Some studies have shown that the combined effects of system measurement and modelling errors can range from 5%–10% (Thevnard et al. 2010; Cameron et.al. 2008; Freeman 2014).

Some examples of the sources of these errors are as follows:

- Meteorological data measurement

  Onsite environmental sensors that measure irradiance and temperature for systems >100 kW. For large plants, adding an extra irradiance sensor for each 2 MW or so would help discern irregularities caused by cloud movement over the array. Radio communication- based weather sensor (such as a Deno Watts weather station) would help to avoid the wiring for the weather stations.

- Irradiance—plane of array (POA)

  IEC 61724 Class A pyranometer uncertainty: ±3 % POA model uncertainty if using GHI: 2%–5%

  If there is more than one orientation of the PV array (e.g., part fixed and part tracking), then a separate pyranometer would be required for each orientation (in the POA), and each pyranometer must be properly assigned to that portion of the system for calculation of performance ratio.

  The pyranometer must be kept clean to provide an actual measurement of the solar resource. Condition of the on-site pyranometer and data acquisition system must be checked frequently (daily) to ensure proper operation and to avoid loss of data.

  Irradiance measurements should be recorded at a minimum interval of one hour, and 15- minute or 1-minute data are often specified.

- Satellite-based irradiance measurement

  Services are available that take data from satellites and process them with models to create an estimate of ground-level irradiance at a site. Although less accurate than a well- maintained and calibrated on-site pyranometer, satellite measurements can be more accurate than an on-site pyranometer that is dirty, out of calibration, or installed incorrectly.

  Temperature-module back sheet

  A back-of-module temperature sensor with an uncertainty of ±1 °C and an ambient temperature sensor with an uncertainty of ±1 °C (IEC 61724)

  Intra-array temperature variation: 2 °C–5 °C

  Firmly affix the temperature sensor with thermal conduction adhesive in the middle of a cell, in the middle of the module, and in the middle of the array. Arrays with sections of different orientation or mounting conditions would require multiple temperature measurement.

- Measurement of system electrical performance

Combiner-level data generally come from current transformers (CTs) measuring current from combiner-box home runs measured at the inverter. Monitoring at the string level is also available (instrumented combiner box).

IEC 61869 Class 1 CT uncertainty is 1%

Inverter-direct monitoring (no external AC meter) with an uncertainty of ±5% for systems <100 kW. For modular plants, adding an external AC meter for each inverter 500 kW and greater would help to give visibility to the production of each inverter (necessary if the inverter does not include direct monitoring, and providing an independent check and redundancy if it does)

Measurements at the inverter also include: instantaneous power (AC); cumulative energy delivery (kWh); inverter alarms; inverter control settings; input (DC) current and voltage; plus any other information available from inverter data interface such as inverter temperature. If the inverter does not report temperature, then it is recommended to add a temperature sensor to the inverter enclosure to identify overheating.

Figure 16 - Inverter

Energy meter: There is often a separate high-accuracy "revenue-grade" AC meter for energy-revenue invoicing or independent measurement of performance for a performance guarantee or other purpose. Specified accuracy is sometimes required for plants where third-party financing is involved or where solar renewable energy credits (SRECs) generate revenue. This should be a high-accuracy, high-reliability meter with accuracy within ±0.5% and with communications that is compatible with both the on-line monitoring system and also a separate automatic meter reading (AMR) service or advanced metering infrastructure (AMI) at the site. The meter should report at a minimum cumulative energy delivery, but may also include advanced "smart meter" functions such as power-outage notification and power-quality monitoring.

Figure 17 - Meter and Disconnects

- Model errors

Measured performance is meaningful only when compared to a model of expected performance. The accuracy of the model is affected by:

  - Wire length affecting losses between combiner and measurement CT’s
  - Actual power rating of modules
  - Actual module mismatch
  - Shading
  - Soiling
  - Degradation.

The following can act to increase the uncertainty in system measurement and modelling:

  - Failure to re-calibrate instruments per manufacturer instructions. Most pyranometers must be re-calibrated every two years.
  - Failure to clean pyranometers on a regular basis. Pyranometers should be mounted in such a way as to allow regular access by service personnel.
  - Detachment or poor adhesion of module temperature sensors to modules. The adhesive should allow good thermal conductivity between the module backsheet and temperature sensor.
  - Poor temperature sensor placement. The module temperature sensor should be placed away from inverter exhaust, disconnected modules (those used for soiling measurement only), and the edges of roads that will be more acutely affected by wind. Temperature variation from a module at the edge of a road to a module in the center of an array can be as high as 5 °C due to wind effects.
  - Poor documentation of system as-builts. It is important to understand the power capacity connected to any monitored section of the array.

A dedicated or shared network connection such as a cellular, satellite, or dedicated broadband backhaul is required to retrieve the data from a monitoring system. In remote areas where

utility-scale projects may be located, a satellite data connection may be necessary. It is often not reliable to use the offtaker’s network to back-haul monitored data, and in many cases, that is not possible due to security reasons. It is important to perform automated or manual quality checks frequently on the data to detect failed or dirty sensors. All raw data should be archived and backed up automatically and regularly. Onsite data storage helps to prevent loss of data when the communication link is down.

12.7. Transparency of Measurement Protocols and Procedures

The benefits of adopting open standards for information and communication are well- established. As it relates to the quality of the solar monitoring system, open standards are applied at four levels:

1. Device communication and plant sensor readings
2. Data collection and storage at the plant
3. Information transmission from the plant to the information data store
4. Information access to the data store from applications.

High-quality monitoring systems can be built with proprietary methods that encourage lock-in to a single vendor. But a standard information model used across all four levels ensures high fidelity and eliminates poor or inconsistent mappings from one model to another. A standard information model allows systems to be compared to one another, independent of the monitoring vendor. The SunSpec Alliance standard information models—combined with standard transport protocols such as Modbus, Ethernet, and WiFi—are recommended, with support information models as defined in IEC 61850 and/or Smart Energy Profile 2.0. SunSpec standards are harmonized with both of these technologies. Sandia National Laboratories has developed an open-source data-filtering and analysis platform, “Pecos” (https://github.com/sandialabs/pecos), that can be used to provide insight into PV system data quality and roll up raw data into energy tests, such as those outlined by IEC 61724.

Data quality is an issue that should be addressed. Recent work in standards recognizes that data collection anomalies do occur, such as missing data or highly inaccurate instrument readings for a period of time. Quality checks should be established to quickly screen data so that they do not skew reported results and so that repairs can be made in a short time. Sandia National Laboratories, perhaps among others, is working on a set of data-handling techniques that will be open to the industry once released. It is also worth noting that some requirements may include third-party certification of data collection, calculation, and reporting. Proper application and maintenance of instrumentation should also be mentioned because it can be vital to accurate readings.

13. O&M Supporting Systems and Implementation Strategies

13.1. Workflow and Decision Support Software

For plants where onsite environmental sensing equipment is not practical (i.e., most residential plants), measurements of irradiance and ambient temperature should be supplied by a nearby weather station or estimated from satellite data. These proxies for actual irradiance measurements may only be accurate to < ±7% for global horizontal radiation and ±12% for direct normal radiation (http://solargis.com/support/knowledge-base/accuracy/overview/) and temperature measurements to ±5 °C—which increases uncertainty, but is currently acceptable in the residential setting as opposed to onsite measurements for such small systems. In fact, this accuracy of satellite data can be more accurate than a poorly maintained or dirty sensor on site.

A dedicated network connection such as a cellular, satellite, or dedicated broadband backhaul is required for plants that are greater than 100 kW. For smaller plants, where it is not practical to implement a dedicated network connection, a shared network connection may be used; but this raises the service risk profile considerably. In fact, shared Internet Protocol (IP) network outages have been reported by industry-leading vendors as the number-one source of service calls.

Where possible, a dedicated network connection is highly recommended.

Onsite data storage is required to prevent data loss during communication network outages. The amount of storage needed depends on the expected mean-time-to-repair should an outage occur. An amount of storage that is equal to two times the highest-recorded communications outage is recommended. Six months of data storage is recommended.

Standard data-encryption techniques should be employed to protect the confidentiality and integrity of the data in transit over wide-area networks. For example, the SunSpec Alliance Logger Upload protocol specifies the use of Transport Layer Security standards (e.g., https, SSL) for data transmission over the IP-based networks.

Trouble-report codes definitions, corrective action taken, and results should be standardized at the fleet or large-system level. This allows more definitive tracking of cause-and-effect, repetitive problems, corrective action deficiencies, and more. This also leads to better operating efficiencies, better preventive techniques, identification of large-scale equipment problems, and more. The lists below are at a level that helps describe the work done, but do not include standard descriptions of the cause of repair or the actual work performed. All asset management and O&M management strategies and systems must achieve the following:

- Document archive for complete plant documentation upkeep and reference
- Customer/plant interaction tracking logs
- System/portfolio analysis
- Budget tracking
- Trouble ticket or incident tracking
- Mobile work-order flow management and documentation systems.

Fleet management and aggregation requires developing or adopting software systems termed enterprise asset management (EAM); these are specialized workflow platforms similar to enterprise resource planning (ERP) software.

EAM/O&M software platforms and services are available from several companies including Meteocontrol, Alectris, Draker Labs, TruSouth, and others, whereas several large-fleet operators such as SolarCity and First Solar have developed their own custom platform. Deployment of these software platforms, which are now a requirement for large-fleet operators, enables tight resource control to optimize O&M cost, especially administration and document cost.

13.2. O&M Implementation Strategies

The asset owner or asset manager should allocate sufficient internal resources and secure any required external resources to implement the O&M plan.

Operating and maintaining a fleet of PV systems requires active resource management and data acquisition and analysis by the asset and operation manager(s).

The choices for resourcing O&M are:

- Use the EPC company, or the installer who built and warrants the system (who have a dedicated plant O&M department to provide the necessary care)
- Bring the O&M service in-house
- Outsource the service to a specialized third-party O&M provider.

Often, a mix of these three strategies is chosen, depending on the age of the PV system, the provider's business model, system composition (either commercial or residential), fleet geographic density/distribution, and strengths of the available resources in house.

For commercial systems, the EPC/installer O&M model is common because most early failures will be warranted and the provider can perform routine maintenance at the same time. One disadvantage of this model is that the EPC/installer may lack dedicated O&M resources; thus, O&M services will compete with higher-margin installation and construction business. As warranties expire, the dedicated third-party O&M model gets more attractive because fleets can be combined or allocated to specialists who may have many systems in geographic concentrations to gain cost advantages.

For residential systems, "vertically integrated" developers/installers are using more in-house services because they can gain an advantage in providing uniform quality across the whole PV system life-cycle. Meanwhile, developers using the "partner" residential model—in which the finance and development company partner with an installer—rely on the installer for O&M services and/or a dedicated third-party O&M provider as needed.

13.3. O&M Contract and Performance Guarantee

Detailed contract terms are beyond the scope of this document. However, it is important to define the parameters for the O&M of a PV project during its life. As stated earlier, these conditions must, as a minimum, cover the maintenance requirements to ensure compliance with the individual component warranties and EPCs or the installer's contract guarantee.

Most contracts will specify a fixed cost for plant operations, standard preventive maintenance, and agreed-upon response time, with additional fees for corrective maintenance and non-covered services.

So-called "performance contracts" cite KPIs, which are agreed-to measures of whether the contracted-for level of performance is achieved or not. It is sometimes required for third-party- owned systems to provide a guarantee for the energy yield output and/or the availability of the PV system when plant operations is included in the contract or an O&M provider is not well known or does not have significant financial backing. It is also possible for the system warranty to include targets for the energy yield, performance ratio, or availability (Klise and Balfour 2015). In fact, these warranties are also available from third parties, O&M contractors, and insurance companies. How each indicator is calculated must be specified in detail, and standards are under development (IEC TC82) to provide standard definitions that distinguish, for example, availability as a fraction of time or as a fraction of energy. The agreed limits are often based on the independently verified energy yield report, produced at the time of commissioning. For an example of the calculation method, see Appendix A. As time goes on, comparison to the initial yield report, from before a system starts operation, becomes less accurate. A multi-year yield report uses average historical weather and irradiance to predict output. Actual output will vary year to year based on actual weather and irradiance. It is more important for the stakeholders to have a yield report based on an acceptable model, and then use that same model to measure performance each year based on measured weather and irradiance, as well as operations that may affect the yield such as curtailment of output.

To summarize, important items to observe regarding warranty coverage and performance guarantees include:

- Define what is involved in plant operations. Who is watching the system, identifying the issue, and dispatching the required personnel to fix the issue in a timely manner.
- Examine the parameters for the PV project preventive maintenance requirements documented during its life, which are required to keep the warranty in effect and identify issues that may void the warranty.

- Examine the warranty in terms of KPIs (plant availability, specific energy delivery, and performance ratio) to ensure that each is defined in enough detail such that all parties calculate the same value.
- Ensure at the conclusion of an installer warranty, which may be only 1–10 years, that any equipment warranties (which may be as long as 25 years for PV modules) transfer or are designated to the responsible O&M provider.
- Current status of KPIs should be available to all parties to the performance contract, both present values and trends over time.

14. Estimating PV O&M Costs

Research of the PV O&M Working Group has concentrated on three estimates related to the cost of delivering a PV O&M program: annual cash flow, net present value, and reserve account.

1. Annual Cash Flows: Costs for administrative or preventive maintenance that are scheduled on regular intervals are escalated according to an inflation rate to the year in which they occur. Costs for corrective maintenance are the replacement cost of the component multiplied by the probability that a failure will occur in that year. The probability that a component will fail in any given year is calculated by a Weibull, log- normal, or other distribution that is informed (ideally) by actuarial data. Warranties affect whether a failure will result in hardware costs, labor costs, or both if the year is within the warranty period. This provides a cash flow for each year of an analysis period.
2. Net Present Value: Each of the future years' cash flows thus calculated are then discounted to their present value according to a discount rate. The discount rate is the owner's corporate bond rate or "minimum attractive rate of return." Net present value is useful for evaluating an overall financial prospectus and for calculating the impact of O&M on LCOE.
3. Reserve Account: The Weibull distribution of failure gives us a good estimate of life- cycle cost, but the method spreads the costs over the years and shows a rather uniform average cost per year—when, in fact, expensive repairs can occur all at once (Figure 14). Financiers and operators want to know "maximum exposure"; in other words, what dollar amount of a "reserve account" or "line of credit" would a bank offer to sell to a project? Reserve account is calculated for each year of the analysis period.

Consider a simple example regarding reserve account: Consider a PV system with two inverters, each with a replacement cost of $10,000 in year 1; and each with a Weibull Failure Distribution of Mean Interval 20 years and Shape Factor 5.0. In Year 20, this failure distribution would predict a probability of failure of Q = 0.092, and thus, a probability of non-failure of P = 0.908. If we have enough in reserve or in stock to replace NEITHER of the two inverters, then P1P2 = P^N = (0.908)^2 = 0.824 (you get this level of probability that the reserve account would be sufficient even with no funds in the reserve account). If we have enough in reserve to replace EITHER ONE of the two inverters, the reserve account would be = $10,000 (inflated to year 20), and the resulting probability that the reserve amount would be sufficient is P1P2 + P1Q2 + P2Q1 = 0.824+(0.908*0.092)* 2 = 0.991. If we have enough in reserve to replace BOTH of the inverters, the reserve account = $20,000, and the probability that the reserve account is sufficient is P1P2 + P1Q2 + P2Q1 + Q1Q2 = 0.666+0.300+ (0.092)^2 = 1.00. So, in this simple example, if the desired availability is 0.824, then we would require $0 in reserve; if the desired availability is 0.991, then we would need $10,000; and if the desired reliability is 1.0, we would then need to keep $20,000 in reserve.

We generalize this approach to a very large number of components, N, where n/N is the fraction of the total number of components funded in the reserve account; R is the desired probability that the reserve account will be sufficient; and Q is the probability of failure in each year of the analysis period according to the failure distribution. This is done for each measure (PV module replacement, inverter replacement, each other type of component) and added up to calculate the total amount in the reserve account for each year of the analysis period.

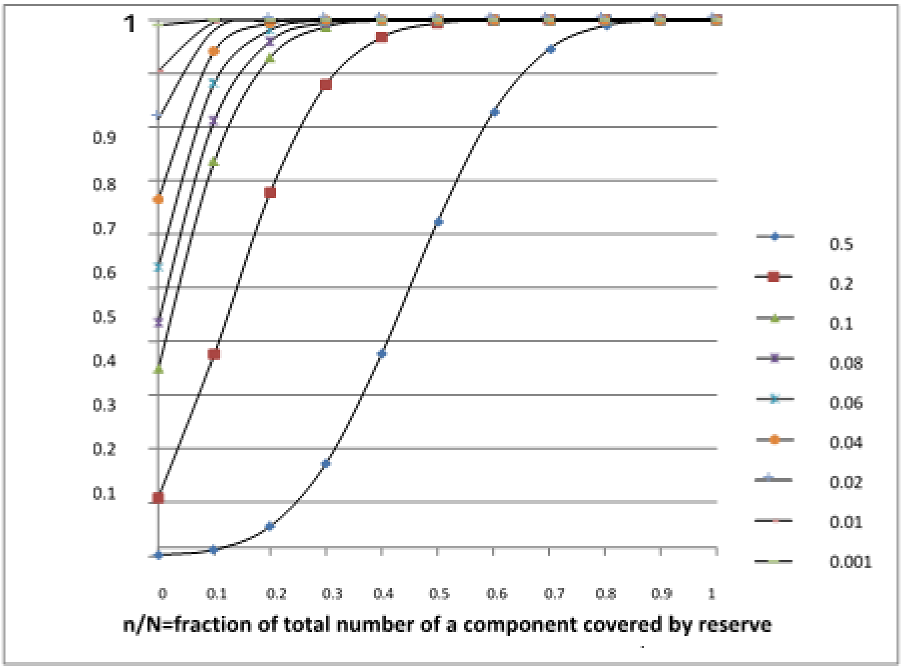


Figure 18 - Calculating Probability of Inverter Failure in a Given Year

Figure 18 illustrates a fraction of components to be covered by reserve account will depend on the probability of failure in a given year and desired confidence that the reserve account will be sufficient. For example, if we had 10 inverters and the probability of each inverter failing in a given year was Q = 0.1, and if we desired a probability of 99% that our reserve account would be sufficient, then we would need to have enough in the reserve account to cover 3.25 times the cost of a single inverter replacement. In reality, low values of Q and high values of R are of interest, but this chart shows the behavior of the relationship over the whole range. (figure by Andy Walker)

The PV O&M Working Group has developed a PV O&M cost model (version 1.0) with a long list of O&M measures (Figure 16). Each measure has an estimated materials, equipment, and labor cost, many of which are on a per-unit basis (per kW or per square meter). Each measure is applicable based on system type (commercial rooftop, residential, and ground-mount); micro-, string, DC optimized, or central, inverter plant; fixed tilt or tracking, attached or ballasted rack, and a list of environmental conditions (snow, pollen, bird populations, sand/dust, humid, hot, high wind, hail, salt air, diesel soot, industrial emissions, construction site nearby, high insolation). Cost also depends on warranty/service plan modeling switches. The PV O&M cost model is available from NREL and SunSpec.org as a standalone Excel spreadsheet tool for O&M cost modeling and planning, and an on-line version is currently being developed at SunSpec Alliance.

The model contains selections of scheduled and corrective maintenance tasks that are also detailed in Appendices B and C. A list of job roles, requirements, and sample costs are included in Appendix D. As noted above, the model allows customization of all these variables to suit system configuration, job time estimates, failure rates, and local costs.

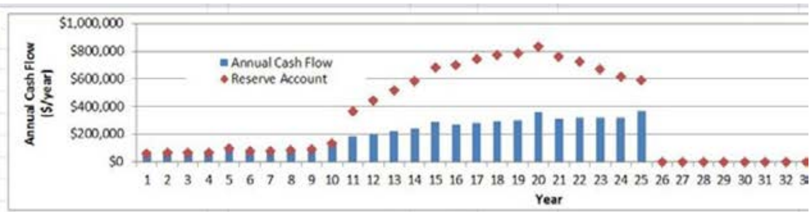
Administrative and preventive-maintenance measures are on defined schedule intervals (for example, once per year), whereas corrective-maintenance measures are scheduled according to a failure distribution curve (Weibull distribution) for each measure. Selection by the user of the environmental conditions (e.g., bird populations, pollen, snow) trigger measures such as additional cleanings or snow-removal costs.

This cost model based on failure distribution (Weibull distribution) is an accepted way to estimate net present value of the O&M program, which is useful in a life-cycle cost analysis (for a feasibility study) or to estimate metrics such as cents/kWh delivered or average $/kW/year.

However, financiers and system operators also need to know the maximum exposure. This is the amount that should be secured in a line-of-credit or reserve fund to cover worst-case scenario of O&M costs. The need for this is exemplified by a 924-kW carport system that was down for two years because the Navy did not have funds immediately available to replace a failed inverter.

Accurately estimating this maximum exposure based on statistics has proven to be prohibitively complex if the number of components exceeds 10 or so, which is the case even for a small PV system. Thus, the PV O&M cost model takes a simpler approach of identifying (with a “1” or a “0”) which of the long list of measures costs should be included in the reserve account, and this would include major items such as complete inverter replacement.

System Name	Ground Mount Tracking
Results	
Annualized O&M Costs ($/year)	$126,471
Annualized Unit O&M Costs ($/kW/year)	$12.65
Maximum Reserve Account	$831,685
Net Present Value O&M Costs (project life)	$1,800,124
Net Present Value (project life) per Wp	$0.180
NPV Annual O&M Cost per kWh	$0.011



Lifetime NPV by Service Type			
Service	Avg. Cost/Yr	NPV (Life)	% of Total
Administrator	$7,717	$88,635	5%
Cleaner	$23,932	$274,892	15%
Inverter specialist	$61,545	$550,944	31%
Inspector	$25,487	$286,646	16%
Journeyman electrician	$19,424	$216,399	12%
PV module/array Specialist	$10,876	$114,939	6%
Network/IT	$178	$1,825	0%
Master electrician	$4,790	$53,383	3%
Mechanic	$1,083	$14,926	1%
Designer	$0	$0	0%
Pest control	$1,614	$18,536	1%
Roofing	$0	$0	0%
Structural engineer	$6	$69	0%
Mower/Trimmer	$15,574	$178,884	10%
Utilities locator	$4	$44	0%
Total	**$172,230**	**$1,800,124**	**100%**

Lifetime NPV by Component Type			
Component	Avg. Cost/Yr	NPV (Life)	% of Total
AC Wiring	$2,055	$22,299	1%
Asset Management	$4,549	$52,249	3%
Cleaning/Veg	$39,487	$453,566	26%
DC Wiring	$14,726	$158,395	9%
Documents	$3,115	$35,784	2%
Electrical	$1,796	$20,351	1%
Inverter	$62,096	$555,708	32%
Mechanical	$5,317	$53,304	3%
Meter	$18	$205	0%
Monitoring	$70	$783	0%
PV Array	$11,839	$135,644	8%
PV Module	$15,219	$175,764	10%
Roof	$0	$0	0%
Tracker	$7,548	$86,694	5%
Transformer	$4,395	$49,377	3%
Total	**$167,835**	**$1,750,747**	**100%**

Figure 19 - Cost Model

Figure 19 shows results of PV O&M cost model for a 10-MW ground-mount PV system with tracking, central inverters, and pollen as an environmental condition (figure by Andy Walker).

15. Current PV O&M Cost Survey Information

The U.S. Federal Energy Management Program (FEMP) has tabulated O&M costs for grid-tied distributed generation-scale systems varying from $21 ± $20 /kW/year for systems < 10 kW to $19 ± $10 /kW/year for large systems > 1 MW (see NREL 2013). In 2010, EPRI reported costs of $6/kW/year to $27/kW/year (<1% to 5% of installed cost per year) for systems less than 1 MW and costs of $47 to $60/kW/year for larger utility-scale systems depending on PV type and fixed or tracking mounts (EPRI

2010). An early study reports O&M costs of $12/kW/year or at 0.17% of capital cost without tracking and 0.35% of initial cost with tracking (Mortensen 2001).

Another estimate approximates O&M of PV systems at $40/kW/year (about 0.5% of initial cost per year for these early systems), about half of which amortized inverter replacements (Wiser et al. 2009).

Data collected by Tucson Electric Power from 2002 to 2006 (Tucson Electric Power 2007) reports annual preventive maintenance at 0.04% to 0.08% of initial cost per year and corrective/reactive unplanned maintenance at 0.01 to 0.22% of initial cost per year. The average combined cost for these utility-scale ground-mounted systems was 0.16%/year. Costs are not evenly distributed, with several years of low cost punctuated by a year of high cost when the inverter is replaced.

Arizona Public Service reports 0.35% of initial cost for O&M exclusive of inverter replacements (Moore et al. 2008) for large grid-connected systems. For small off-grid systems with batteries, Arizona Public Service reports that the average annual O&M cost is 5% to 6% of the initial capital cost (Canada et al. 2005) and that travel time and mileage account for 42% of the unscheduled maintenance cost of these remote systems.

Members of the Working Group have discussed these results and are currently recommending 0.5% for large systems and 1% of system initial cost per year for small systems as a reasonable expectation of PV system O&M costs.

These heuristics inform an expectation of PV system O&M cost. The PV O&M cost model allows a customized, if not more accurate, estimate of system cost based on system type and components and also on environmental conditions. Survey data on cost and backup services providers is being correlated with model test data to “calibrate” the cost model. The cost model can also lay out year-by-year fluctuations in O&M cost based on scheduled intervals for preventive measures, failure distributions that increase with age, and inflation in the cost of O&M services.

Appendix A. System Performance Guarantee Example Calculation (without Shade Correction)

EXHIBIT

COMMERCIAL SYSTEM: SYSTEM PERFORMANCE GUARANTEE

IEC 61724 describes a performance ratio (PR), a temperature-corrected PR, and PRs based on either standard test condition (STC) data or performance test condition data. Performance ratio is actual energy delivery divided by the energy delivery estimated based on environmental conditions and exclusions such as clipping (when DC output exceeds AC output). In other words, performance ratio is the measured electrical yield divided by plane-of-array (POA) irradiance, divided by nameplate rating, and multiplied by the reference irradiation value (e.g., 1000 W/m2) corresponding to the nameplate rating, where the electrical yield and POA irradiance are integrated over the same time period. If conducted over a short time period, this example of PR will be inaccurate because this PR will vary substantially based on the time of year it is calculated and weather, which could be improved using energy performance index and availability. PR can vary, up or down, year to year, and this operator gets penalized for a year when it is down, but they do not get rewarded for a year when it is up. In addition to using different metrics for a guarantee, multi-year averaging, or a penalty/reward type of system for calculating the guarantee can address this inequity.

The PR of the system is defined as follows:

$$PR = \frac{Y_f}{Y_r} = \frac{E}{P_n} * \frac{I_{STC}}{H_m}$$

Where:

Yf = number of production equivalent hours recorded at the standard condition (STC);

Yr = number of irradiation equivalent hours at the standard condition (STC);

E = actual energy output (kWh) plus that number of kWh based on operator’s good-faith calculation lost during the contract year due to force majeure event(s) and/or by any action or inaction of owner, utility, or host.

Pn = nominal peak power of the PV plant (kWp) equal to XXXX.00 kWp

Hm = actual irradiance during the performance period recorded through a pyranometer (kWh/m2). The performance ratio is usually defined relative to the POA irradiance. Global horizontal (historical reported weather) data are fed into a model to correct for PV module orientation.

ISTC = Standard condition of the irradiation equal to 1 kWh/m².

1. Within twenty (20) business days of the end of each contract year, operator shall provide to owner a written report setting forth the following information:
    a. The actual energy output produced by the system in kWh as recorded by the data acquisition system (DAS) for the 12-month period of the contract year, plus that number of kWh based on operator’s good-faith calculation lost during the contract year due to

force majeure event(s) and/or by any action or inaction of owner, utility, or host, and as reviewed by the owner's technical representative at the owner sole discretion.

b. The actual annual insolation for the contract year calculated as the sum of the monthly insolation levels measured in the plane of array or measured in the global horizontal plane and corrected for orientation of the PV modules in units of kWh/m2 for the system as recorded by the DAS for the 12-month period of the contract year.

2. With respect to the data set forth in each annual report provided by operator in accordance with Section 6 above, operator guarantees for each combined period i of one contract year ("**PR Performance Period**") during the twenty (20) contract years following the effective date that the actual relevant performance ratio during the performance period, exceeds or equals the expected PR of the system for the contract year I ("**PRiExpected**") during the same i performance period:

$$PRi \geq PRiExpected$$

where:

PRi is the PR directly measured onsite, as described above, for the performance period "i";

PRiExpected is the expected PR to be achieved by the operator under its obligations pursuant this agreement ("Expected Performance Ratio").

The operator shall achieve a performance ratio contracted after availability for as listed below: PR

$$iExpected = 82.\ 8 \text{ x } K \text{ x } (1 - Y\ iDegradation) \text{ x } (Y\ Availability)$$

where:

Y iDegradation is 0.5% from the previous year

Y Availability is 98% (for the first year) and 99% (for the second and subsequent years)

K is the corrective factor equal to 1.3 for mono-axial tracker-based systems and 1 for fixed systems.

Table 11 - 20 Year Degradation Calculation

Year	Degradation % from Previous Year Y Degradation	Cumulative Degradation of the Modules Y Degradation	Availability Y Availability	PRi Expected (for each year i)
0	0.50%	0.00%		
1	0.50%	0.50%	98%	108.20%
2	0.50%	1.00%	99%	107.66%
3	0.50%	1.50%	99%	107.12%

Year	Degradation % from Previous Year Y Degradation	Cumulative Degradation of the Modules Y Degradation	Availability Y Availability	PRi Expected (for each year i)
4	0.50%	2.00%	99%	106.59%
5	0.50%	2.50%	99%	106.06%
6	0.50%	3.00%	99%	105.52%
7	0.50%	3.50%	99%	105.00%
8	0.50%	4.00%	99%	104.47%
9	0.50%	4.50%	99%	103.95%
10	0.50%	5.00%	99%	103.43%
11	0.50%	5.50%	99%	102.91%
12	0.50%	6.00%	99%	102.40%
13	0.50%	6.50%	99%	101.89%
14	0.50%	7.00%	99%	101.38%
15	0.50%	7.50%	99%	100.87%
16	0.50%	8.00%	99%	100.37%
17	0.0%	8.50%	99%	99.86%
18	0.50%	9.00%	99%	99.36%
19	0.50%	9.50%	99%	98.87%
20	0.50%	10.00%	99%	98.37%

Non-availability due to willful act or willful negligence of the owner, force majeure, or interruptions requested by or agreed with owner will imply an equivalent reduction in Hm. These outages may vary and should be defined and agreed to by the stakeholders when crafting the guarantee language.

3. Should the PRi of the system for a performance period as calculated in accordance with Section 2 above fall short of the PRiExpected of the system during the i performance period as described in the table above, operator shall pay owner an amount in U.S. dollars equal to:

$$LDs = H_m * P_p * (PR\ i_{Expected} - PR\ i) * R$$

where:

LDs = amount of performance liquidated damages

Hm = Reference horizontal plane irradiation during the PR performance period

Pp = Installed nameplate capacity of the plant (kWp)

PR = PR measured on the plant during the reference period

PR iExpected = is the PR expected as defined in Section 1

R = Average post-time of day (TOD) PPA contracted revenue per unit of electricity generated, equal to ________$/kWh.

Appendix B. Service Descriptions for Preventive Maintenance Selections Available in the PV O&M Cost Model Tool

Consult equipment manuals for maintenance activities and intervals as required by manufacturer.

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
General cleaning	General cleaning/veg mobilization	Cleaning	PV Array	Condition or study dependent	Mower/ Trimmer	N/A	Site
Array cleaning	Array cleaning	Cleaning	PV Array	Condition or study dependent	Cleaner	N/A	Acre
Snow cleaning	Snow removal	Cleaning	PV Module	Condition or study dependent	Cleaner	N/A	Acre
Dust cleaning	Dust removal: agricultural /industrial	Cleaning	PV Module	Condition or study dependent	Cleaner	N/A	Acre
Pollen cleaning	Pollen cleaning	Cleaning	PV Module	Condition or study dependent	Cleaner	N/A	Acre
Vegetation management	Determine if any new objects, such as vegetation growth, are causing shading of the array and move them if possible. Remove any debris from behind collectors and from gutters.	Cleaning	PV Array	As needed	Mower/ Trimmer	N/A	Acres
Bird cleaning	Bird Cleaning	Cleaning	PV Array	Bi-annual	Cleaner	N/A	Acres

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Contractor response	Contractor available by email and phone 24x7x365	Emergency Response	PV Array	Ongoing	Administrator	N/A	System
Corrosion inspection	Inspect electrical boxes for corrosion or intrusion of water or insects. Seal boxes if required.	Inspection	AC Wiring	Annual	Inspector	N/A	Combiner Box
AC disconnect switch inspection	Check position of disconnect switches and breakers.	Inspection	AC Wiring	Annual	Inspector	N/A	Disconnect Box
Protection device inspection	Exercise operation of all protection devices.	Inspection	AC Wiring	Annual	Journeyman Electrician	N/A	
AC disconnect box inspection	AC disconnect box inspection	Inspection	Electrical	Annual	Electrician	N/A	Disconnect Box
Grounding inspection	Test system grounding with"megger"	Inspection	DC Wiring	Annual	Master Electrician	N/A	Strings
Cable inspection	Inspect cabling for signs of cracks, defects, pulling out of connections; overheating, arcing, short or open circuits, and ground faults.	Inspection	DC Wiring	Annual	Inspector	N/A	Strings
DC disconnect switch inspection	Check proper position of DC disconnect switches.	Inspection	DC Wiring	Annual	Inspector	N/A	
Combiner box inspection	Open each combiner box and check that no fuses have blown and that all electrical connections are tight. Check for water incursion and corrosion damage. Use an infrared	Inspection	DC Wiring	Annual	Journeyman Electrician	N/A	Combiner Box

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
	camera for identifying loose connections because they are warmer than good connections when passing current.						
Electrical box inspection	Look for any signs of intrusion by pests such as insects and rodents. Remove any nests from electrical boxes (junction boxes, pull boxes, combiner boxes) or around the array. Use safe sanitation practices because pests may carry disease.	Inspection	DC Wiring	Annual	Pest Control	N/A	
Inverter inspection	Observe instantaneous operational indicators on the faceplate of the inverter to ensure that the amount of power being generated is typical of the conditions. Compare current readings with diagnostic benchmark. Inspect inverter housing or shelter for physical maintenance required if present.	Inspection	Inverter (Electrical)	Annual	Inspector	N/A	Inverter
Instrument inspection	Spot-check monitoring instruments (e.g., pyranometer) with hand-	Inspection	Monitoring	Annual	Inspector	N/A	

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
	held instruments to ensure that they are operational and within specifications.						
String inspection	Test open-circuit voltage of series strings of modules	Inspection	PV Array	Annual	PV Module/ Array Specialist	N/A	Strings
Corrosion inspection	Check all hardware for signs of corrosion, and remove rust and re-paint if necessary.	Inspection	PV Array (Mechanical)	Annual	Inspector	N/A	Connection
Array inspection	Walk through each row of the PV array and check the PV modules for any damage. Report any damage to rack and damaged modules for warranty replacement. Note location and serial number of questionable modules.	Inspection	PV Array	Annual	Inspector	N/A	Acres
Mounting system inspection	Inspect ballasted, non-penetrating mounting system for abnormal movement	Inspection	PV Array	Annual	Inspector	N/A	Rows
Hot-spot inspection	Use infrared camera to inspect for hot spots; bypass diode failure	Inspection	PV Module	Annual	Inspector	N/A	Strings
Transformer inspection	Inspect transformer, oil and temperature gauges, include housing container, or concrete housing if present	Inspection	Transformer	Annual	Master Electrician	N/A	

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Tracker inspection	Check electrical connection and enclosure for tracking motor/controller	Inspection	Tracker	Annual	Inspector	N/A	Controller
Electrical connection inspection	Check electrical connections	Inspection	Tracker	Annual	Inspector	N/A	Motor
Grounding braids inspection	Check grounding braids for wear	Inspection	Tracker	Annual	Inspector	N/A	Structure
Switchgear inspection	Switchgear inspection	Inspection	Electrical	Annual	Inspector	N/A	Transformer
Anemometer inspection	Anemometer Inspection	Inspection	Tracker	Annual	Inspector	N/A	
Driveshaft inspection	Driveshaft torque check and visual inspection	Inspection	Tracker	Annual	Inspector	N/A	Driveshaft
Inclinometer inspection	Inclinometer inspection	Inspection	Tracker	Annual	Inspector	N/A	
Limit switch inspection	Limit switch inspection	Inspection	Tracker	Annual	Inspector	N/A	Block
Module table inspection	Module table inspection	Inspection	Tracker	Annual	Inspector	N/A	Connection
Screw jack inspection	Screw jack inspection	Inspection	Tracker	Bi-annual	Inspector	N/A	Block
Slew gear inspection	Slew gear torque check and wear inspection	Inspection	Tracker	Annual	Inspector	N/A	Slew Gear
Torque inspection	Torque inspection	Inspection	Mechanical	Annual	Inspector	N/A	Block
Tracking controller inspection	Tracking controller inspection	Inspection	Tracker	Annual	Inspector	N/A	
Gear inspection	Universal joint inspection, gears, gear boxes, bearings as required or documented by manufacturer	Inspection	Tracker	Annual	Inspector	N/A	Driveshaft

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Module torque inspection	PV module torque check and visual inspection	Inspection	Mechanical	5 years	PV Module/Array Specialist	N/A	Rail/ Fastener
Racking torque inspection	Racking torque check and inspection	Inspection	Mechanical	5 years	Inspector	N/A	Structure
Galvanization inspection	Galvanization inspection	Inspection	Mechanical	Annual	Inspector	N/A	Connection
Manage operations	daily operations and performance monitoring	Management	Asset Management	Ongoing	Administrator	N/A	
Manage alarms	Monitor alarms and site-specific alert parameters	Management	Asset Management	As needed	Administrator	N/A	
Manage inventory	Manage inventory of spare parts	Management	Asset Management	As needed	Administrator	Monitoring	
Manage service package	Monitoring annual service package	Management	Asset Management	Ongoing	Administrator	Monitoring	System
Manage O&M services	Document all O&M services in a workbook available to all service personnel	Management	Documents	Ongoing	Administrator	N/A	
Manage documentation	Confirm availability and take any measures to secure operating instructions, warranties and performance guarantees, and other project documentation.	Management	Documents	Annual	Administrator	N/A	
Manage O&M agreements	Review O&M agreements and ensure that services are actually provided	Management	Documents	As needed	Administrator	N/A	

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Manage preventive services	Update record with preventive maintenance services and track any problems or warranty issues and secure the record on site.	Management	Documents	Ongoing	Administrator	N/A	
Meet with site staff	Meet with key site staff to continue awareness, question any issues, and report on findings.	Management	Documents	Annual	Administrator	N/A	
Maintain log	Maintain a log of cumulative power delivery (kWh to date) and chart this value against date. Chart the value even for uneven or infrequent intervals. Explain variation by season or weather.	Management	Meter	Monthly	Administrator	N/A	
Mobilize electrical labor	Electrical labor mobilization	Management	Electrical	Annual	Master Electrician	EPC	Site
Mobilize mechanical labor	Mechanical labor mobilization	Management	Mechanical	Annual	Mechanic	EPC	Site
Check central SCADA	Check central SCADA/network manager, include software IT and IT hardware updates as required	Management	Electrical	Annual	Network/ IT	N/A	NCU
Re-torque AC connection	Re-torque all electrical connections on AC side of system.	Service	AC Wiring	Annual	Journeyman Electrician	N/A	

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Re-torque combiner box connections	Re-torque all electrical connections in combiner box	Service	DC Wiring	Annual	Electrician	N/A	Combiner Box
Replace weather sensors	Calibrate or replace weather sensors and meters	Service	Electrical	As per manuf.	Network/ IT	N/A	Weather Station
Replace transient voltage surge suppression device	Replace transient voltage surge suppression devices	Service	Inverter	As per manuf.	Master Electrician	Inverter	
Install software upgrades	Install any recent software upgrades to inverter programming or data acquisition and monitoring systems	Service	Electrical	As upgrades become available, max 5 years	Inverter Specialist	EPC	NCU
Dust cleaning from heat rejection fins	Clean (vacuum) dust from heat rejection fins	Service	Inverter	Annual	Cleaner	N/A	Inverter
Replace air filters	Replace any air filters on air-cooled equipment such as inverter.	Service	Inverter	As needed	Inverter Specialist	N/A	Inverter
Remove bird nest	Remove bird nests from array and rack area.	Service	PV Array	Annual	Pest Control	N/A	Acres
Tracker lubrication	Lubricate tracker mounting bearings/ gimbals as required by manufacturer	Service	Tracker	Annual	Mechanic	N/A	
Gearbox lubrication	Lubricate gearbox as required by manufacturer	Service	Tracker	Bi-annual	Mechanic	N/A	Block
Screw jack greasing	Screw jack greasing as required by manufacturer	Service	Tracker	Bi-annual	Mechanic	N/A	Block

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Slew gear lubrication	Slew gear lubrication as required by manufacturer	Service	Tracker	3 years	Mechanic	N/A	Slew Gear
Universal joint greasing	Universal joint greasing (zerk fitting) as required by manufacturer	Service	Tracker	Bi-annual	Mechanic	N/A	Driveshaft
Performance testing	Perform performance test: measure incident sunlight and simultaneously observe temperature and energy output. Calculate PV module efficiency as a function of temperature and calculate the balance- of-system efficiency. Compare readings with diagnostic benchmark (original efficiency of system).	Testing	Inverter	Annual	Inspector	N/A	
Overvoltage surge suppressor testing	Test overvoltage surge suppressors in inverter	Testing	Inverter	5 Years	Inverter Specialist	Inverter	Inverter
Module output testing	Test output of modules that exhibit cracked glass, bubble formation oxidation of busbars, discoloration of busbars, or PV module hot spots (bypass diode failure)	Testing	PV Module	5 years	Journeyman Electrician	N/A	Modules
Module testing	Test modules showing corrosion of ribbons to junction box	Testing	PV Module	5 years	Journeyman Electrician	N/A	Modules

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Combiner box inspection	DC circuit test and combiner-box inspection	Testing	Electrical	Annual	PV Module/ Array Specialist	N/A	Combiner Box
Module electrical connection testing	PV module electrical connection check	Testing	Electrical	5 years	PV Module/ Array Specialist	N/A	PV Module
Grounding hardware testing	Check grounding hardware	Testing	Electrical	Annual	Master Electrician	N/A	Structure

Appendix C. Service Descriptions for Corrective Maintenance Selections Available in the PV O&M Cost Model

The following is a list of corrective/reactive maintenance measures that would be performed to fix problems encountered in operation of a PV system over time.

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Dispatch contractor	Dispatch contractor in response to alarms, alerts, or contact by others	Emergency Response	PV Array	As needed	Administrator	Monitoring	
Replace inverter AC fuse	Replace inverter AC fuse(s)	Repair	AC Wiring	As needed	Journeyman Electrician	EPC	
Replace protective devices	Replace protective devices (breakers) in building panel	Repair	AC Wiring	As needed	Master Electrician	N/A	
Replace AC wiring conduit	Replace broken/crushed AC wiring conduit and fittings	Repair	AC Wiring	As needed	Journeyman Electrician	N/A	Strings
Repair line-to-line fault	Repair line-to-line fault	Repair	AC Wiring	As needed	Master Electrician	N/A	
Locate line-to-line fault	Locate line-to-line fault	Repair	AC Wiring	As needed	Master Electrician	EPC	
Replace combiner box fuses	Replace failed fuses in combiner box	Repair	DC Wiring	As needed	Journeyman Electrician	N/A	Strings
Replace connectors between module	Replace MC Connectors between modules	Repair	DC Wiring	As needed	PV Module/ Array Specialist	Module (Product)	Modules
Replace MC connector lead to combiner box	Replace MC connector lead to combiner box	Repair	DC Wiring	As needed	PV Module/ Array Specialist	Module (Product)	Modules

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Re-route conduit	Re-route conduit	Repair	DC Wiring	As needed	Journeyman Electrician	N/A	
Replace DC wiring conduit	Replace broken/crushed DC wiring conduit and fittings	Repair	DC Wiring	As needed	Journeyman Electrician	N/A	
Repair ground fault	Repair ground fault	Repair	DC Wiring	As needed	Master Electrician	EPC	
Locate ground fault	Locate ground fault	Repair	DC Wiring	As needed	Master Electrician	EPC	
Locate underground DC wiring	Locate underground DC wiring as part of repairs to faults	Repair	DC Wiring	As needed	Utilities Locator	N/A	
Repair DC direct- bury wire	Carefully dig to expose fault and repair wire	Repair	DC Wiring	As needed	Journeyman Electrician	EPC	
Replace fuse on DC source circuits to inverter	Replace fuse(s) on DC source circuits to inverter	Repair	DC Wiring	As needed	Master electrician	EPC	
Repair junction box	Seal leaking junction box	Repair	DC Wiring	As needed	Journeyman Electrician	Module (Product)	Modules
Reboot inverter	Start/stop inverter (reboot to clear unknown error)	Repair	Inverter	As needed	Inspector	EPC	Inverter
Replace inverter fan motor	Replace inverter fan motor	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace inverter DAQ	Replace inverter data acquisition card/board; diagnose with fault code	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Replace inverter control card	Replace inverter control card (PWM signal, voltage, phase, frequency, shut-down); diagnose with fault code	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace (Insulated-Gate Bipolar Transistor (IGBT) driver	Replace IGBT driver card/board; diagnose with fault code	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace maximum power-point tracker	Replace maximum power-point tracker card/board; diagnose with fault code	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace AC contactor in inverter	Replace AC contactor in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace IGBT matrix in inverter	Replace IGBT matrix in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace power supply for inverter controls	Replace 24VDC power supply for inverter controls	Repair	Inverter	As needed	Inverter Specialist	EPC	Inverter
Replace DC contactor in inverter	Replace DC contactor in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace Ground Fault Interuption components	Replace GFI components in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace capacitors	Replace capacitors in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace induction	Replace inductors (coils) in inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Replace fuses internal to inverter	Replace fuses internal to inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace inverter relay/switch	Replace inverter relay/switch	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Replace overvoltage surge suppressors	Replace overvoltage surge suppressors for inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Re-install software	RE-install inverter control software	Repair	Inverter	As needed	Inverter Specialist	EPC	Inverter
Reset arc-fault trip	Manual reset of arc-fault trip (NEC 690.11)	Repair	Inverter	As needed	Inverter Specialist	EPC	Inverter
Restore Internet	Restore lost Internet connection	Repair	Monitoring	As needed	Network/ IT	N/A	Site
Replace foundation element	Excavate and replace failed foundation element	Repair	PV Array	As needed	Structural Engineer	N/A	
Replace rack parts	Repair or replace rack parts damaged by corrosion or physical damage	Repair	PV Array	As needed	Mechanic	EPC	
Replace modules	Replace modules failing performance test and infrared scan after showing cracks in glazing, discoloration of metallic contacts, delamination, or signs of water	Repair	PV module	As needed	Journeyman Electrician	Module (Product)	Modules

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Repair module backsheet	Repair cracking of PV module backsheet	Repair	PV module	As needed	Journeyman Electrician	Module (Product)	Modules
Repair module frame	Repair or replace damage to module frame	Repair	PV module	As needed	Mechanic	Module (Product)	Modules
Repair roof leaks	Repair roof leaks as related to PV structure penetrations problems	Repair	Roof	As needed	Roofer	N/A	Acres
Re-roof	Re-roof (new roof) as related to PV structure penetrations problems	Repair	Roof	As needed	Roofer	N/A	Acres
Repair tracker drive shaft	Repair/replace tracker drive shaft	Repair	Tracker	As needed	Mechanic	N/A	Row
Replace tracker drive bearing	Replace tracker drive bearing	Repair	Tracker	As needed	Mechanic	N/A	Row
Replace tracker mount bearing	Replace tracker mount bearing	Repair	Tracker	As needed	Mechanic	N/A	
Replace tracker motor controller	Replace tracker motor controller	Repair	Tracker	As needed	Journeyman Electrician	N/A	
Upgrade tracker software	Replace/upgrade tracker control software	Repair	Tracker	As needed	Network/ IT	N/A	
Replace tracker power supply	Replace tracking-controller power supply fan filter	Repair	Tracker	2 years	Mechanic	EPC	Controller
Replace hydraulic cylinder	Replace hydraulic cylinder	Repair	Tracker	As needed	Mechanic	N/A	

Service Name	Service Description	Service Category	O&M Category	Interval	Service Provider	Warranty Type	Applicable Unit
Replace transformer (e.g., GSU)	Replace transformer	Repair	Transformer	As needed	Master Electrician	N/A	Transformer
Re-tap transformer	Re-tap transformer	Repair	Transformer	As needed	Master Electrician	N/A	Transformer
Replace terminal block	Replace terminal block	Repair	Inverter	As needed	Journeyman Electrician	Inverter	Combiner Box
Replace inverter	Replace inverter	Repair	Inverter	As needed	Inverter Specialist	Inverter	Inverter
Locate underground AC wiring	Locate underground AC wiring	Repair	AC wiring	As needed	Utilities Locator	N/A	