PV Reliability Operations Maintenance (PVROM) Database Initiative

2013 Project Report

3002001399

PV Reliability Operations Maintenance (PVROM) Database Initiative

2013 Project Report

3002001399

Technical Update, December 2013

EPRI Project Manager

T. Coleman

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATIONS PREPARED THIS REPORT:

Electric Power Research Institute (EPRI)

Sandia National Laboratories

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2013 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The following organizations prepared this report:

Electric Power Research Institute (EPRI)
3420 Hillview Avenue
Palo Alto, CA 94304

Principal Investigator
N. Enbar

Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185

Principal Investigators
C. Hamman
R. Hill

This report describes research jointly sponsored by EPRI and Sandia National Laboratories.

EPRI and Sandia would like to acknowledge the U.S. Department of Energy for both its support of the multi-year PVROM initiative as well as for its guidance in shaping associated research activities. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

This publication is a corporate document that should be cited in the literature in the following manner:

PV Reliability Operations Maintenance (PVROM) Database Initiative: 2013 Project Report. EPRI, Palo Alto, CA: 2013. 3002001399.

ABSTRACT

To fill a major knowledge gap, EPRI and Sandia National Laboratories are jointly engaged in a multi-year research effort to examine photovoltaic (PV) plant reliability performance obtained through documented field data. Findings and analyses, derived from the PV Reliability Operations Maintenance (PVROM) database, are intended to inform industry best practices around the optimal operations and maintenance (O&M) of solar assets.

Currently being populated with initial PV plant information, the PVROM database aims to house a broad sampling of availability and reliability information for a diverse mix of PV plants located throughout North America. Among the variables being captured: locational and plant size factors; inverter and balance of system (BOS) equipment types and components; failure events, causes, frequencies; uptime/downtime metrics; applied solutions; and O&M actions and costs.

This report provides a comprehensive background on the joint research initiative, discussing its objectives and analytical framework, while also describing the PVROM data collection tool's technical capabilities. Preliminary results based on initial database content are subsequently related, as are next research steps to forecast plant health outcomes (e.g., system component availability and component wear out). Finally, the rationale and activities of a parallel volunteer effort to develop PV O&M standards are described.

Insights from ongoing research, informed by analysis of larger data samples as well and by scenario-based modeling exercises, will be documented in future reports. Ultimately, ongoing investigation is meant to identify contextual O&M trends, cost-effective maintenance and mitigation approaches, and indicators of predictive plant performance. The upshot: guidance on viable planning, operation, and asset management oversight strategies that can be implemented to further the grid-connected build-out of centralized and distributed solar PV systems.

Keywords

Solar photovoltaics (PV)
Operations and maintenance (O&M)
PV reliability
Inverter performance
PV system failure rate
Module degradation

EXECUTIVE SUMMARY

EPRI and Sandia National Laboratories are jointly engaged in a multi-year research effort to examine photovoltaic (PV) plant reliability performance obtained through documented field data. Findings and analyses, derived from data in the PV Reliability Operations Maintenance (PVROM) database, are intended to inform industry best practices around the optimal operations and maintenance (O&M) of solar assets.

This report provides a comprehensive background on the joint research initiative, discussing its objectives and analytical framework, while also describing the PVROM data collection tool's technical capabilities. In addition, it provides preliminary results based on initial database content, along with next research steps to forecast plant health outcomes (e.g., system component availability, component wear out, etc.). It concludes by describing related PV O&M standards development rationales and activities.

Project Background and Primary Objectives

The primary objectives of the PVROM initiative encompass the data gathering and empirical analysis of PV reliability and performance field data. Although PV system installations have spiked over the last several years—approaching nearly 10 GW of capacity in the United States alone—access to PV field data information has, to date, been limited given its proprietary nature. Most plant owners, investors, and third-party O&M providers have, by and large, been unwilling or unable to share solar system data due to contractual obligations and/or competitive concerns. As a result, industry-wide knowledge concerning optimal plant design, operation, and upkeep, as well as lifecycle economic outcomes, is deficient.

The PVROM effort, founded on industry collaboration along with technical research and development (R&D), is intended to help remedy this situation. In co-developing the PVROM database and a standardized data collection tool, Sandia and EPRI have devised a method for collecting, analyzing, and assessing events and failures that occur in large (>100 kW) PV systems. The two organizations are now engaged in ongoing recruitment of industry partners—utilities, owner/operators, third-party O&M providers, and others—to facilitate plant data entry into PVROM and, in turn, enable wide-ranging analysis and data exchange.

Ultimately, the PVROM initiative is meant to abet and accelerate the adoption of PV systems as a primary power generation source in the United States and beyond by providing benchmark reliability and O&M analysis. A parallel volunteer effort is meanwhile attempting to develop consensus O&M standards over the next several years.

PVROM Data Collection Tool

To facilitate PV reliability and O&M research founded on real-world field data, Sandia with input from EPRI, created the PVROM data collection and analysis tool. This tool is powered by ReliaSoft's XFRACAS™ platform, a web-based, closed-loop, incident (failure) reporting, analysis, and corrective action system software package. It is specifically designed for the acquisition, management, and analysis of quality and reliability data from multiple sources. The ability to export PV system times-to-failure and times-to-suspension for ready analysis by other ReliaSoft analysis tools was a primary consideration in choosing XFRACAS™ as a reliability data collection tool for the PVROM initiative.

The tool enables:

- Reporting of reliability-related issues for PV systems and components in the field,
- Specification of failure analysis details,
- Tracking of failure analysis and mitigation actions associated with resolving identified field problems,
- Reporting of installation details when a PV system is installed/commissioned,
- Review of PV system Bills of Material (BOM),
- Search of customer support, incident, problem resolution report, action, failure analysis, and system configuration records based on specified criteria, and
- Data export to other tools beyond XFRACAS for additional analyses.

The PVROM database resides on a Sandia server and is accessed through the Sandia Open Network (SON). Access restrictions ensure that only source users (industry partners) can access the database. Sandia administers security protocols and XFRACAS™ source permissions ensure that individual source users can access only their own data.

Data Inputs

The PVROM database is currently being populated with initial PV plant information that is intended to yield analytical insight into PV plant performance trends, maintenance outcomes, and lifecycle economics. Among the variables being captured in the database are: Locational and plant size factors; inverter and balance of system (BOS) equipment types and components; failure events, causes, frequencies; uptime/downtime metrics; applied solutions; and O&M actions and costs.

The PVROM analytic process begins with industry partner input of plant Bills of Material (BOMs). The BOMs consist of the major components in a PV system where failures can be anticipated. They are documented in PVROM at an appropriate level of detail to support expected reporting needs for both field O&M and other analyses. BOMs form a sort of taxonomy, derived from the physical construction of the PV system, by which to assign failures. They are created to capture the inventory of a system down to a desired level.

The other major inputs to the PVROM database are *incidents*, which represent maintainability data, such as outages, maintenance actions, and power losses. Outages caused by either failures of system components or external disturbances on the system itself are recorded as incidents. Meanwhile, the way that an issue is documented in PVROM is through an *Incident Report***,** which captures the following information regarding an outage event:

- Date of occurrence,
- Description of the problem,
- Affected component and location within the system by serial number,
- Corrective action taken to restore availability of the component,
- Repair and restoration time of the component, and
- Estimated power loss from the system caused by the component outage.

Database Outputs

Through incident data input, it is possible to mine the PVROM database using the XFRACAS™ application, and thereby extract failure frequencies and restoration times per component type. Times to failure data for each PV component are automatically processed. The PVROM database automates the organization and output of this information. These outputs are readily useful for analysis by other tools and can provide a "best fit" for a distribution model. The following are readily available as outputs of PVROM:

- *Incident Frequency* – the rate of occurrence for any particular outage events for systems or components
- *Repair Duration* – the difference between event service response date/time and service completion date/time, to nearest hour (reliability metric)
- *Restored to Duty Date/Time* – the date/time that the system, subsystem, or component is once again performing its intended function following failure or out-of-service event
- *Down Time* – the difference between event occurrence date/time (date/time failed or out of service [OOS]) and restored to duty date/time, in hours (availability metric)
- *Service Down Time* – the difference between event occurrence date/time (date/time failed or OOS) and service completed date/time, in hours (availability metric)

Analysis Capabilities

Indicators within the PVROM database can effectively be leveraged to track the causes and effects of incidents to improve upon O&M practices and 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 following events:

- The elapsed time until the event has been detected by maintenance personnel,
- The elapsed time for isolating the failure to affected component(s),
- Logistical downtime due to retrieving parts or tools to complete repairs or replacements of 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, 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: Enhanced characterization of expected PV system output and a more comprehensive understanding of lifecycle economics.

Preliminary Results and Next Steps

Initial information input into the PVROM database has provided a starting point for analysis that will be expanded upon in future years. First year findings are based on incident data—information covering plant operational deviations/failures, unplanned outage events, and associated mitigation activity—from one PVROM partner with two systems located in the desert Southwest. The Pareto chart of incidents for these two systems in Figure 1 illustrates the components and numbers of maintenance actions observed over a 20-month observation period.

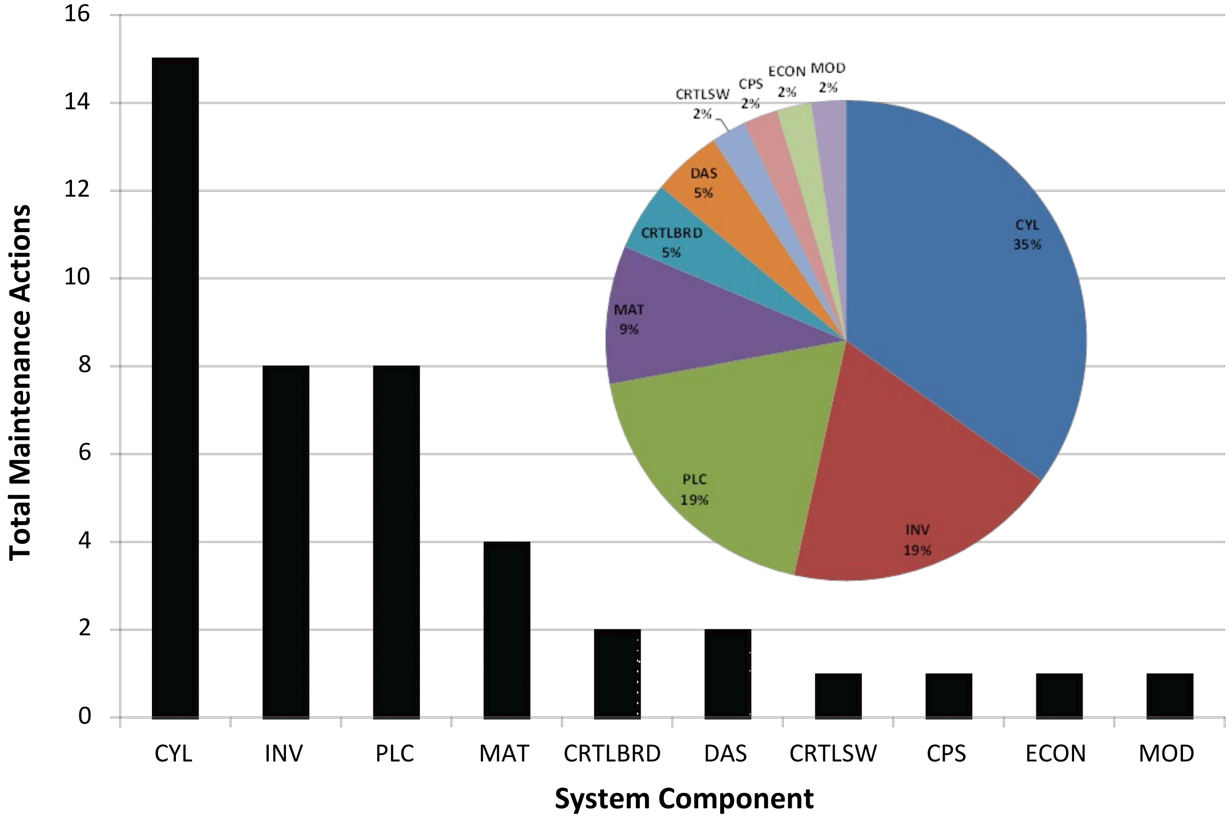


Figure 1
System Component Pareto Chart with Pie Chart Insert

Note: CYL = hydraulic cylinder, INV – Inverter; PLC = Programmable Logic Controller, MAT = Inverter Matrix; CTRLBRD = Inverter Control Board; DAS = Data Acquisition System; CRTLSW = Inverter Control Software; CPS = Inverter Control Power Supply; ECON = Misc. Electrical Devices, Cables, Connectors; MOD = PV Module.

The hydraulic cylinders (CYL) for the tracking subsystem account for 35% of the total incidents, with each incident resulting in a field repair. Inverters were, meanwhile, found to command the second highest amount of incidents. To date, the frequency of incidents has been on the order of 1-2 incidents/MW-month. On the whole, it appears that the reliability and maintainability of the two observed systems are generally in good order. The incident reports, designed to capture useful information for digging down into the root causes, support this observation. Greater data collection should enable deeper dive analysis in the future.

The value of the PVROM tool is directly linked to the number and size of industry partners that affiliate with the research effort. As of this writing, the PVROM database project has six partners who have decided to participate, representing around 30 MW of PV plant capacity. This participation indicates proof of concept and EPRI-Sandia aim to sign up tens of partners to incorporate dozens of systems with up to hundreds of megawatts into the PVROM database.

With greater amounts of data, quantitative-based findings along with modeling and statistical analyses can be incorporated into published benchmark O&M data reports (scheduled for publication at the end of 2014 and 2015) that are designed to increase industry confidence—particularly for those who do not have access to privately held data. This output is also expected to be useful to O&M practitioners who do not or have not yet established protocols for optimizing approaches to O&M—especially based on the history of each unique plant's O&M reliability data and trends.

At bottom, the depth of research that the PVROM tool is capable of delivering is considerable. Based on the aggregation of greater sample data and on feedback from PVROM partners as well as the industry at-large, future PVROM research possibilities include:

- System optimization with regards to costs, reliability, and power production,
- Baselining of failure models and repair models for families of PV system components,
- Failure Modes and Effects Analysis to improve component and system design,
- Systems comparison across various environmental conditions to understand their effect on component reliability and maintainability,
- Context-specific sparing analysis, and
- Merging Reliability Block Diagram analyses with physics modeling of PV systems to obtain the total systems perspective on power production capability.

These and potentially other types of analyses are anticipated to help both optimize O&M practices and advise standards development activities being performed on a parallel track.

PV O&M Best Practices and Standards Development

In addition to the PVROM database initiative, EPRI and Sandia are working alongside industry volunteers (mostly O&M service providers), to develop O&M best practices, maintenance protocols, definitions, and analysis techniques. This effort is intended to result in a set of consensus-based standards that can enable more efficient and responsible PV market expansion. Anticipated high level outcomes of this standards development activity include:

- Improved project economics derived from reduced uncertainty in project reliability, performance, and maintenance estimates,
- Better informed, more segmented O&M approaches that address various PV asset management contexts, and
- Increased predictability around O&M costs and requirements.

An outgrowth of an EPRI-Sandia O&M workshop held in Palo Alto, CA in 2013 (see http://energy.sandia.gov/?page_id=14860), a multi-year effort to standardize O&M best practices is initially focused on identifying the tools, techniques, and data analysis approaches that can enable operational improvements and high levels of plant reliability. Subsequently, best practices are intended to be drafted and further refined into standards.

To this end, three volunteer working groups have been formed—composed of O&M providers, system integrators, solar industry professionals, independent power providers, independent engineers, academics and laboratory researchers—to address specific high priority needs:

1. *Definitions* – Develop standardized definitions of reliability, maintenance and key performance indicators, among other terms,
2. *Best Practices* – Determine O&M best practices focused on safety, failure reporting, and preventative maintenance, and
3. *Design and Installation* – Create guidelines that consider safety, O&M scope and budget, commissioning, and other information relevant to project development.

Thus far, an initial prioritization of PV O&M knowledge gaps and practical needs has been identified and content from other standards development efforts has been referenced to help direct activities. Best practices are expected to be drafted in 2014 and subsequently communicated to the broader PV industry for comment. Further consensus body standards development and/or turnover are then slated to occur in 2015.

EPRI and Sandia welcome participation from a broad assortment of volunteers to assist in the development of PV O&M standards. To learn more and become a contributor, please contact Sandia Laboratories via email at: pvo&m@sandia.gov.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Project and Report Overview

To fill a major knowledge gap, EPRI and Sandia National Laboratories are jointly engaged in a multi-year research effort to examine photovoltaic (PV) plant reliability performance obtained through documented field data. Findings and analyses, derived from information in the PV Reliability Operations Maintenance (PVROM) database, are intended to inform industry best practices around the optimal operations and maintenance (O&M) of solar assets.

Currently being populated with initial PV plant information, the PVROM database aims to house a broad sampling of reliability and availability information for a diverse mix of PV plants located throughout North America. This expansive data set is, in turn, intended to yield analytical insight into PV plant performance trends, maintenance outcomes, and lifecycle economics. Among the variables being captured in the database are: Locational and plant size factors; inverter and balance of system (BOS) equipment types and components; failure events, causes, frequencies; uptime/downtime metrics; applied solutions; and O&M actions and costs.

This report provides a comprehensive background on the joint research initiative, discussing its objectives and analytical framework, while also describing the PVROM data collection tool's technical capabilities. Preliminary results based on initial database content are subsequently related, as are next research steps to forecast plant health outcomes (e.g., system component availability, component wear out, etc.). Finally, PV O&M standards development rationales and activities are described.

Insights from ongoing research, notified by analysis of larger data samples as well as by scenario-based modeling exercises, will be documented in future reports. Ultimately, ongoing investigation is meant to identify contextual O&M trends, cost-effective maintenance and mitigation approaches, and symptoms of predictive plant performance. The upshot: guidance on viable planning, operation, and oversight strategies that can be implemented to further the grid-connected build-out of centralized and distributed solar PV systems.

Primary Objectives

The primary objectives of the PVROM initiative, led by Sandia National Laboratories and the Electric Power Research Institute (EPRI), encompass the data gather and empirical analysis of PV reliability and performance field data. Although PV system installations have spiked over the last several years—approaching nearly 10 GW of capacity in the United States alone—access to PV field data information has, to date, been limited given its proprietary nature. Most plant owners, investors, and third-party O&M providers have, by and large, been unwilling or unable to share solar system data due to contractual obligations and/or competitive concerns. As a result, industry-wide knowledge concerning optimal plant design, operation, and upkeep, as well as lifecycle economic outcomes, is deficient.

The PVROM effort, founded on industry collaboration along with technical research and development (R&D), is intended to help remedy this situation. In co-developing the PVROM database and a standardized data collection tool, Sandia and EPRI have devised a method for collecting, analyzing, and assessing events and failures that occur in large (>100 kW) PV systems. The two organizations are now engaged in ongoing recruitment of industry partners—utilities, owner/operators, third-party O&M providers, and others—to facilitate plant data entry into PVROM and, in turn, enable wide-ranging analysis and data exchange.

With this is mind, specific project objectives, further elaborated upon later in this report, include:

- Recruitment of industry partners to input their PV plant data into the PVROM database,
- Training and consultation with industry partners to assist with their data entry and retrieval,
- Empirical analysis of plant reliability, availability, and other metrics,
- Publication of reports on trends observed from the PVROM data as well as data collection methods, and
- Development of standardized O&M protocols for broad industry use.

Ultimately, the PVROM initiative is meant to abet and accelerate the adoption of PV systems as a primary power generation source in the United States and beyond.

Core PVROM Project Participants

The multi-year PVROM project's core contributors include Sandia National Laboratories, EPRI, and industry partners. Sandia and EPRI have co-developed the PVROM database and standardized tool. In addition, the two organizations are jointly:

- Overseeing the operation and maintenance of the database,
- Providing database access usage training to industry partners,
- Performing research and data analysis of plant data housed in the database via existing PVROM algorithms,
- Developing further technical and administrative functionality embedded in PVROM (e.g., new algorithms, additional database parameters to collect specific kinds of PV O&M information, etc.), and
- Supplying cyber security capabilities for the PVROM database.

PVROM partners are, meanwhile, the principal sources of PV plant field data. In exchange for inputting their plant information into the PVROM database, industry partners gain access to the PVROM's repository of solar plant data as well as to the database's functionality to benchmark system performance, identify root causes of system failures, and recognize cost-benefit tradeoffs in making value chain improvements. The data entry requirements for industry partners encompass initial input of PV system characteristics (e.g., bills of materials [BOMs], etc.) and periodic entry of information from planned and unplanned downtime incidents.

Following are brief descriptions of each of the core contributors to the PVROM research effort. Note: Contact information for principal PVROM project researchers is contained in Appendix C.

Sandia National Laboratories

Sandia National Laboratories, managed and operated by the Sandia Corporation (a wholly owned subsidiary of Lockheed Martin Corporation), is comprised of two United States Department of Energy research and development national laboratories located in Albuquerque, NM and Livermore, CA. Although Sandia's primary mission is national security, the Lab's R&D activities also extend to alternative energy technologies, such as solar photovoltaics.

Specific to solar, Sandia's work is focused on developing cost-effective, reliable PV energy systems and accelerating the integration of PV technology. The lab's PV department provides the technical lead for systems integration and balance-of-systems manufacturing technologies as well as technical support to the U.S. DOE in deployment and validation of PV systems for federal agencies, utilities, and other institutional users. Sandia assists industry and users by providing technical assistance, accurate performance measurements, component development and improvement, and system evaluation. A major thrust of the department is to evaluate and improve the performance, reliability, and cost effectiveness of systems and balance-of-systems components.

Sandia brings the technical expertise of standardized data collection and reliability analysis to the cooperative PVROM project. It is applying this expertise toward the further refinement of the PVROM database and collection tool, and to developing standardized methods for analyzing O&M data for predicting PV systems lifetime.

For more information: http://www.sandia.gov.

The Electric Power Research Institute (EPRI)

The Electric Power Research Institute (EPRI), established in 1972, conducts research, development and demonstration (RD&D) relating to a range of generation, delivery, and use of electricity issues. An independent, nonprofit organization, the institute brings together scientists and engineers as well as experts from academia and the industry to address challenges germane to the electricity segment. Solar-related research includes field and laboratory technology testing, grid integration modeling, O&M approaches, and distributed generation business models.

Worldwide membership exceeds 1,000 organizations, predominately composed of electric utilities that collectively represent ~90% of the electricity generated in the United States and that reside in over 30 countries internationally.

For the PVROM initiative, EPRI is assisting with the further technical development of the PVROM database in order to inform, validate, and update the existing PVROM data collection tool. It is also performing outreach to third party PV system owners with the aim of contractually incorporating greater amounts of PV reliability and availability field data into the database. Additionally, the Institute is, in collaboration with Sandia, performing analysis of empirical data derived from the PVROM database.

For more information: http://www.epri.com.

PVROM Partners

PVROM Partners—utilities, owner/operators, third-party O&M providers, and others—are responsible for initially entering and periodically updating field data information about their respective PV plants into the PVROM database. The value of the PVROM tool is directly linked to the number and size of industry partners that affiliate with the research effort. As of this writing, six partners have agreed to participate in the initiative, representing approximately 30 MW of PV systems. EPRI-Sandia are in active negotiations with a number of others with the aim of ultimately signing up tens of partners to incorporate dozens of systems with up to hundreds of megawatts into the PVROM database.

It is anticipated that additional partners will join the project initiative as it progresses. This would permit the inclusion of more solar technologies for assessment, as well as broaden the universe of solar asset management issues that can be explored. To this end, utility and third-party PV project owners are actively encouraged to contribute their solar plant data for input into PVROM in order to further cultivate the depth of the database resource.

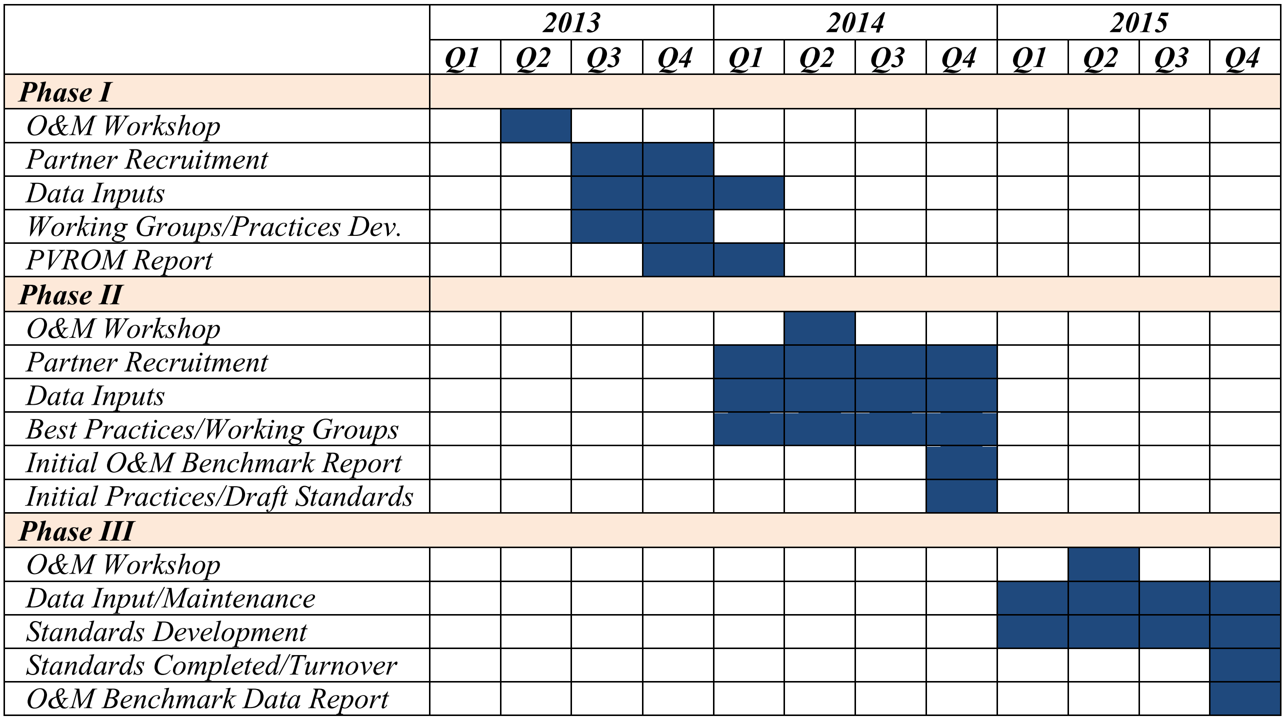
Among the multiple benefits that PVROM Partners receive via project participation are:

- Data anonymity enforced by a Non-Disclosure Agreement.
- Full database access to individual Partner-entered data.
- Access to aggregated database content entered by other Partners, normalized for use (contingent upon database sample size).
    - Analysis of aggregated data is intended to provide Partners with a way to benchmark their plant performance/reliability results with a larger sample, while also maintaining a level of anonymity.
- Increased recognition and understanding of PV availability versus reliability (and associated O&M options based on output).
- Better understanding of system costs and cost-benefit of multiple O&M approaches based on various factors.
- Ability to, for example, provide plant performance/expectation to insurance companies at five-year increments and better determine true plant value (and, in turn, renew insurance contracts via more favorable bank terms).
- Better understand of the risk of possible future PV plant states (e.g., ID insurance products).

PV plant operators who are interested in participating in the PVROM program should feel free to contact any of the project researchers listed in Appendix C for more information.

Scope and Schedule

The PVROM project has initially been funded to run over 36 months, beginning in 2013. (It is possible that the program will be extended beyond 36 months if findings prove valuable.) Figure 1-1 illustrates the initiative’s research plan. The Benchmark PVROM reports, scheduled for publication in late 2014 and 2015, are anticipated to be the key deliverables of the project. Separately, PV O&M best practices are expected to be drafted in 2014, leading to further standards development by consensus bodies and/or turnover in 2015.



	2013				***2014***				***2015***			
	Q1	***Q2***	***Q3***	***Q4***	***Q1***	***Q2***	***Q3***	***Q4***	***Q1***	***Q2***	***Q3***	***Q4***
Phase I												
O&M Workshop		■										
Partner Recruitment			■	■								
Data Inputs			■	■	■							
Working Groups/Practices Dev.			■	■								
PVROM Report				■	■							
Phase II												
O&M Workshop						■						
Partner Recruitment					■	■	■	■				
Data Inputs					■	■	■	■				
Best Practices/Working Groups					■	■	■	■				
Initial O&M Benchmark Report								■				
Initial Practices/Draft Standards								■				
Phase III												
O&M Workshop										■		
Data Input/Maintenance									■	■	■	■
Standards Development									■	■	■	■
Standards Completed/Turnover												■
O&M Benchmark Data Report												■

Figure 1-1
PVROM Project Plan

2

PVROM TOOL AND CAPABILITIES

The PVROM database project is intended to address a knowledge gap in the O&M of megawatt-scale solar photovoltaic systems. By inputting observed field data for a diversity of geographically dispersed plants into the database, EPRI and Sandia researchers aim to apply analytic techniques to gain valuable performance-related insights. The underlying supposition of the PVROM research effort is that accurate plant data reporting can help both recognize and characterize the events that affect PV system production—such as component and system failures—and better understand their associated impacts. In addition, spare parts needs and other maintenance requirements can, for example, be discerned, and plant design best practices determined.

PVROM Data Collection Tool

To facilitate PV reliability and O&M research founded on real-world field data, Sandia with input from EPRI, created the PVROM data collection and analysis tool. This tool is powered by ReliaSoft's XFRACAS™ platform, a web-based, closed-loop, incident (failure) reporting, analysis, and corrective action system software package.[1] It is specifically designed for the acquisition, management, and analysis of quality and reliability data from multiple sources. The ability to export PV system times-to-failure and times-to-suspension for ready analysis by other ReliaSoft analysis tools was a primary consideration in choosing XFRACAS™ as a reliability data analysis tool for the PVROM initiative.

The tool enables:

- Reporting of reliability-related issues for PV systems and components in the field,
- Specification of failure analysis details,
- Tracking of failure analysis and mitigation actions associated with resolving identified field problems,
- Reporting of installation details when a PV system is installed/commissioned,
- Review of PV system configurations Bills of Material (BOM),
- Search of customer support, incident, problem resolution report, action, failure analysis, and system configuration records based on specified criteria,
- Data export to other tools beyond XFRACAS for additional analyses.

The PVROM database resides on a Sandia server and is accessed through the Sandia Open Network (SON). Access restrictions ensure that only source users (industry partners) can access

---

[1] The FRACAS (Failure Reporting, Analysis, and Correction Action System) in XFRACAS™ is a general term for a database used in quality, reliability, or maintainability engineering applications that tracks problem in a system. Ultimately these problems can be corrected through root-cause analysis using the recorded data as well as generate reliability/maintainability statistics for prediction in future analyses.

the database. Sandia administers security protocols and XFRACAS™ source permissions ensure that individual source users can access only their own data.

PVROM Data Entry and Analysis Capabilities

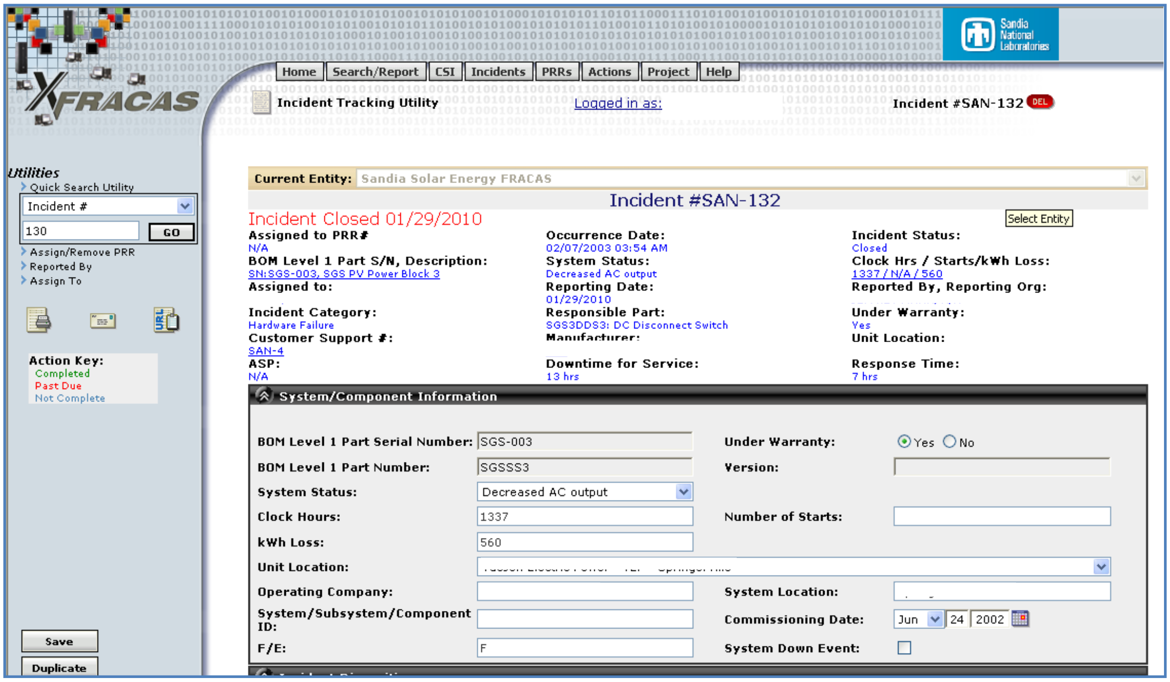
Industry partners are responsible for inputting PV plant design information into the PVROM database to establish a baseline understanding of a system's equipment makeup and layout. Subsequently, they are expected to capture planned and unplanned incidents and events and record them into the PVROM database. This is done through a process of documentation in incident reports that each reflect single plant outage events. The detailed information in the incident reports allows for vital numerical data to be generated—such as times to failure and time to restoration per component per outage event—and lays the foundation for more nuanced trend analysis and statistical modeling.

What follows is a brief explanation of primary PVROM data inputs, outputs, as well as operational and analytical capabilities.

Incident Data

Incidents, the primary inputs to the PVROM database, are defined as failures, faults, or trips of PV plant systems or components that lead to outages. These outages can occur when a system is operative and performing as designed, or conversely when a system is malfunctioning. Innocuous incidents such as nuisance trips can be quickly addressed without major effort, while failures causing loss of component function can necessitate greater repair or replacement actions.

Incidents of all types are intended to be logged into the PVROM database along with additional information that can assist in the analysis of the outage's cause(s). Note: Deliberate de-energizing of systems or equipment for purposes such as repair or preventative maintenance are included as incidents that are being recorded in the database. Figure 2-1 provides a screenshot depicting the look and feel of an XFRACAS incident data report.



Incident #SAN-132

Current Entity: Sandia Solar Energy FRACAS

Incident #: 130

Action Key: Completed, Past Due, Not Complete

Incident #SAN-132

Incident Closed 01/29/2010

Assigned to PRR# N/A	**Occurrence Date:** 02/07/2003 03:54 AM	**Incident Status:** Closed
BOM Level 1 Part S/N, Description: SN:SGS-003, SGS PV Power Block 3	**System Status:** Decreased AC output	**Clock Hrs / Starts/kWh Loss:** 1337 / N/A / 560
Assigned to:	**Reporting Date:** 01/29/2010	**Reported By, Reporting Org:**
Incident Category: Hardware Failure	**Responsible Part:** SGS3DDS3: DC Disconnect Switch	**Under Warranty:** Yes
Customer Support #: SAN-4	**Manufacturer:**	**Unit Location:**
ASP: N/A	**Downtime for Service:** 13 hrs	**Response Time:** 7 hrs

System/Component Information

BOM Level 1 Part Serial Number:	SGS-003	**Under Warranty:**	● Yes ○ No
BOM Level 1 Part Number:	SGSSS3	**Version:**	
System Status:	Decreased AC output		
Clock Hours:	1337	**Number of Starts:**	
kWh Loss:	560		
Unit Location:			
Operating Company:		**System Location:**	
System/Subsystem/Component ID:		**Commissioning Date:**	Jun 24 2002
F/E:	F	**System Down Event:**	☐

Figure 2-1
A Screenshot of XFRACAS Incident Data

Failure Data

Through incident data input, it is possible to mine the PVROM database using the XFRACAS™ application, and thereby extract failure frequencies and restoration times per component type. Times to failure data for each PV component are automatically processed. The PVROM database automates the organization and output of this information. These outputs are readily useful for analysis by other tools and can provide a "best fit" for a distribution model.

PVROM Database Outputs

PVROM functions as a database tool by which pertinent information can be harvested for analysis proposes. The following are readily available as outputs of PVROM:

- *Incident Frequency* – the rate of occurrence for any particular outage events for systems or components,
- *Repair Duration* – the difference between event service response date/time and service completion date/time, to nearest hour (reliability metric),
- *Restored to Duty Date/Time* – the date/time that the system, subsystem, or component is once again performing its intended function following failure or out-of-service event,
- *Down Time* – the difference between event occurrence date/time (date/time failed or out of service [OOS]) and restored to duty date/time, in hours (availability metric), and
- *Service Down Time* – the difference between event occurrence date/time (date/time failed or OOS) and service completed date/time, in hours (availability metric).

Analysis

Metrics within the PVROM database can effectively be leveraged to track the causes and effects of incidents to improve upon O&M practices and optimize preparedness techniques. 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 following events:

- The elapsed time until the event has been detected by maintenance personnel,
- The elapsed time for isolating the failure to affected component(s),
- Logistical downtime due to retrieving parts or tools to complete repairs or replacements of 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.

Corrective Actions

Through incident statistics, 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: Enhanced characterization of expected PV system output and lifecycle economics.

For example, maintainability data—such as outages (caused by either failures of system components or external disturbances on the system itself), maintenance actions, and power/energy loss—can be used to create failure and restoration statistics used for predictive models, O&M planning, and budgeting.

Analytical Methodology

The PVROM analytic process begins with industry partner input of plant BOMs. The BOMs consist of the major components in a PV system where failures can be anticipated. They are documented in PVROM at an appropriate level of detail to support expected reporting needs for both field O&M and other analyses.

BOMs form a sort of taxonomy, derived from the physical construction of the PV system, by which to assign failures. They are created to capture the inventory of a system down to a desired level. As such, they organize a PV system in a hierarchical manner and can track what system components may be subassemblies of other components.[2]

---

[2] System components may include hardware parts and software components.

Often, system components are tracked by serial number or by another unique identifier that relates to an individual component in the system. For example, there may be multiple inverters in a photovoltaic system, but each individual inverter could be tracked separately from initial operations to its exit out of the system when either removed or replaced. By gathering this life data for each system component, statistics can be generated that help lead to the understanding of potential failure trends in a family of components (i.e. all inverters). This methodological approach can also facilitate the comparison of components across different systems to, in turn, better understand how location or environment can affect component reliability.

As previously discussed, the other major inputs to the PVROM database are identified as *incidents*, which represent maintainability data, such as outages, maintenance actions, and power losses. Outages caused by either failures of system components or external disturbances on the system itself are recorded as incidents.

Meanwhile, the way that an issue is documented in PVROM is called an *Incident Report***,** which captures the following information regarding an outage event:

- Date of occurrence,
- Description of the problem,
- Affected component and location within the system by serial number,
- Corrective action taken to restore availability of the component,
- Repair and restoration time of the component, and
- Estimated power loss from the system caused by the component outage.

Table 2-1 defines the range of incident categories recorded into PVROM.

Table 2-1
Specified Incident Categorizations

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 • Example: inverter failure due to incorrect limits in the code
Hardware upgrade required to operate	Hardware upgrade requirement based on changes in the electrical code or to utility requirement • Example: changes to anti-islanding policy requiring new inverters
Software upgrade required to operate	Software upgrade requirement based on changes in the electrical code or to utility requirement • Example: changes to anti-islanding policy
Equipment installation problem	System downtime due to incorrect installation • Example: 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 • Example: 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 prior to failure • Example: 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 • Example: tracker controllers, monitoring systems
Planned maintenance	Scheduled maintenance (routine or otherwise) such as cleaning operations, hardware modification or replacement, tracker mechanical maintenance
Troubleshooting issue	A failure or suspension due to the troubleshooting process • Example: while changing a fan in an inverter, a capacitor is broken
System upgrade	A general upgrade to the system • Example: another PV array with inverter is added to an existing PV system
End of useful life failure	The failure cannot be repaired

Incident reports offer a failure history that can be used to generate numerical data such as times to failure and time to restoration per component per outage event. This fundamental data, in turn, can then be utilized to create failure and restoration statistics useful for predictive models. Power loss can also be incorporated into more detailed models that predict total delivered power outage of a simulated plant. At bottom, the recorded data forms the foundation for analysis and for the subsequent development of plans for improving plant operations.

3

PRELIMINARY RESULTS AND FINDINGS

This section discusses results and findings derived from initial O&M data entered into the PVROM database. Details encompass system component makeup as well as metrics surrounding recorded failures and repair times. These preliminary findings are intended to offer introductory insights into plant performance and reliability issues and will be expanded upon in future reports. Ongoing research will also document trends (potential and active) that may impact future system performance as well as posit consistent findings regarding the robustness and maintainability of PV components across multiple PV systems.

The analysis below is based upon incident data—information covering plant operational deviations/failures, unplanned outage events, and associated mitigation activity—from one PVROM partner with two systems located in the desert Southwest. Both systems are similar in architecture (though one is slightly larger than the other in terms of total components). As a result of their comparable technologies and orientations, results and findings have been aggregated for the two arrays.

Table 3-1 lists the combined system components for the two installations, along with their total quantities. A summary of the number of maintenance actions, hardware repairs, and average downtime for the period January 1, 2012 to August 31, 2013 is also shown. Both systems have been operable for approximately 5 years, but the PVROM database has so far only captured their latest 20 months of system performance. (Researchers are attempting to retroactively insert incident data from earlier dates of plant operation.)

Table 3-1
System Components, Maintenance Actions, Repairs, and Average Downtimes

System Component	Abbreviation	Quantity	Maintenance Actions	Active Repairs	Avg. Corrective Maintenance Time (hrs)
AC Disconnect Switch	ADS	7	0	0	-
Combiner Box	CB	45	0	0	-
Data Acquisition System	DAS	2	2	2	1.0
Electric Motor	MOTOR	35	0	0	-
Hoses and Fittings	HOSE	35	0	0	-
HV Transformer	TXL	2	0	0	-
Hydraulic Cylinder	CYL	35	15	15	9.2
Hydraulic Pump	PUMP	35	0	0	-
Inverter	INV	7	8	0	0.5
Control Power Supply	CPS	7	1	1	8.0
Control Fan	FAN	7	0	0	-
Inverter Control Board	CRTLBRD	7	2	2	1.7
Inverter Control Software	CRTLSW	7	1	1	0.6
Matrix	MAT	14	4	4	2.8
LV Transformer	TXS	7	0	0	-
Misc. Electrical Devices, Cables, Connectors	ECON	2	1	1	8.0
Programmable Logic Controller	PLC	35	8	8	2.6
PV String	STRING	540	0	0	-
PV Module	MOD	8100	1	1	8.0
Solenoid	SOL	35	0	0	-
Tank	TANK	35	0	0	-
Utility Disconnect Switch	UDS	2	0	0	-
Valve Stack	VALVE	35	0	0	-
Variable Frequency Drive	VFD	35	0	0	-

Note: Abbreviations are shown for each component as they appear in the PVROM database. Maintenance Actions are recorded where an incident report was created for a component whenever maintenance staff needed to either inspect or replace a component. One incident could require more than one maintenance action to be conducted.

As illustrated in the table, the inverter and photovoltaic string component categories are each aligned with a number of associated subcomponents. Note: The subcomponent quantities reflect their totals for the two assessed PV systems; they are not for a single inverter unit or photovoltaic string.

Overall, thirty-four incident reports were recorded in the PVROM database over the course of the 20-month evaluation period. Given the size of the systems, this represents 1-2 incidents per MW-month. These incidents were reported when there was any issue related to a possible degradation in operations or maintenance to either of the PV installations. In general, the severity of an incident can range from a minor impact that, if left unmanaged, may eventually degrade system capabilities (e.g., vegetation overgrowth), to an outage of a critical system component resulting in a major loss of power production (e.g., inverter hardware failure).

Of the total number of recognized incident reports, 29 were diagnosed and closed, while 5 remain open. For the closed incidents, outcomes have been documented that indicate how the issues were resolved, either through maintenance actions (where maintenance staff responded) or other diagnoses (e.g., reset of a nuisance alarm). Meanwhile, investigations are actively attempting to determine the root causes of the remaining open incidents, at the time of this report.

One incident report may include several components that require either inspection or corrective maintenance action. Figure 3-1 shows system components that required corrective maintenance during the observation time period and the total number of occurrences. The Pareto chart organizes the system components by most to least number of maintenance actions (left to right). With the exception of the inverters, each incident resulted in some corrective maintenance (repair, replacement, or software patch). All eight inverter incidents resulted either in the inverters being reset after faults were detected or in no action being taken because the events were triggered by a simple loss of monitoring capability.

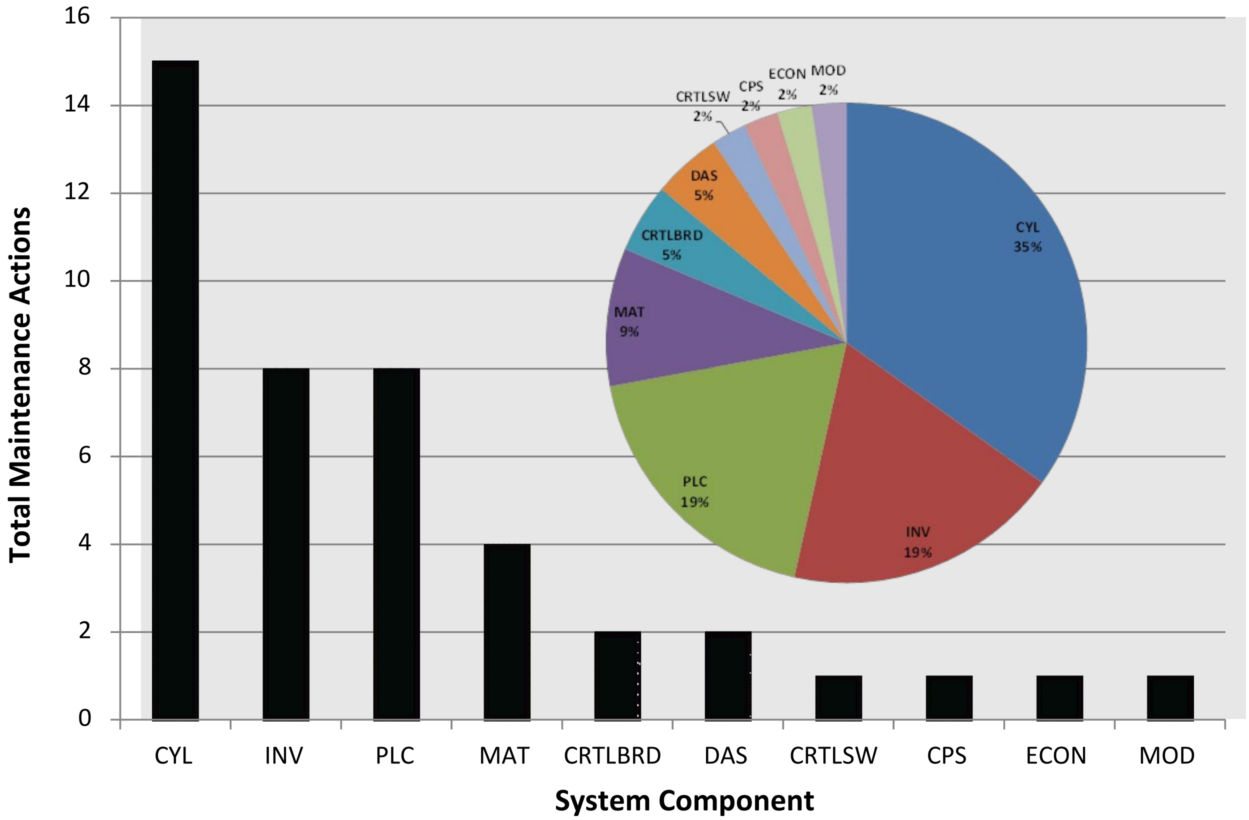


Figure 3-1
System Component Pareto Chart with Pie Chart Insert

The Pareto principle prioritizes events according to their consequence, distinguishing between the significant few from the trivial many.[3] In Figure 3-1, the Hydraulic Cylinders, Inverters (System Level), Programmable Logic Controllers, and Inverter Matrix Board comprise the majority of maintenance actions (~81%) and are sorted most to fewest in terms of number of failures from left to right (see abbreviations defined in Table 3-1).

System Component Failure Analysis

The hydraulic cylinders (CYL) for the tracking subsystem account for 35% of the total incidents recorded, with each incident resulting in a field repair. The mechanical nature of the CYL and its constant daily use likely provide an underlying explanation for why this system component experienced the highest observed failures. Most of the cylinders were replaced in June 2013 (see Figure 3-2) when several were found to be leaking during an inspection. The tracking subsystem was still functioning, but to replace the cylinders required the affected tracking subsystems to be taken offline.

---

[3] Also known as the 80–20 rule, the Pareto principle states that, for many events, roughly 80% of the effects come from 20% of the causes.

Inverters were found to command the second highest amount of incidents. These incidents were tracked independently at two different levels:

1. Per selected inverter subcomponent, including Matrix Boards, Controller Boards, Inverter Software, Cooling Fans, Power Supplies, and Tranformers, and
2. At the level of the inverter as whole (where incidents such as those that require inverter resets and that are not associated with failures in the aforementioned subcomponents could be discerned).

In this way, researchers were able to glean a more nuanced understanding of root cause failures and frequencies. As incident tracking continues, the PVROM component database may be updated to further breakout inverter equipment parts (or other system component categories) if recognized to be worthwhile. Entirely new equipment types can also be added if needed.

During the evaluation period, 3 matrix boards, 2 controller boards, and 1 power supply were replaced on the inverters—all as a result of hardware failures. All other inverter incidents required either a reset due to some unknown power distribance to the system or no action at all. (In the latter cases, there was simply a loss of inverter monitoring capability.) While the non-hardware failure incidents are not "true" failure events, in that the inverter is designed to go offline under certain grid conditions, they may still have an impact on system availability, and thus impact performance. For instance, if the inverters cannot be monitored, then system availability would be unknown to the operators. Overall, the hardware-related inverter incidents mostly occurred in the last five months of the observation period.

Controller software is among the subcomponents being tracked under the Inverter category, and potentially requires both corrective and preventative maintenance. Corrective maintenance is necessary whenever a software fault causes the inverter to either trip offline or operate outside of its specifications. Preventative maintenance is typically undertaken to avoid potential faults. Meanwhile, logs that the software generates can be inspected to detect an incipient fault. Only one incident was recorded for inverter controller software that required it to be patched due to an upgrade of inverter power supplies in August 2013.

Figure 3-2 shows the number of failures per component for each month of the observation period, and offers a general comparison of component-to-component failures over time. In this way, comparisons between different system components and trending over time can be discerned. For example, it appears that some PLCs failed earlier during the observation period, while inverters and CYLs failed later. Whether this constitutes a trend or not is difficult to determine given the amount of failure data available.

In the case of the CYLs, there was a spike of failures in June 2012, though these were all discovered during a single inspection of the tracking systems. All of the CYLs were found to be leaking, but may have been leaking for some time. Due to their high number of failure relative to other system components, both the PLCs and CYLs have been designated "watch" items, and will be scrutinized as more data is gathered on the system. No other corrective action is, however, recommended other than continued inspection, especially of the CYLs as leaks could be an indication of aging seals. As the observation time increases, the ability to discriminate trends from more clusters of random failures will be enhanced.

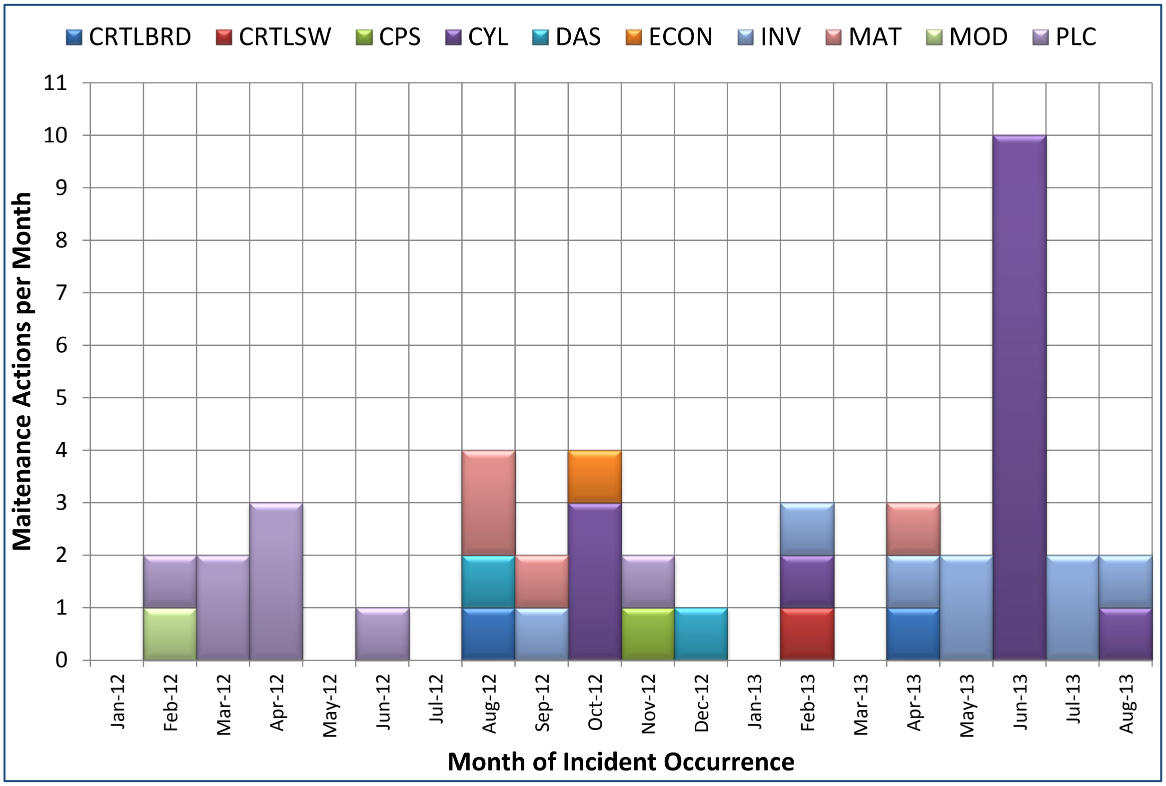


Figure 3-2
Total Maintenance Actions per Component

> *Note: This "button" chart shows the total number of maintenance actions across all system components per month. Color coding is used to differentiate each component. Abbreviations defined in Table 3-1.*

While Figure 3-2 gives an absolute measure of failures it does not provide an adequate comparison of component failures relative to their different population sizes. It might be expected that, on average, those components with larger populations would have a greater number of failures than those with smaller populations. A failure rate comparison considers this factor. Table 3-2 compares the cumulative failure rate for each system component category. The failure rate is calculated by dividing the total number of components by the total component operating hours (population × 20 months). The table is sorted in descending order by failure rate, referred to in the table as "maintenance action" rate as not all incidents documented are true failures (as was the case for the inverters).

Table 3-2
System Component Cumulative Maintenance Action Rate

System Component	Maintenance Action Per Million Hours
INV	78.2
DAS	68.4
ECON	34.2
CYL	29.3
CRTLBRD	19.5
MAT	19.5
PLC	15.6
CRTLSW	9.8
CPS	9.8
MOD	8.4

As can be seen in Table 3-2, inverters (INV) have the highest rate of maintenance actions, with eight events recorded for of a total population of seven inverters. Data acquisition system (DAS) and miscellaneous electronic devices (ECON) rank second and third, respectively. Importantly, though, DAS and ECON represent a system of components unto themselves; ECON could even be said to represent a "basket" of diverse equipment. Consequently, a higher relative failure rate would not be unexpected in these categories. PV modules (MOD), meanwhile, have the lowest failure as there was only one failure out of a population of 8,100. This latter finding has potential implications regarding module lifetime and, in turn, long term plant health.

Maintenance Data Analysis

Figure 3-3 shows the repair times for each system component incident on a monthly basis. With the exception of the hydraulic cylinders (CYL), the downtime for each of the component incidents did not exceed 24 hours in a given month. As previously noted, there were 9 cylinders replaced during an inspection of the tracker system in June of 2013. This effort required a total of 84 hours of active repair. Excluding CYL mitigation, no single repair action took more than 12 hours.

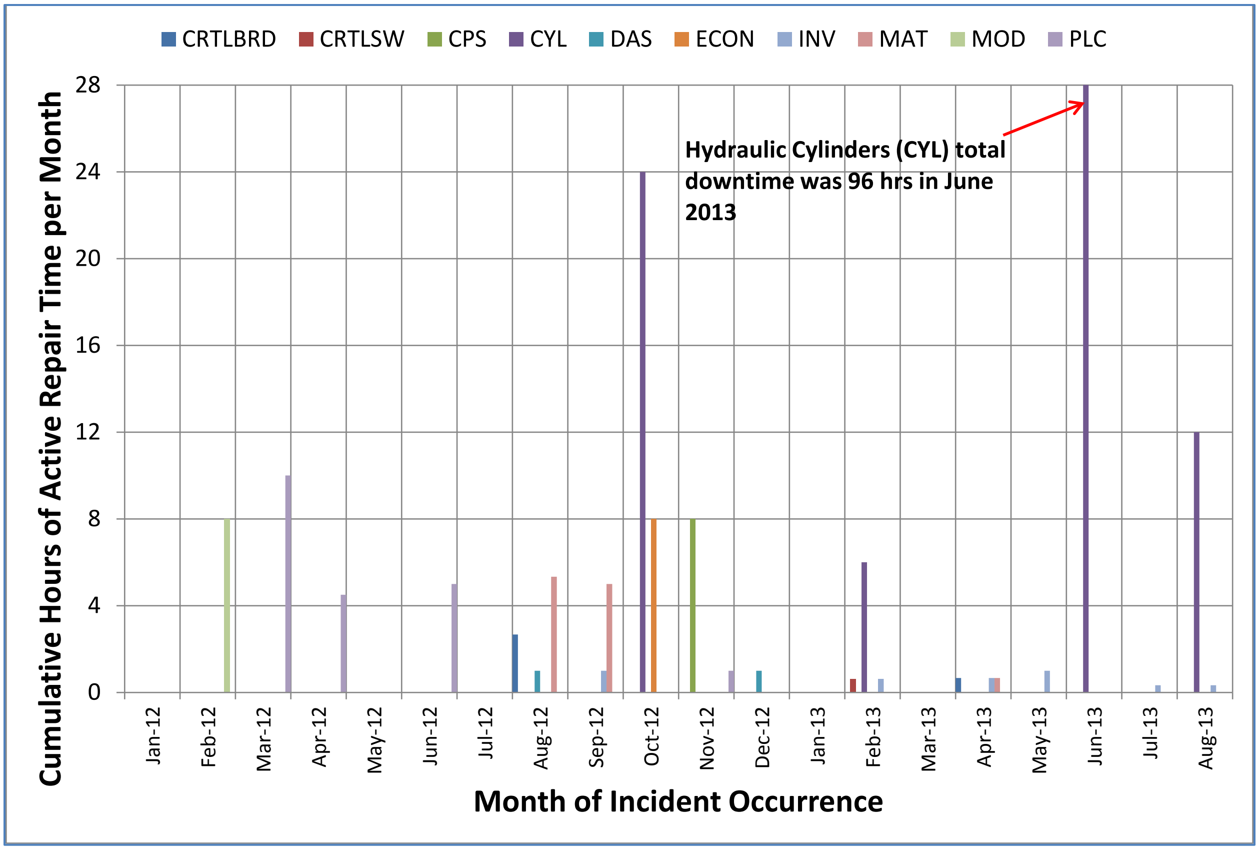


Figure 3-3
System Component Repair Times per Month

Note: Active repair represents the "hands on" time by maintenance staff to affect corrective maintenance on the component. Logistical delays are not included.

For nearly half (14) of the closed incidents, the service response time was zero; in these instances the on-site maintenance crew both observed and fixed the failure issue. In the other 15 incidents, the issue was observed by someone other than the onsite maintenance crew or required another team (i.e., vendor support) to facilitate resolution. In the latter scenario, service response occurred over an average of 4 days, after which active repairs commenced. The longest service response time was almost 21 days by the inverter vendor, while the median response time was one day. No significant trending has, thus far, been observed regarding service response times.

Summary of the Observed Data

On the whole, it appears that the reliability and maintainability of the two observed systems are in good order. The 20 months of analyzed data does not indicate any significant negative trends. However, future data for programmable logic controllers (PLC) and hydraulic cylinders (CYL) will be closely monitored to ascertain whether there is notable degradation in their performance over time. In particular, the main failure mode for CYL is leaking of hydraulic oil and it is recommended that seals be regularly inspected.

Only the last one-third of the systems' operating history has been entered into PVROM and categorized. Therefore, from the existing failure statistics alone, it is difficult to determine possible wear-out trends with a high degree of certainty. Efforts are underway to fold the earlier history of these systems into PVROM as resources permit.

Future research steps, detailed next, will include more advanced modeling and statistical analysis of an anticipated larger data set. In turn, greater insight around component uptime and availability, optimal system design, equipment failure probabilities, and anticipated O&M needs and costs will be reported.

Building Block Analysis for Future Research

As more reliability data is captured by the PVROM database, more sophisticated and comprehensive analysis and modeling will be pursued to provide a nuanced understanding of optimal PV system O&M and management pathways. For example, with broader datasets, the PVROM tool can be leveraged to verify advantageous PV plant engineering designs, characterize component reliability, and predict future system performance (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 PVROM data described above. The narrative is intended to offer a sense of the depth of research that the PVROM tool is capable of delivering in the foreseeable future. Prospective insights are, among other things, expected to be thoroughly derived from:

- Reliability Block Diagrams (RBD),
- Statistical modeling of component reliability and maintainability,
- Assessments of system availability and utilization,
- Sensitivity analyses of major contributors to system failure and downtime, and
- Sparing analyses.

Reliability Block Diagrams (RBD)

A reliability block diagram (RBD) is 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.[4] For a PV plant, it indicates how component failures and maintenance actions impact system reliability, availability, and utilization rate. These terms are defined in the following ways:

- Reliability measures include the average amount of time between critical system failures.
- Availability is the percentage of time the system is in a predefined minimal operational condition to produce power.
- Utilization is a measure of the percent throughput based on the total capability of the system to produce power.

---

[4] An RBD is not necessarily equivalent to a functional-flow diagram topologically.

Reliability, availability, and utilization rate parameters can be important not only for better understanding a plant's operational characteristics but also for informing the terms of O&M service contracts. For instance, the availability of a plant may be a performance benchmark for the service provider.

When failure and repair models are assigned to each component in an RBD, quantitative impacts to reliability and availability can subsequently be measured. A sensitivity analysis can also be performed to understand the likelihood of failure for each component based on where it is in the system and how it may interact with other system components. Based on existing functionality embedded in the XFRACAS^{TM} software platform, the PVROM tool can be leveraged to work with other software packages, such as ReliaSoft BlockSim^{TM}, to both construct PV system RBDs as well as run analyses for creating appropriate reliability and maintainability measures.

PV System RBDs in Brief

A PV system RBD is initially constructed through analysis of the PV system's configuration. This approach enables an understanding of how the system's constituent components connect and interact to produce power. Generally, an RBD is developed to show serial and parallel paths. Components are in series when they must all work for the system to be operable; they are in parallel when they are fault-tolerant or when there is system redundancy. In the latter case, one or more failures could occur but the system would remain in an operable state.

Figures 3-4 thru 3-6 portray a set of RBDs for one of the PV systems profiled earlier in this report. The system topology is somewhat modular—there are many copies of the same subsystem configuration (RBDs represent a hierarchy of subsystems). Figure 3-4 shows the lowest level of the system topology: strings of photovoltaic modules connected to a combiner box.

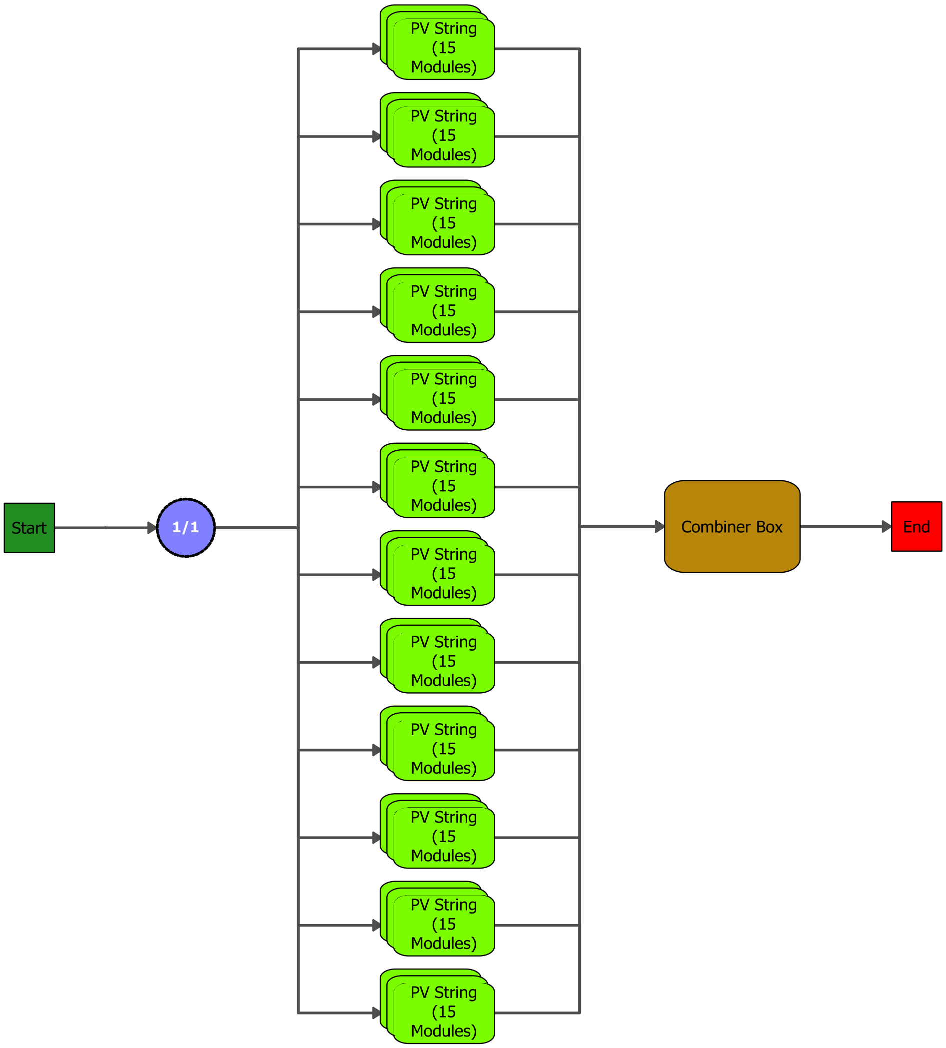


Figure 3-4
Reliability Block Diagram at the Combiner Box String Level*Note: Each PV String is representative of 15 photovoltaic modules (MOD) in electrical series. Conceptually, the flow must continue from the "Start" block to the "End" block for system availability to be achieved. Failures of blocks could prevent this flow and cause loss of power to the system.*

There are 12 sets of PV modules connected in parallel to a combiner box. Each green box represents a string of 15 individual photovoltaic modules connected in series. As such, the failure of only one of the 15 modules would cause the entire string to become inoperable and therefore unable to produce power for the system. However, because each string is in parallel with the other 11 sets, one string failure will not prevent the other sets of modules from producing power. (Note: The failure of a combiner box will, however, cause all of the strings to be unavailable to the system. The combiner box is a single-point-of failure in this block diagram.)

The next level in the system topology is represented by the connection of many combiner boxes to one inverter. Per Figure 3-5, each combiner box string (depicted in Figure 3-4) is connected in parallel to the inverter. Again, a critical failure in a combiner box string would not inhibit the other strings. However, a failure of an inverter or AC disconnect switch, which is in series, would cause a critical failure at this level of the system hierarchy.

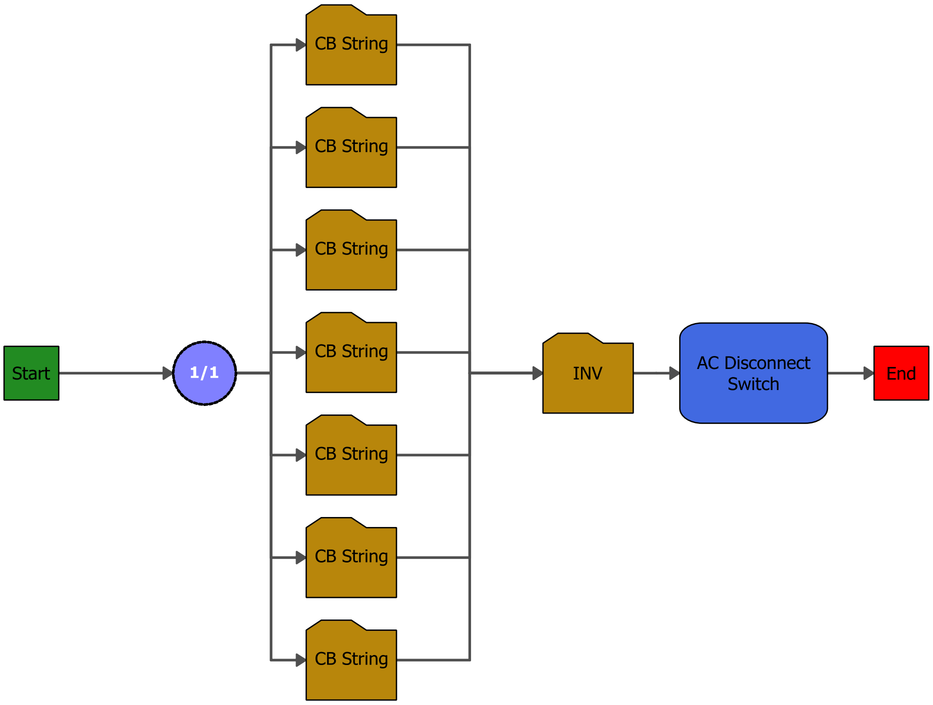


Figure 3-5
Reliability Block Diagram at the Inverter String Level*Note: Each CB String block is a single and independent representation of the RBD in Figure 3-4. The INV block is representative of the inverter and its subcomponents. In this RBD seven CB Strings are shown, but there is one Inverter String with only six combiner boxes attached.*

Finally, the highest level of the system's hierarchy is illustrated in Figure 3-6 and shows all of the inverter strings in the system that deliver power to the grid. The four inverters all connect to a High Voltage Transformer (HVT) which, in turn, connects to the grid via a utility disconnect switch (UDS). Each inverter string is independent from one another. Also, importantly, the HVT and UDS are in series and therefore both represent single-points-of-failure for the system. While the loss of a single inverter can cause an approximately one fourth drop in power production, a loss of the HVT or UDS would bring everything in the system to a standstill.

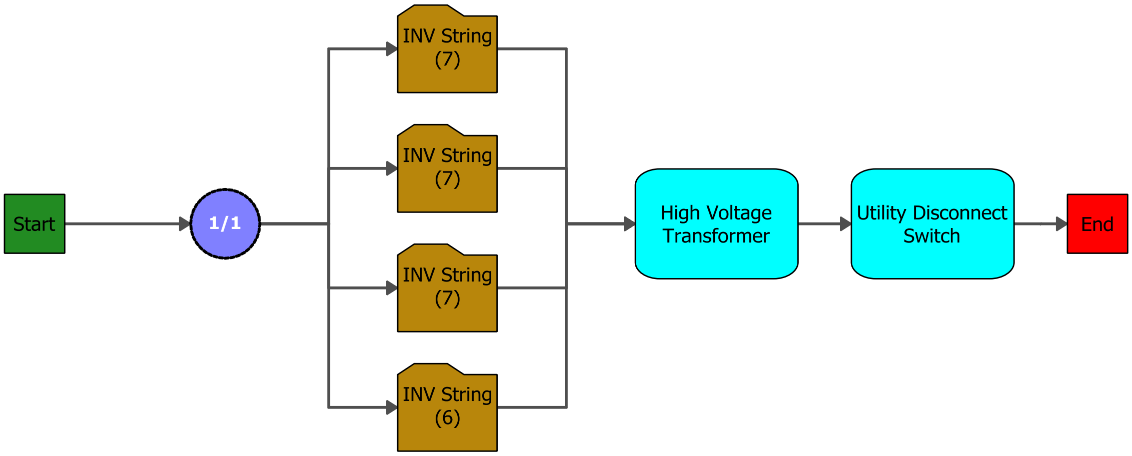


Figure 3-6
Reliability Block Diagram at the System Level*Note: Each INV String is a single and independent representation of the RBD in Figure 3-5. The number shown in the parenthesis for each INV String block represents the number of CB Strings (Figure 3-4) attached to the particular inverter.*

Figure 3-7, offers a simplified illustration of the PV plant's overarching RBD. It incorporates all of the levels of the system's topology. If successfully constructed, the RBD should ultimately enable users to quickly ascertain what system components must remain available for a minimum amount of power to be generated from the system. It can also reveal possible plant weak points and where a higher maintenance posture may be needed to ensure that system power production goals are achieved.

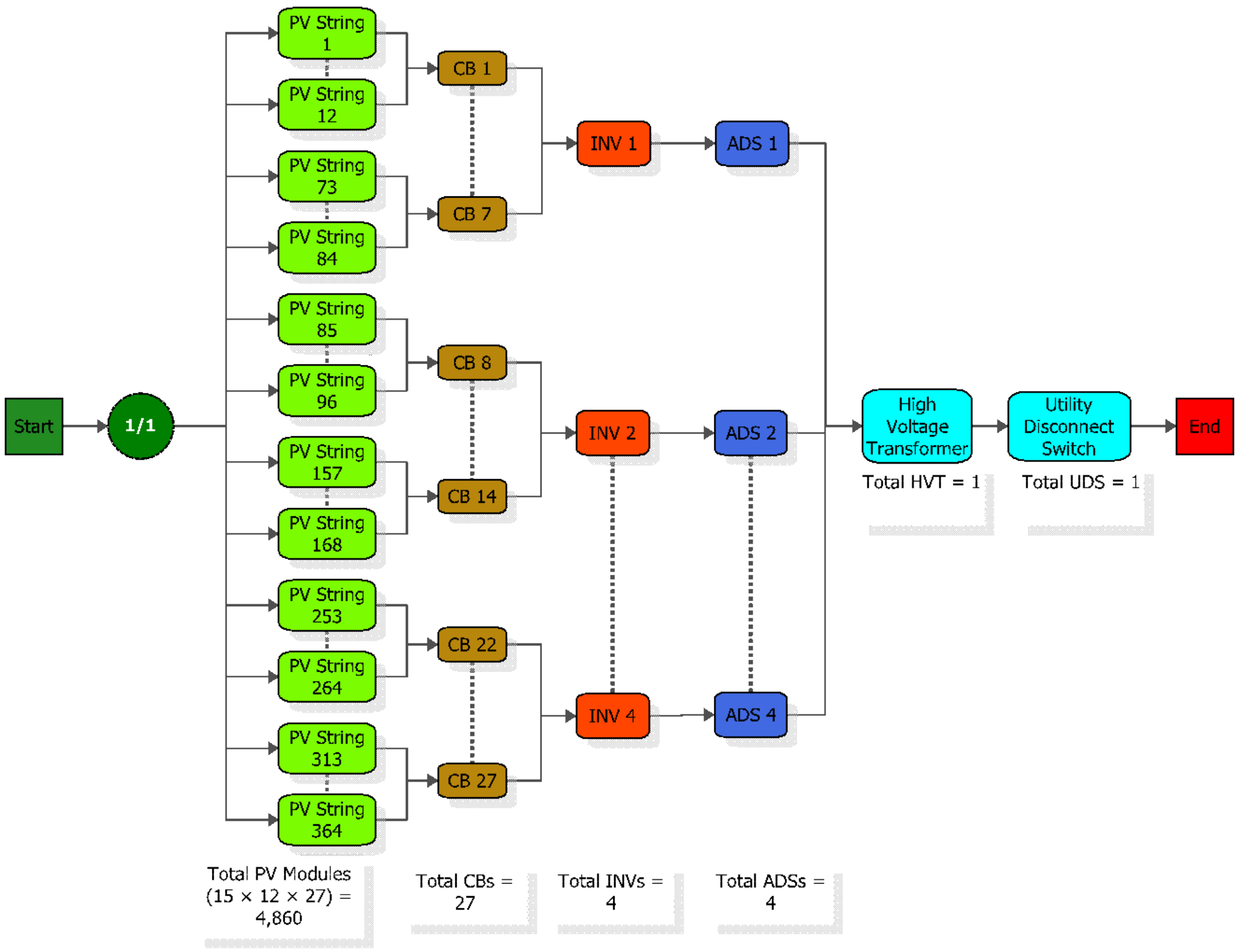


Figure 3-7
Compressed Reliability Block Diagram of a PV Plant

Note: The RBD is a compressed topographical view of the RBD in Figure 3-6 showing, in general, all the system's components. Dotted lines represent that system components are repeated in the system. This system includes 4,860 PV Modules, 27 combiner boxes (CB), 4 Inverters (INVs + subcomponents), 4 AC Disconnect Switches (ADS), 1 High Voltage Transformer (HVT), and 1 Utility Disconnect Switch (UDS). The effect of a tracking subsystem failure is not shown in this example.

RBDs as a Foundation for Modeling and Statistical Analysis

One of the major advantages of RBDs is that they can be used to guide stochastic simulations of PV (and other) plants to subsequently notify O&M and reliability strategies. Failure rates, either estimated for different plant designs or documented and captured in tools like the PVROM database, provide the underlying data for predicting plant system and component availabilities. As a result, O&M production modeling can, for example, be statistically formulated with greater accuracy and effectively overlay a PV plant RBD. In turn, system owners can be better positioned to develop optimal maintenance solutions for their PV plants by altering maintenance parameters (logistics delay times, sparing, maintenance staffing, repair effectiveness). Moreover, they can be better informed to potentially modify system designs to harness increased reliability.

Statistical Modeling of Component Reliability and Maintainability

As stated above, each block in an RBD represents a system component and can be assigned failure and repair models based on the data gathered from PVROM. Times between each component failure, times of repair, and even maintenance logistics and durations can be modeled stochastically. The data related to each component can be fitted to an appropriate model based on engineering understanding of the underlying causes of failure and the nature of assigned maintenance tasks. Statistical tests can be used to assess whether or not the model accurately represents the data.

Typical stochastic models include 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). As a point of reference, the power law model is also used when a component is considered a repairable "black box," meaning the component is repaired and the effect of repair is the minimal needed to make the component operational. Weibull, lognormal, exponential, and gamma distributions can also be used to model maintenance durations such as repair times and logistic delays.

This in mind, reliability analysis software tools—such as ReliaSoft's BlockSim^{TM} software, used in conjunction with the XFRACAS^{TM} platform—can be harnessed to stochastically model PV system parameters in a manner that most accurately conveys the factors that impact system reliability and maintainability. These simulations allow for constraining factors (and their uncertainties) such as the number of maintenance personnel or the available number of spares, to be recognized and incorporated into subsequent analysis.

What follows are several examples of statistical modeling, along with preliminary findings, developed using existing data in the PVROM database. Given the small data sample (20 months of operating history from two observed PV systems), the analysis is intended for illustrative purposes only. As the PVROM captures additional data for these two systems, and also incorporates data for other systems, the overall fidelity of these types of analyses is expected to increase.

For a brief illustration, statistical distributions have been "fitted" with two sets of data—failure time of inverter matrix boards (MAT) and repair times of programmable logic controllers (PLC)—to create models that can respectively predict new failures and repairs over time. *Fitting* a model means finding a parameterized distribution that can accurately describe the behavior of current data within a user defined error tolerance. In this way, a fitted model can be assumed to be good a predictor of future behavior. This assumption can be tested as new data is gathered through future failures and repairs. Also, as new data is obtained the model can be modified to give it better predictive power.

The failure time and repair time models can be used in conjunction with reliability block diagrams to discern component behavior as it relates to overall system objectives, such as producing power. Also, these models can be used to compare similar components across various systems to ascertain important differences which may be of importance to PV system O&M

activities (e.g., comparing the effect of the warm and humid Florida climate on component lifetime versus that of the dry deserts' of Arizona).[5]

Figure 3-8 illustrates inverter matrix boards (MAT) failures identified in Table 3-1, fitted with a lognormal distribution. The linearized plot, called a probability plot, shows how well the data conforms to the chosen lognormal distribution (blue line). With only four failures there is much statistical uncertainty in the true failure rate behavior of these items over time. The curved confidence bound lines (in red) represent the statistical uncertainty of the probability of failure (y-axis) at a particular time (x-axis).

The model allows for the calculation of point estimates of interest such as the Mean Time To Failure (MTTF, in this case 72,788 hrs) or the predicted probability of failure at a given time. It can be used in a reliability block diagram model for simulating MAT failures and may also be used for sparing analyses that predict the number of spares required to support a PV system's availability requirements.

---

[5] For an excellent resource that discusses the technical details of creating statistical models for reliability and maintainability data see: Meeker, William Q. and Escobar, Luis A., *Statistical Methods for Reliability Data*, Wiley & Sons, Canada, 1998

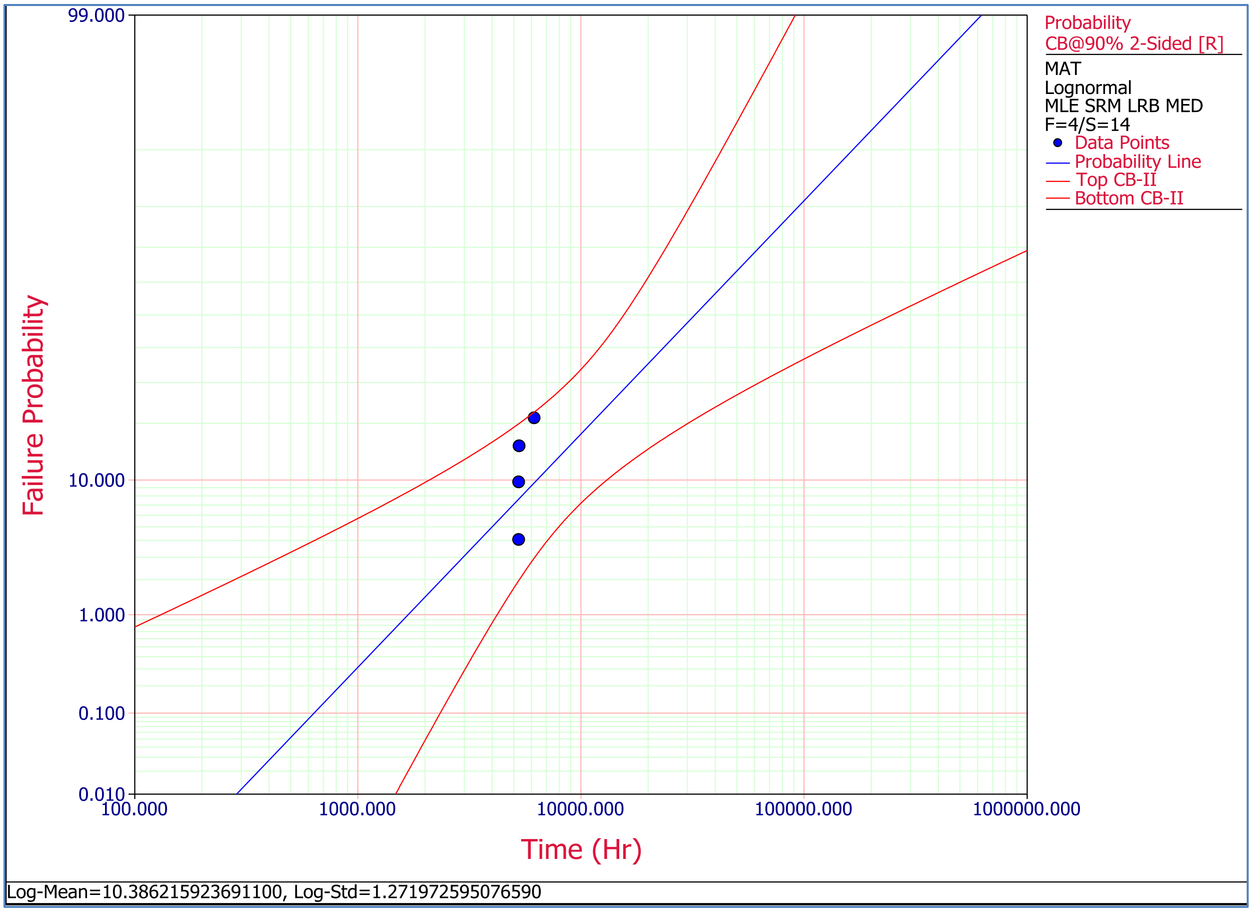


Figure 3-8
Lognormal Probability Plot for Inverter Matrix (MAT) Board Failures

Note: This figure illustrates the fit of a lognormal model with parameters μ (log-mean) = 10.4 and σ(log-std) = 1.3 to the failure time data of an Inverter Matrix Board. This model can be used to predict future failure times. The red curves show the confidence bounds of the failure probability as a function of time.

Figure 3-9 presents a probability plot that shows how recorded programmable logic controller (PLC) repairs identified in Table 3-1 match against a fitted Weibull repair time model. The fitted parameters of the Weibull model are 1.23 for the shape parameter (Beta, β) and 3.02 hours for the scale parameter (Eta, η). From these parameters we can calculate maintenance measures of interest such as Mean Time to Repair (MTTR)—in this case 2.8 hours—and the 95th percentile of repair, where 95% of repair times should occur by, in this case, 7.4 hours. This model can be used as a baseline for improving the maintainability of the PLCs. Operation and maintenance plans can also be developed based on the knowledge of the repair time behavior.

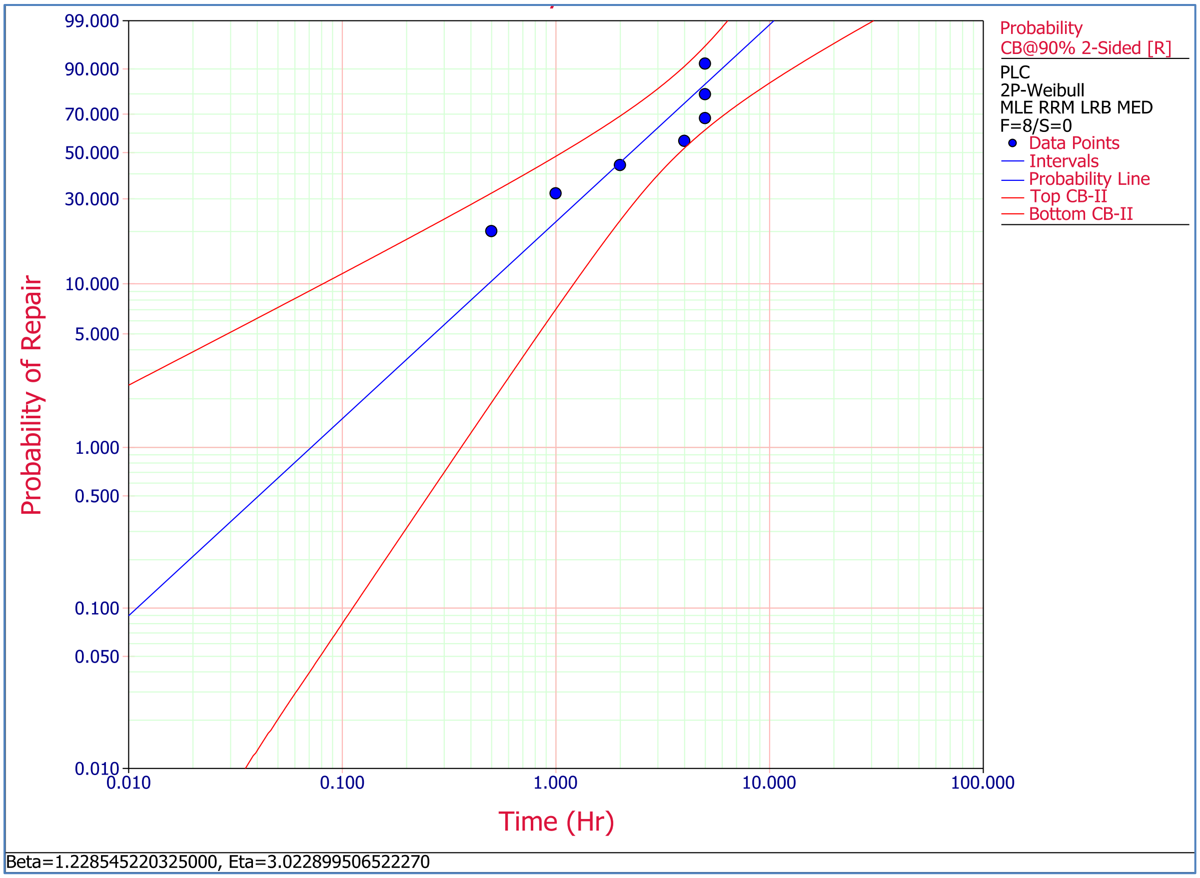


Figure 3-9
Weibull Probability Plot for Programmable Logic Controller Repair Times

> *Note: The figure illustrates the fit of a Weibull model with parameters β= 1.2 and η= 3.0 to the repair time data of a Programmable Logic Controller. This model can be used to predict future repair times. The red curves show the confidence bounds of the repair probability as a function of time.*

The above examples show how recorded data can be taken from the PVROM database and directly applied to system modeling. In the figures, statistical models have been fitted to time-to-failure and time-to-repair data for Inverter Matrix and PLC system components, respectively. This exercise can essentially be repeated for every system component until each component has an associated reliability and maintainability model. If data is available regarding a particular component's failure modes, then more than one reliability and maintainability model can be applied to each component for each failure mode.

Using model data, users can construct "what if" scenarios to compare various design options or maintenance plans. Different systems, technologies, and environments can also be compared to look for significant factors contributing to reliability. Again, the feasibility of performing these more in-depth analyses will improve as more PVROM participants join the effort and provide greater data to the database.

System Availability Analysis

The RBD model and the times-to-failure and repair models described above can be combined into a single model to enable system availability/utilization analysis. System utilization is defined as the power generating efficiency of a system and accounts for only failures and downtimes in the system. It does not directly account for other physical factors that can impact efficiency, such as the solar irradiance of the PV panels, weather, or environment.[6] As such, system utilization effectively answers the question: How much power is actually getting upstream to the power grid? This measure can be considered an availability measure as it is both a function of the system reliability and system maintainability.

Figure 3-10 illustrates an example system utilization plot based on time-to-failure, time-to-repair, and maintenance logistical delay metrics captured in the PVROM database and presented in Table 3-1. In the case where no failure or repair data was observed for a component, conservative assumptions were made regarding their reliability and maintainability distributions. Figure 3-10 plots predictions of a system's utilization over 5 years of operating time, starting from January 1, 2012 (the start of the observation period for existing data in PVROM), with 90% confidence bounds on the predicted system utilization.

---

[6] For example analysis showing the combination of reliability, maintainability, and other physical factors, see Sandia Laboratories report: Miller, et al, *The Comparison of Three Photovoltaic System Designs Using the Photovoltaic Reliability and Performance Model*, SAND2012-10342, 2012.

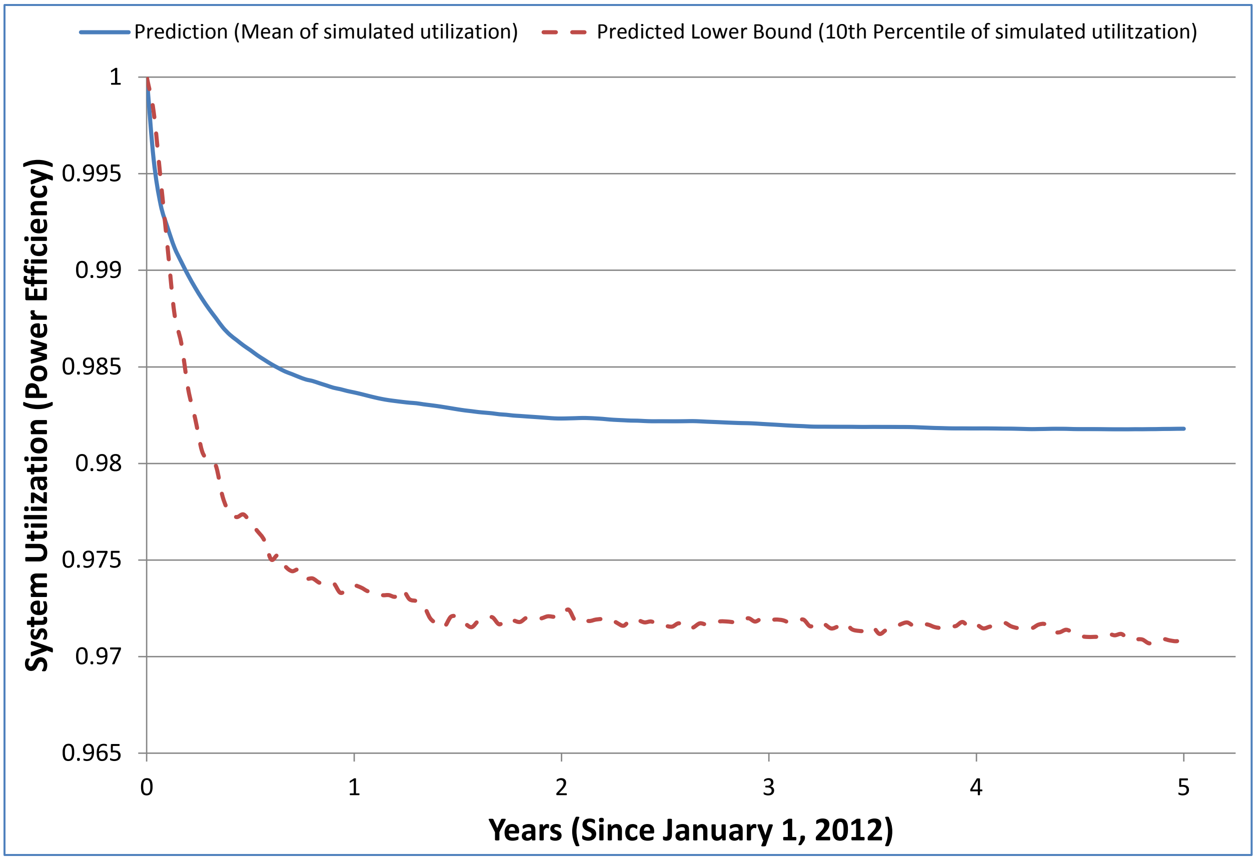


Figure 3-10
System Utilization Plot – Example PV System over 5 Years

Note: The figure shows the percentage of total generated power as it is generated over time upstream to the grid. The blue line represents predicted plant utilization with 90% lower confidence bound (red line). The lower bound does not consider the statistical uncertainty from the estimated model parameters. For this example it is assumed that all system components begin operation on January 1, 2012

Per Figure 3-10, the point estimate at 5 years of the percentage of power delivered to the grid (based on the average of 10,000 simulation runs) is 98.18%, with a 90% lower confidence bound (10th percentile of the simulation runs) of 97.09%. In other words, with 90% confidence, the "true" system utilization is equal to or greater than 97.09%.[7] These results should be considered in light of the fact that the input data is only based on a fraction of the total observed time of the PV plant's operation. Also, tracker subsystem failures are not considered in this analysis and their failures would be expected to slightly impact power generation efficiency. These are all elements that can be incorporated in a more detailed model. The system utilization analysis can be expanded to include as many factors and constraints that would be of interest with the intention of either optimizing design or maintenance policy so as to maximize power production while minimizing operational costs.

---

[7] This confidence bound does not account for the statistical uncertainty from estimated model parameters.

Other metrics of interest calculated for this preliminary availability/utilization analysis include system Mean Time Between Failures (MTBF) and system Mean Time to Restoration (MTR). Assuming that all photovoltaic modules are needed to be available to deliver full power to the grid, the predicted system MTBF is 1,154 hours and the MTR is 51.2 hours over the five-year period. This would result in a predicted five-year full power system availability (A_s) of 0.9575 (A_s=MTBF÷[MTBF+MTR]).

The estimated system MTBF illustrates how often we expect a component failure within the system, though not every failure has the same criticality. A failure of a photovoltaic module (MOD) has a smaller impact on system utilization then an inverter (INV) or even a high voltage transformer (HVT), which can cause the whole system to cease power production. Finally, it is worth noting that maintenance logistical delays have a substantial impact on system availability as the Mean Time to Repair (MTTR, not counting maintenance delays) is estimated to be 2.6 hours. Therefore, there is approximately a two-day average delay time in the modeled maintenance crew response.

Sensitivity Analysis of System Component Failure and Downtime Contributions

Another layer of analysis can be achieved by running sensitivity analyses on RBD model simulations 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.

Based on the data sample derived from the PVROM database and assuming all photovoltaic modules in the observed systems are required to be operable, Table 3-3 shows the inverters (INV) to be the largest contributors to system failures and system downtime by a significant margin. The photovoltaic modules are second, mostly due to their sheer number (4,860) in the systems. Taking one step further, assigning cost to each component, repair, and even maintenance crew "truck roll" can enable a sensitivity analysis on maintenance costs. These types of analyses get to the heart of system improvement that can lead to maximized returns on investment. The PVROM tool has the capabilities to directly support this undertaking.

Table 3-3
System Component Failure and Downtime Contributions

System Component	% of Failures	% of Downtime
Utility Disconnect Switch (UDS)	2.75%	5.18%
High Voltage Transformer (TXL)	2.70%	5.04%
AC Disconnect Switch (ADS)	3.12%	5.83%
Inverter (INV, including subcomponents)	80.19%	57.03%
Combiner Box (CB)	3.28%	2.29%
Photovoltaic Modules (MOD)	7.95%	24.63%

Sparing Analysis

Another useful metric that can be obtained by system modeling afforded by the PVROM tool 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. Assessments must be made on the stock of these items and/or the sourcing of the replacement parts (if reliant upon an original equipment manufacturer).

Through failure models, inventory usage can be projected on a quarterly or yearly basis. This can be helpful in determining what material costs may be in future years for budget planning. Typical sparing metrics denote the number of failures that are expected to occur, on average, in a component population, or the upper percentile of failures that could occur to mitigate the risk of exhausting spares.

If component sparing is based on the average number of failures expected to occur over a time period, then sometimes there will be more spares than needed and sometimes not enough. However, it may be desired to have a certain confidence that a spare will be available when needed. It is assumed in this situation that an accessible spares pool would be maintained so as to avoid extended downtimes due to critical parts not being available for immediate procurement. Also, this approach lends itself to budget planning as spares could be purchased in bulk over a financial cycle.

It may be that a system operator would only accept a 10% risk of not having a critical component on-hand (or one that can be made rapidly available) when a failure occurs. If so, the number of spares required to achieve at least a 90% chance of having a spare when a failure occurs may be a more sensible type of metric. If trade-offs need to be made regarding the number of spares versus their cost, then a more detailed analysis could be conducted regarding the likelihood of having a spare available given a fixed number of spares purchased for the year.

Again, as presented in Table 3-1, available PVROM data discussed herein indicates that the hydraulic cylinders (CYL) of the tracking subsystem had the highest number of failures over the 20-month observation period. Based upon this information, how many more failures can be expected and how many spares may be needed to ensure quick access by maintenance crews? Analysis indicates that a Weibull distribution of $\beta = 3.1$ and $\eta = 17{,}974$ hours (MTTF = 16,082 hours) fits the CYL failure time data well.[8] As such, the number of failures over a five-year period was simulated for 35 hydraulic cylinders (the current population) and is depicted in Table 3-4. The table also shows the number of recommended spares based on a 90% availability criterion. In addition, it depicts the likelihood that there will be more failures than spares available.

---

[8] The CYL data was fitted to this distribution for illustrative purposes only. Only the latest third of the systems' operational history for CYLs was considered.

Table 3-4
Hydraulic Cylinders (CYL) Sparing Recommendations

Year	Expected Number of Failures (in year)	Required Spares (for year)	Risk of Not Having a Spare
1	3.5	6	9.4%
2	18.7	23	9.4%
3	20.1	24	9.2%
4	18.4	22	9.1%
5	19.5	23	9.0%

Note: The expected number of failures per year for a population of 35 CYLs with a recommended level of sparing assuming an incurred risk of no more than 10%. For this analysis it is assumed that all CYLs were installed at the beginning of Year 1.

This sparing analysis example demonstrates one method of controlling system availability by ensuring availability of parts and being able to predict certain system costs. A more practical sparing analysis approach would be to optimize total system costs with respect to system power production. An assignment of costs to maintenance crews (crew size, skill level, onsite response, etc.), initial costs of system components (purchase, installation), spares, and cost of repairs could all be considered in such an analysis. The PVROM tool, using Reliasoft BlockSim^{TM} software, can conduct this kind of optimization analysis.

A Note on Uncertainty

It's important to recognize that all modeling endeavors are endowed with degrees of uncertainty. There is uncertainty in a model's fitted parameters and even with which model to choose. There is also the uncertainty in the data collection itself, as failures are not only observed when they occur; they may also be captured during inspection after failure has already occurred or perhaps is in process (as exemplified by the hydraulic cylinders failures mentioned above). In addition, there is measurement uncertainty. For instance, system repair times are not recorded to the second; they may only be recorded to the nearest half-hour. Some uncertainty can be theoretically quantified (confidence bounds on distribution parameters), where as some is not practically measurable at all (choice of distribution). The bottom line: All of these factors must be considered when a PV system is modeled and results are interpreted.

Data scarcity represents the greatest source of uncertainty in the analysis of the two PVROM installations under observation and reported in this document. As of this writing, the failure and repair data captured in PVROM only covers approximately the latter part of both systems' total operating lifetime. Failure and repair data exists for the first two-thirds of the plants' operational history; however it has not been recorded as rigorously. If possible, the historical plant history prior to joining the PVROM data collection process will be captured to gain more precise data for modeling purposes. What may be missing from the data could be indications of diverse failure modes, initial quality defects (known as "birth defects"), and early wear out trends.

The use of PVROM early in a system's lifecycle, if not at its beginning, ensures that high quality data is captured over most of the plant's operational life. One of the PVROM tool's advantages is that it provides a consistent method of collecting maintenance data that can be immediately categorized and analyzed. That said, many new partners joining the PVROM initiative will likely have existing and mature systems that may or may not have maintenance data for previous years, or partial data. In these cases the limitations of analysis will need to be understood, though as data collection ensues, these risks will diminish.

Future Analyses

With greater PVROM sample data, researchers intend to expand upon and also customize the analyses contained in this report. The types of analyses that may potentially be pursued in the future is wide ranging. Candidates include:

- System optimization with regards to costs, reliability, and power production.
- Baselining of failure models and repair models for families of PV system components.
- Failure Modes and Effects Analysis to improve component and system design.
- Systems comparison across various environmental conditions to understand their effect on component reliability and maintainability.
- Merging Reliability Block Diagram analyses with physics modeling of PV systems to obtain the total systems perspective on power production capability.

Ultimately, future efforts will be directed by feedback from PVROM partners as well as the industry at-large. Some of these expanded types of analyses are expected to be useful in optimizing O&M practices and potentially in developing standards.

4

PV O&M STANDARDS DEVELOPMENT

The rapid worldwide growth of PV systems is placing increasing need to develop consensus O&M standards, maintenance procedures, definitions, and analysis techniques to sustain the industry's health. Definition and industry adherence has the potential to spur more efficient and responsible market and industry expansion in several key ways:

- *Improved project economics* – Well-established O&M practices would reduce the level of uncertainty in project estimates surrounding reliability, performance, and maintenance requirements.
- *Better informed, more segmented O&M activity* – Utilities, owner-as-operators, and also 3rd-party O&M service providers are among those who perform O&M. Each brings a unique approach to asset management. Technical standards will set recognized approaches for handling PV asset management.
- *Increased predictability of O&M costs and requirements* – Standardized maintenance protocols will improve confidence among market participants by enabling greater insight into measured performance outcomes.

EPRI and Sandia are, in fact, engaged with industry stakeholders in a multi-year effort to advance O&M standards. This undertaking is occurring primarily through facilitated workshops, working group activities, and other outreach efforts. First, O&M best practices and protocols for measuring PV system efficiency and quality are being identified and drafted. Subsequently, these best practices are anticipated to be further developed into standards.

Volunteer working groups have recently been formed—composed of academics, laboratory researchers, O&M and solar industry professionals, among others—and charged with developing a set of draft standards. Once completed over the next several years, they will be communicated to the broader PV industry for comment, and ultimately to standards organizations for formal codification. As shown in the PVROM project plan in Chapter 1, best practices will be drafted in 2014 leading to further consensus body standards development and/or turnover in 2015.

What is a Standard?

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.

Background and Overview of Activities

The current effort to standardize O&M best practices emerged from an EPRI-Sandia O&M workshop held in Palo Alto, CA in 2013 (see http://energy.sandia.gov/?page_id=14860). Part of the broader 2013 EPRI-Sandia PV Systems Symposium, the workshop included a full day of interactive presentations, brainstorming, and dialog to explore current knowledge gaps and lay the groundwork for industry standards and protocols. The fully subscribed event—attended by O&M providers, system integrators, independent power providers, independent engineers, utilities, and laboratory and university representatives—examined the tools, techniques, and data analysis approaches that can enable operational improvements and high levels of plant reliability.

Topics of discussion surrounded the identification of key PV O&M challenges, as well as their potential operational and cost impacts; planning required for characterizing reliability through data and metrics; and predictive methods for reducing O&M risk. Information was, in turn, conveyed through case studies, panel debate, and breakout session ideation. A number of insights from O&M providers sprung out of the workshop that, among other things, identified the most pressing PV reliability and O&M challenges (see Figure 4-1).

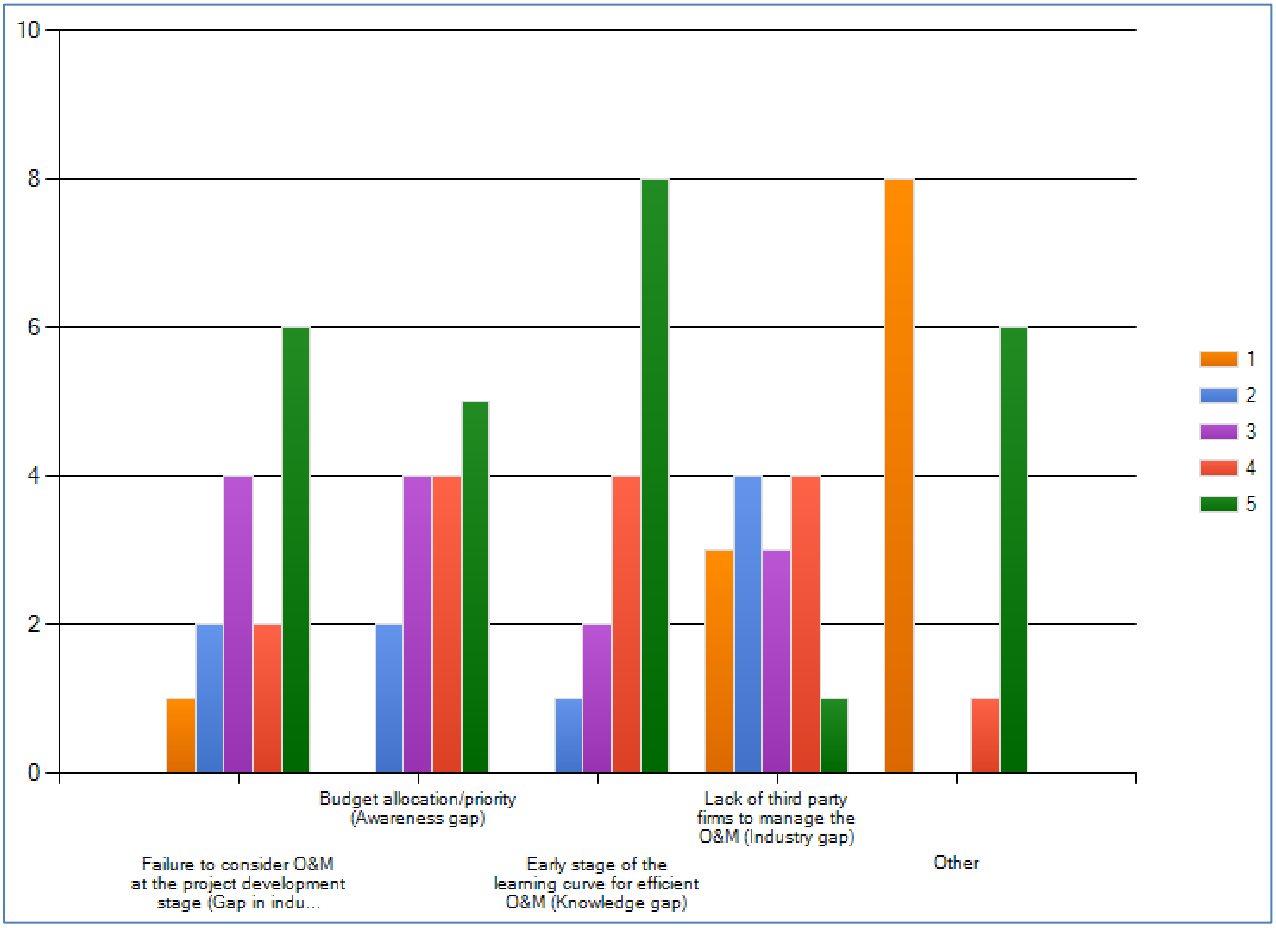


Figure 4-1
Most Pressing PV Reliability and O&M Challenges (1: low, 5: high)

The pressing challenges depicted in Figure 4-1 are intended to be addressed through O&M standards working group efforts and by Sandia and EPRI research. Some of the O&M challenges identified during the 2013 EPRI-Sandia PV O&M workshop are elaborated upon below, along with potential solutions.

Problem: Limitations due to the early stage of the learning curve for efficient O&M.
Solution: With the formation of best practices working groups, those in the O&M community have the opportunity to learn from each other. In addition, the PVROM database tool can benchmark performance data and provide analyses to inform lessons learned to help optimize O&M.

Problem: Failure to consider O&M at the project development stage.
Solution: This issue is a communication failure. It can be addressed through the development of best practices base upon O&M scope requirements and supported by PVROM analysis models. For example, best practices defined for minimum scope with corresponding O&M budgets, as well as optimization approaches, can be devised.

Problem: O&M budget allocation priority.
Solution: Again, PV project benchmarking, achieved via PVROM and other means, can offer accurate O&M scope and cost estimates that can be incorporated into institutionalized practices.

Problem: SCADA/DAS optimized as an O&M tool.
Solution: Time series data collection is very important for project performance. While PVROM currently doesn’t use this data directly, the time stamps for incidents and outage duration are key measures of performance. Automation of SCADA systems for reporting is expected to play an important role in the future. Condition-based monitoring is especially important for its predictive value. O&M working groups will remain cognizant of this opportunity and target needs for technology improvement.

Problem: Premature inverter failures and unplanned and extended outages early on in projects.
Solution: Development of a failure and analysis standard is a partial approach for addressing this issue. Inverter research will benefit from benchmark data as well as industry and laboratory research programs that aim to improve inverter reliability.

Problem: A lack of O&M standards, standardized data, and accurate cost information.
Solution: This general sentiment was expressed consistently throughout the workshop and is a driver for the PVROM database and associated development of standards. Based on these insights and the high level of motivation exhibited by workshop attendees, 40+ O&M service providers subsequently volunteered to participate in one of three O&M standards working groups, described below. This industry participation, combined with EPRI and Sandia research efforts will address many of the identified issues and challenges identified in the course of the workshop and continuing discussions.

Working Group Descriptions

Three working groups were formed in mid-2013 with the aim of ultimately lowering PV plant performance and financial risk. The working groups are each intended to address specific high priority needs, and are broken out as follows:

1. *Definitions*. Develop standardized definitions of reliability, maintenance and key performance indicators, among other terms.
2. *Best Practices*. Determine O&M best practices focused on safety, failure reporting, and preventative maintenance
3. *Design and Installation.* Create guidelines that consider safety, O&M scope and budget, commissioning, and other information relevant to project development.

Definitions Working Group

Objective: Standardize definitions of reliability, maintenance, and key performance indicators, among other terms. A common basis of understanding is needed, especially as may be referenced in contracts. It is not unusual, for example, to have multiple definitions of the term “availability.” As such, it is incumbent upon this group to work through appropriate definitions to support contract language, specify O&M terms, as well as delineate plant performance reporting aims.

Table 4-1
Initial List of Terms to be Defined by Definitions Working Group

Action	Availability	Derating
Downtime	Failure	Fault
Incident	Item	Maintainability
Maintenance	Power Throughput	Reliability
Repair	System	Uptime

O&M Best Practices Working Group

Objective: Develop best practices governing field operations, including safety, failure reporting, and preventative maintenance. This body of work is intended to provide guidance on how to conduct day-to-day O&M activities. Lessons learned can be shared to standardize approaches. The end goal is to improving O&M efficiencies and set project stakeholder expectations.

Working Group activity has thus far prioritized core O&M practice areas for which best practices will be developed:

1. Safety
2. Training
3. Failure analysis and reporting
4. Interconnection
5. Preventive maintenance
6. Cleaning/soiling (this likely depends on site-specific conditions, and can be informed by PVROM-developed operations modeling).

Design and Installation Working Group

Objective: Communicate features for O&M to those developing projects and plant designs to facilitate safety, appropriate O&M scope and budgets, commissioning, and other information for project development inputs. This working group activity is intended to address the scarcity of O&M information that is referred to by project developers and correct misunderstandings regarding the scope and need for plant maintenance.

As identified in Figure 4-1, failure to consider O&M at the project development stage, combined with budget allocation and priority are major issues. A best practice/standard, provided for bankability purposes, should advance better understanding of O&M's role in ensuring optimum performance.

Working Group activity has thus far prioritized plant design and installations areas for which best practices will be developed:

- Safety
- O&M budgeting
- Vegetation control
- Standard signage
- Commissioning
- O&M checklist

Systematic assessment of the needs of stakeholders and involved parties requires industry engagement in the development of these best practices. Safety is a big issues and more than one working group will address it. Further, many of these issues have been and are being addressed by others. As such, communication, coordination, and consensus will be required for best practices to be implemented as standards.

Status and Next Steps

Thus far, an initial prioritization of PV O&M knowledge gaps and practical needs has been identified and content from other standards development efforts has been referenced to help direct activities.

It is evident that others in industry are working on O&M issues and standards. As a result, the future may bring collaboration with these other organizations, especially as PV best practices evolve. For example, the American Society for Testing and Materials (ASTM) is initiating a standard on photovoltaic installation, O&M, and commissioning. Their intent is to apply lessons learned from current PV industry experiences as well as other technologies that may have applicability toward PV standards.

The wind industry's experiences may also be instructive. For instance, IEC 61400-26 is currently being implemented as a technical specification on wind turbine availability and addresses many of the reliability, definitional, data reporting, and contract term elements that may be relevant to the operation of any variable generation plant. Since this standard addresses various operational states it has some potential instructive value for guiding PV standards as well.

All told, best practices for O&M are expected to be drafted in 2014 and subsequently communicated to the broader PV industry for comment. Further consensus body standards development and/or turnover is then slated to occur in 2015.

EPRI and Sandia welcome participation from a broad assortment of volunteers to assist in the development of PV O&M standards. To learn more and become a contributor, please contact Sandia Laboratories' via email at: pvo&m@sandia.gov.

5

CONCLUDING THOUGHTS

As installed PV capacity grows, the costs and benefits of PV O&M—including its impact on long-term plant reliability, availability, and operational management—will become ever more important. Furthermore, informed O&M strategies that positively affect the financial bottom line will be reliant upon holistic perspectives that consider plant design and installation quality, power output predictability, as well as failure management requirements and resultant maintenance schedules.

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.

The PVROM database program is designed to directly identify the metrics that improve overall PV production and performance, reduce events that act to reduce both plant energy and financial productivity, and provide a pathway for their mitigation. Its overarching aim is to provide data-driven PV system reliability and O&M findings that can be utilized to notify more strategic long-term thinking around solar plant operation and value. Specifically, the PVROM effort intends to enable:

1. Identification of system component inadequacies and quantification of their associated system impacts.
2. Knowledge growth surrounding failure and repair time impacts that can be shared among PV industry operators and asset managers.
3. Shared O&M best practice insights among a broad spectrum of PV stakeholders, including those who develop, finance, perform due diligence, and/or underwrite projects.

Initial information input into the PVROM database has provided a starting point for analysis that is expected to be built upon in future years. For example, the first year of the PVROM database program has revealed some interesting observations. Based on the data from initial systems input into the PVROM database, the frequency of incidents has been on the order of 1-2 incidents/MW-month. The limited number of incidents over the course of the 20 month observation period is arguably less a reflection of data scarcity, and more of an indication that the assessed systems are generally in good working order. The incident reports, designed to capture useful information for digging down into the root causes, support this hypothesis. Greater data collection should enable deeper dive analysis in the future.

To be sure, the value of the PVROM tool is directly linked to the number and size of industry partners that affiliate with the research effort. As of this writing, the PVROM database project has inked agreements with six partners representing around 30 MW of PV plant capacity. This participation indicates proof of concept and EPRI-Sandia aim to ultimately sign up tens of partners to incorporate dozens of systems with up to hundreds of megawatts into the PVROM database.

With greater data, quantitative-based findings along with modeling and statistical analyses can be incorporated into published benchmark O&M data reports (scheduled for publication at the end of 2014 and 2015) that are designed to increase industry confidence—particularly for those who do not have access to privately held data. This output is also expected to be useful to O&M practitioners who do not or have not yet established protocols for optimizing approaches to O&M—especially based on the history of each unique plant's O&M reliability data and trends.

At bottom, the depth of research that the PVROM tool is capable of delivering is considerable. Based on the aggregation of greater sample data and on feedback from PVROM partners as well as the industry at-large, future PVROM research possibilities include:

- System optimization with regards to costs, reliability, and power production.
- Baselining of failure models and repair models for families of PV system components.
- Failure Modes and Effects Analysis to improve component and system design.
- Systems comparison across various environmental conditions to understand their effect on component reliability and maintainability.
- Context-specific sparing analysis.
- Merging Reliability Block Diagram analyses with physics modeling of PV systems to obtain the total systems perspective on power production capability.

These and potentially other types of analyses are anticipated to help both optimize O&M practices and advise standards development activities being performed on a parallel track.

A

FREQUENTLY ASKED QUESTIONS

PV Reliability O&M Database (PVROM)

Frequently Asked Questions

OVERVIEW

1. What is the basis of the Sandia-EPRI PV Reliability O&M (PVROM) database architecture?
2. What data fields have thus far been set up in PVROM?
3. Is it mandatory that Partners use XFRACAS to input data into PVROM? Is data automation/export available?
4. Are Partners obligated to input a minimum number of PV facilities into PVROM?
5. What quality standards will Partner-entered data be held to?
6. Is there a way to view and evaluate the quality of the data in PVROM before deciding to join the effort?
7. Bill-of-Materials details of serial numbers for PV modules seems like a substantial effort. Is this necessary?
8. Can Sandia-EPRI provide a format for the bulk importing of performance data?
9. How are equipment categories defined and made reasonably consistent with varying plant designs?
10. What is the overall level of effort necessary to properly input site data into PVROM?
11. How long does PVROM Partner training take?
12. Are all PVROM configuration and code changes done in-house?
13. To what degree can proprietary Partner data be protected?
14. Are failure analysis results publicly shared for particular PV plants?
15. Given that the bill of materials is kept private, what value does it have for failure analysis? Will poor performing components across multiple owners' plants be shared?
16. What reporting capabilities does PVROM offer?
17. At what frequency do Sandia-EPRI intend to publish reports based on PVROM data findings and analysis?
18. Is there a licensing fee associated with using PVROM?
19. What, to date, is the current number of PVROM Partners? What is the goal?
20. Is the methodology governing Sandia's PV Reliability and Performance Model available for review?

FAQ

1. What is the basis of the Sandia-EPRI PV Reliability O&M (PVROM) database architecture?

PVROM is run by a Web-based incident (failure) reporting, analysis, and corrective action system software package made by ReliaSoft and named XFRACAS (Failure Reporting, Analysis and Corrective Action System). A standard product, XFRACAS supports the acquisition, management and analysis of system quality and reliability data from multiple sources. The XFRACAS platform supports real-time and legacy failure/suspension (or non-failure events) *data acquisition via real-time incident records created by an Incident Wizard and Incident Tracking Utility.*

2. What data fields have thus far been set up in PVROM?

The following fields have been established in PVROM for Partners to input their data:

- *Incident Occurrence Date/Time;*
- *Bill of Material Part Number;*
- *Part Serial Number;*
- *Part Commissioning Date;*
- *Incident Description;*
- *Incident Category;*
- *Service Response Date/Time;*
- *Service Completion Date/Time; and*
- *Restoration to Duty Date/Time.*

Partners are welcome to recommend additional PVROM data fields to Sandia-EPRI for future implementation.

3. Is it mandatory that Partners use XFRACAS to input data into PVROM? Is data automation/export available?

For those Partners who already have a PV plant monitoring and data collection system in place, legacy data can be imported into PVROM via an Excel template. Note: bill of material (BOM) information is needed for each system input into PVROM, and Sandia-EPRI can input that information into PVROM for Partners. Legacy data is typically first exported, and then Partners can begin inputting real-time data (e.g., incidence).

4. Are Partners obligated to input a minimum number of PV facilities into PVROM?

No. Partners are free to, for example, engage in a test case and input data for a single site to evaluate the tradeoff in effort versus value. If Partners find participation to be of value, then they are encouraged to expand upon the number of PV systems they input into PVROM.

5. What quality standards will Partner-entered data be held to?

The data collection process is primarily a human input process as the data set includes O&M events, not SCADA data. Sandia-EPRI will provide training to each Partner and will be available to answer questions as needed. In addition, Sandia-EPRI will review the input of the BOM and incident data with the responsible management of each Partner. This is a qualitative way of ensuring what is entered into the PV-ROM is accurate and/or expected. Sandia-EPRI will also recommend preferred methods for calculating and reporting kWh lost for consistency across the database.

PV Reliability O&M Database (PVROM)

Frequently Asked Questions

6. Is there a way to view and evaluate the quality of the data in PVROM before deciding to join the effort?

PVROM is a work-in-progress. Data evaluation prior to partnership is not currently available. However, Sandia-EPRI intend to work with early adopters to develop a quality index and training that helps ensure data integrity. A requirements document will be developed early in 2014 that will provide a better understanding of the nature of the data and outputs of the PVROM database and reports.

7. Bill of Materials (BOM) details of serial numbers for PV modules seems like a substantial effort. Is this necessary?

Including details down to the serial numbers for all primary components increases the usefulness of the data. A lower level of detailed monitoring can be used, but the results may not be helpful in the long run if module issues are batch-related, for example. Sandia-EPRI includes "shortcuts" for entering serialized information in the training process.

8. Can Sandia-EPRI provide a format for the bulk importing of performance data?

Yes. During a training session, templates will be provided to Partners along with direction on the level of information that needs to be included in the templates.

9. How are equipment categories defined and made reasonably consistent with varying plant designs?

As part of a training process, Sandia-EPRI provide a User's Guide that defines category and equipment fields. The guide also includes recommendations for categorizing equipment based on differing plant arrangements.

10. What is the overall level of effort necessary to properly input site data into PVROM?

EPRI-Sandia have contracted with PVROM's initial Partner to track the amount of time it takes to perform data upload/entry as well as the various issues encountered surrounding this task. This information is now available and can be shared upon request.

11. How long does PVROM Partner training take?

Typically, PVROM training occurs at a Partner site and requires a full day—½ day for a user orientation, product overview, and questions; and ½ day to complete hands-on, scenario-based exercises.

12. Are all PVROM configuration and code changes done in-house?

Reliasoft's XFRACAS software product contains a level of flexibility for customization (e.g., the ability to add fields or set up email notifications to parties responsible for issues germane to a certain part of the system, such as reviewing incidence reports). Sandia-EPRI can make custom changes to the database in-house and personalize field parameters within each

Partner entity. Sandia-EPRI encourage Partner feedback on additional fields to incorporate into PVROM in order to enable greater learning and overall value.

13. To what degree can proprietary Partner data be protected?

Sandia-EPRI sign Non-Disclosure Agreements (NDAs) with each provider of database content (typically plant owners) that clearly state the terms of data share. In general, these terms can be customized to satisfy Partner sensitivities and expectations. For example, terms can specify that Sandia-EPRI seek approval from Partners on all content intended to be included in both public and private reports prior to their publication. (The 2014 requirements document for reporting will be informative in this regard) In addition, anonymity will be maintained by publishing findings based on an aggregate data level.

Moreover, XFRACAS, the platform upon which the PVROM database resides, provides a login ID and password to each Partner to ensure secure database access. XFRACAS resides on Sandia's restricted network server and Sandia-EPRI have access to each Partner "entity," or individual data input area, to perform comparative analysis at an aggregate level. No Partners have access to other Partner data. XFRACAS source permissions ensure that source users can only access their own data.

14. Are failure analysis results publicly shared for particular PV plants?

All proprietary data will be protected under non-disclosure agreements. As such, failure analysis data for specific plants will only be shared publicly if the Partner agrees in writing to the publication of such data. Sandia-EPRI intend to publish non-manufacturer specific, non-plant specific, aggregated failure rate estimates based on a category of part, climate, module technology, etc. We plan to use aggregated data for public presentations to protect plant owners.

15. Given that the Bill of Materials is kept private, what value does it have for failure analysis? Will poor performing components across multiple owners' plants be shared?

The BOM and the system layout are necessary for data analysis to understand the statistics of what is failing and any location-dependent issues. Data analysis can be presented in aggregate formats to demonstrate general trends. If Sandia-EPRI observe an issue with a particular component across multiple sites and designs, we may request that the Partners share the data themselves or in aggregate to bring awareness to the issue, with or without Sandia-EPRI assistance.

16. What reporting capabilities does PVROM offer?

XFRACAS supports incident record searches and report generation. In addition, it supports export of data to ReliaSoft reliability life data analysis and reliability growth analysis software products, which allow Sandia-EPRI to perform predictive analyses, sensitivity *studies, and to assess optimal O&M strategies. Program Partners may use other XFRACAS capabilities as well (e.g., failure analysis, corrective action tracking, etc.)*

17. At what frequency do Sandia-EPRI plan to publish reports based on PVROM data findings and analysis?
Sandia-EPRI intend to publish a joint report starting in 2013, for several years. The first report will provide introductory material and preliminary results that will set the stage for greater analysis and reporting in future years. As discussed above, no proprietary information will be released to the public without consent from Partners.

18. Is there a licensing fee associated with using PVROM?
Yes. Licensing costs are, however covered by Sandia-EPRI for the first five early adopter Partners. As of December 2012, two early adopters have signed-up for PVROM. Looking ahead, it is unclear whether these fees will be covered for future, non-early adopter Partners. It is possible that licensing fees for the first 10 Partner enrollees may be able to be covered. It is unknown, however, whether these fees can be covered in perpetuity.

19. What, to date, is the current number of PVROM Partners? What is the goal?
As of September, 2013about six partners have indicated participation in this effort representing approximately 30 MW of PV systems. Eventually, Sandia and EPRI seek a total of 10 -20 partners with hundreds of MW as part of the PVROM database.

20. Is the methodology governing Sandia's PV Reliability and Performance Model available for review?
Yes, the methodology can be shared, and a demonstration is available on the Sandia website at: http://energy.sandia.gov/?page_id=6367. Sandia-EPRI welcome Partner feedback.

For more information:

Roger Hill, Technical Staff, Photovoltaics and Distributed Systems Integration Department, Sandia National Laboratories, 505.844.8813, rrhill@sandia.gov,

Nadav Enbar, Senior Project Manager, Power Delivery & Utilization, Electric Power Research Institute (EPRI), 303.551.5208, nenbar@epri.com.

PV Reliability O&M Database (PVROM)

Frequently Asked Questions

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

B

PVROM MARKETING COLLATERAL

PV Reliability O&M Database (PVROM)

Descriptive Summary

BACKGROUND

Sandia National Laboratories and the Electric Power Research Institute (EPRI) have co-developed the Photovoltaic Reliability Operations and Maintenance (PVROM) database and a standardized data collection tool as a method to collect, analyze, and assess events and failures that occur in large (>100 kW) photovoltaic (PV) systems and plants. The PVROM tool is intended to enable data analysis exploring PV plant performance, reliability, and the economics associated with system maintenance and upkeep. It is, furthermore, aimed at using real world field data to examine trends that may inform optimal approaches to performing PV plant O&M.

Through their participation, PVROM Partners gain access to a repository of solar data to benchmark system performance, identify root causes of system failures, and recognize cost-benefit tradeoffs in making value chain improvements. Ultimately, PVROM is meant to abet and accelerate the adoption of PV systems as a primary power generation source in the United States.

STAKEHOLDER ROLES

Sandia & EPRI

For ease of use and oversight, Sandia and EPRI operate and maintain the database as well as provide database access requirements to Partners. This includes:

- Providing training materials and consultation to assist Partners in entering and retrieving data, performing data analysis via existing PVROM algorithms, and completing other activities, as appropriate;
- Developing technical and administrative functionality embedded in PVROM (e.g., development of new algorithms, potentially adding database parameters to collect specific kinds of PV O&M information, etc.); and
- Supplying cyber security for the database.

Partners

PVROM Partners—which encompass utilities, EPC/integrators, and third-party O&M providers—are responsible for initially entering and periodically updating field data information about their respective PV plants into the PVROM database. Activities include:

- Data entry detailing PV system characteristics (BOM, etc.) as well as planned and unplanned downtime incidents; and
- Use of PVROM functionality to perform data analyses, including comparative analyses.

Sandia National Laboratories

EPRI | ELECTRIC POWER RESEARCH INSTITUTE

PV Reliability O&M Database (PVROM)

Descriptive Summary

BENEFITS

PVROM Partners receive multiple benefits via project participation, including:

- Data anonymity enforced by a Sandia-generated Non-Disclosure Agreement.
- Full database access to individual Partner-entered data.
- Database access to aggregated data entered by other Partners, normalized for use (contingent upon database sample size).
    - Analysis of aggregated data is intended to provide Partners with a way to benchmark their plant results with a larger sample while maintaining a level of anonymity.
- Increased recognition and understanding of PV availability versus reliability (and associated O&M options based on output).
- Benchmarking PV performance/reliability with that of other Partners' input data that has been aggregated into PVROM.
- Better understanding of system costs and cost-benefit of multiple O&M approaches based on various factors.
- Ability to, for example, provide plant performance/expectation to insurance companies at five-year increments and better determine true plant value (and, in turn, renew insurance contracts via more favorable bank terms).
- Better understand the risk of possible future PV plant states (e.g., ID insurance products)

For more information:

Roger Hill, Technical Staff, Photovoltaic and Distributed Systems Integration Department, Sandia National Laboratories, 505.844.6111, rrhill@sandia.gov

Nadav Enbar, Senior Project Manager, Power Delivery & Utilization, Electric Power Research Institute (EPRI), 303.551.5208, nenbar@epri.com.

U.S. DEPARTMENT OF ENERGY

C

PROJECT CONTACTS

Table C-1
Contact information for Principal PVROM Project Researchers

Name	Title	Email	Phone
EPRI			
Travis Coleman	Project Manager	tcoleman@epri.com	505.715.1561
Nadav Enbar	Sr. Project Manger	nenbar@epri.com	303.551.5208
Cara Libby	Project Manager	clibby@epri.com	650.776.6009
Sandia National Laboratories			
Colin Hamman	Principal Member of Technical Staff	cjhamma@sandia.gov	505.844.3368
Roger Hill	Principal Member of Technical Staff	rrhill@sandia.gov	505.844.6111
Geoffrey Klise	Senior Member of Technical Staff	gklise@sandia.gov	505.284.2500

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

3002001399

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com