



Operation and Maintenance of PV Systems: Data Science, Analysis, and Standards

Andy Walker,¹ Jal Desai,¹ Thushara Gunda² and Nicole Jackson²

1 National Renewable Energy Laboratory

2 Sandia National Laboratory

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National Renewable Energy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Final Technical Report (FTR)
Cover Page

a. Federal Agency	Department of Energy	
b. Award Number	34172	
c. Project Title	Operation and Maintenance of PV Systems: Data Science, Analysis, and Standards	
d. Recipient Organization	NREL	
e. Project Period	<i>Start:</i> 10/1/2018	<i>End:</i> 12/31/2022
f. Principal Investigator (PI)	Andy Walker PhD PE Senior Research Fellow Andy.walker@nrel.gov 303 384 7531	
g. Business Contact (BC)	Kristen Ardani, Solar DAT/BOS Program Lead Phone: 303-384-6461 Email: kristen.ardani@nrel.gov	
h. Certifying Official (if different from the PI or BC)	N/A	

Andy Walker

4/14/2023

Signature of Certifying Official

Date

- 1. Acknowledgement:** This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the **Agreement Number 34172**.
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Project Summary: This effort improves the effectiveness and reduce uncertainty in O&M cost through four primary objectives/tasks: **1) institutionalize standards for reliability and availability reporting for large PV power plants; 2) bridge systemic O&M knowledge gaps around important topics affecting O&M; 3) characterize systemic failure modes and patterns and accelerate O&M experiential learning cycles using field data; and 4) Establish a baseline understanding of UPVS O&M Cost drivers**

Key results associated with this effort include production of a technical specification and report to the IEC committee, published case studies on O&M topics, conduct training, and characterize field data for climate- and service-related patterns (additional details below). Integrating these results (e.g., using case studies and data to inform and standardize O&M practices) serves to reduce performance risk and facilitate improvement in the way solar projects are operated and maintained.

- Objective #1: Institutionalize standards for reliability and availability reporting for large PV power plants.
 - Key Result #1: Produced an IEC Reliability Technical Specification Comment Draft that incorporates needs of PV power asset and O&M managers with at least 20 GW of global PV installations (≥ 2 MW), approved and published by IEC
 - Key Result #2: Provided Reliability Technical Report (TR) approved and published by IEC
 - Key Result #3: Participated in NERC's rule making process for mandatory reporting availability of PV power plants (i.e., 75 MW) in the Generating Availability Data System (GADS) to ensure at least 40% compatibility reporting with IEC 63019 Technical Specification, and issue guidance to asset managers describing how to comply with NERC's Solar GADS mandatory reporting by December 2020
- Objective #2: Bridged systemic O&M knowledge gaps (information asymmetries) around topics related to costs, performance ratios, system types, climates, extreme weather events, cyber-physical security, grid reliability, hazard insurance and procurement of O&M services.

- Key Result #1: Published a paper/case study on each of six topics identified as priorities for knowledge gap analysis.
- Key Result #2: Educated asset owners of small commercial, state, local, and federal PV systems by producing service procurement specification samples for distributed generation- and utility-scale PV. Demonstrated that participants improved their understanding of O&M procurement issues by 80% as measured by knowledge assessments.
- Key Result #3: Published a self-guided training, with knowledge assessments, accessible to the public.
- Objective #3: Characterized systemic failure modes and patterns and accelerate O&M experiential learning cycles using field data.
 - Key Result #1: Expanded current database of large PV systems event/failure logs to cover climatological regions and increase climatological region resolution using the Köppen classification for regions currently represented in the database.
 - Key Result #2: Expanded sample reliability distributions for inverter faults, failures, and O&M practices to cover all climatic regions represented in the database and demonstrate accuracy improvement of the O&M Cost Model with these higher resolution reliability distributions.
 - Key Result #3: Published public guidance to help PV asset managers conduct their own conversions of maintenance field data into reliability distributions.
 - Key Result #4: Used machine learning techniques to characterize predictive correlations between O&M issues, climatological regions, extreme weather events and variability of O&M practices on system performance ratios; and publish paper with results to help augment expert insights-based practices with data-driven quality control methods.
- Objective #4: Established a baseline understanding of UPVS O&M Cost drivers
 - Key Result #1: PV + Storage systems owners/operators/O&M providers contributed, through interviews/surveys, to a baseline understanding of UPVS O&M Cost drivers
 - Key Result #2: Analyzed datasets of different data sources that “systemically” track O&M costs for UPVS in different climatic U.S. regions as defined by NOAA
 - Key Result #3: Conducted outreach (webinar) on factors and findings from interviews as well as data considerations.

Project Objectives and Outcomes:

Task 1 has resulted in three (3) published IEC Standards. Task 2 has resulted in 9 publications on topical investigations. Task 3 is complete with results reported in Sandia NL reports, IEEE journal and other knowledge outlets. Task 4 is complete with delivery of report and webinar on drivers of O&M cost in PV and battery systems. The webinar “Drivers of O&M Cost in PV+storage Systems” was attended by a global audience of 340 people.

Deliver Reliability Technical Specification Report to IEC for Review and Approval 12/31/2020

On June 28, notice was received that the submitted IEC TS 63265:2022 (TC82) **Reliability practices for the operation of photovoltaic power systems (PVPS)**, a new standard, was released. This completes the work on this contract task. The following deliverables are available through American National Standards Institute (ANSI) or IEC webstore.

Published IEC/ANSI Standards:

- IEC/TS 63019 Ed. 1.0 en:2019 **Photovoltaic Power Systems (PVPS) – Information Model For Availability** <https://webstore.ansi.org/Standards/DS/DSIECTS630192019>
- IEC TR 63292:2020 **Photovoltaic power systems (PVPSs) - Roadmap for robust reliability** <https://webstore.ansi.org/Standards/BSI/PDIECTR632922020>
- IEC CD 63265:2020 **Reliability Practices for the Operation of Photovoltaic Power Systems.** <https://webstore.ansi.org/Standards/DS/DSIECTS632652022>

Publications to Bridge Systemic O&M Knowledge Gaps Quarterly Q3 and Q4 in FY 19 and Q1, Q2, Q3 and Q4 FY20

Please see below the status for publications under Task 2 Agreement 34172.

Table 1. Publications under Task 2 Bridge Systemic Knowledge Gaps

Topic /Paper Title	Link	Download Total (as of (1/10/23))
<i>Model of Operation and Maintenance Costs for Photovoltaic Systems*</i>	https://www.nrel.gov/docs/fy20osti/74840.pdf	37099
<i>Performance of Photovoltaic Systems Recorded by Open Solar Performance and Reliability Clearinghouse (oSPARC)*</i>	https://www.nrel.gov/docs/fy19osti/75162.pdf	2294
<i>Best Practices in Operation and Maintenance of PV Systems*, 3rd Ed.</i>	https://www.nrel.gov/docs/fy19osti/73822.pdf	87301 (#16 in top NREL Pubs)
<i>Severe Weather Impacts on Photovoltaic Plant Operations</i>	https://www.osti.gov/biblio/1837045-weather-impacts-solar-pv-operations-summary-current-body-knowledge-implications-further-investigation	tbd
<i>Insurance in the Operation of Photovoltaic Plants</i>	https://www.nrel.gov/docs/fy21osti/78588.pdf	3899
<i>Best Practices at the End of the Photovoltaic System Performance Period</i>	https://www.nrel.gov/docs/fy21osti/78678.pdf	6130
<i>PV Fleet Performance Data Initiative: Performance Index-Based Analysis</i>	https://www.nrel.gov/docs/fy21osti/78720.pdf	1289
<i>Cybersecurity in Photovoltaic Plant Operations</i>	https://www.nrel.gov/docs/fy21osti/78755.pdf	1760

Sample Procurement Specifications

This task is complete. Gerald Robinson of LBNL produced PV OPERATIONS AND MAINTENANCE SERVICES AGREEMENT (60 pages). Available for free download at <https://buildings.lbl.gov/solar-photovoltaic-operations-and-maintenance>

Task 3 Milestone #1: Leverage machine learning and data analytics to gain insights into O&M practices (Year 2 Report)

Milestone Status: Complete. Distribution analysis has been completed and the associated how-to report is complete. We’ve also completed a paper on the analysis of weather events implementing machine learning models to identify any systemic variations (e.g., location or operator) in weather impacts. This paper has been published at *Applied Energy*. Another paper focused on using topic modeling for inverter failures was published in *IEEE Access* in Nov 2020 as listed in the following table.

Table 2. Publications describing the data science of Task 2 by Sandia National Laboratory

<u>Topic /Paper Title</u>	<u>Publication Date</u>	<u>Next Step(s)</u>
<u>Evaluation of Component Reliability in Photovoltaic Systems using Field Failure Statistics</u>	<u>Sep 2020</u>	Sandia Natl Lab report (SAND): https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2020/209231.pdf
<u>A Machine Learning Evaluation of Maintenance Records for Common Failure Modes in PV Inverters</u>	<u>Nov 2020</u>	<i>IEEE Access</i> : https://doi.org/10.1109/ACCESS.2020.3039182
<u>Evaluation of Extreme Weather Impacts on Utility-scale Photovoltaic Plant Performance in the United States</u>	<u>Nov 2021</u>	<i>Applied Energy</i> : https://doi.org/10.1016/j.apenergy.2021.117508

Task 4: Establish a baseline understanding of UPVS O&M Cost drivers

Compiled initial findings from the literature regarding insights into current O&M practices for PV + storage titled “Literature Review Deliverable” and satisfies the 9/30 milestone deliverable.

Developed and deployed a questionnaire for PV+storage owners and operators available at : <https://survey.alchemer.com/s3/6537904/PV-O-M> (meeting Dec 2021 deliverable).

Data collection from PV+storage owners and operators regarding their experiences and observations related to O&M has been completed. Below is a summary of the data collection effort:

Table 3. Status of data collection effort in terms of number of sites and people contacted and number of responses received.

	Summary	Goal	Goal Completion
Number of contacts	250	-	-
Number of sites	81	-	-
Total PV (MW)	51.1	125	41%
Number of responses	14	30	47%

Approximately 250 practitioners, industry groups, and government agencies were contacted the goal of 30 responses representing 125 MW will not be achieved. Information has been completed for 14 responses. These responses cover 81 sites (51.1 MW of PV with 64.1 MWh of storage) across 13 states. Synthesis of findings into a final report will be the focus on next quarter’s activities.

Completed a technical brief containing evaluation of data for UPVS systems within PVROM to identify patterns for performance and operations. Document is titled “Summary of Storage-Related Entries in PVROM” and satisfies 06/30/2022 milestone deliverable.

Sandia National Laboratory provided data regarding Battery Energy Storage Systems and delivered for Task 4.4 Deliverable to NREL and to DOE. This information was used in this report on storage cost drivers and also available for future proposed O&M cost modeling. Fourteen sites within PVROM currently contain storage-related O&M tickets. These sites are all located within North Carolina and managed by one of our partners. The sites were generally commissioned between Nov 2016 to Dec 2017. Most of the sites have solar capacity of <1000 kWDC (1 MWDC), except for two that are ~4000 kWDC (4 MWDC) and ~27000 kWDC (27 MWDC; sites C3S161 and C3S179, respectively). The smaller systems use a string inverter while the two larger systems are on a central inverter. All of these sites are utility-scale systems with most having fixed systems except one that’s a tracker. A total of 152 O&M tickets were labeled under either “Energy Storage/Battery” or “Battery (Solar + storage facilities)” asset labels. A small portion of the tickets (<5%) had manufacturer-related warranty claims associated with them. Additional details about these tickets are captured below. Generally, the tickets were distributed across all of the fourteen sites. Interestingly enough, the two largest sites had the lowest number of tickets. Rather than fewer issues per se, the relatively low number of tickets at these sites could reflect alternate agreements with O&M services/documentation than the other sites. The tickets lasted in duration from one minute to over 79 days. Generally, the failure initiated throughout the year, with higher prevalence in winter and spring months and a spike towards the end of summer. A majority of the tickets related to underperformance-related issues (64%), while some discussed production outages (19%) or communications-related outages (16%). The specific completion activity ranged from remote troubleshooting to repairs and self-resolutions to combinations of activities.

- 3. Path Forward:** The “Best Practices” guide is a very successful product with 90,000 downloads and should be kept updated. Battery storage should also be added to the Best Practices guide. The “Cost Model” is also a very successful effort with 40,000 downloads and battery storage should be added to that product. The topical investigations involve some very dynamic topics such as cybersecurity and disposal of waste which should be kept

updated as these issues evolve. Presentation at more workshops, conferences, and trainings could leverage the impact of this work.

4. Inventions, Patents, Publications, and Other Results:

TITLE	CONF/JOURNAL	AUTHORS	DATE
Classification of photovoltaic failures with hidden Markov modeling, an unsupervised statistical approach	Accepted in <i>Energies</i>	Michael Hopwood, Lekha Patel, and Thushara Gunda	07/11/2022
PV+ Storage Operation and Maintenance	Photovoltaic Specialists Conference	Nicole D. Jackson et al.	06/08/2022
Operations and Maintenance Considerations for PV+ Storage	PV Reliability Workshop	Nicole D. Jackson	2/24/2022
Weather impacts on utility-scale photovoltaic plant performance	NOAA Workshop on Leveraging AI	Nicole D. Jackson	09/14/2021
Evaluation of extreme weather impacts on utility-scale photovoltaic plant performance in the United States	Applied Energy	Nicole D. Jackson and Thushara Gunda	8/16/2021
Masking of Photovoltaic System Performance Problems by Inverter Clipping and other Design and Operational Practices	Renewable and Sustainable Energy Review	John Balfour et al.	4/17/2021
Weather Impacts on Utility-Scale Photovoltaic Plant Performance	American Geophysical Union Fall Meeting	Nicole D. Jackson, Thushara Gunda, and Andrea Staid	12/10/2020
A Machine Learning Evaluation of Maintenance Records for Common Failure Modes in PV Inverter	IEEE Access	Thushara Gunda et al.	11/09/2020
PV Hardware Vulnerabilities Presentation: Revealed During Storm Stresses	PV QAT	Gerald Robinson and James Elsworth	06/02/2020
Multi-site assessment of extreme weather impacts on PV plant performance and reliability	PV Reliability Workshop	Nicole D. Jackson and Thushara Gunda	2/17/2020
Inverter Faults & Failures: Common modes & patterns.	PV Reliability Workshop	Thushara Gunda	02/17/2020
Progress in IEC PV Availability and Reliability	PV Reliability Workshop	Roger Hill	02/17/2020
Inverter O&M Strategies	New Energy Update	Andy Walker	11/14/2019
Achieving Excellence in Solar O&M	PV O&M USA Conference	Andy Walker et al.	11/6/2019
Achieving Operational Excellence in Solar O&M	New Energy Update Webinar, 488 participants	Andy Walker	09/09/2019
Methods to Optimize Maintenance in PV Plants	PV Reliability Workshop	Michael Bolen, Sean Hackett, and Thushara Gunda	02/27/2019
PV in Severe Weather Events Gap Analysis	PV Reliability Workshop	Gerald Robinson and Andy Walker	02/26/2019

5. Project Team:

National Renewable Energy Laboratory: Andy Walker; primary responsibility for overall agreement coordination and delivery of work under Task 2.

Sandia National Laboratory: Thushara Gunda; primarily responsible for delivery of work under Task 3, Nicole D. Jackson primarily responsible for delivery of work under Task 4

Lawrence Berkeley National Laboratory: Gerald Robinson; supporting technical contribution to Task 2

Standards Consultant: Roger Hill; primarily responsible for Task 1.