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Precursor Report of Data Needs and Recommended Practices for PV Plant Availability, Operations and Maintenance Reporting

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ABSTRACT

Characterizing the factors that affect reliability of a photovoltaic (PV) power plant is an important aspect of optimal asset management. This document describes the many factors that affect operation and maintenance (O&M) of a PV plant, identifies the data necessary to quantify those factors, and describes how data might be used by O&M service providers and others in the PV industry. This document lays out data needs from perspectives of reliability, availability, and key performance indicators and is intended to be a precursor for standardizing terminology and data reporting, which will improve data sharing, analysis, and ultimately PV plant performance.

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

This document identifies certain methods and approaches to collecting photovoltaic (PV) system data:

1. quantifying the relevant aspects of faults, partial and total failures (events), and maintenance actions associated with a PV power plant;
2. monitoring approaches to track PV power-plant performance and component conditions that are precursors to failures;
3. identifying and tracking the key performance indicators (KPIs); and
4. collecting data for understanding and reporting of PV plant performance.

This document correlates the PV plant data with how it might be used. Operations and maintenance (O&M) decisions are vital and should be informed from the data obtained from plant performance. Analysis of plant performance data also offers the opportunity to improve future PV system specification and design.

Many data types must be collected to understand different PV system performance aspects. But specifically what data is needed and how much data should be collected? What are the required data attributes (accuracy, data frequency, etc.)? Similarly and significantly related, data is needed for reporting on the full power plant's overall health. In addition to plant performance, station availability and grid constraints may reduce the plant's energy performance. Data is needed to more precisely determine what reduces energy yield.

The utility, many of the PV plant project stakeholders, energy off-takers, customer(s), the PV plant operator, and power marketing firms will have reporting needs that rely on data collected at the PV plant. These include real-time production, forecast(s) production, forecast accuracies, outages and generation derating conditions, and performance in response to grid conditions. Data collection must respond to specific stakeholder needs, with some stakeholders needing specific KPIs. This precursor report will address the question, "What data should be collected?"

The authors recognize that the term *availability*, often used in contracts, has many different definitions. In fact, there are many causes of unavailability, and clarity is needed to facilitate information exchange on performance indicators among owners, utilities, lenders, operators, manufacturers, consultants, regulatory bodies, certification bodies, insurance companies, and other stakeholders involved with the PV power plant. Appendix D shows a proposed information model to support clear understanding of plant performance referenced in contract terms. This information model specifies how time designations are proposed to be allocated to information categories in a standardized manner. This information model is intended to be a precursor to a specific future standard effort.

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FIGURES

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NOMENCLATURE

ac	alternating current
BOM	bill of materials
BOS	balance of systems
CMMS	computerized maintenance management system
CPR	(temperature-) corrected performance ratio
dc	direct current
EEAF	equipment equivalent availability factor
EEFOF	equipment equivalent forced-outage factor
EFOR	equipment forced outage rate
$EFOR_d$	equivalent forced outage rate–demand
EPC	engineering procurement construction
EPI	energy performance index
EPRI	Electric Power Research Institute
GADS	Generating Availability Data System
IEC	International Electrotechnical Commission
IV	current-voltage
ISO	International Standards Organization
KPI	key performance indicator
kW	kilowatt
kWh	kilowatt-hour
LCOE	levelized cost of energy
MTBF	mean time between failures
MTBM	mean time between maintenance actions
MTTR	mean time to repair
MW	megawatt
MWh	megawatt-hour
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
O&M	operation and maintenance
ORAP®	Operational Reliability Analysis Program
PAM	preemptive analytic maintenance
POA	plane of array irradiance
PR	performance ratio
PV	photovoltaic
PVPMC	PV Performance Modeling Collaborative
PVROM	PV Reliability Operation Maintenance
RAM	reliability, availability, maintainability
RCM	reliability centered maintenance
SCADA	supervisory control and data acquisition
SNL	Sandia National Laboratories
STC	standard test conditions

1. INTRODUCTION

Accurately characterizing photovoltaic (PV) power-plant reliability factors is an important aspect in achieving optimal asset management. This document attempts to collect the many factors that affect a PV plant's operation and maintenance (O&M), identifies the data necessary to quantify those factors, and describes how data might be used by O&M service providers and others in the PV industry. Equipment availability, for instance, is dependent on the full plant infrastructure, whose events, whether in the PV modules or balance of system (BOS, e.g., substation transformer) may result in plant outages or partial performance. Similarly and significantly related, data is needed for reporting on a full power plant's overall health. Furthermore, grid constraints and interuptions will affect plant availability, and data is needed for accounting for reduction of energy yield. In some cases, there will be contracted terms and performance guarantees for certain condition states, for production, or allowances for certain state causes relieving production obligations. The contract should define what level of precision is needed for data collection or cite an appropriate standard. This document lays out data needs from the perspective of reliability, availability, and key performance indicators (KPIs), and is intended to be a precursor for standardizing both terminology and data reporting.

Sandia National Laboratories (SNL) has been working with O&M service providers to identify areas where improvements to data collection and plant performance reporting can be made. The challenge many face is providing O&M services for a plant that they did not design or specify, but must operate with a high degree of equipment availability and energy performance. This document seeks to provide a higher degree of clarity on the data to be collected and reported. The authors observe that for metrics such as availability, many different approaches exist—and standardization is needed. This document can inform standardization efforts. It also recommends "best practices" for data collection and the metrics for reporting PV plant performance to different stakeholders. The term *plant* is used generically and encompasses systems of various sizes that include utility-scale, commercial-scale and residential-scale, as they all have the need for O&M and data that facilitates an understanding of performance.

The PV power plant consists of more than just PV array(s), it is a power plant, whether for production of energy for sale to a utility, or to offsetting a customer's own electricity use. As identified in Sections 4, 5, and 6, designating a system as class A, B, or C is a typical convention found in the revised International Electrotechnical Commission (IEC) 61724 "Photovoltaic System Performance Monitoring" standard,[1] which is currently in development, as well as the IEC New Work Item Proposal for "Maintenance of PV Systems,"[2] where maintenance intervals are defined for the system classifications. It is the goal of this document to identify where standards are applicable and not conflict or duplicate content.

[1] At the time of this publication, this standard is under update and revision as Edition 2—Part 1.
[2] In IEC standards process.

This precursor report identifies certain methods and approaches to collecting data:

1. quantifying the relevant aspects of faults, partial and total failures, and maintenance actions associated with a PV power plant;
2. monitoring approaches to track PV power plant performance and component conditions that are precursors to failures; and
3. identifying and tracking KPIs.

The report will define what data is needed in this comprehensive process, why it is needed, and for what purpose it can be used.

The definitions and methodologies presented in this paper are expected to facilitate improved PV plant performance and asset management by

- identifying pathways toward improving information management and asset-management performance that will help optimize O&M decisions and performance reporting,
- clarifying definitions for 3rd-party engineers and financial institutions,
- improving plant designs and component selection,
- providing a common basis of reference in plant supply and warranty contracts,
- suggesting common definitions for operations reporting,
- improving communications among all stakeholders,
- documenting performance for insurance benefits and claims resolution,
- defining project performance and compatibility attributes,
- facilitating continuous improvement analysis, and
- building a basis for optimizing annual energy production.

2. GOALS AND OBJECTIVES

The goal is to provide descriptions of quantitative numerical PV plant performance metrics, including statistical distributions of failures and failure rates, fault times, restoration times, and related effects on the plant O&M functions. This information is useful to ongoing plant performance assessment. Reliability, availability, and maintainability (RAM) methodology tools are used to measure asset performance, which includes rigorous record-keeping and data analysis to inform maintenance decisions and improve power-generation facility reliability. (See Appendix B for definitions used throughout this document.) RAM metrics have an important role as they quantitatively describe trends, causes, sources, reasons, and impacts for PV plant downtime at the component level, and provide plant performance feedback to both design and manufacturing. When combined with energy production and other plant KPIs, issues related to operational capabilities can be recognized, tracked, and eventually mitigated.

Before a 2013 SNL O&M workshop,[3] a survey was conducted to gauge gaps in PV O&M practices. The following responses indicate the need for greater clarity, procedures, data management, and standardization.

- Clarity around what maintenance can be done without voiding warranties.
- Supervisory control and data acquisition (SCADA)/data-acquisition system optimized as an O&M tool.
- Merging operational data with maintenance data. Keeping good maintenance records. Standardizing procedures.
- Cost-benefit calculations for when O&M is justified.
- Effective system-integration practices and standards combined with the experiential education to provide skilled, competent, and more productive PV professionals. An effective systems-level process covering all system-delivery phases, from cradle to grave, and a better understanding of how the components work as a system and impact each other in the environment in which they are placed.
- Standardized failure modes, standardized failure codes from inverters.
- Quality analytics.
- Lack of understanding that PV systems *need* maintenance.
- Commissioning, recommissioning.

This document will, through industry adoption and continued refinement, provide standardization measures for PV plant reporting, by identifying data needs and by correlating the O&M data with how it might be used.

[3] See: http://energy.sandia.gov/wp/wp-content/gallery/uploads/OM-Survey-Summary.pdf.

> *Why standardization?*
>
> Standards are a prescribed set of rules, conditions, or requirements concerning definitions of terms; classification of components; specification of materials, performance, or operations; delineation of procedures; or measurement of quantity and quality in describing materials, products, systems, services, or practices. They are vital tools of industry and commerce and provide the basis for buyer-seller transactions. Their function is to achieve a level of enhanced safety, quality and consistency in products and processes. Standardized best practices are attempts to advance an industry's maturity.
>
> Successfully administered, best practice service approaches can lower lifetime system costs and financial exposure to project beneficiaries. These approaches estimate lifetime plant O&M needs that are based on maintenance regimens, for example, featuring component replacement with high confidence and quantified uncertainty. The upshot: streamlined O&M activities that can lower PV levelized cost of electricity (LCOE) by increasing lifetime energy production, improving system bankability, and reducing insurance premiums.

It should be noted that one of the functions stated above is *quality analytics*. While quality may be primarily a subjective measure for PV systems, it can be seen as the alignment of requirement, needs, functionality, and expectations. Requirements are typically defined through contract terms and they should reflect the system owner's needs. Expectations may be held, but unless they are stated as *requirement* or otherwise reflected as contract terms they will not be actionable.

Another aspect is to track system performance over time. This information is valuable as feedback to component and system designers, manufacturers, and researchers. This concept has been well discussed and data will help these stakeholders in future projects, perhaps even as a competitive advantage. The expectations may also be stated as production estimates that may have been used for pro forma statements during development. As the industry matures, metrics with appropriate definitions for quality can be established based upon an evolving set of best practices later codified into standards.

> *One example is to use failure and restoration statistics to calibrate reliability models that can be used in a predictive value for O&M planning.*
>
> *Converting unplanned outages into planned maintenance will improve energy performance and reduce costs.*

The PV industry holds data closely, and much of it is not used beyond immediate production, maintenance, and operations. In the short term, data can improve operations, maintenance, budgeting, and scheduling and inventory control. In the long term, this data can provide benefits toward future design, specification, and manufacturing/construction applications and processes. Data can provide a more complete picture of PV operational aspects, and both successes and failures, can emerge. The data requirements addressed are driven by the need to demonstrate compliance with performance requirements and expectations. Quality, in the long term, is a function of how well the components function in their operating environment over the plant system's lifetime.

One example of the need for greater standardization is the use of the "availability" metric. There are various definitions across the industry and a lack of consistency in the term's use in the same context. This has become apparent in PV O&M working group discussions. The availability concept is important, as it is a function of component reliability and how efficiently maintenance actions are performed to restore service. Service restoration enables the resumption energy production, which is tied to PV plant return on investment. As grid-tied PV systems without storage only operate when the sun is shining, traditional definitions need to be changed accordingly. The definition of availability for wind power plants that has been codified in recent standards takes into account takes into account resource variability (see Appendix D). A similar approach can potentially define PV system availability. Tracking production (in parallel with availability) is fundamental because it is correlated to revenues and contractual obligations.

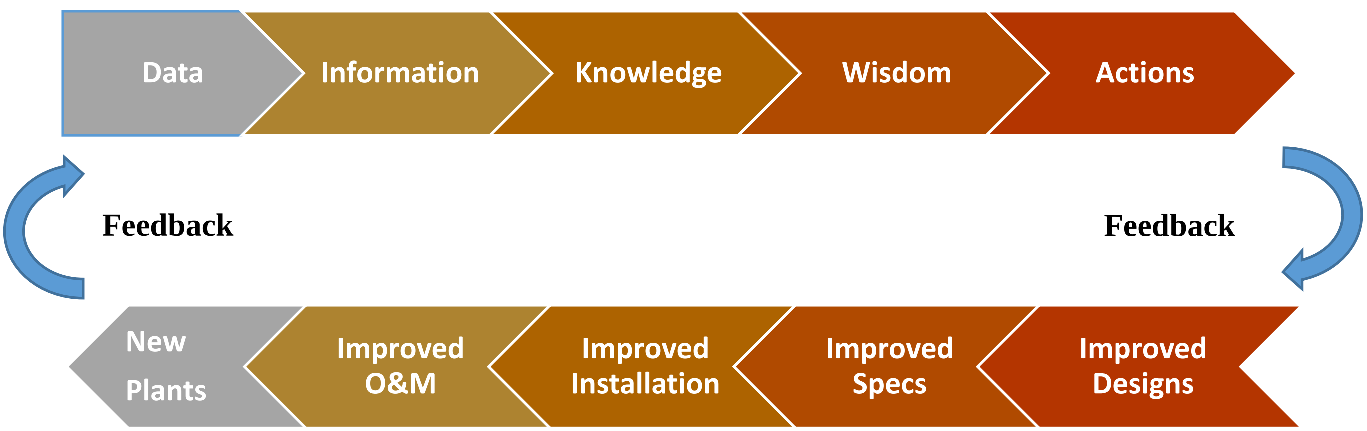

Figure 1. Wisdom Hierarchy concept.

Actions have been included in the typical Wisdom Hierarchy concept shown above in Figure 1. In addition to O&M actions performed to improve PV plant reliability, a feedback process to future projects is also illustrated. Data is critical to support this process, and with standards, these are actions appropriate at this stage of industry maturation where many PV plants are entering the phase where long-term asset management plans are being developed and implemented.

3. DATA OVERVIEW

3.1. Data Users

The utility, many of the PV plant project stakeholders, energy customer(s), the PV plant operator and power marketing firms will have reporting needs that rely on data collected at the PV plant. These include real-time production, forecast(s) production, forecast accuracies, outages and generation derating conditions, future smart grid operational conditions and short to long-range project and O&M planning.

These requirements, derived from metering at the interconnection point, will be imposed by the energy off-taker, with other possible metrics needed by the system generation dispatcher, transmission operator, independent system operators, etc.

Depending on the type of sales agreement, and whether the power is sold directly to a utility or a power marketing firm, also considering who takes market responsibility, forecasting, curtailment, environmental suspension, and force majeure situations, successful operations will require special operational communications with and between affected parties. Figure 2 illustrates many of the stakeholders who need and use the data from a producing PV power plant, with those at the top of the diagram representing external data users and those at the bottom, the internal data users.

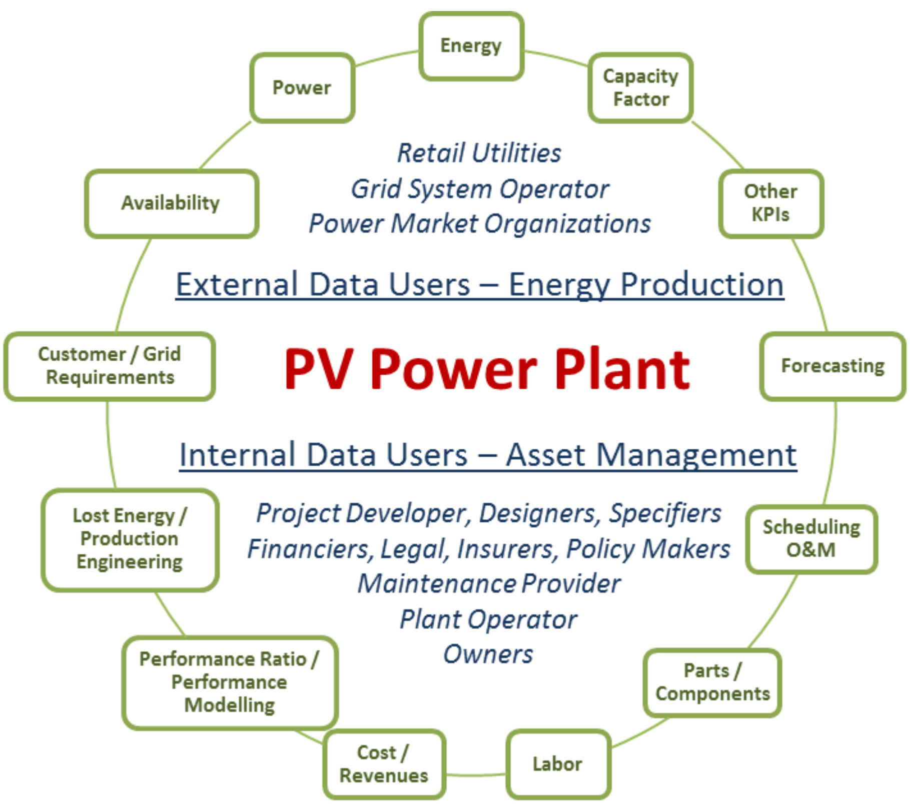

Figure 2. Data users and types.

A number of standards and regulatory requirements exist for reporting power plant operations. Many of these are not yet mandatory for PV systems. Such standards have and will continue to require more substantial communication and reporting of reliability performance. For instance IEEE 762, and ISO 3977 (see Appendix C), which apply to power generation plants in general, contain statistical metrics to be applied. They are useful for keeping track of outages, availability, maintenance, and output and include definitions of terms as formulas for calculation. An information model derived from IEC standard 61400-26 is described in Appendix D and has considerable relevance for PV as well.

With so many potentially applicable standards, it is appropriate to examine where coordination and/or collaboration is needed. The SunSpec Alliance has crafted a white paper (SunSpec, 2014) on PV performance assessment with a focus on the medium commercial size systems. The expected North American Electric Reliability Corporation (NERC) Generating Availability Data System (GADS) reporting (NERC, 2014) in particular has been identified for future mandatory reporting for large renewable-energy power plants. If enacted for large PV systems, coordination with other reporting requirements would be necessary. Various utility-sector jurisdictions may also have requirements that result in differing physical equipment (i.e., data/control) that need to be considered in the PV plant's design phase. All requirements imposed by contract, regulation, or company practices should be identified and can impact system specification, design and may necessitate additional reporting.

3.2. Data Collection Responsibilities

As part of asset management, the operator (or alternatively a monitoring company) typically has the assigned responsibility for the collecting whatever information may be needed and/or required to perform various monitoring functions. Most of the data collected will support energy-production reporting purposes or derivation of O&M service metrics.

The decision of what data to collect depends upon the party that specifically needs it, how it will be used, and what will be done with it. The need for data may be is driven by both contractual and regulatory requirements of the different stakeholders. The data should also provide a continuous picture of the power plant's performance over its expected lifetime, and is should be transferred to each new owner and O&M service provider.

To determine the value of data to the plant operation, it must first be determined what data is needed, when it is needed, and why or for what purpose. "Data" is a collection of technical information and facts and written procedures. Data storage, formatting, and accessibility are important considerations for the design of data systems.

Data uses may include:

- Condition assessment
- Basis for deviation, derating, aging and degradation—lost production analysis
- Optimizing O&M procedures
- Optimizing future production improvements
- Component failure trends and root-cause analysis
- Assessing technical risks for financial institutions and insurance companies

While various stakeholders may have different viewpoints on the use and meaning of data, the general goal shared by these stakeholders is to optimize profits with the assets lifetime capabilities.

Data should also support performance metrics and feed into a specific analysis or reporting needs. Included in the categories of useful information are the environmental conditions of operation, electrical parameters of the grid, energy and power production, reliability data (e.g., outages/parts/labor, data needed for performance analytics), and information that may have predictive value, such as condition monitoring of components and degradation rate predictors.

3.3. Long-Term Data-Collection Challenges

Data collection varies in usefulness, the effectiveness of analysis, and interpretation, and can be a competitive advantage, depending on how it is used. It will have additional benefits, far beyond O&M, when owners and operators investigate further into the information that exists yet may be seldom considered due to lack of understanding or time constraints. Some of this data provides feedback for those in manufacturing, project development, design, finance, construction, research, and other aspects involved in asset management throughout the project life cycle. Who gets what data should be determined in the project-development stage. Financiers, insurers, and asset managers (and other stakeholders) are encouraged to clearly define the data requirements so as to clarify accountability and transparency for sustaining industry roles and feedback practices.

One of the existing challenges facing the PV industry is the amount of data that should be collected. Substantial amounts of data do not always exhibit initial relevance, unless proven to have a positive financial impact when both the costs and benefits are weighed. This issue is one that will drive long-term system reliability, performance, system viability, and industry maturity as many attempts to filter through data for meaningful insights will be attempted, with both success and failure. It is possible that systems that favor more comprehensive forms of data gathering may have additional benefits as valuable new intellectual property when proven to improve performance and reduce costs. Over the long term, data that can support root cause analyses, as an example of reliability-centered maintenance (RCM), is expected to fall into this category. Currently, the incentive for data collection may be external to the immediate project stakeholders; and this is currently a "big data" issue for industry stakeholders to address.

4. ENVIRONMENTAL & PRODUCTION DATA

There is a need to collect environmental data in which the plant must operate. For this data type, straightforward measurements can largely be made and recorded through a SCADA-type system or by the monitoring system(s). Extreme temperatures, for instance, affect many PV power plant components and cause failure modes. In particular, irradiance is the major determining factor for module performance for solar energy conversion. PV plant output can be characterized in terms of active power, voltage magnitude, current magnitude, and power factor. Some form of revenue metering will be required for systems, with the possible exclusion of a separate meter for residential systems in some jurisdictions, and this data will be of primary interest to project stakeholders because energy generation and associated revenue is the primary purpose of a PV power plant.

Table 1. Recommended Environmental and Production Data

Data Area/System Class	**A**	**B**	**C**
Environmental and Production Data	**Utility-Scale**	**Commercial-Scale**	**Residential- and Small Commercial-Scale**
Environmental Data			
Module temperature(s) (variable, see Figure 3 photo)	X	X	—
Air temperature, wind speed/humidity/elevation	X	X	X[1]
Plane of array (POA) irradiance	X	X	—
Biological fouling	X	X	X
Climate and environmental variability	X	X	—
Production Data			
I_{mp}, P_{mp}, V_{oc}, V_{mp}, fill factor determined	X	X	X[2]
MW (hours/min) (ac power) “revenue grade”	X	X	X
MWh metered	X	X	X
Power factor	X	X	X
Inverter(s) monitoring (hours/min)	X	X	X[3]
Inverter(s) availability (hours/min)	X	X	X
Inverter(s) temperature	X	X	X[4]
Plant availability, uptime, and downtime[5]	X	X	X
Component(s) unavailability	X	X	—

Data Area/System Class	**A**	**B**	**C**
Environmental and Production Data	**Utility-Scale**	**Commercial-Scale**	**Residential- and Small Commercial-Scale**
External Conditions			
Curtailment events	X	X	X
Loss of grid availability/quality/constraints	X	X	X

[1] Whether a system is owned by a homeowner or an organization that has assembled a number of systems, air temperature, wind speed/humidity/elevation are important short- and long-term data. Site-based or equivalent local, near-site conditions can provide a reasonable level of accuracy, which can be used in troubleshooting, performance, and system evaluation.

[2] Most if not all inverters monitor these: I_{mp}, P_{mp}, V_{oc}, power, voltage, and current entering the inverter. This data may or may not be available through monitoring for the residential owner. With existing Internet monitoring applications for owners, historic data can assist in evaluating system changes in production over time. Through comprehensive evaluation of these energy values over the whole system life, this information can signal performance challenges as they develop thereby allowing for corrective maintenance.

[3] Most if not all new inverters have the capability of providing Internet access to system data, which is often available through Internet portals or other monitoring applications. This provides a window into how many hours or minutes the system is operating, while addressing any operation gaps such as grid, monitoring, system interruption and restart, or hardware related. This critical data provides value both from the PV-plant side and may indicate issues on the ac and grid side.

[4] Most inverter manufactures have temperature sensors and this is recommended as system data. This information is important in evaluating inverter performance.

[5] Availability for system components is important as it correlates with energy production across the plant and is a key element in system troubleshooting.

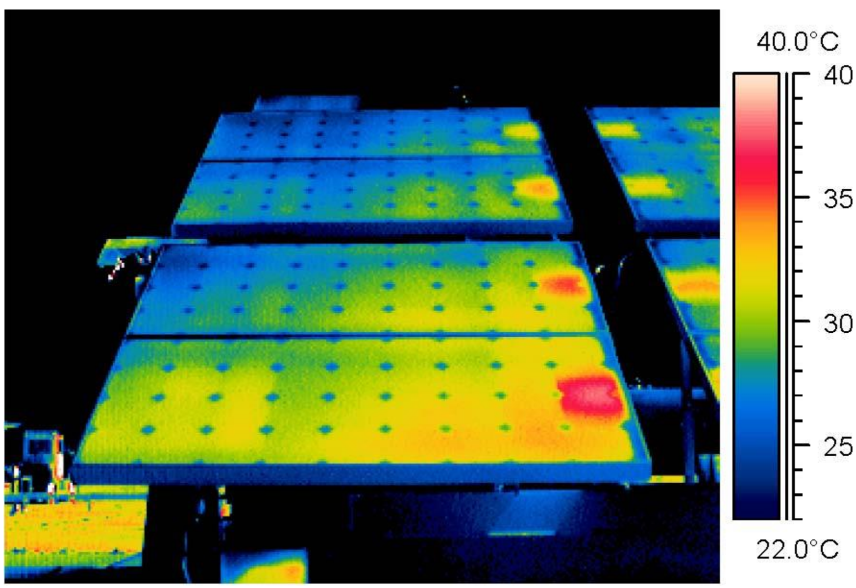

Figure 3. Thermal images of PV modules.

System classes are defined in IEC 61724, where the classes typically correspond to system sizes. As also indicated in that standard, users can select any classification they chose to be appropriate. Additional metrics associated with performance may be partially or wholly derived or calculated from some of these measured parameters. IEC 61724 Table 3 lists parameters and equations for electrical energy flow. Additional metrics are also described in the following performance-modeling and derived-results section. Expectations of plant performance made by calculation in the design stage play an important role for evaluating project success and are built into some of the indicators. Some of the metrics are impacted by plant availability and reliability performance and are also addressed in this document. Crucial metrics may be known as KPIs (key performance indicators), which are discussed in Section 6.2.

PV plant downtime and stop hours by event will be facilitated by the capabilities of the SCADA systems' time-series data or if not, should instead be recorded, possibly in a maintenance management system. It is recommended that plant states be recorded in the operation of where contractual impacts are dependent upon cause, especially if due to external causes. The information model presented in Appendix D provides examples of this.

Much of a plant's energy production depends on its capabilities, which includes components such as PV modules, inverters, transformers, and utility interconnection equipment, including the data-collection system itself. How well the system was designed, specified, and the quality of construction will affect the energy production too. Component failures are inevitable and will range in consequences from minimal to large depending on a multitude of factors that may range from anticipated wear-out, faulty equipment, poor installation, and factors outside an operator's control. Common mode faults and failures, that is, those affecting multiple layers of system components, will have large and negative impacts on production and associated components. For instance, a grid outage will stop the energy flow of the array feeding the inverter (unless an alternative storage or conversion system is part of the design). On the other hand, the failure of a single module in a field of thousands of modules might not even be evident though yield measurements, but may require inspection techniques for detection. Failures are elaborated upon in the reliability section that follows.

5. RELIABILITY AND MAINTENANCE DATA

The O&M function is focused on maintaining equipment and generation to meet or exceed guaranteed energy-production levels by conducting preventative and corrective maintenance on the modules, inverters, their components, and all other BOS components. To sustain these high energy-production levels, detailed histories of all of these system elements with additional data beyond their state conditions should be maintained. Some of the recommend data is presented in Table 2.

Table 2. Recommended Reliability and Maintenance Data

Data Area/System Class Reliability and Maintenance Data	A Utility-Scale	B Commercial-Scale	C Residential- and Small Commercial-Scale
Incident Data (Events, Outages, and Alarms)			
Inverter fault codes	X	X	X
Breaker trips	X	X	X
Blown fuses	X	X	X
Status data (period as specified measurements for times series monitored equipment)	X	X	X
Observed Data/Inspections			
Breakage	X	X	X
Wiring issues	X	X	X
Non-normal operation	X	X	X
Loss of production	X	X	X
Hot spots	X	X	—
Advanced spectral imaging	X	X	—
Maintenance Actions			
Preventive maintenance	X	X	X
Condition based maintenance	X	X	X
Corrective or reactive maintenance	X	X	X
Inventory depletion data	X	X	X
Plant upgrades (system improvements modifying original design limitations)	X	X	X
Outage Information for Faults and Failures			
Date and time of occurrence	X	X	X
Description of the problem (by fault code as applicable)	X	X	X
Affected component and location within the system by serial number	X	X	—

Data Area/System Class	A	B	C
Reliability and Maintenance Data	**Utility-Scale**	**Commercial-Scale**	**Residential- and Small Commercial-Scale**
Outage Information for Faults and Failures			
Corrective action taken to restore availability of the component (documented)	X	X	X
Repair and restoration time of the component (documented)	X	X	X
Estimated power loss from the system caused by the component outage	X	X	X

Residential and small commercial system data should be made available to the system owner, service company, and potentially others to give enough information to compare maintenance- and fault-related performance reductions. Records will facilitate troubleshooting and corrective actions. Stakeholders should be able to access inverter records that indicate these outages as a normal part of small-system O&M.

5.1. Faults & Failures Recorded as Incidents

When collecting data, it is important to clearly identify and know what the systems and components are. This requires documenting the equipment breakdown or bill of material (BOM, sometimes referred to as a taxonomy). This ensures that the component data that is captured will be useful and time to a specific subsystem or component.

There will likely be many different reasons for outages to occur. Outage information for faults and failures is often identified as incident or event data. General information is needed, which contributes to answering the basic questions of how often something fails, how long it is out of operation, and associated financial impacts of that down time. In other words, the symptom's cause and corrective actions for any failure or maintenance activity must be determined. To find answers to these questions, the following information (Table 3) is described in an incident report (SNL, 2014).

Table 3. Incident Categories that Result in Outages and/or Need Maintenance Attention

Incident Category	Definition
Hardware failure	Any hardware component of the system in the BOM that has failed or stopped working (includes operational suspensions resulting from degraded electrical connections).
Software problem	A fault or failure due to a software error, glitch, or incompatibility; the root cause is not a hardware failure (e.g., inverter failure due to incorrect limits in the code).

Incident Category	Definition
Hardware upgrade required to operate	Hardware upgrade requirement based on changes in the electrical code or to utility requirement (e.g., changes to anti-islanding policy requiring new inverters or evolving standards or improved techniques).
Software upgrade required to operate	Software upgrade requirement based on changes in the electrical code or to utility requirement (e.g., changes to anti-islanding policy).
Equipment installation problem	System downtime due to incorrect installation (e.g., incorrect grounding of modules or inverters, misaligned trackers).
Grid-induced failure/suspension	Any system upset condition caused by a disturbance on the power grid to which power is being supplied.
Lightning-induced failure/suspension	System or component failure due to lightning strike.
Environment-induced failure/suspension	Degraded system condition caused by environmental factors other than lightning (e.g., hail, wind, wildlife, etc.) or by array maintenance activities (e.g., grass or weed control).
Hardware application problem	Power loss due to poor design for the application (e.g., unaccounted for building shading).
Vandalism	System or component failure caused by vandalism (e.g., cracked modules from thrown rocks).
Unknown	The incident source is unknown and either does not fit into any categorization or is not categorized by the user.
Hardware upgrade	A batch of identical components replaced with upgraded versions before failure (e.g., all inverters replaced, new AC disconnects installed per utility upgrade).
Software upgrade	The system, in part or in whole, is offline in order for the manufacturer to install new software (e.g., tracker controllers, monitoring systems).
Planned maintenance	Scheduled maintenance (routine or otherwise) such as cleaning operations, hardware modification or replacement, or tracker mechanical maintenance.
Troubleshooting issue	A failure or suspension due to the troubleshooting process (e.g., while changing a fan in an inverter, a capacitor is broken).
System upgrade	A general upgrade to the system (e.g., another PV array with inverter is added to an existing PV system).
End of useful life failure	The failure cannot be repaired.

It should be noted that these incident category definitions can be tracked to more general availability states. For instance, reliability issues that were caused by inadequate inspection or poor installation practices (i.e., quality) could be found in hardware failures, hardware application problems, or equipment installation problems. To the degree that these issues/serial failures may occur, Appendix D's information model identifies "planned corrective actions" to remedy asset deficiencies. While that will be useful for contract compliance, any increased granularity in incident reports is useful in performing root cause analyses, especially for repeated events. With respect to data collection, some information must be produced manually, which in itself may be an issue—especially with respect to providing consistency across incidents, systems, and operators. Computerized maintenance management systems (CMMSs) may be recommended for large installations, although manual inputs, if well-structured, may be appropriate. A final decision may be based on what works best for the party that needs to collect and analyse the data. Further, a work-order record extends the vendor's data records by adding additional maintenance attributes. The contents of the work-order record should, where possible, be drawn from controlled vocabularies. When describing the action taken to repair the fault, the list of actions should be well defined and preferably taken from a relevant standard, when possible.

Practices will vary by service provider; engineering, procurement, and construction (EPC) contractor; and ownership. The authors acknowledge that customers, financiers, other parties, and contract terms will have differing requirements. While standardizing O&M practices in data collection and reporting is hopefully advantageous from a market sense, individual cases will vary. In this precursor report, we recommend using controlled vocabularies and taxonomies, though we do not go so far as to recommend a particular one. This document can be viewed as an interim step toward a more formal development of consensus standards. Appendix D includes a discussion of future possibilities where this document may be applied.

5.2. Other Forms of Data

Not all data is represented in numerical form. Photographs, electrical signatures, etc. may be best for documenting certain problems that arise. In the photo below, the elevated temperature indicated in red is the junction box on a PV module's backside. This thermal signature may be revealing a potential failure mode to be monitored over time, especially if a replacement may be covered by warranty or it becomes a safety issue. It also clearly indicates that temperatures differentials, across a module or array, can vary dramatically in all types of weather.

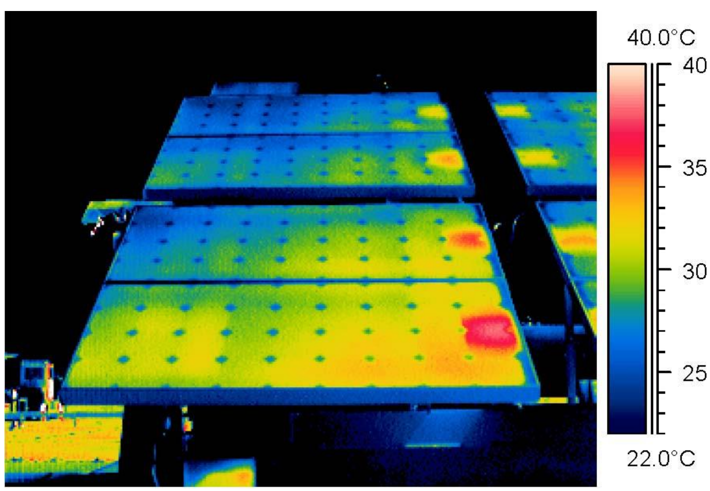

Figure 4. Thermal images of PV modules.

Note: There are also KPIs in the conduct of the maintenance function—these could be the number of work orders, time for completion/close out, response time, replacement parts/components delay time, repeated site visits, etc. The asset manager may choose to monitor *these elements as the efficiency of maintenance will have an impact on the availability of the plant and energy produced, as well as operating cost.*

6. PERFORMANCE MODELING AND DERIVED RESULTS

Some of the data collected from a PV system supports analytic efforts of one sort or another. For performance modeling or ensuring the plant is operating as modeled, a number of data points need to be collected including those shown in Table 4.

Table 4. Performance Modeling Data

Data Area/System Class	A	B	C
Performance Modeling and Derived Results[1]	**Utility-Scale**	**Commercial-Scale**	**Residential- and Small Commercial-Scale**
Performance Modeling			
Irradiance and weather (localized and multiple data collection for large systems)	X	X	X
Incident irradiance	X	X	X[2]
Shading, soiling, and reflection losses	X	X	X
Cell temperature	X	X	X[2]
Module output	X	X	X
dc and mismatch losses[3]	X	X	X
dc-to-dc maximum power point tracking	X	X	X
dc-to-ac conversion efficiencies	X	X	—
ac losses[4]	X	X	X
Derived Results			
Performance index	X	X	—
Performance ratio	X	X	—
Temperature corrections to standard test conditions (STCs)[5]	X	X	—
Yield: forecasted, reference, and final	X	X	—
Average annual irradiation	X	X	X
Forced outage(s)	X	X	X
Capacity factor	X	X	—
Degradation	X	X	X[2]
Lost energy	X	X	X[2]

1 Sensor accuracy specifications/uncertainties will determine accuracy of results.

2 Should be available by or to the seller, leasing organization, and/or service providers.

3 dc and mismatch losses are the result of a number of conditions, many of which go back to specification, design, and installation. Although these are often considered minor losses, they can add up to be substantive.

Over time, multiple dc and mismatch losses can result in extensive performance and revenue losses. In some cases, they result in cascading module and string failures.

4 ac losses may be more substantial than originally expected. They are estimated for modeling purposes, however in field operations they may be higher from unplanned events or situations that may go unnoticed for some time.

5 Temperature correction as correlated with STCs is often prescriptive, while relying on assumptions about actual ambient temperature and solar radiation effects on single cells, modules, and arrays. However, the need is the same for inverters. In

reality, actual temperature readings are often not adequately adjusted for real site conditions, which impacts performance, yield, degradation, and component life.

A better understanding of these variations, linked to STC temperature corrections, can improve the accuracy of project performance early on in the planning, modeling, and design phases for modules.

6.1. Performance Modeling

The objective of performance modeling is to accurately predict expected PV plant output given (1) the system design and (2) the environment in which it is operating, including the solar resource. To evaluate the output from a PV performance model, data needs can include:

- simultaneously measuring the system output and the system environment, including the solar resource;
- modeling system output, using the measured system environment data along with the system design; and
- comparing modeled to measured output on an annual, monthly, daily, hourly, and/or subhourly basis—as a function of various parameters.

PV performance modeling—and comparison to actual measured data—is important because many tools use expected performance as a baseline against realized production for assessments.

A PV Performance Modeling Collaborative (pvpmc.sandia.gov) has been formed to assemble and organize the most complete, transparent, and accurate set of information about PV performance modeling. This effort identifies and defines modeling steps, provides examples that can be used to more accurately and transparently model a PV plant, and has supporting code and reference documents (PVPMC, 2014). Some form of performance modeling, usually done in the project-development phase, is relevant to PV plant operation, and it is recommended that this process be verified periodically with *actual* plant performance data—especially after the first year, when assumptions about weather conditions or environmental variables may need to be adjusted.

Using techniques from the performance-modeling approach to the RAM methodologies to RCM with common power-industry metrics of power-plant performance and NERC GADS, derived results will be included and evaluated as key or supplemental performance metrics that will need to be defined for the PV power plant. These techniques are further described below.

6.2. Key Performance Indicators

KPIs are vital measures of how a generating plant is operated and managed. They represent high-level, derived results that can be viewed and understood by any number of stakeholders to track PV plant performance over time. Energy production is the single most important performance indicator. The collective availability of components is also very important, but in practice may be confusing, as is discussed in Appendix D. Both are relevant to the plant's primary purpose, which is to generate a desired amount of electricity over time.

Other KPIs often include instantaneous power—and the capacity factor is also recommended, as it measures plant performance such a way that factors in the site's resources and constraints. Capacity factor is also a common metric for any form of power generating plant. The performance ratio is a common measure for PV plant performance. A number of other metrics keyed to performance modeling can also be included, such as energy performance index (EPI), which is the actual kWh ac energy divided by expected kWh ac energy, as determined from an accepted PV model using actual climate data input to the model over the assessment period. To determine expected energy, the irradiance must also be tracked. All of the metrics used in this discussion are defined in Appendix B.

One common measure of component reliability is the forced outage rate. Equivalent forced outage rate (EFOR) is the hours of unit failure given as a percentage of the total hours of the availability of that unit. This metric is a key measure of unavailability of equipment impacting production (Table 5).

Some measure of degradation is warranted because the equipment can degrade, and modules can have that metric built into their performance warranty. Recommissioning and other forms of periodic testing, including recurring IV curves of select modules or module strings can measure the PV plant performance in this regard.

Table 5. Recommended Key Performance Indicators

Indicator	Component or System	Frequency
MW	Solar Power Plant	Minute
MWh	Solar Power Plant	Monthly
Irradiance	Solar Power Plant	Minute and Monthly
EPI	Solar Power Plant	Monthly
EFOR	Components and Solar Power Plant	Monthly
System Availability	Subsystems and Solar Power Plant	All time periods
Degradation	Components and Solar Power Plant	Tracked throughout system life

While the above KPIs may be recommended, it is noted that they are "key" for purposes of gauging plant performance over time. The full list of data identified in Sections 4 through 8 of this precursor report is still recommended for their intended purposes and there remains a need for greater data collection than just the KPIs. The "key" is a shorthand way of condensing significant and vital indicators.

Further, it is evident that a need for KPI standardization is widespread, and some existing industry organizations have also made efforts to address performance metrics. The SunSpec Alliance (SunSpec, 2014) has created a performance-metric summary, with a focus on the commercial and industrial market sector and fleet leasing sector. Their work also identified the purpose of the metrics, method, and uncertainly. SunSpec-defined KPIs include:

- PR – Performance ratio
- CPR – Temperature-corrected PR
- EPI – Energy performance index, SAM model
- EPI – Energy performance index, regression model
- kWh production
- Yield
- Power performance index

It is also recognized that there may be other optional KPIs that companies may choose to use internally as metrics of their own performance. Aspects of maintenance efficiency have already been introduced, and others may be designated. Evidence from industry has identified the following for consideration:

- Operating efficiency
- Equipment equivalent availability factor (EEAF)
- Equipment equivalent forced-outage factor (EEFOF)

Note that EEAF, EEFOF are listed in Appendix C. Obviously, all of these metrics require clear and accepted definitions. Proliferation of multiple, especially vague or contradictory, definitions can be an issue and demonstrates the need for standardization. Appendix B includes candidate definitions for use, but as appropriately codified through a future standardizing body, which will be an industry process, hence the "precursor" nature of this report.

7. OTHER RECOMMENDED ANALYSIS TECHNIQUES

7.1. Reliability Modeling

Using RAM methodology techniques, as more reliability data is captured and collected into the plant database, more sophisticated and comprehensive analysis and modeling can be pursued to provide a nuanced understanding of optimal PV system O&M and management pathways. As the database grows, it should have some modicum of predictive value (e.g., system component availability, equipment wear-out projections, etc.). This knowledge also provides the ability to design O&M services based on the predictive value of the data.

What follows is a brief overview of selected reliability modeling and statistical research methods, accompanied by rudimentary analysis derived from the PV Reliability Operation Maintenance (PVROM) database incident data previously described in Table 3 and in (EPRI 2013). This excerpt is intended to offer a sense of the depth of research that the PVROM process is capable of delivering in the foreseeable future. Prospective insights are, among other things, expected to be thoroughly derived from the following:

Reliability Block Diagram (RBD) A method for showing how component reliability contributes to the success or failure of a complex system. Essentially, it is a logic diagram that shows what items must remain available for the system to be considered minimally operable. For a PV plant, it indicates how component failures and maintenance actions impact system reliability, availability, and throughput. An example is shown in Figure 5.

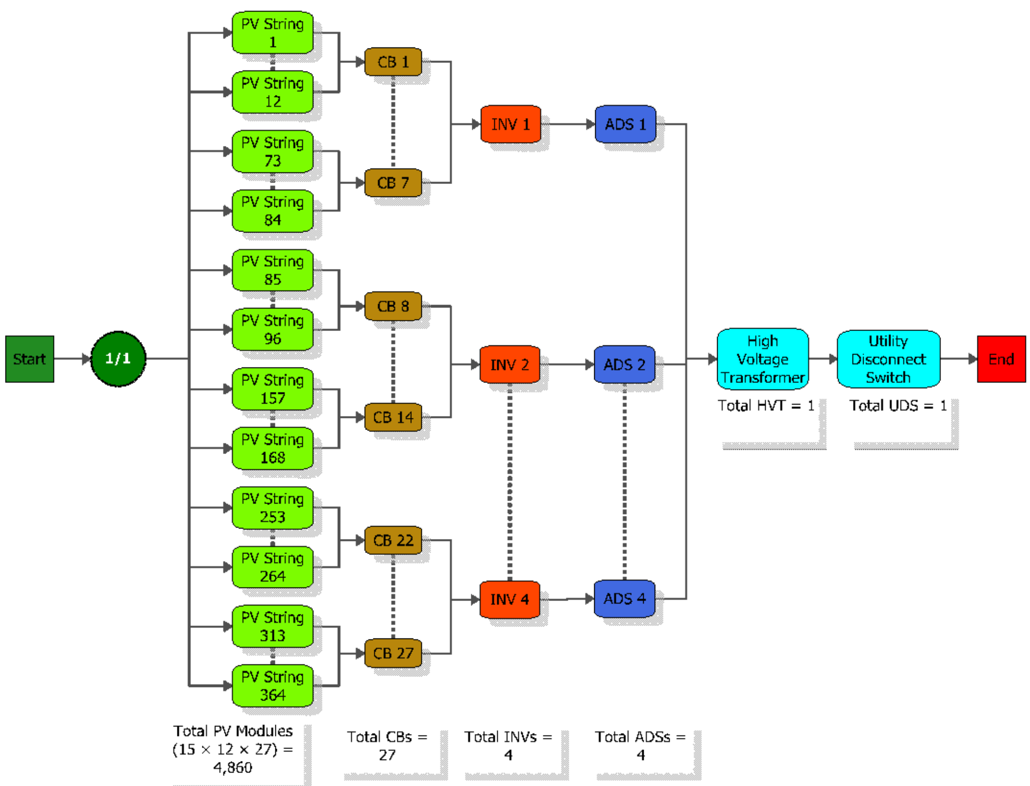

Figure 5. Reliability block diagram.

<u>Statistical modeling</u> of component reliability and maintainability, including Weibull, lognormal, exponential, and gamma distributions, which are popular in reliability analysis for non-repairable components (i.e., components that are replaced in whole when failed).

<u>Assessments of where times-to-failure and repair models</u> described above can be combined into a single model to enable system availability/utilization analysis.

<u>Sensitivity analyses</u> of major contributors to system failure and downtime to better understand the extent to which components contribute to system reliability and downtime. With this insight, plant operators can focus their O&M strategies on the possible "bad actors" in their systems and better prioritize system improvements.

<u>Sparing analysis</u> Another useful metric that can be obtained by system modeling is the number of spares (i.e., inventory) required to sustain high plant availability. Spares not only consist of system components, but also consumables, such as fuses or cleaning supplies, or special parts, such as the IGBT bridge of an inverter. The PVROM process provides an example of how this is done (EPRI, 2013).

In summary, for the O&M strategy to impact and improve availability, increase reliability, and reduce O&M costs, baseline performance must first be establish to understand the current conditions, identify drivers that reduce performance, determine their root causes, and finally create action plans for addressing those drivers that will have the high beneficial impact to the PV plant. The analysis thoughts above were drawn from the PVROM process, where additional information can be obtained related to reliability analysis.

7.2. Evaluating O&M Practices

Indicators within a PV plant's performance and reliability database can effectively be leveraged to track the causes and effects of incidents to (1) improve upon O&M practices, and (2) optimize preparedness. For example, restoration time, for the purposes of modeling system outages, is the total downtime experienced after a disruption to the component event being modeled. This total downtime can reflect the aggregation of

- the elapsed time until maintenance personnel detect an event;
- the elapsed time for isolating the failure to affected component(s);
- logistical downtime due to retrieving parts or tools to complete repairs or replace components;
- judicious delaying of maintenance due to other important factors not directly related to restoration of the failed component;
- actual hands-on repair, replacement, or reset actions performed by maintenance personnel or automated actors; and
- testing of component functionality and reintegration into the system, as necessary.

By tracking these O&M events and examining related trending over time, researchers can assess their impact on performance and system availability. Moreover, incident statistics and reliability and availability models can be developed based on observed system data. These models, informed by ongoing data collection, can be used to estimate maintenance requirements and their associated disruption to PV plant production. The upshot of this effort is enhanced characterization of expected PV system performance (EPRI, 2013; SNL, 2014).

This data can also allow for analysis of other operations and reliability metrics such as availability, mean time between events, mean downtime, and capacity factor. These metrics can be applied to the total plant or to plant subsystems in the case of multiple arrays and inverters. These subsystems can be compared against each other as well.

7.2.1. Operation and Maintenance Philosophy

The need for O&M has historically been subjected to myths and assumptions that range from systems not requiring any maintenance to only requiring very minimal maintenance. This was pointed out clearly in the paper titled “Addressing Solar Photovoltaic Operations and Maintenance Challenges: A Survey of Current Knowledge and Practices” (EPRI, 2010), which states “Contrary to popular belief, PV power plants are not maintenance free; they require a regimen of continual monitoring, periodic inspection, scheduled preventive maintenance, and service calls.” Lack of attention to O&M results in costs higher than presented in pro formas, increasing project risks; a situation not conducive to market confidence.

One of the most critical aspects for how a system is designed is based on the quality of an effective O&M philosophy—where the focus is on total cost of energy over time—which if based on accurate data, also provides an effectively accurate LCOE. Beginning at the project concept stage and flowing through the whole PV system-delivery process, defined O&M approaches will have influences through the project stages. Effective and communicated O&M plans will have positive impacts that include:

- the type and quality of O&M services to be provided,
- consideration and selection of component choices that improve system reliability,
- effective modeling that accurately represents the life cycle,
- an effective feedback system that delivers information and lessons learned back into future specifications and design,
- reduced risk, and
- improved stakeholder communications.

A robust O&M philosophy focused on long-term system production improves both modeling results and system performance. This requires system design specification and installation choices that go beyond the traditional PV system-development practices. Transitioning to a more typically acceptable utility-sector lifetime window of a few decades necessitates a focus on total lifecycle in project considerations and choices. Addressing items of additional sensors that will be more accurate in locating losses, education and training, and labor cost are essential. The results include greater economic/fiscal value given through minimizing assumptions and the resultant imprecisions about performance.

7.2.2. Reliability-Centered Maintenance

Similarly, an RCM approach is a process to ensure that assets continue to perform under dynamic operating conditions, based on user requirements. Applying this concept improves system O&M, and not only establishes a maintenance philosophy, but enables modifications to operating procedures and strategies and levels of required maintenance, with asset-management objectives incorporated. Cost management; component/system uptime; and a greater understanding of the failure modes, consequences, and mitigations through actions will be realized when RCM is effectively applied.

RCM is defined by the technical standard SAE JA1011, “Evaluation Criteria for RCM Processes” (SAE, 1998), which sets out the minimum criteria that any process should meet before it can be called RCM. This starts with the seven questions below, worked through in the order that they are listed:

1. What is the item supposed to do and its associated performance standards?
2. In what ways can it fail to provide the required functions?
3. What are the events that cause each failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What systematic task can be performed proactively to prevent, or to diminish to a satisfactory degree, the consequences of the failure?
7. What must be done if a suitable preventive task cannot be found?

As an example of this type of assessment, some wind-plant operators have stated that every failure undergoes a root-cause analysis to assess the inherent impact and risk to operations. This illustrates an RCM approach to asset management.

7.2.3. Preemptive Analytic Maintenance, Considerations for the Future

Preemptive analytic maintenance (PAM) is a coherent total-cost analysis form of maintenance, which is fully integrated into the PV system delivery process. The PAM foundation states that for effective PV system delivery (concept through site restoration), O&M considerations must drive PV system specification and other planning and installation choices. PAM is systematically based on the development of an effectively integrated PV system engineering systems approach to system delivery. This requires

- a focus on the lifecycle cost of energy, based on real data;
- more granular and effective data must be gathered, secured, and analyzed where O&M lessons learned are effectively fed back into the specification process before traditional system design;

- using a variety of technologies while dramatically expanding the effectiveness and use of existing technology, including developing new electrical and electromagnetic sensing, metrics, equipment, and analysis;
- employing a level of robotics and related technologies that can carry the sensors to the data and accurately transmit it back for analysis through both near and remote sensing using minimal human labor;
- using data and lessons learned throughout the whole PV system delivery process, from site selection through system dismantling and site restoration, to provide cost-effective use of these technology transfers; and
- that these technologies and data analyses are multipurpose, and as a result deliver soft- and hard-cost reductions through multiple usages to response to a diverse set of project purposes.

A more detailed treatment on PAM is expected to be published in a SNL PAM report in 2015 to address the subject in far greater detail. It will define PAM, provide a clear scope of what PAM provides as a baseline minimum scope, and tiers of best practices that follow different development and O&M service levels currently or soon to be offered by industry. Plans include reaching out to O&M service providers, asset owners, EPC firms, contractors, and others to contribute as they identify components. The value is O&M and PV system delivery soft- and hard-cost reduction as determination is made as to what constitutes appropriate service levels.

7.3. NERC GADS Database

The GADS (Generating Availability Data System) is a database produced by NERC (NERC, 2014). Renewable generation (i.e., wind and solar) are not part of the mandatory requirements. However, some O&M service providers use GADS on a voluntary basis. Included in its process is data pertaining to forced outages and unplanned unit failures. It makes the fine distinction between immediate, delayed, and postponed outages.

An important statistic calculated from the raw GADS data is the EFOR, which is the number of hours of unit failure (unplanned outage hours and equivalent unplanned derated hours) given as a percentage of the total hours of the availability of that unit (unplanned outage, unplanned derated, and service hours). The equivalent forced outage rate–demand ($EFOR_d$) is important because it characterizes failure rates. O&M service providers who have experience in fossil plants have expressed endorsement with the GADS practices and consideration of it. Indeed, many of its metrics are applicable. See Appendix C as GADS is influenced by IEEE 762.

7.4. Availability

PV systems are complex technology systems. Understanding those complexities and the effective integration of components into high-functioning systems requires not only using its components, it requires awareness of how they operate and perform as a part of an intricate system.

It should be noted that for a PV power plant, many parallel component strings exist, and if modeled in a reliability block diagram might *appear* redundant. However, they are not redundant—unless they exist to replace the function of other strings. Instead, a PV system is a modular design. Given the magnitude of the total system, interconnected subsystems, and system components, it is reasonable to expect some failures throughout the system at any given time, albeit frequently unnoticed or with minor consequences on overall performance, depending on the failure. The use of "clipped" inverter operation may mask a number of system partial and/or subsystem complete failures. The consequence of masked failures is that the system is, unknown to its operators, only fractionally available and in partial performance. This reveals the fallacy of the assumption that availability is a simple condition—when in reality it consists of layers of availability and conditions.

Through interactions with O&M service providers, many different contract definitions and equations for availability terms have been observed. This lack of common, industry-wide definitions is slowly beginning to be addressed more seriously at many levels within the industry. The initial trend in viewing, understanding, and defining availability; what it means; its metrics; and how it is to be effectively defined begins with the process of looking at different levels and types of availability. This results in greater accuracy through a family of specific definitions and KPIs, some of which stand alone with other requiring better clarification of exclusions.

The greatest value in applying effective, accepted, and standardized terms related to an availability lexicon include

- improved, accurate, and more effective communications;[4]
- clarity in contacts to reduce costs and risk;
- differentiation of levels of availability within a system, both connected and independent of grid operation;
- greater accuracy though the ability to clearly identify complete or partial failures, reflecting their impact on total availability and linking them directly to specific choices, locations, and their impact on revenue and performance;
- the ability to accurately compare a system or subsystem with other systems and subsystems;[5]
- improved isolation of the point (or points) of failure, to achieve performance goals and meet revenue norms; and
- improved financial confidence.

One of the fundamental requirements in assessing system reliability or availability is to define the complete set of components and equipment into a BOM—as is common in the PV industry,

[4] The lack of clear availability definitions masks hidden, anticipated and unanticipated, systemic problems, which can be dramatically reduced with more specific and effective communications.

[5] This becomes valuable when the qualitative and quantitative rating of a system impacts the selling or equitizing of a system and also in localizing issues that will impact choices on other systems yet to be designed or built.

or a taxonomy as used in reliability assessments. A simple system example for a PV power plant is illustrated below (Figure 6).

The availability of a system depends on the components from which the system is assembled.

In the case of a PV plant, the many components are assembled in levels, and the interconnections and other interfaces between components are illustrated by the myriad arrows between the levels.

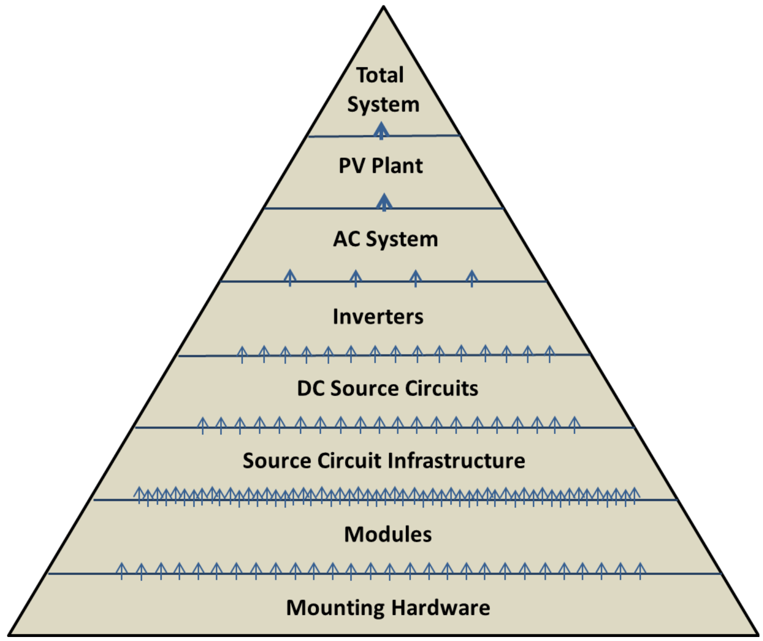

Figure 6. Levels in a PV power plant.

Given the levels of components in a total PV system, the simple terms of "available" or "availability" for a PV plant are a generally inadequate measure because the plant may not be operating at full performance. It is often seen that a modifier like "operational," "average," "utilization," or other descriptor is used to further clarify the availability term to make it more closely related to production or throughput. Another aspect is that nighttime repairs don't require downtime that affects power generation. While this may be a good strategy, care must be exercised with how availability definitions are affected by this practice. A "family" of availability terms might be more useful.

- *Component availability* is the fraction of a given operating period in which a component is performing its intended services within the design specification. An average component availability term might be useful when addressing a system with multiple components of the same equipment, like a*verage availability* or the average of the sum of the individual like components. Practically, the component would be specified in the term to be "average inverter availability" or "average module availability." When discussing a fleet of such components, it is common that it would be shortened to "inverter availability" during the warranty period, for instance.
- *System availability,* by extension, is therefore defined that a system, or subsystem, is performing its intended services within the design specification. Like the above example with inverters, the system should be defined. Per the illustration in Figure 6, the total system includes the grid receiving the energy, and its unavailability or constraints will affect the

plant. The PV power plant's availability is complex and is dependent upon full subsystem operation, possibly as levels in the figure and their operations. The subsystems can fall out of performance of the design specification. With so many modules, and dc source circuits in the energy-collection process, minor amounts of failures and even partial or intermittent failures pose a challenge to determining the availability, or even failure detection. The challenge remains as one of awareness of plant condition at all levels and its performance.

Inspection techniques, instrumentation, analytical maintenance, degradation tracking, and analyzing large datasets may lead to advancements in the future. Further, it is reiterated that the term availability may be a term often used in contracts with many definitions. In fact, there are many causes of unavailability, and clarity is sought to facilitate information exchange on performance indicators between owners, utilities, lenders, operators, manufacturers, consultants, regulatory bodies, certification bodies, insurance companies, and other stakeholders involved with the PV power plant. In Appendix D, a model is put forward for consideration to provide a common basis for defining requirements to support a clear understanding of contract terms. This information model specifies how time designations are proposed to be allocated to information categories as a standardized basis.

The IEC has addressed availability of wind plants and has published technical specifications to measure production and even lost production to account for any number of causes. The IEC 61400-26 technical specifications for wind turbines, contains an information model for plant conditions, both generating and nongenerating, that are designed to provide a common basis for information exchange on performance indicators and contract language. It is described further, for consideration, in Appendix D and may have potential cross-technology applicability to PV.

8. FINANCIAL INFORMATION

Production data by plant availabilities, kWh sales, revenue, resource (by time series), power factor (by utility contract), capacity factor, lost production, and lost revenue are expected to all be key metrics of plant performance and production operations, and hence important financial data.

Work orders (or truck rolls) are often generated by plant managers to capture the need for repairs or other types of maintenance. A work order may have multiple purposes. It may be used for human resource tracking or for tracking the time component(s) spent offline. For purposes of reliability tracking, work orders should document the investigation into the cause of outage and which component failed and/or was replaced i.e., the root cause. In this way, work orders may provide insight into component performance and document circumstances that indicate a failure's root cause.

Work orders can be used for normal preventative maintenance. Scheduled maintenance activities, which may not be detailed in the SCADA/monitoring system, will be identified by work orders. It is important to account for these actions as they contribute to unavailability, in the strictest sense. Ideally, work orders will be automated in a CMMS. Work orders can be used to track manpower, parts, restoration of service, and some of the incident data described earlier.

- MWh sales
- Revenue
- Lost revenue
- Maintenance costs
- Operations costs (taxes, insurance, interest, sales/customer costs, etc.)
- LCOE

It is expected that only select stakeholders will receive the financial reporting.

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APPENDIX A: DRAFT OUTLINE OF A PERIODIC REPORT

This outline was produced as the result of a working group discussion of the important parts to a periodic report. This is an example and the content may be considered for future best practices or contract statements.

1.	Sunnyside Solar Plant
2.	Operating companies
3.	Environmental Safety and Health a) Safety: Incident, cause, consequence, corrective actions. b) Environmental: Incident, cause, consequence, corrective actions.
4.	Plant performance (table) a) Solar Resource: Actual, expected, year to date (YTD), ratio of expected. b) Production: Actual, expected, YTD, ratio of expected. c) Availability: by inverter, by BOS, by utility system availability/external/curtailment, etc., typical. d) Percent of contracted delivery, period, YTD.
5.	Faults, Failures, Repairs, Replacements, Outages — Table of events/incidents/actions—number, time, lost energy.
6.	Scheduled Maintenance — Upcoming planned actions.
7.	PV modules status — Summary condition.
8.	Inverters status — Summary condition.
9.	Structures and trackers status — Summary condition.
10.	SCADA and communications status — Summary condition.
11.	Electrical collection/transformers status — Summary condition.
12.	Energy Metering — Summary condition.
13.	Contracts — Status.
14.	Other — Summary condition.
15.	Performance Charts — Multiple and key aspects.

APPENDIX B: NOMENCLATURE, DEFINITIONS, AND COMMON TERMINOLOGY

The authors have endeavored to identify relevant and descriptive terms for describing important terms of reliability, availability, and O&M. In some cases, references are cited (e.g., the International Electrotechnical Commission [IEC], the North American Electric Reliability Corporation [NERC], the Institute of Electrical and Electronics Engineers [IEEE], or the National Aeronautics and Space Administration [NASA]), but in many more cases they were not because of the logical excursions needed for applicability for PV systems. These definitions and descriptions are not expected to be final—but rather an early working approach for the terms. The authors acknowledge that like efforts with standards, there is a necessary process for full inputs by many parties to meet the needs of many perspectives across industry. Final forms of the terms/definitions that follow will necessarily come from use and standardization efforts by a standards body effort. Like the rest of this precursor document, recognizing that standards require a participatory process, this precursor document seeks to inform perspectives of reliability, availability, and performance.

Actual Energy Production

Energy measured at the point of connection to the power-collection system (according to International Electrotechnical Vocabulary and IEC 60050-415) to the grid [IEC 61400-26-2]. The grid connection point may be at a low-voltage level or at medium- or high-voltage level depending on plant design.

Aging

Gradual process in which the properties of a material, structure, or system change (for better or worse) over time or with use, due to biological, chemical, or physical agents. This is a temporal process.

Air Temperature(s) aka Ambient Temerature

The immediate atmospheric environment in which photovoltaic modules and inverters operate. Large systems may require multiple points of measurement. It is noted that cell temperatures will deviate considerably from this temperature.

Availability

The fraction of a given operating period in which a component or system is performing its intended services within the design specification. Uptime divided by the time (for the period identified) [modified from IEC 61400-26-1].

Available

A component or system is performing its intended services within the design specification. [modified from IEC 61400-26-1].

Balance of System

The balance of system consists of the remaining system components and subsystems beyond the photovoltaic modules that include other components and structures that comprise the complete plant.

Capacity Factor

The amount of energy produced by a plant compared to how much energy *could* have been produced if the plant had operated at its rated power during the specified time period—may be defined in terms of actual production or potential production.

Common Mode Failure

A failure of two or more components, systems, or structures due to a single specific event or cause [NASA].

Component Availability

Uptime divided by the total time (for the period identified).

Conditioned-Based Maintenance

Preventative maintenance that is conducted when one or more indicators is triggered. Usually, indicators are the result of active monitoring showing an item may be deteriorating to the point that it will need immediate maintenance or it will fail otherwise.

Corrective Maintenance (Reactive)

All actions performed, in response to failure, to restore an item to a specified condition. Actions can include localization of failure, isolation of failure, disassembly of item, interchange of item components, reassembly of item, alignment and reconfiguration, test of item, and release back to operation.

Data

Data is a set of values of qualitative or quantitative variables. Restated: Pieces of data are individual pieces of information.

Daylight Availability

The percentage of time for inverters in performance compared to the total daylight time calculated from sunrise to sunset. The window when the system is prepared to start-astronomic sunrise to sunset.

Degraded

A component or system is degraded when it is operative, but at reduced power/with reduced performance because of internal constraints [modified from IEC 61400-26-1]. A decline to a lower condition, quality, or level. The gradual failing of a component or system.

Derated

A derating can be used for a period when a component or system is operative, but at reduced power/with reduced performance because of external commands or external constraints [modified from IEC 61400-26-1].

Design Specifications

The collection of precise and explicit information about requirements for a product design. It provides in-depth details about the functional and nonfunctional design requirements to meet needs, including operating environment, assumptions, constraints, performance, dimensions, weights, reliability, and standards [modified from IEC 61400-26-1].

Downtime

The time period that an item is in an inoperable (unavailable) state.

Energy Performance Index

Actual kWh ac energy divided by expected kWh ac energy as determined from an accepted photovoltaic model using actual climate data input to the model over the assessment period.

Event

A significant occurrence or incidence that affects the performance or operation of components or systems, often resulting in an outage.

Expected Energy

The photovoltaic system's energy generation that is calculated with a specific performance model, using actual weather data collected at the site during operation of the system [IEC 61724].

External Conditions

Conditions outside of the plant that affect its operation, for example (i) out of environmental specification and (ii) out of electrical specification. The interconnecting grid, the environment, and human activity may affect plant operations [modified from IEC 61400-26-].

Equivalent Forced Outage Rate

The hours of unit failure (unplanned outage hours and equivalent unplanned derated hours) given as a percentage of the total hours of the availability of that unit (unplanned outage, unplanned derated [NERC Generating Availability Data System (GADS)].

Failure

An event that causes an item to be inoperable or causes an item not to perform to its specifications.

Failure Distribution

Probability density functions for describing time-to-failure in many situations.

Fault

A recognized defect in a component, circuit, device, piece of equipment, or system, which impairs operation significantly or that causes a failure. Also, a failure caused by such a defect. Note: In some cases a fault can exist and not be recognized by the operation of a fuse or breaker, i.e., arc fault.

Fill Factor

The fill factor, more commonly known by its abbreviation, FF, is a parameter that, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc} [www.pveducation.org/pvcdrom/solar-cell-operation/fill-factor]. The FF affects yield.

Force Majeure

Extraordinary event or circumstance beyond the control of parties under contract and prevents the parties from fulfilling their obligations.

Forced Outage

Action taken as unforeseen damage, faults, failures, or alarms are detected. An unplanned outage of a component.

I_{mp}

In a normal IV curve, the maximum power point for current is I_{mp}, the point at which the array generates maximum electrical power.

Incident

See Event.

Information Unavailable

Period where the plant data-collection and monitoring functions become unable to detect data or communicate the data to storage or are not transmitted through supervisory control and data acquisition equipment.

Inherent Availability

The proportion of time that a system is in an operable and usable state over a specified time period that only includes failures and repairs inherent to the design of the system and excludes preventative maintenance and any other logistics downtime. (Also, see Technical Availability)

Item

A nonspecific term used to denote any product, including systems, materials, parts, subassemblies, sets, accessories, etc.

Intermittent Failure

An item being in an inoperable or partially operable state for a limited period of time, followed by the item's recovery to an operable state without any remedial action.

Key Performance Indicators

Key performance indicators are high-level performance measurements that reflect how a generating plant is operated and managed.

Logistics Downtime

The downtime incurred due to waiting for spare equipment, facility support, personnel, and administrative activities such as paper work that do not directly attribute to the restoring of item from an inoperable to an operable state.

Lost Production

Energy not supplied [IEC 61400-26-2]. The lost production is the difference between expected energy and the actual (or measured) energy production.

Lost Revenue

Calculated revenues not received due to lost production, curtailment, or contract limitations.

Maintainability

The measure of the ability of an item to be retained or restored to a specified condition when maintenance is performed by qualified personnel having specified skill levels (to be specified and documented) using prescribed procedures and resources, at each prescribed level of maintenance and repair.

Maintenance

All actions necessary for retaining an item in or restoring it to a specified condition. The process or function in a plant to keep equipment operative.

Mean Time Between Failures

The arithmetic mean time between inherent failures of a component or system during operation.

Mean Time to Repair

The basic measure of the maintainability of repairable items. It represents the average time required to repair a failed component or device.

Module Temperature

The operating temperature of a photovoltaic module, often a cell temperature. Note that this can vary—it is not monlithic. (See Figure 4.)

Nameplate Rating

The normal maximum operating rating applied to a piece of electrical equipment. This can include volts, amperes, horsepower, kilowatts, or any other specific item specification for the equipment. For photovoltaic modules, the nameplate rating is based on standard test conditions.

Operational Availability

This is primarily an operator's or user's view of the system as a whole and measures how often the asset was actually generating power and revenue. The reasons for the lost operting hours are less important than the overall view that operation and production were lost [modified from IEC 61400-26-1].

The proportion of time that a system is in an operable and usable state over a specified time period that includes any necessary corrective maintenance, preventative maintenance, or any other logistics downtime required for the system to either remain operable or recover from inoperability (failure).

Operational Efficiency

In a business context, operational efficiency can be defined as the ratio between the input to run a business operation and the output gained from the business. When improving operational efficiency, the output-to-input ratio improves. [Wikipedia].

Operation and Maintenance Philosophy

Defined operation and maintenance approaches based on predetermined plans for staffing, equipment, monitoring, and repair/replacement strategies.

Out of Electrical Specification

The electrical parameters are out of the operational design specifications, i.e., grid outage information model. However, the usage may not be consistent with the equipment operating specifications, i.e., string voltage in cold weather exceeding voltage specification of the system.

Out of Environmental Specification

Operative, but not functioning as the environment is out of component design specifications or range.

Partial Failure

Partial failure modes are modes that are catastrophic to a part, but not to the system [IEEE Transactions on Reliability, Vol. R-18, No. 4, November 1969].

Partial Performance

Functioning with limitations and/or restrictions. Performance may be limited by degradation or other factors.

Performance Index

See Energy Performance Index.

Performance Ratio

Final yield divided by reference yield over an assessment period. Performance ratio with final yield corrected for cell temperature over an assessment period.

Planned Corrective Action

Actions required to retain, restore, or improve the intended functions that are not part of normal scheduled maintenance.

Plant Availability

The plant is performing its intended services within the design specification, or the fraction thereof.

P_{mp}

In a normal IV curve, the maximum power point is where both current and voltage are at the point of maximum power, the point at which the array generates maximum electrical power.

Plane of Array Irradience

Measurement of the irradiance on an array with instruments physically oriented in the same plane as that of the photovoltaic array.

Potential Energy Production

Calculated energy based on the plant design criteria, technical specifications and the site conditions [IEC 61400-26-2].

Power Performance Index

Actual instantaneous kilowatt ac power output divided by expected instantaneous kilowatt ac power output.

Predicted Energy

The photovoltaic system's energy generation that is calculated with a specific performance model, using historical weather data that is considered to be representative for the site [IEC 61724 updated].

Preemptive Analytic Maintenance

Preemptive analytic maintenance is a coherent total-cost-analysis form of maintenance, which is fully integrated into the photovoltaic system delivery process.

Preventative Maintenance

All actions performed in an attempt to retain an item in a specified condition to eliminate or delay incipient failures. Actions can include systematic inspection, detection, and early replacement of the item. Preventative maintenance may or may not cause the item to become unavailable.

Qualification PLUS

The purpose of Qualification PLUS is to implement testing that goes beyond IEC 61215 in a way that can identify potential module defects that may result in failures much later during the module's lifetime. If these failures can be detected using this new testing procedure, it may result in modules that are highly reliable over time—thus resulting in fewer failures and lower degradation rates [TUV-R 71732-01:201X: Qualification PLUS (Q+)].

Quality

A high or fine standard. The pragmatic interpretation is the noninferiority or superiority of the plant or operations. It may also be defined as fitness or meeting or exceeding expectations.

Reliability, Availability, and Maintainability

Reliability, availability and maintainability is a methodology/discipline of reliability analytics, which includes maintenance actions that can be applied to power-generation facilities.

Reliability-Centered Maintenance

Reliability-centered maintenance is a process to ensure that assets continue to do what their users require in their present operating context.

Reliability

The probability that an item can perform its intended function for a specified interval under stated conditions. The duration or probability of failure-free performance under specified conditions.

Repair

Activity whereby components of a system are restored to a safe operating condition following a failure [modified from IEC 61400-26-1]. The act of performing corrective maintenance on a repairable item.

Repairable Item

An item which can be restored to perform all of its required functions by corrective maintenance.

Requested Shutdown

Operative, but stopped by an external request, i.e., curtailment.

Retrofit

The incorporation of new technology or new design parts resulting from an approved engineering change to an already supplied item [IEC 61400-26-1].

Supervisory Control and Data Acquisition

Supervisory control and data acquisition is a system operating with signals over communication channels so as to provide control of equipment and for gathering and analyzing real-time data.

Scheduled Maintenance

Preventative maintenance that is planned at a particular time, usually based on manufacturer's recommendation or warranty mandate. Scheduled maintenance may also be based on environmental and temporal experience.

Scope of Work

The scope of work, sometimes call a statement of work, is a document that determines what work will be done.

Site Conditions

Conditions affecting the energy production of the photovoltaic power plant, including but not limited to topographic and meteorological conditions, sector management, and other environmental and contractual constraints [modified from IEC 61400-26-2].

Solar Performance Factor

A nonexclusionary metric for comparing photovoltaic systems and their performance against other systems: ac watt output/dc watts Nameplate over 365 contiguous days.

Specification

A specification is a document that establishes the measureable, verifiable, and achievable design parameters, such as size, weight, power, reliability, and quality metrics (such as noise, transients, etc.).

Suspended

Activities for scheduled maintenance, planned corrective actions, and forced outages that are interrupted or cannot be initiated due personal safety or equipment integrity, e.g., extreme weather.

System

A composite of equipment, skills, and techniques capable of performing or supporting an operational role, or both. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered self-sufficient in its intended operational environment.

System Availability

The system is performing its intended services within the design specification, or the fraction thereof.

System Process

A practice of engineering that focuses on how to design and manage engineering systems over their life cycles. Issues such as requirements management, reliability, logistics, and evaluation measurements are fully considered for impacts on the "total system."

Technical Availability

This is primarily the component vendor's view of a component and measures how the equipment was intended to operate. Lost production due to maintenance as specified, environmental conditions outside the specification, standby for internal checks, etc. are not considered as unavailable in the definition [modified from IEC 61400-26-1].

Technical Standby

Temporarily nonfunctioning due to controlled and/or predefined tasks required, e.g., self-testing, ramp-up.

Total Time

The total calendar time of the period selected [IEC 61400-26-1].

Unavailability

The fraction of a given operating period in which a component is not performing its intended services within the design specification. (The percent of known time that components are experiencing downtime events.)

Unavailable

A component is not performing its intended services within the design specification.

Unscheduled Maintenance

Unpredicted maintenance requirements that had not been previously planned or programmed but require prompt attention and must be added to, integrated with, or substituted for previously scheduled workloads.

Uptime

The time period in which an item is in an operable state.

V_{mp}

In a normal IV curve, the maximum power point for voltage is V_{mp}, the point at which the array generates maximum electrical power.

V_{oc}

The voltage point in a module or array that is in an open-circuit state.

Windspeed

The measure of air movement in the immediate atmospheric environment in which PV modules and inverters operate. Large systems may require multiple points of measurement.

APPENDIX C-1: BASE STATISTICS

Those in the PV industry who also have experience with conventional power plants have indicated acceptance and even endorsement of the Data Reporting Instructions of NERC GADS metrics (NERC, 2014). Many of the GADS metrics come from the indicated source standards that follow, and because many of these metrics are or could be viewed as KPIs, this table is provided because it is relevant to the discussion of data and O&M reporting. Appendix F of the of Data Reporting Instructions has over 100 such metrics with provided definitions and formulas for calculation of the terms and a few have been selected for note in the following tables. The tabulations were provided to Sandia for use in this report by Strategic Power Systems, Inc., which has proprietary software ORAP® (Operational Reliability Analysis Program) to collect and analyze operational, failure, and maintenance data on operating thermal and wind plants. This information is used by clients to reduce costs and operate with optimal performance and conforms in many cases to NERC GADS. With regard to the GADS system in PV power plants, a task force is currently assessing the proper method for data collection and reporting. A separate report outlining the voluntary data reporting instructions will be drafted in the future (NERC GADS FAQs 8/2014).

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Planned Outage Factor	POF	The percentage of a given operating period in which a unit is not available due to planned outages.	POH, PH	$POF = \left(\frac{POH}{PH}\right) * 100$	✓	
Maintenance Outage Factor	MOF	The percentage of a given operating period in which a unit is not available due to maintenance outages.	MOH, PH	$MOF = \left(\frac{MOH}{PH}\right) * 100$	✓	
Scheduled Outage Factor	SOF	The percentage of a given operating period in which a unit is not available due to scheduled outages.	POH, MOH, PH	$SOF = \left(\frac{SOH}{PH}\right) * 100$ $SOF = \left(\frac{POH + MOH}{PH}\right) * 100$ $SOF = POF + MOF$		

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Forced Outage Factor	FOF	The percentage of a given operating period in which a unit is not available due to forced outages.	FOH, PH	$FOF = \left(\frac{FOH}{PH}\right) * 100$	✓	✓
Unplanned Outage Factor	UOF	The percentage of a given operating period in which a unit is not available due to unplanned outages.	MOH, FOH, PH	$UOF = \left(\frac{UOH}{PH}\right) * 100$ $UOF = \left(\frac{MOH + FOH}{PH}\right) * 100$ $UOF = MOF + FOF$	✓	
Unavailability Factor	UF	The percentage of a given operating period in which a unit is not available.	POH, MOH, FOH, PH	$UF = \left(\frac{UH}{PH}\right) * 100$ $UF = \left(\frac{POH + MOH + FOH}{PH}\right) * 100$ $UF = POF + MOF + FOF$	✓	
Availability Factor	AF	The percentage of a given operating period in which a unit is in the available state without any outages.	POH, MOH, FOH, PH	$AF = \left(\frac{AH}{PH}\right) * 100$ $AF = \left(1 - \frac{POH + MOH + FOH}{PH}\right) * 100$ $AF = 100 - UF$	✓	✓
Reliability Factor	RF	The percentage of a given operating period in which a unit is not available due to forced outages.	FOH, PH	$RF = \left(1 - \frac{FOH}{PH}\right) * 100$ $RF = 100 - FOF$		✓
Resource Unavailability Factor	RUF	The percentage of a given operating period in which a unit was available, but not in operation due to ambient wind conditions.	RUH, PH	$RUF = \left(\frac{RUH}{PH}\right) * 100$		

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Service Factor	SF	The percentage of a given operating period in which a unit was in the in-service state.	SH, PH	$SF = \left(\frac{SH}{PH}\right) * 100$	✓	✓
Starting Reliability	SR	The probability that a unit will start successfully when required.	SS, AS	$SR = \left(\frac{SS}{AS}\right) * 100$ $SR = \left(\frac{SS}{SS + FS}\right) * 100$	✓	✓
Average Run Time	ART	The average or mean time a unit is in the in-service state.	SS, SH	$ART = \frac{SH}{SS}$	✓	✓
Planned Outage Rate	POR	The probability that a unit will not be available due to planned outages.	POH, SH	$POR = \left(\frac{POH}{POH + SH}\right) * 100$		
Maintenance Outage Rate	MOR	The probability that a unit will not be available due to maintenance outages.	MOH, SH	$MOR = \left(\frac{MOH}{MOH + SH}\right) * 100$		
Scheduled Outage Rate	SOR	The probability that a unit will not be available due to scheduled outages.	POH, MOH, SH	$SOR = \left(\frac{SOH}{SOH + SH}\right) * 100$ $SOR = \left(\frac{POH + MOH}{POH + MOH + SH}\right) * 100$		
Forced Outage Rate	FOR	The probability that a unit will not be available due to forced outages.	FOH, SH	$FOR = \left(\frac{FOH}{FOH + SH}\right) * 100$	✓	✓
Forced Outage Rate Total	FOR_T	The probability that a unit will not be available due to forced outages including the exposure to nongenerating functions.	FOH, SH, SHNG	$FOR_T = \left(\frac{FOH}{FOH + SH + SHNG}\right) * 100$	✓	
Demand Forced Outage Rate	FOR_d	The probability that a unit will not be available due to forced outages when there is demand on the unit to generate.	FOH_d, SH	$FOR_d = \left(\frac{FOH_d}{FOH_d + SH}\right) * 100$	✓	

Metric	**Acronym**	**Definition**	**Inputs**	**Formula(s)**	**IEEE 762-2006**	**ISO 3977-1999**
Unplanned Outage Rate	UOR	The probability that a unit will not be available due to unplanned outages.	MOH, FOH, SH	$UOR = \left(\frac{UOH}{UOH + SH}\right) * 100$ $UOR = \left(\frac{MOH + FOH}{MOH + FOH + SH}\right) * 100$		
Availability Rate	AR	The probability that a unit will not be available due to outages.	POH, MOH, FOH, SH	$AR = \left(\frac{SH}{SH + UH}\right) * 100$		✓

APPENDIX C-2: EQUIVALENT STATISTICS

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Equivalent Planned Derated Hours	EPDH	The number of hours a unit was in a time category involving a planned derating expressed as equivalent hours of a full outage.	MW, PDH, MC	$EPDH = \sum_i \frac{PD_i * PDH_i}{MC}$	✓	✓
Equivalent Maintenance Derated Hours	EMDH	The number of hours a unit was in a time category involving a maintenance derating expressed as equivalent hours of a full outage.	MW, MDH, MC	$EMDH = \sum_i \frac{MD_i * MDH_i}{MC}$	✓	
Equivalent Scheduled Derated Hours	ESDH	The number of hours a unit was in a time category involving a scheduled derating expressed as equivalent hours of a full outage.	MW, PDH, MDH, MC	$ESDH = \sum_i \frac{(PD_i * PDH_i) + (MD_i * MDH_i)}{MC}$ $ESDH = EPDH + EMDH$		✓
Equivalent Forced Derated Hours	EFDH	The number of hours a unit was in a time category involving a forced derating expressed as equivalent hours of a full outage.	MW, FDH, MC	$EFDH = \sum_i \frac{FD_i * FDH_i}{MC}$	✓	✓
Equivalent Unplanned Derated Hours	EUDH	The number of hours a unit was in a time category involving a unit derating expressed as equivalent hours of a full outage.	MW, MDH, FDH, MC	$EUDH = \sum_i \frac{(MD_i * MDH_i) + (FD_i * FDH_i)}{MC}$ $EUDH = EMDH + EFDH$		✓
Equivalent Unit Derated Hours	EUNDH	The number of hours a unit was in a time category involving a unit derated expressed as equivalent hours of a full outage.	MW, UDH, MC	$EUNDH = \sum_i \frac{UND_i * UNDH_i}{MC}$ $EUNDH = EPDH + EMDH + EFDH$	✓	

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Equivalent Reserve Shutdown Forced Derated Hours	ERSFDH	The number of hours a unit was in a time category involving a reserve shutdown during which a forced derating was in effect expressed as equivalent hours of a full outage.	MW, RSFDH, MC	$ERSFDH = \sum_i \frac{RSFD_i * RSFDH_i}{MC}$	✓	✓
Equivalent Seasonal Derated Hours	ESDH	The number of hours a unit was in a time category involving a seasonal derating expressed as equivalent hours of a full outage.	MW, SDH, MC	$ESDH = \sum_i \frac{SD_i * SDH_i}{MC}$	✓	✓
Seasonal Derating Factor	SDF	The percentage of a given operating period in which a unit is not available due to seasonal deratings.	ESDH, PH	$SDF = \left(\frac{ESDH}{PH}\right) * 100$	✓	
Unit Derating Factor	UDF	The percentage of a given operating period in which a unit is not available due to equipment deratings.	EUNDH, PH	$EDF = \left(\frac{EUNDH}{PH}\right) * 100$	✓	
Equivalent Planned Outage Factor	EPOF	The percentage of a given operating period in which a unit is not available due to planned outages and planned deratings.	POH, EPDH, PH	$EPOF = \left(\frac{POH + EPDH}{PH}\right) * 100$	✓	
Equivalent Maintenance Outage Factor	EMOF	The percentage of a given operating period in which a unit is not available due to maintenance outages and maintenance deratings.	MOH, EMDH, PH	$EMOF = \left(\frac{MOH + EMDH}{PH}\right) * 100$	✓	
Equivalent Scheduled Outage Factor	ESOF	The percentage of a given operating period in which a unit is not available due to scheduled outages and scheduled deratings.	POH, MOH, EPDH, EMDH, PH	$ESOF = \left(\frac{SOH + ESDH}{PH}\right) * 100$ $ESOF = \left(\frac{POH + MOH + EPDH + EMDH}{PH}\right) * 100$ $ESOF = EPOF + EMOF$		

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Equivalent Forced Outage Factor	EFOF	The percentage of a given operating period in which a unit is not available due to forced outages and forced deratings.	FOH, EFDH, PH	$EFOF = \left(\frac{FOH + EFDH}{PH}\right) * 100$	✓	
Equivalent Unplanned Outage Factor	EUOF	The percentage of a given operating period in which a unit is not available due to forced and maintenance outages and forced and maintenance deratings.	MOH, FOH, EMDH, EFDH, PH	$EUOF = \left(\frac{UOH + EUDH}{PH}\right) * 100$ $EUOF = \left(\frac{MOH + FOH + EMDH + EFDH}{PH}\right) * 100$ $EUOF = EMOF + EFOF$	✓	
Equivalent Unavailability Factor	EUF	The percentage of a given operating period in which a unit is not available due to outages and equipment deratings	POH, MOH, FOH, EUNDH, PH	$EUF = \left(\frac{POH + MOH + FOH + EUNDH}{PH}\right) * 100$ $EUF = EPOF + EMOF + EFOF$	✓	
Equivalent Availability Factor	EAF	The percentage of a given operating period in which a unit is available without any outages and equipment deratings.	POH, MOH, FOH, EUNDH, PH	$EAF = \left(\frac{AH - EUNDH}{PH}\right) * 100$ $EAF = \left(1 - \frac{POH + MOH + FOH + EUNDH}{PH}\right) * 100$ $EAF = 100 - EUF$	✓	✓
Equivalent Reliability Factor	ERF	The percentage of a given operating period in which a unit is not available due to forced outages and forced deratings.	FOH, EFOH, PH	$ERF = \left(1 - \frac{FOH + EFOH}{PH}\right) * 100$ $ERF = 100 - EFOF$		
Equivalent Forced Outage Rate	EFOR	The probability that a unit will not be available due to forced outages or forced deratings.	FOH, EFDH, ERSFDH, SH	$EFOR = \left(\frac{FOH + EFDH}{SH + FOH + ERSFDH}\right) * 100$	✓	

Metric	**Acronym**	**Definition**	**Inputs**	**Formula(s)**	**IEEE 762-2006**	**ISO 3977-1999**
Equivalent Forced Outage Rate Total	$EROR_T$	The probability that a unit will not be available due to forced outages and forced deratings including the exposure to nongenerating functions.	FOH, EFDH, ERSFDH, SH, SHNG	$EFOR_T = \left(\frac{FOH + EFDH}{SH + SHNG + FOH + ERSFDH}\right) * 100$	✓	
Equivalent Demand Forced Outage Rate	$EFOR_d$	The probability that a unit will not be available due to forced outages or forced deratings when there is demand on the unit to operate.	FOH_d, $EFDH_d$, SH	$EFOR_d = \left(\frac{FOH_d + EFDH_d}{FOH_d + SH}\right) * 100$	✓	

APPENDIX C-3: MEAN TIME STATISTICS

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Mean Service Time to Planned Outage	MSTPO	The average or mean time between planned outages.	SH, Count PO	$MSTPO = \frac{SH}{Count\ Planned\ Outages}$	✓	
Mean Service Time to Maintenance Outage	MSTMO	The average or mean time between maintenance outages.	SH, Count MO	$MSTMO = \frac{SH}{Count\ Maintenance\ Outages}$	✓	
Mean Service Time to Forced Outage	MSTFO	The average or mean time between failures which initiate a forced outage.	SH, Count FO	$MSTFO = \frac{SH}{Count\ Forced\ Outages}$	✓	✓
Failure Rate	λ	The frequency with which a system or component fails.	SH, Count FO	$\lambda = \frac{1}{\mathrm{MSTFO}}$ $\lambda = \frac{\mathrm{Count\ Forced\ Outages}}{\mathrm{SH}}$	✓	
Mean Time between Failure	MTBF	The average or mean time between Class 1, 2, and 3 forced outages.	SH, Count Class 1, 2, 3 FO	$MTBF = \frac{SH}{Count\ Class\ 1,2,3\ Forced\ Outages}$		
Mean Time between Faults	$MTBF_{FT}$	The average or mean time between faults.	SH, Count Faults	$MTBF_{FT} = \frac{SH}{Count\ Faults}$		
Mean Planned Outage Duration	MPOD	The average or mean duration of planned outages.	POH, Count PO	$MPOD = \frac{POH}{Count\ Planned\ Outages}$	✓	
Mean Maintenance Outage Duration	MMOD	The average or mean duration of maintenance outages.	MOH, Count MO	$MMOD = \frac{MOH}{Count\ Maintenance\ Outages}$	✓	

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Mean Forced Outage Duration	MFOD	The average or mean duration of forced outages.	FOH, Count FO	$MFOD = \frac{FOH}{Count\ Forced\ Outages}$	✓	
Mean Time to Repair	MTTR	The average or mean duration of Class 1, 2 and 3 forced outages.	Class 1, 2, 3 FOH, Count Class 1, 2, 3 FO	$MTTR = \frac{Class\ 1,2,3\ FOH}{Count\ Class\ \ 1,2,3\ FO}$		
Mean Time to Repair Fault	$MTTR_{FT}$	The average or mean duration of faults.	Fault Hours, Count Faults	$MTTR_{FT} = \frac{Fault\ Hours}{Count\ Faults}$		
Mission Reliability	MR	The probability that a unit is operable and capable of performing its required function for a stated mission duration or for a specified time.	λ, ART	$MR = e^{-\lambda * \mathrm{ART}}$		✓

APPENDIX C-4: CAPACITY-BASED METRICS

Metric	Acronym	Definition	Inputs	Formula(s)	IEEE 762-2006	ISO 3977-1999
Gross Capacity Factor	GCF	The gross energy that was produced by a unit in a given period as a percentage of the gross maximum generation.	GAAG, PH, GMC	$GCF = \left(\frac{GAAG}{PH * GMC}\right) * 100$	✓	✓
Net Capacity Factor	NCF	The net energy that was produced by a generating unit in a given period as a percentage of the net maximum generation.	NAAG, PH, NMC	$NCF = \left(\frac{NAAG}{PH * NMC}\right) * 100$	✓	✓
Gross Output Factor	GOF	Gross capacity factor when the period is applicable only to the in-service state.	GAAG, SH, GMC	$GOF = \left(\frac{GAAG}{SH * GMC}\right) * 100$	✓	✓
Net Output Factor	NOF	Net capacity factor when the period is applicable only to the in-service state.	NAAG, SH, NMC	$NOF = \left(\frac{NAAG}{SH * NMC}\right) * 100$	✓	✓
Average Load	Ave. Load	The average or mean MWhr the unit was generating over a given operating period.	GAAG, SH	$Ave.Load = \frac{GAAG}{SH}$		

For a complete legend of the acronyms the reader is referred to the standards. For instance POH is planned outage hours, PH is period hours, and MOH is the maintenance outage hours, and the formulas successively build on new metrics somewhat geometrically.

APPENDIX D: AVAILABILITY INFORMATION MODEL

An IEC Committee has been tasked to develop three technical specifications for IEC-61400-26 for wind-turbine and wind-plant availability. The first specification is on the definitions of operating states and availability conditions and was published in 2011. The second specification is on time-based energy production, and it defines a methodology for production accounting for differing operational states of a wind turbine, considering internal and external conditions. For example, it defines accounting for potential production, actual production, and lost production—with determination and example verification scenarios. The second specification has also been published. The third is for production-based availability for a full wind power station, including balance of plant. It is currently being drafted and will be followed by an update and rewrite of the three technical specifications into a full IEC standard.

This work will lead to standardized and mandatory reporting metrics for full wind plants when the technical specifications are invoked as a standard and/or requirement. These standards help to define requirements to support clear understanding of contract terms for performance of wind turbines and wind plants. This is achieved by providing an information model specifying how time designations shall be split into information categories. The accompanying table and illustration identifies the information model accounting for time, as well as measured and calculated energy.

Table D-1. Availability Information Model Condition States

Condition State	Example
Full performance	Function with no limits or restrictions.
Partial performance	Functioning with limitations and/or restrictions.
Technical standby	Temporarily nonfunctioning due to controlled and/or predefined tasks required, e.g., self-testing, ramp-up.
Out of environment spec	Operative but not functioning as the environment is out of design specs.
Requested shutdown	Operative but stopped by an external request, i.e., curtailment.
Out of electrical spec	Operative but not functioning as the electrical parameters are out of design specs, i.e., grid outage.
Scheduled maintenance	Scheduled maintenance prevents system components for performing the intended functions.
Planned corrective action	Actions required to retain, restore, or improve the intended functions that are not part of normal scheduled maintenance.
Forced outage	Action taken as unforeseen damage, faults, failures or alarms are detected.
Suspended	Activities in SCHEDULED MAINTENANCE, PLANNED CORRECTIVE ACTION and FORCED OUTAGE are interrupted or cannot be initiated due personal safety or equipment integrity, e.g., extreme weather.
Force Majeure	Extraordinary event or circumstance beyond the control of the parties, prevents the parties from fulfilling their obligations.

There is an order of logic in the model as the condition states are listed. A "hierarchy" exists in that while full performance is the desired state, incidents happen to pull it off of the preferred operational mode. Progressive exit and entry into new states will affect performance and the model accommodates these transitions. For example, when the sun goes down, this is an out of environmental state for the PV plant and it will not generate even if fully operative and available for operation. Likewise, a forced outage will prevent generation for the affected parts of the plant, and that state will prevail until restoration of the availability of the components to perform their intended function.

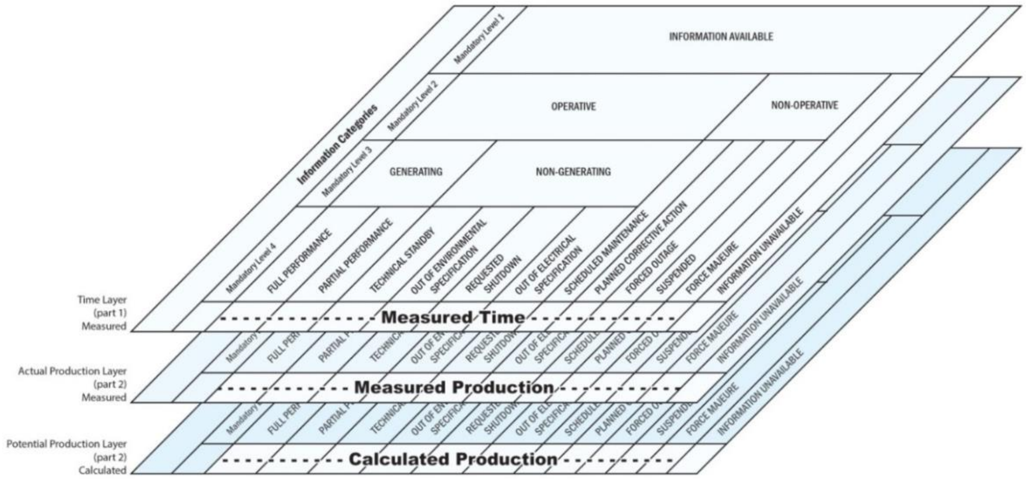

Figure D-1. Information model for IEC technical specification 61400-26-2, "Production-Based Availability for Wind Turbines."

IEC 61400-26 identifies a common basis for information exchange on performance indicators between owners, utilities, lenders, operators, manufacturers, consultants, regulatory bodies, certification bodies, insurance companies, and other stakeholders in the wind-power business. It is used to help define requirements to support clear understanding of contract terms.

Reconstructing this for a PV power station, a decision chart enables the analyst to navigate pathways through whether the information (typically data) is available or not, whether the plant is operative, and if the plant is generating. One very unique PV plant feature is the "throttled" production aspect, where inverters are operating in a clipping mode. This needs to be further evaluated, but it may be a form of partial production. It also has elements of requested (contractually) shutdown (limit) and should be appropriately accounted for in the information model with an informative example.

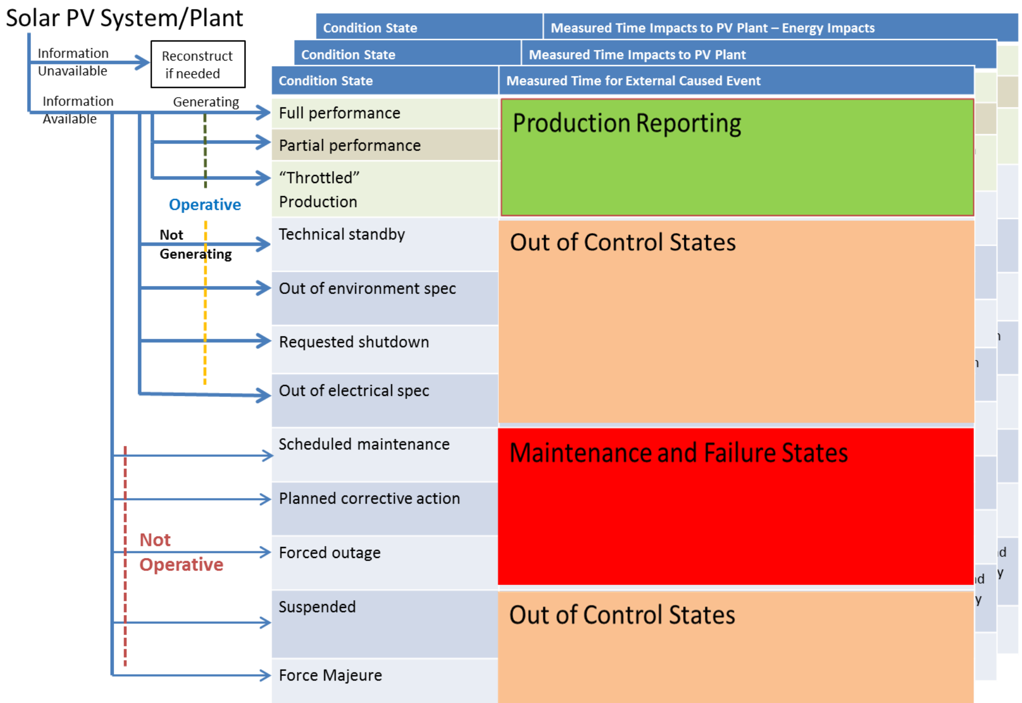

Figure D-2. Candidate information model for a PV power plant.

Based on the information model states presented above, an accounting for time- and production-based tracking of performance can be created. In Figure D-2, the time in the various states of operation is recorded. The production that corresponds to these states is also measured and recorded. From this production basis, many accounting and performance comparisons can be accomplished. Outages will be correlated with the component taxonomy impacted, that is to say what systems and components were affected on a time-and-production basis. Deviations can be determined and assessed in terms of optimal performance, contractual demands, allocations of production levels, and where excursions may excuse the obligation of the operator from delivery based on cause.

Working through an example, an outage would occur in some component of the taxonomy. It may have a larger system impact as a common mode failure across a larger portion of the plant. Depending on the cause of the outage, it may relieve the operator of the obligation of production. For instance, a grid outage or a curtailment would be treated differently than a component failure. But both might have further consequential impact, perhaps as an out-of-electrical-specification state or requested shutdown. The time-and-energy impact should be recorded through operational incident reporting or data maintained by a SCADA system or other monitoring function.

With categories for production, nonoperational, maintenance, and external factors affecting availability, such a standard for PV power plants could be largely consistent with the recommendations put forward in this precursor report. The authors note that this organizing method can be used for reporting various aspects of perfromance and also be used as criteria in contracts. With appropriate and tested defintions, the model can approppriately allocate:

- production, full or partial including “throttled production;”
- external events;
- types of maintenance; and
- failures states.

While Figure D-1 shows three “layers,” it is primarily an organizing method and can be applied in a number of ways. For instance, it can be used to record loss of availability for the full plant or in detail down to components. At some point, this becomes a database function, and other layers can be added such as contract terms, calculated availability, outage rates for RCM, or performance measurement and modeling.

New Work Item Proposal: At the time of this writing, efforts are underway to submit a proposal to the IEC to address availability for PV power plants. It is proposed that the IEC 61400-26 information model be used as an initial basis for the development of a technical specification to define generic terms of PV systems and environmental and operational constraints in describing system and component availability, lifetime expectancy, repairs, and criteria for determining maintenance intervals. A technical specification such as this will define terminology and generic terms for reporting PV power produced based on generating-unit availability measurements. Availability measurements are concerned with fractions of time a unit is capable of providing service, taking operational aspects into account. [Fractions of time a unit or the total system indicates partial performance, a key factor to consider for a PV plant in estimates and accounting of production.] Environmental aspects will be temperatures and other weather conditions, applicable to the whole plant. The technical specification will define terminology, generic terms, and proposed algorithms for reporting performance indicators based on time and production or capacity terms for a PV power plant. Each category is described in terms of how it can be detected, categorized, and related to other categories by defining transitions, which help to facilitate exchange of information on performance indicators. Age-related effects can also be accounted for by addressing degradation and derating, depending on whether such impacts were expected, or better than or worse than expected.

Using controlled vocabularies, the descriptions of categories shall be described in terms of how the information model states can be detected, categorized and related to other categories by defining transitions, in order to facilitate exchange of information on performance indicators. The specification shall include all functions up to the electrical interconnection agreed between the generation party and the distribution/transmission party. The work item will include considerations of how the technical specification shall be based on, harmonized, or appropriately deviate from the definitions and methods described in IEC/TS 61400-26 parts 1, 2, and 3.

Purpose and justification: The intention of the technical specification is to define a common basis for exchange of information on performance indicators between owners, utilities, lenders, operators, manufacturers, consultants, regulatory bodies, certification bodies, insurance companies, and other stakeholders in the PV power-generation business. This is achieved by providing an information model specifying how time designations shall be allocated into information categories.

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