

Understanding Solar Photovoltaic System Performance

An Assessment of 75 Federal Photovoltaic Systems

December 2021

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Authors

The authors of this report are:

Andy Walker, National Renewable Energy Laboratory (NREL)

Jal Desai, NREL.

Acknowledgments

Support for this work from the U.S. Department of Energy’s Federal Energy Management Program (FEMP) is gratefully acknowledged. Within FEMP, the authors would especially like to thank Program Manager Rachel Shepherd and American Association for the Advancement of Science (AAAS) Science & Technology Policy Fellow Nichole Liebov. The assistance of the staff of 16 federal agencies and subagencies that provided system descriptions and performance data is gratefully acknowledged. Jake Bever and Pragadeesh Meenakumar of NREL processed site data, performed computer simulations, and prepared reports for each site. The assistance of Katie Wensuc and Caitlin Dorsey in editing the document is gratefully acknowledged.

List of Acronyms

ANSI	American National Standards Institute
API	Application Programming Interface
ARRA	American Recovery and Reinvestment Act
DC	direct current
DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOT	Department of Transportation
EERE	Energy Efficiency and Renewable Energy
FEMP	Federal Energy Management Program
GSA	General Services Administration
IEC	International Electrotechnical Commission
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
O&M	operations and maintenance
POA	Plane of Array
PV	photovoltaic
SAM	System Advisor Model
TWC	The Weather Company
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
VA	Veterans Affairs

Nomenclature

δ	Temperature coefficient of power ($1/^{\circ}\text{C}$), for example, $0.004/^{\circ}\text{C}$
η_{BOS}	Balance-of-system efficiency; typically, 80% to 90%, but stipulated based on published inverter efficiency and other system details such as wiring losses.
A	Availability, (total time – downtime)/total time
CV	coefficient of variation for population
degr	An age degradation factor that is 1.0 initially but degrades at the rate R_d (per year) to represent the cumulative lost production over a multiyear analysis period
E	Energy, expressed in units of kWh
ER	Energy Ratio, total measured production divided by total model production, thus considering the effects of both Availability and Performance Ratio.
G	Irradiance, incident flux of radiant power per unit area, expressed in units of W/m^2
G_{ref}	Reference value of Irradiance, equal to $1000 \text{ W}/\text{m}^2$
G_{POA}	Plane of Array Irradiance, the sum of direct, diffuse, and ground-reflected irradiance incident upon an inclined surface parallel to the plane of the modules in the photovoltaic array, also known as POA Irradiance and expressed in units of W/m^2 .
H	Irradiation, irradiance integrated over a specified time interval expressed in units of kWh/m^2
P	Power, instantaneous power, or product of current and voltage, expressed in units of kW
PR	Performance Ratio based on measured production divided by model-estimated production over the same time period, considering only when the plant is “available.”
PTC	PV USA test conditions, reference values of in-plane irradiance ($1,000 \text{ W}/\text{m}^2$), photovoltaic cell junction temperature (25°C), and the reference spectral irradiance defined in International Electrochemical Commission Standard 60904-3
r	desired relative error
STC	Standard test conditions, reference values of in-plane irradiance ($1,000 \text{ W}/\text{m}^2$), photovoltaic cell junction temperature (25°C), and the reference spectral irradiance defined in International Electrochemical Commission Standard 60904-3
T_{ambient}	Ambient temperature ($^{\circ}\text{C}$), averaged over the duration of the time interval $t_2 - t_1$

R_d Degradation rate expressed as percentage reduction in output from the previous year; reportedly on the order of 0.6% to 1% per year (Kurtz et al. 2016)

Executive Summary

This report presents a performance analysis of 75 solar photovoltaic (PV) systems installed at federal sites, conducted by the Federal Energy Management Program (FEMP) with support from National Renewable Energy Laboratory and Lawrence Berkeley National Laboratory. Results are based on production data collected from these systems, provided by federal agencies participating in the FEMP's Solar PV Performance Initiative. Production data was combined with coincident insolation and ambient temperature to analyze how actual performance compares with a performance model. FEMP collaborated with staff of 16 federal agencies and subagencies to collect the information required to analyze the performance of each PV system. The systems represent a total capacity of 30,714 kW and range in size from 1 kW to 4,043 kW, with an average size of 410 kW, and were installed between 2011 and 2020.

System data is analyzed for key performance indicators including availability, performance ratio, and energy ratio by comparing the measured production data to modeled production data. The analysis utilized the National Renewable Energy Laboratory's System Advisor Model (SAM), which combines a description of the system (such as inverter capacity, temperature derating, and balance-of-system efficiency) with environmental parameters (coincident solar and temperature data) to calculate predicted performance. The performance metrics are calculated by aligning the measured production data with the model estimate on an hour-by-hour, day-by-day, or month-by-month basis (depending on the interval resolution of the production data). A report with a system description, photographs of the system, special assumptions made for the site, a graph of measured and modeled production, a table of key performance indicators, and links to operations and maintenance resources that might improve performance was produced and delivered to site and agency staff with a short online briefing. This report summarizes the results across the 75 systems for which this analysis was conducted.

Table ES-1 shows data for each site anonymized and combined in a statistical analysis to characterize performance of the entire set of federal PV systems analyzed.

Table ES-1. Key Performance Indicators Resulting From the Analysis of 75 Federal PV Systems

	Minimum	Average	Median	Maximum	Standard Deviation
Availability	31.0%	95.1%	98.0%	100.0%	8.8%
Performance Ratio	46.0%	78.6%	79.0%	101.0%	11.7%
Energy Ratio	29.0%	74.6%	76.0%	101.0%	14.1%

Average availability of this sample of federal systems was measured at 95%, suggesting that federal agencies are doing a good job of reacting quickly and minimizing downtime. When available, these systems delivered, on average, 79% of the power estimated by the model. In contrast, the energy ratio, which combines the effects of both downtime and partial performance, averaged 75%. The performance ratio featured a standard deviation of 11.7%, indicating

significant variability in the performance of individual systems, with only one or two systems achieving model-estimated energy delivery. Some level of underperformance is expected, and 100% availability would be prohibitively expensive to pursue.

The measured performance metrics presented here are useful in two respects:

- 1) Future feasibility studies will be better informed regarding realistic expectations of performance.
- 2) Owners of existing systems may compare their own measured performance to this average when thinking about performance and focusing corrective actions.

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1 Introduction

As of 2020, the federal government has installed more than 3,000 solar photovoltaic (PV) systems. PV systems can have 20- to 30-year life spans. As these systems age, their performance can be optimized through proper operations and maintenance (O&M). This report presents the findings of the Federal Energy Management Program's (FEMP's) Solar PV Performance Initiative, which aims to understand the performance of the federal PV fleet as compared to expected performance. The study was motivated by a desire to help agencies to understand system performance, address underperformance, and anticipate realistic performance in future feasibility studies. The study also supports FEMP in making recommendations to agencies regarding the design, implementation, and maintenance of PV systems. Figure 1 displays the distribution of 3,041 federal PV systems among agencies, including National Aeronautics and Space Administration (NASA), Army Corps of Engineers (USACE), Department of Transportation (DOT), Veterans Affairs (VA), General Services Administration (GSA), U.S. Department of Agriculture (USDA), Department of Homeland Security (DHS), Department of Energy (DOE), Department of the Interior (DOI), and Department of Defense (DoD). As the largest energy consumer in the federal government, DoD predictably has the greatest number of PV systems installed. With many small, remote sites, DOI has a large number of small systems.

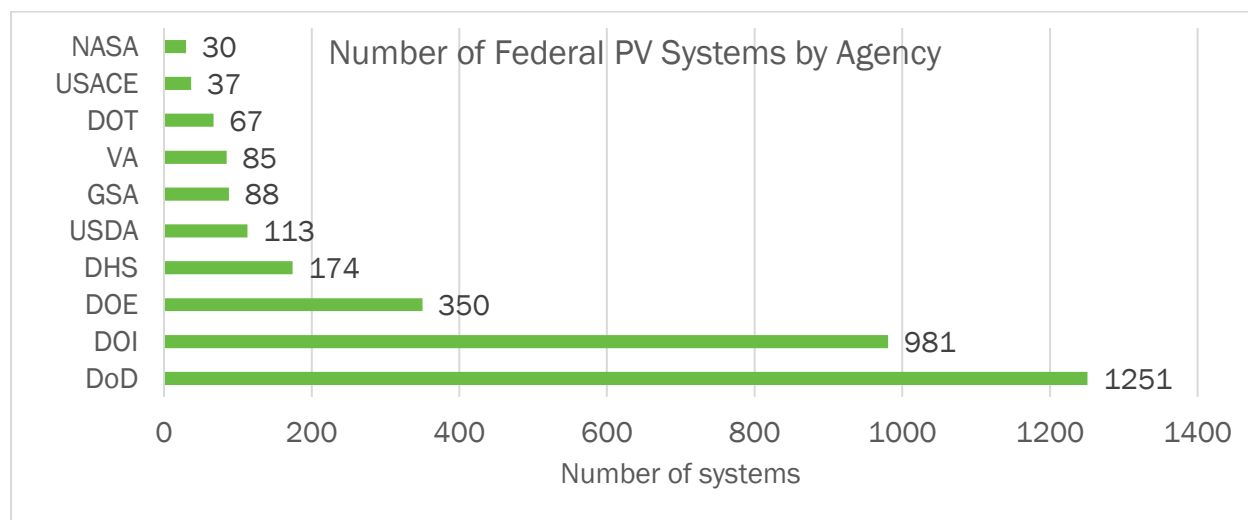


Figure 1. Number of PV systems installed by federal agency. Excludes agencies reporting fewer than 30 systems.

Source: DOE (2021)

Figure 2 groups quantities of federal solar PV systems according to the year in which they were placed in service. Many federal PV systems were installed between 2010 and 2014, funded through the 2009 American Recovery and Reinvestment Act (ARRA). Over a decade later, the way in which these PV assets are performing in real-world conditions may provide valuable insights to agencies and other entities considering installing solar PV systems.

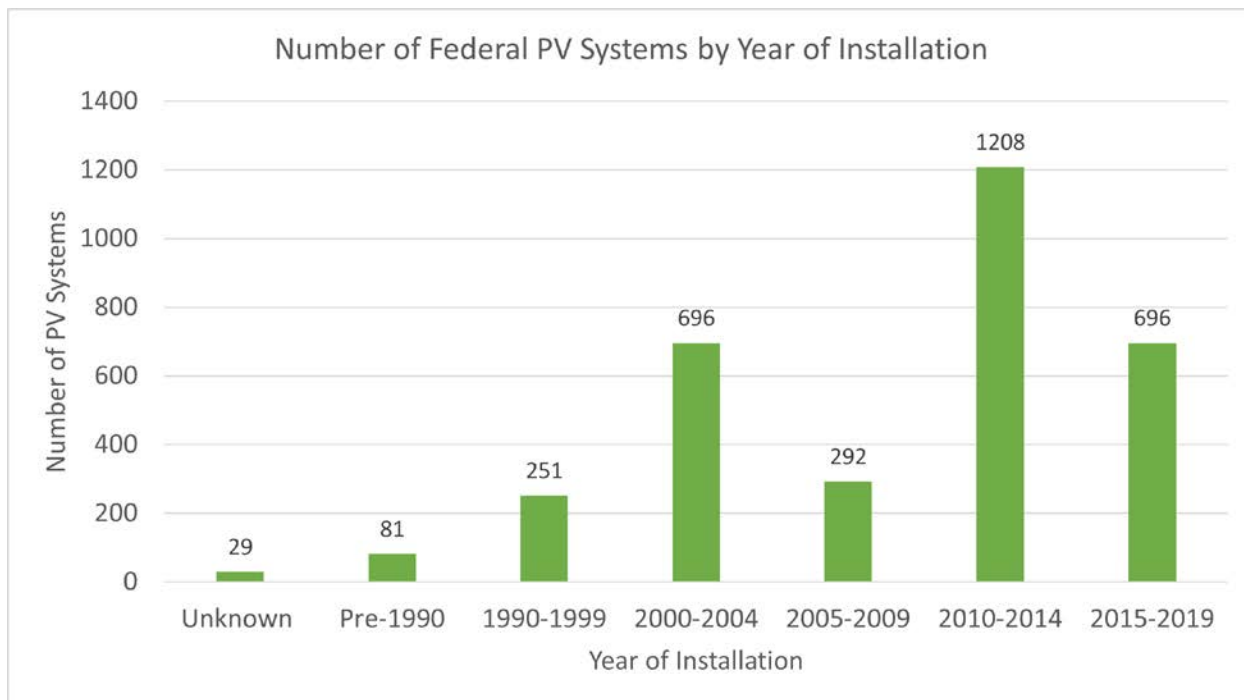


Figure 2. Number of federal solar PV systems by year of installation.

Source: DOE (2021)

Three key metrics are useful for understanding PV performance and reliability: availability, performance ratio (sometimes abbreviated as PR), and energy ratio.

- **Availability** is the actual measured hours of production divided by the modeled hours of production. An unavailable hour is easily identified by an output of zero, but values are often not exactly zero—an hour is therefore tallied as unavailable if the measured output is less than 5% of the model output.
- **Performance ratio** is the measured production divided by modeled production during timesteps when the system is available.
- **Energy ratio** is the total measured production divided by total modeled production, and thus includes both the effects of availability (downtime) and performance ratio (inefficiency) in the same metric.

Availability and performance definitions may be found in International Electrotechnical Commission (IEC) standards 63019 (2019) and 61724 (2017). Availability and performance ratio are reported separately because they affect management actions and life cycle cost in different ways as described in Walker et al. (2020b)—lower availability reduces operating hours and a lower performance ratio reduces power output. After presenting early reports to agency staff, we realized what staff are really interested in is the “bottom line”—how much energy was produced (in kWh or MWh) in each year—so we introduce an energy ratio metric as the ratio of measured

energy delivery to model-prediction of energy delivery, thus including the effects of both availability and performance ratio.

These three performance indicators were calculated for each system for which agencies provided data, and the data for each was anonymized and consolidated to provide distributions for these three performance indicators across the sample of 75 systems.

2 Background

Performance ratings of PV modules are measured under standard test conditions (STC) of 1,000 W/m² of sunlight and 25°C cell temperature. In practice, however, the intensity of sunlight is usually less than 1,000 W/m², and the cell temperature is typically hotter than 25°C.

Additionally, once PV systems are deployed, several factors can impact their expected production (electric energy generated), including solar resource, temperature, and degradation due to the age of the system. Although the solar resource is variable, most of the variability is predictable based on time of day, time of year, and the angle that sunlight hits the PV module surface. In fact, the solar resource would be perfectly predictable based on clear-sky models if not for clouds, which are not as predictable. Therefore, we rely on reported satellite data for clouds and solar resource at each location when assessing the expected performance of a PV system. PV module output decreases with temperature according to a temperature coefficient, δ , which is the percent reduction in power per degree Celsius above a reference temperature. PV module efficiency unavoidably degrades with age at a rate, degr , of about 0.5% per year. Electrical losses will also occur throughout the balance of system, which can be estimated. Failure rates are also higher in later years as the equipment ages, increasing downtime. Events such as severe weather can also impact PV system performance in unpredictable ways. A comparison of the system's actual output with the expected output can be used to quantify underperformance.

Standard methods to characterize PV system performance have evolved over time and methods still vary among different reports. Even IEC 61724-1, a single standard, outlines three different calculations of performance ratio. The definition of PR is in all three cases the quotient of the system's final yield to its reference yield, which is an expectation of performance. The three cases in IEC 61724-1 differ in the definition of the reference yield. Reference yield may be based on STC rating; on PVUSA Test Conditions (PTC) rating; on PTC rating adjusted for solar resource and temperature, or as determined by simulation model results. When interpreting results, the definition of "reference yield" should be specified explicitly, and when comparing values, it is important to consider the calculation method. Dierauf et al. (2012) describe how to account for weather patterns and adjust the performance ratio based on sunlight and temperature to give consistent results and to use as a metric for performance guarantees. In this study, we use the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM) to calculate the reference yield in the denominator of the PR because this is the most detailed, non-proprietary, and widely recognized performance assessment software (NREL 2021).

2.1 Key Performance Indicators of PV Systems Measured in Other Studies

In the paper “Performance ratio revisited: is $PR > 90\%$ realistic?” Reich et al. (2012a) report the performance ratio (based on STC, called PR_{STC}) of 100 systems in Germany to be between 70% and 90% for the year 2010, with a median of 84%. They also found that measurements based on irradiance from reference cells were 2%–4% higher than those based on more accurate pyranometers. In “Review of PV Performance Ratio Development,” Reich et al. (2012b) present performance ratio data and how it has evolved over the past 30 years, ranging from as low as 50% in the 1980s to over 90% currently due to improvements in components and reductions in shading. In the book chapter “Introduction to Photovoltaic System Performance,” Pearsall (2017) covers the basics of PV system performance and the different parameters that may affect the PV system performance ratio. “Weather-Adjusted Performance Guarantees” (Hollingsworth 2010) illustrates a methodology that uses the monthly production data set and location-specific solar index to calculate accurate weather-based performance of PV systems, which can be useful to suppliers and insurers when they offer performance guarantees.

Deline et al. (2020) reported on the performance of 250 PV systems throughout the United States, comprising 157 megawatts (MW) direct current (DC) capacity, to have an average PR of 93.5%. First-year start-up issues, snowfall, and inverter downtime were cited as the reasons for PR averaging less than 1. Analysis from 2,200 PV systems in California reporting into the open System Performance and Reliability Clearinghouse reports an average weather adjusted performance ratio of 91.7% (Walker et al. 2019).

While these other studies use differing definitions and calculations of performance ratio, they all indicate that performance equivalent to 100% of reference yield is an unrealistic expectation. Based on the authors’ judgement as well as the above data, and considering that phenomena like soiling are not included in our reference yield (so that we can measure soiling as underperformance in actual data), availability of 95%, performance ratio of 85%, and energy ratio of 79% may be realistic expectations.

3 Research Methodology

The research methodology is illustrated in Figure 3. For each PV system, the agency provided the record of measured production over a time period (often several years) and the system description. The production data was often delivered as an Excel spreadsheet of time series data but in many cases the agency provided NREL with log-in credentials to the monitoring platform to download the production data. Solar radiation and temperature data was then obtained from the National Solar Radiation Database (NSRDB) or The Weather Company (TWC, an IBM data company), depending on the year of measured production provided by the agency. NREL staff estimated the modeled hourly production in SAM based on the system description and solar resource data. An hour-by-hour comparison of measured production to model production was then used to calculate the key metrics of system performance. A report with system description, photograph of the system, special assumptions made for the site, graph of measured production

and model production, table of key performance indicators, and links to O&M resources that might improve performance was produced and delivered to site and agency staff with a short on-line briefing.

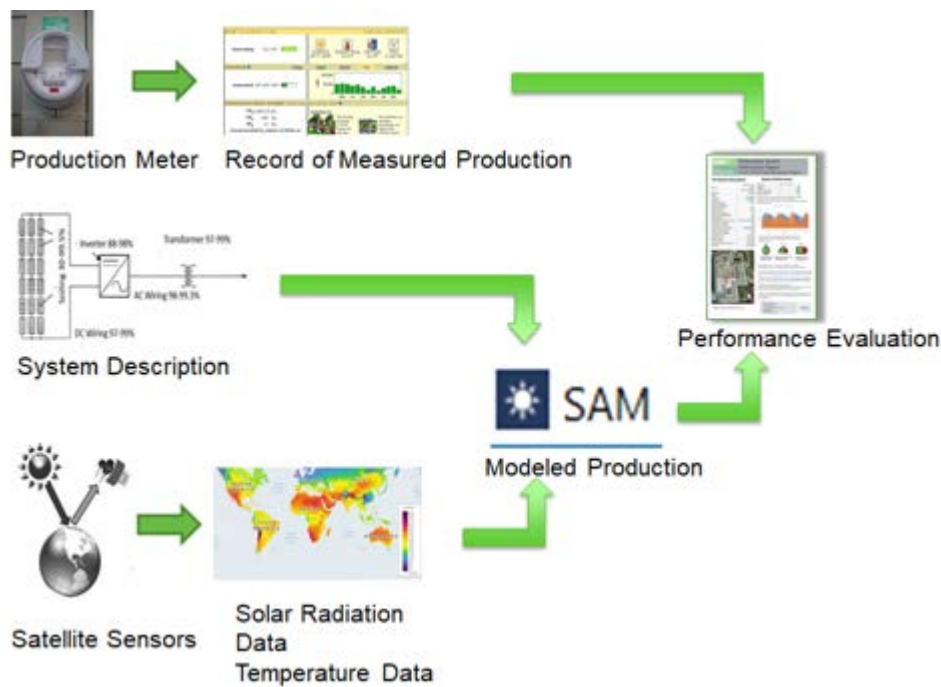


Figure 3. Methodology of the performance assessment to compare records of actual measured production with computer models based on system description and climate data.

Illustration by Andy Walker, NREL

3.1 Data Collection

In Fiscal Year 2019, FEMP alerted federal agencies of the opportunity to participate in the FEMP Solar PV Performance Initiative. Sixteen federal agencies and subagencies participated in the initiative including the Architect of the Capitol, Bureau of Land Management, U.S. Drug Enforcement Administration, U.S. Army, U.S. General Services Administration, Hawaii Army National Guard, Immigration and Customs Enforcement, Internal Revenue Service, Kentucky Army National Guard, NASA, National Park Service, New Jersey Army National Guard, Department of State, USDA Forest Service, U.S. Marine Corps, and VA.

We sought a statistically significant sample size to characterize the fleet of federal PV systems. From Holman (2012), the sample size required to achieve a desired relative error is $n = \frac{t^2 \cdot CV^2}{r^2 [1 + \frac{t^2 \cdot CV^2}{N}]}$ where N = total number of systems, CV = coefficient of variation for population, r = desired relative error, and $t = 2$ for 95% confidence level. Using this equation, the sample size was estimated at 75 systems required for a desired relative error of 5%, and value for CV from oSPARC (Walker et al. 2019). The coefficient of variation is the standard deviation divided by the mean. Now that the study is complete, we can revise this with the measured standard deviation of 14.1% divided by average of 74.6% for a $CV = 18.9\%$ (for energy ratio),

and update the population to $N = 3,041$ systems. These revisions result in a relative error of 4.3% associated with the sample of 75 systems actually analyzed.

The 75 fielded systems analyzed represent a total 30.7 MW of installed capacity. While the average system size was 409.6 kW DC (Table 1), the system sizes range from 1 kW to 4,043 kW. The high proportion of small systems contributes to a median value of 56.7 kW.

Table 1. Minimum, Average, Median, and Maximum Size (kW DC) of PV Systems Included in the Sample of 75 Systems

	Minimum	Average	Median	Maximum
System Size (kW DC)	1.0	409.6	56.7	4043.2

System Description

NREL and FEMP requested a “system description” from each agency or subagency with information about each PV system sufficient to inform the SAM inputs, including:

1. Location (longitude and latitude)
2. System size (kW DC)
3. System installation date
4. Tilt angle up from the horizontal
5. Azimuth angle east or west of due south
6. Tracking option (fixed tilt or tracking)
7. PV module make and model number
8. Inverter make, model, and topology of inverter arrangement.

The SAM computer program includes a library of PV modules and inverters, and for most sites the exact make and model could be selected. When not already in the library, NREL staff obtained the product specifications from manufacturers’ websites and added the inverter or PV module to the program library. Important information on PV modules includes rated capacity (Watts) and a temperature coefficient affecting efficiency. For the inverter, important information includes the rated capacity and curve of efficiency versus power level.

Coincident Weather Data

The SAM model computes power output each hour based on coincident solar radiation and temperature obtained from satellite data rather than on-site measurements. Most of the sites do not have on-site solar measurements, and some of those that do are affected by sensor calibration and maintenance, sensor cleaning, and data connectivity. High-spatial-and-temporal-resolution satellite-based weather data for the location of each PV system and the coincident times was obtained from either The Weather Company,¹ an IBM data service that provides solar resource

¹ <https://www.ibm.com/weather>

information, or from the National Solar Radiation Database (NSRDB)² (Sengupta 2018). The NSRDB data set is serially complete, is available at high (four-kilometer) spatial resolution across the United States, has a 30-minute time resolution, and avoids the complications of imperfect instrument maintenance. The selection of the weather source was dependent on the proximity to the actual site and year of production data received. NSRDB has data for preceding years, whereas data from TWC has more recent data and was used for the current year. NSRDB coverage is limited to the United States, Puerto Rico, and Guam, so TWC was used for international sites. The data for each location was downloaded on an hourly basis to match hourly production data, or down-sampled to match data provided at daily rather than hourly intervals. The important parameters in the weather data for each timestep are the direct normal solar radiation, diffuse radiation, and the temperature. With these weather parameters, SAM can calculate the incident solar radiation in the Plane of Array (POA), the PV module and inverter efficiency, and the power output for each hour.

3.2 Data Analysis

NREL used the PV system characteristics and weather data to model estimated performance using SAM, and then compared modeled generation to measured generation.

Inputs to SAM are chosen strategically to include the effect of some losses and isolate other losses in the measurement of performance. For example, losses in wiring resistance are included in SAM but losses due to soiling or system age are not. A PV system operator might only be interested in the magnitude of losses that can be measured by comparison to a model that does not correct for those losses (“measurable losses”), such as soiling, whereas predictable sources of losses like wiring resistance are included in the expected model energy calculation and reduce the model estimate, so losses due to these “predictable” losses do not show up in the analysis as a source of underperformance because the model has been corrected for them. For this effort, we choose to include losses for predictable effects like wiring loss and other balance-of-system efficiencies while omitting measurable losses like array soiling and inverter downtime from the expected energy production. Table 2 shows a complete listing of both measurable and predictable loss assumptions. Figure 4 shows the SAM user interface by which site-specific parameters are entered into the SAM computer program for analysis.

² <https://nsrdb.nrel.gov/>

Table 2. Expected Energy Loss Assumptions Used in the SAM Estimate of Production

Predictable Losses	Value in SAM
Mismatch	2%
Wiring	2%
Connections	0.5%
Light Induced Degradation	1.5%
Nameplate	1%
Measurable Losses	
Soiling	0%
Snow Cover	0%
Shading	0%
Availability	0%
Degradation Due to Age	0%

In other words, by setting the effect of measurable losses to zero in the model, these losses will be exposed as underperformance in a comparison of measured to modeled production. For example, the measured performance ratio might decline from the model performance over the years, exposing degradation due to age.

An hour-by-hour comparison of measured production to modeled production was then used to calculate the three key metrics of system performance—availability, performance ratio, and energy ratio.

The screenshot displays the SAM (System Advisor Model) user interface for Photovoltaic, Commercial systems. The interface is divided into several sections:

- Photovoltaic, Commercial**: The main category selected.
- Location and Resource**: A dropdown menu.
- Module**: A dropdown menu.
- Inverter**: A dropdown menu.
- System Design**: The current active section, containing:
 - AC Sizing**: Includes fields for Number of inverters (1), DC to AC ratio (1.13), and checkboxes for Estimate Subarray 1 configuration.
 - DC Sizing and Configuration**: Includes a table for Subarray 1, 2, 3, and 4, with fields for Modules per string, Strings in parallel, Number of modules, String Voc, and String Vmp.
 - Tracking & Orientation**: Includes a diagram of a solar panel array and checkboxes for Fixed, 1 Axis, 2 Axis, Azimuth Axis, Seasonal Tilt, and Tilt=latitude.
- Shading and Layout**: A dropdown menu.
- Losses**: A dropdown menu.
- Lifetime**: A dropdown menu.
- Battery Storage**: A dropdown menu.
- System Costs**: A dropdown menu.
- Financial Parameters**: A dropdown menu.
- Incentives**: A dropdown menu.
- Electricity Rates**: A dropdown menu.
- Electric Load**: A dropdown menu.
- Simulate >**: A button to start the simulation.
- Parameters**: A dropdown menu.
- Stochastic**: A dropdown menu.
- PSO / P90**: A dropdown menu.
- Macros**: A dropdown menu.

Figure 4. User interface for SAM used to predict modeled performance of each system.

3.3 Report for Each PV System

NREL provided individual site assessments with these PV reliability metrics to participating sites and agencies or subagencies, followed by phone consultations to review results.

Each report includes:

- System description as provided by the agency (including photo if available) and assumptions
- Graph comparing measured output and modeled production over time
- Key performance indicators (availability, PR, and energy ratio) for each year of the analysis period
- Links to FEMP resources related to O&M online trainings, procurement specifications for O&M contracts, and other useful information regarding PV system O&M.

Figure 5 provides an example of a graph comparing the measured (darker shade) versus modeled (lighter shade) daily production of a PV system over a five-year period. Table 3 provides the annual key performance metrics for this same system. Year-over-year performance metrics show noticeable declines in performance and energy ratios for 2018 and 2019. This was attributed to a problem with the inverter. Site staff worked with their O&M contractor to identify the issue. After the repair was completed, PV production returned to expected levels.

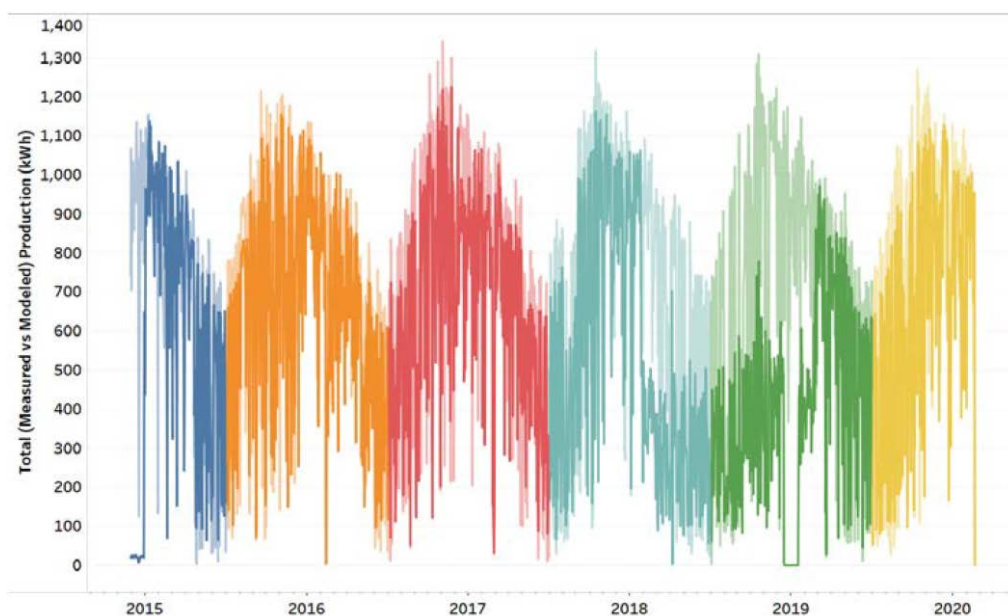


Figure 5. Total daily measured PV production (darker shade) compared to expected modeled production (lighter shade) across five years.

Table 3. Example Site Annual PV Performance Metrics Including Availability, Performance, and Energy Ratio

	2015	2016	2017	2018	2019	2020
Availability	85%	98%	98%	97%	89%	97%
Performance	99%	91%	91%	78%	66%	91%
Energy Ratio	81%	90%	90%	77%	58%	98%

An example of the deliverable that was provided for each system can be found in the Appendix. For the purpose of this report, all the data from the individual reports was then aggregated and anonymized to calculate the key performance metrics of the sample of federal PV systems.

3.4 Limitations and Uncertainty

Identified sources of uncertainty and limitations of the method are described below. Combining these measurement uncertainties in a root-square calculation results in an overall uncertainty of +/-10.6% in the calculation of performance ratio.

Gaps in PV performance data: Some PV assessments relied on incomplete or low-resolution measured production data, which affects calculation of availability metrics. In some cases, the data was missing for ranges of dates. If the team could ascertain that the system was down during that period, it was tallied as “unavailable,” but if the status was unknown, the missing dates were simply excluded from the analysis and calculation of performance metrics. To be included in the analysis, a site had to provide a minimum of one year of production data, although most sites provided multiple years of data.

Moreover, for some sites, the research team received low-resolution (e.g., monthly, quarterly, daily) measured production data instead of the ideal 15-minute or hourly interval data. In these cases, the performance ratio and the energy ratio are meaningful over the monthly time period, but the system would have to be down all month to affect the availability calculations. Many systems or individual inverters are indeed down for months at a time, as reflected in the data. When averaging availability across a population of systems, the data of different time resolutions. Therefore, the fleet-wide average of availability is higher than it would be if high-resolution data were available for all sites.

Sample size limitations: The sample of 75 systems for this assessment was small and not randomly selected—systems lacking good monitoring would be more likely to volunteer for the FEMP assessment. A small sample size increases the relative error; with 75 systems, the relative error would be +/- 5%. Similarly, while the sample has some geographic diversity, located across 20 states and three countries, a large number of sites (31) were provided by one subagency and were all located in the same state. This limited sample size limits our ability to pinpoint specific PV system characteristics based on location and environmental conditions. The small sample size also makes it hard to draw statistical conclusions about the influence of system type (e.g., roof, ground, carport, tracking) on performance.

Uncertain climate data: There is some uncertainty regarding NSRDB and TWC weather files. Expected energy production from the resulting SAM model forms the denominator of the PR calculation; therefore, weather accuracy directly affects the accuracy of the calculations. The accuracy of the NSRDB satellite irradiance resource data is $\pm 10\%$ at the 95% confidence interval. This is based on two components of uncertainty: uncertainty of the global horizontal irradiance reported from the NSRDB taken from Habte and Sengupta (2017) to be $\pm 8.3\%$; and an uncertainty component for horizontal-to-tilted transposition error taken from Hay and McKay (1988) to be $\pm 5\%$.

Accuracy of meter data: Other sources of uncertainty in the method include meter accuracy. According to American National Standards Institute (ANSI) Standard C12.20, meters may have accuracies of 0.1%, 0.2% or 0.5% depending on class of meter (ANSI 2015). For this we assume 0.2% accuracy typical of a revenue meter, although that is negligible compared to other sources of uncertainty.

Other sources of uncertainty: Other sources of uncertainty in the analysis can include uncertainty in inverter efficiency and uncertainty about system DC nameplate rating. Uncertainties in these values could result in over- or underestimates of 1%–2% for modeled energy. Another source of uncertainty is the thermal model used to calculate PV module temperature, which could contribute approximately 2% to uncertainty. In at least one case, modules facing off in different directions were treated as one array in a single orientation, and such assumptions introduce an undetermined amount of error.

4 Key Findings

As of June 2021, FEMP assessed the performance of 75 PV systems using data provided by 16 federal agencies and subagencies located across the United States. Table 4 lists the three key performance indicators—availability, performance ratio, and energy ratio—across the entire sample of systems. Table 4 also lists the standard deviation of the average. While several of these PV systems are performing quite well, as demonstrated by availability and PR approaching and even achieving 100%, the average values are in line with the other performance surveys described in the Introduction; there is meaningful variability in the measured performance as indicated by the minimum values and the significant standard deviation.

Table 4. Statistical Summary of Key Performance Indicators Across All 75 PV Systems

	Minimum	Average	Median	Maximum	Standard Deviation
Availability	31.0%	95.1%	98.0%	100.0%	8.8%
Performance Ratio	46.0%	78.6%	79.0%	101.0%	11.7%
Energy Ratio	29.0%	74.6%	76.0%	101.0%	14.1%

4.1 Availability

Availability ranges from 31% to 100% with an average of 95.1% (Table 5). For each timestep (ideally 15-minute or one-hour intervals), the measured production was compared to the modeled production. If the measured production was less than 5% of the modeled production, the system is counted as “unavailable” in that timestep. Measured availability does vary with this threshold, and 5% seems to strike a good balance by filtering a lot of early morning and late evening hours when the actual output can easily be less than 1% or 2% of the modeled estimate. The resolution of time series data affects the calculation of availability as described in Section 3.4.

Table 5. Availability Statistics

	Minimum	Average	Median	Maximum	Standard Deviation
Availability	31.0%	95.1%	98.0%	100.0%	8.8%

The distribution of availability values across the 75 systems is illustrated in Figure 6.

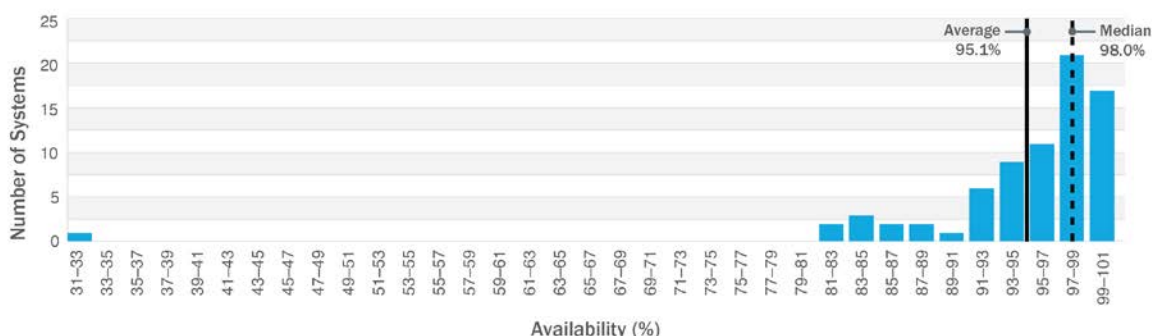


Figure 6. Distribution of values of "Availability" across all 75 PV systems.

4.2 Performance Ratio

Performance ratio is measured production divided by modeled production, including only those timesteps during which the system was available. Performance ratio is thus a measure of partial production. Performance ratio is calculated for each year (or partial year) of the analysis period.

Performance ratio ranges from 46% to 105% with an average of 78.6% and a median of 79% (Table 6). A performance ratio greater than 100% is unusual, but not impossible if the losses in the actual PV system are less than the losses in the model of the system, or if measures, such as overbuild of the array, have been taken to compensate for losses.

Table 6. Performance Ratio Statistics

	Minimum	Average	Median	Maximum	Standard Deviation
Performance Ratio	46.0%	78.6%	79.0%	101.0%	11.7%

The distribution of performance ratio values across the 75 systems is illustrated in Figure 7.

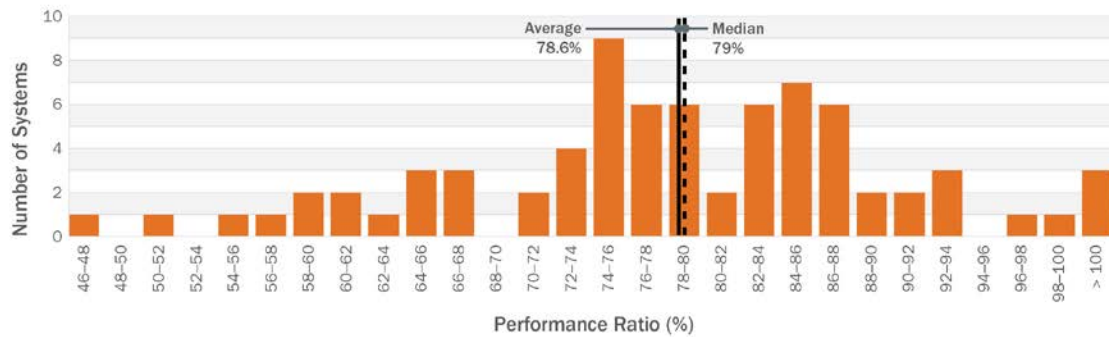


Figure 7. Distribution of values of "Performance Ratio" across all 75 PV systems.

4.3 Energy Ratio

Energy ratio is the total measured production divided by total modeled production, and thus includes both the effects of availability (downtime) and performance ratio (inefficiency) in the same metric.

Energy ratio ranges from 29% to 100% with an average of 74.6% (Table 7).

Table 7. Energy Ratio Statistics

	Minimum	Average	Median	Maximum	Standard Deviation
Energy Ratio	29.0%	74.6%	76.0%	101.0%	14.1%

The distribution of energy ratio values is illustrated in Figure 8.

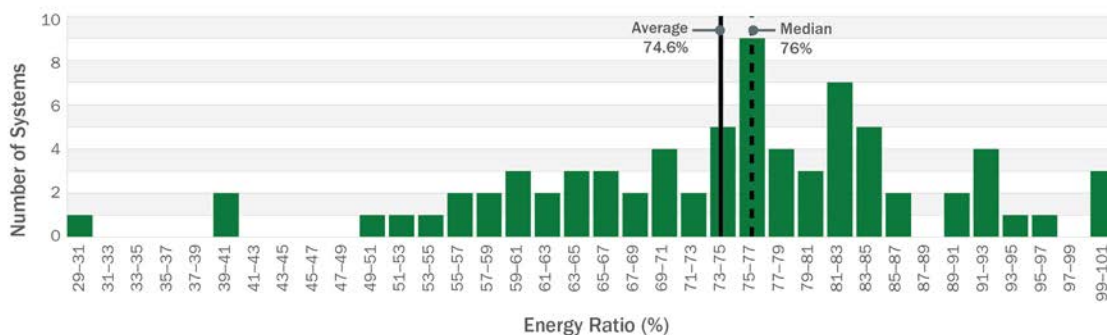


Figure 8. Distribution of values for "Energy Ratio" across all 75 PV systems.

5 Conclusion and Discussion

5.1 Key Performance Indicators

The key performance metrics evaluated in the assessment and presented in this report lead to several important conclusions.

1. **Availability:** All of the systems analyzed were at least partially operational for at least part of the time. Without exception, each system reported delivery of renewable energy, contributing to the achievement of federal renewable energy and sustainability goals. Most of the systems had very high availability as indicated by a median availability value of 98%. Significant, long-duration downtimes caused by delay in repair bring the average availability down to 95%. An availability of 95% might qualitatively be considered to be very good, and expectations of availability higher than 95% are probably not realistic.
2. **Performance ratio:** When available, the PV systems delivered on average 78.6% of the reference yield as modeled in SAM. While this does indicate some room for improvement through attentive monitoring and optimal O&M, the value is consistent with fleet averages reported in the other referenced studies. The median PR of 79.0% is close to the average value of 78.6%, indicating a symmetrical distribution and an average that is not dominated by outliers. However, the standard deviation of 12% and the difference between maximum and minimum values of PR indicate that there is a wide variation in the performance of different systems. A PR value of 85% is probably realistically achievable through optimal O&M, especially addressing the underperforming minority of systems.
3. **Energy ratio:** Combining the effects of availability and performance ratio, the average energy ratio of 79% demonstrates that the systems are delivering the preponderance of their expected energy production. Nevertheless, there is room for improvement. Future performance assessments may gauge improvement in this average as technology and maintenance practices improve. Agencies may also consider this a realistic level of

performance. The average energy ratio of 74.6% is close to the median of 76.0%, confirming that the distribution is not dominated by the outliers.

5.2 Interpretation and Use of Results

It is unrealistic to assume the PV systems will deliver 100% of the model-estimated performance due to the associated maintenance, staff time and attention, and expense required. The statistics presented in this report may be useful in three respects:

1. Owners of existing systems may compare their own measured performance to this median value when thinking about performance and focusing corrective actions. If a system has an energy ratio greater than 75%, they may take comfort that their system is performing as well as others in the federal fleet. If the metrics are much lower than the average values in this report, it indicates that a system would be a candidate for inspection, electrical testing, and corrective maintenance to bring the performance in line with expectations. Many of the underperforming systems in this study had already undertaken diagnostic or corrective actions.
2. Future feasibility studies are better informed regarding realistic expectations of performance. It is not easy to account for possible future downtime or underperformance in a feasibility study. Impacts on the calculated cost effectiveness would be affected by exactly when the downtime occurs (e.g., winter versus summer; at noon versus at sunset). Similarly, underperformance of components is difficult to predict and account for in a feasibility study using conventional means (such as SAM, used in this study to predict performance). One could simply “derate” estimated energy production to account for underperformance in a feasibility study, but availability and performance ratio affect utility cost savings in different ways. Walker (2020b) presents a method based on a duration curve rather than hourly time-series simulation that provides a simple way to calculate the impact of availability and performance ratio on life cycle cost and levelized cost of energy, enlisting a simplified fixed utility rate (\$/kWh delivered).
3. Information on actual performance of fielded PV systems helps organizations such as FEMP refine recommendations to agencies planning their approach to renewable energy and on the design, implementation, and maintenance of systems.

5.3 Other Observations From Site Staff

Discussions with staff and in-person site visits to select PV systems revealed key areas of improvement:

1. Arrays that are not evaluated through a routine O&M program often suffer from underperformance and in most extreme cases may be offline altogether. Unaddressed problems may introduce safety concerns in addition to decreasing cost savings.
2. Power meters and weather stations are often not reporting out due to a number of reasons—including unreliable internet connectivity and new, stricter cybersecurity rules precluding

the use of site networks. Consistent monitoring of PV performance across multiple sites can be a challenge, with specific problems including loss of internet connectivity, loss of internal site network connectivity, programming of parameters if monitoring is performed using a building control system, and staff changes leading to loss of monitoring platform log-in credentials.

3. It is often a lengthy process (e.g., annual) for agencies to budget and allocate funds for diagnosis and repair of PV systems.
4. A variety of approaches to service delivery was encountered. Most sites rely on the installer for continued service, or other providers selected through a bidding process. O&M providers also include on-site federal maintenance staff; on-site base operating contractors; providers affiliated with the installing contractor; providers affiliated with the inverter company (especially for inverter-specific corrective maintenance); and solar companies in the area or traveling to the site in response to site solicitations for system repairs. All of these can be effective but sometimes lead to a disconnected succession of services to keep plants running properly.
5. For small-capacity systems that are underperforming, it can be difficult to make the financial justification for an O&M contract (the per-system savings are small).
6. Sites struggled to get inverter and other failures resolved in a timely manner, thereby losing several months' worth of generation. In many cases, performance assessments show a return to expected generation after repairs.

5.4 Next Steps And Resources for Agencies Interested in Improving Photovoltaic System Performance

Management strategies for improving PV system performance include the following:

1. Check operational indicators often, such as energy production meter and error messages displayed on the inverter faceplate. Consider a subscription to a monitoring service which can report on energy delivery and key performance metrics, send notifications to staff, and diagnose some problems automatically.
2. Consider “bundling” small systems together for more efficient management of contracted services and delivery of preventative O&M services.
3. Develop and/or update an O&M plan and budget that includes contact information, an as-built description of the system, descriptions of operational indicators, a troubleshooting guide with error messages, preventative maintenance measures, an inventory of parts, and sources of replacement parts.
4. Plan ahead for repairs. Private PV system owners have hazard insurance to recover from storm damage, as well as reserve accounts and lines of credit to fund timely repairs and avoid downtime. The government is self-insured, so discuss rapid-access funding of repairs with budget personnel and avoid long delays in funding repairs. Plan ahead for the

replacement of components like inverters, which typically have a shorter lifespan than that of the PV panels.

5. Pursue trainings and certifications for on-site staff involved with PV system maintenance. In addition to available commercial trainings, FEMP offers online training courses:
 - a) Whole Building Design Guide O&M Best Practices for Small-Scale PV Systems³
 - b) Operations and Maintenance for Optimal Photovoltaic System Performance⁴
 - c) Planning, Procuring, and Managing Solar PV Systems For Long-Term Performance: Operations & Maintenance.⁵
6. Consider contracting O&M to local service providers or a base operating contractor. FEMP offers a sample O&M contract template which agencies can adapt and customize as needed.⁶
7. Consider performance contracting as a way to deliver O&M on a basis of cents-per-kWh-delivered. Energy Savings Performance Contracts are often thought of as a way to finance new systems, but are also authorized for use in delivering O&M. O&M for an existing PV system could be provided under an Energy Savings Performance Contract Energy Sales Agreement wherein the agency pays for delivered energy (for example, an O&M cost of \$15/kW/year divided by production of 1,500 kWh/kW/year would equate to 1¢/kWh delivered).⁷

FEMP offers these resources, along with other activities related to PV system performance, including publications, sample procurement specifications, and training materials.⁸ In future years, FEMP seeks to conduct additional PV performance assessments for agency sites, thereby expanding and diversifying the sample of systems to enable more analysis of performance by system type and component selection, as well as performance by location and environmental conditions. This will improve the statistical significance of the results presented in this report, diagnose issues at individual sites, and further inform opportunities for the federal government to realize additional savings from deployed renewable energy systems.

³ <https://www.wbdg.org/continuing-education/femp-courses/fempfts27>.

⁴ <http://www.wbdg.org/continuing-education/femp-courses/femp56>.

⁵ <https://www.wbdg.org/continuing-education/femp-courses/femplw07132021>.

⁶ <https://www.energy.gov/eere/femp/articles/operations-and-maintenance-om-request-proposal-template-government-owned-solar>.

⁷ For more information see <https://www.energy.gov/eere/femp/energy-savings-performance-contract-energy-sales-agreements>.

⁸ Visit <https://www.energy.gov/eere/femp/optimizing-solar-photovoltaic-performance-longevity> for further detail on these and other FEMP resources.

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Appendix

The following four pages provide an example of the report that was generated for each agency PV system.

U.S. DEPARTMENT OF
ENERGYOffice of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Photovoltaic System Performance Report

US DOE Federal Energy Management Program

PV System Description

Agency	Redacted
Site Name	
State	
System/ Building Name	
Latitude	
Longitude	
System Size (kW DC)	192
System Install Month	December
System Install Year	2014
Install Location	Carport
System Tilt (degrees)	5
System Azimuth (degrees)	214
Tracking Option (fixed or tracking)	Fixed
Panel Make and Model	Suniva OPT 250-60-4-100
Inverter make and model	Solecra PVI 95kW-Central
Inverter Efficiency (%)	96
Power Data	Yes
Weather Data	TWC
Time Resolution	15-minutes
Start Date	2015-05-29
End Date	2019-07-26

The project is a grid-tied solar carport of 192 kW (DC) capacity. In total, there are 768 (250 W) modules with 12 modules per string with 64 string in total. There are two inverters. The PV panel portion occupies 13,824 sq. ft of space and meets the 110-mph wind zone for Houston, TX.

This system description is used to prepare a model of the system using NREL's System Advisor Model (SAM).



Figure1. Photovoltaic System at the Site

*Assumptions

1. The PV system capacity in the summary did not match with the size mentioned in the legend. We have used the system size mentioned in the summary (192 kW DC).
2. SAM does not count for leap-year so have assumed 28th and 29th generation to be same for 2016 year.
3. If there is a missing date, kW for that timestamp is assumed to be zero. Also, if the kW data is labeled as "nan" it is assumed to be zero.

System Performance

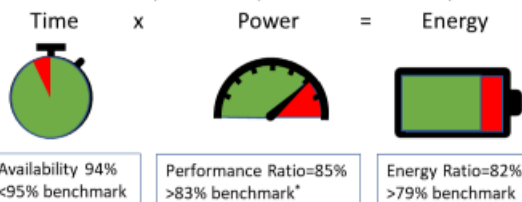
Total Daily Measured and Modeled Production (kWh) from 2015-2019



This graphs shows the total daily Measured Production compared to daily total Model estimate (lighter color) across 5 years of production (kWh).

Date Range	2015	2016	2017	2018	2019	All Years
Downtime (hours)	398	69	87	112	462	1128
Availability	85%	98%	98%	97%	81%	94%
Measured when Available (kWh)	125,138	238,308	241,981	192,706	60,761	858,895
Model when Available (kWh)	126,090	261,174	265,428	246,517	116,914	1,016,122
Performance Ratio (PR)	99%	91%	91%	78%	52%	85%
Measured Total Production (kWh)	125,733	238,345	242,020	192,767	60,772	859,637
Modeled Total Production (kWh)	154,004	263,927	267,413	249,576	116,914	1,051,834
Energy Ratio (ER)	82%	90%	91%	77%	52%	82%

Availability is actual measured days of production divided by model days of production and is 94% over the analysis period. Performance Ratio (PR) is measured production divided by modeled production when plant is available. PR over 5 years analyzed is 85%. Energy Ratio (ER), total measured divided by total model production. ER over all 5 years analyzed is 82%.



This PV System has a **lower PR** than an average of PR=83.5%* while the average availability of 99% (over 7 years) is above the 95% benchmark. The following resources are available to help you optimize performance:

Optimizing Photovoltaic System Performance for Longevity

<https://www.energy.gov/eere/femp/optimizing-solar-photovoltaic-performance-longevity>

Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems; 3rd Edition; <https://www.nrel.gov/docs/fy19osti/73822.pdf>, 153 pages.

PV O&M Cost Model. On-line version <https://sunspec.org/apsuite>; Spreadsheet version by email andy.walker@nrel.gov www.nrel.gov/docs/fy17osti/68023.pdf

"O&M Best Practices for Small-Scale PV Systems"

http://www.wbdg.org/pdfs/FTS27_LearnerGuide.pdf

"Operations and Maintenance for Optimal Photovoltaic System Performance"

<http://www.wbdg.org/continuing-education/femp-courses/femp56>

*Benchmark is Average of (2,200 PV systems in CA)

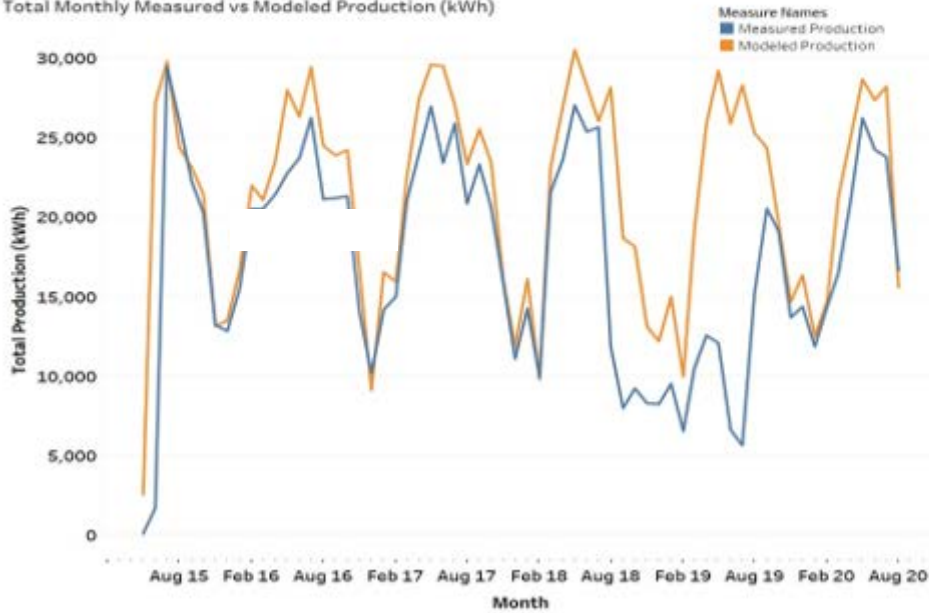
For more information:

Rachel Shepherd, rachel.shepherd@ee.doe.gov
Andy Walker, andy.walker@nrel.gov

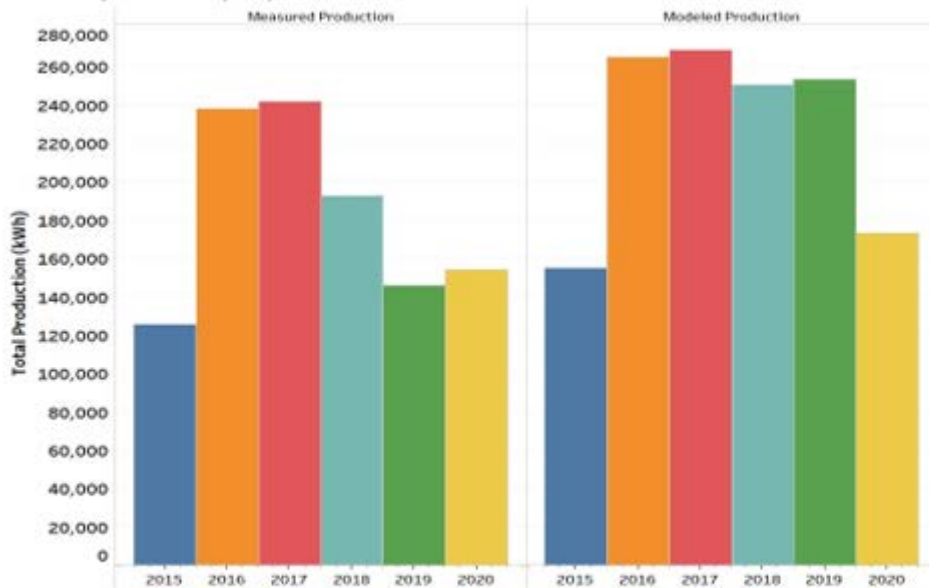


Photovoltaic System Performance Report:

Total Monthly Measured vs Modeled Production (kWh)

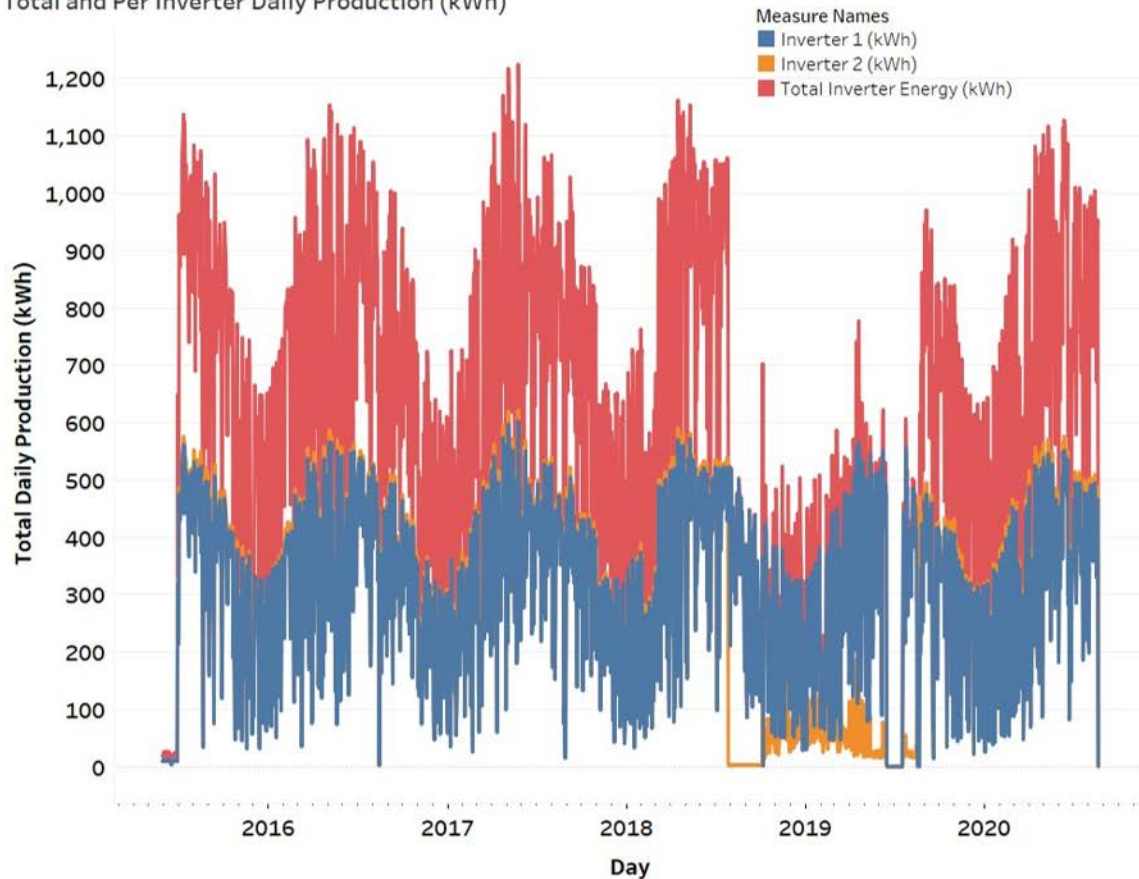


Total Yearly Production (kWh)



Photovoltaic System Performance Report:

Total and Per Inverter Daily Production (kWh)



Notes:

Data Inspection Notes:

1. Data in 2015 was available for the last 6 months, and in 2020 was available for the first 8 months.
2. Both Inverters 1 and 2 seem to be offline from Jun 16 Jul 17, 2019. In addition, inverter 2 seems to be offline from July 27 Oct 6, 2018.
3. The system returns to expected performance once repaired (in August 2019) after the inverter troubles mentioned above

Photovoltaic System Performance Report:

➔ Next Steps & Resources:

While this report does not provide prescriptive measures for this specific PV system, the following next steps may help you optimize performance:

- **Build O&M capabilities in-house.** The following resources are available to help you optimize performance:
 - [Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems](#) 3rd Edition; 153 pages.
 - PV O&M Cost Model: [On-line version](#); Spreadsheet version (or email andy.walker@nrel.gov)
 - [O&M Best Practices for Small-Scale PV Systems](#)
 - [Operations and Maintenance for Optimal Photovoltaic System Performance](#) (5.0-hour video training; 0.5 CEU)
 - [Optimizing Solar Photovoltaic Performance for Longevity](#)
- **Procure professional O&M services.** FEMP has developed a sample O&M contract template that is available upon request. Please contact Gerald Robinson (gtrobinson@lbl.gov)
- **Use energy savings performance contracting to guarantee O&M** The following resources can provide guidance: [Energy Savings Performance Contract/Energy Sales Agreements](#), [Energy Savings Performance Contract](#), [Energy Sales Agreement Toolkit](#)

Additional technical assistance may be available through FEMP. [Please contact us.](#)

❓ For More Information:

Rachel Shepherd
rachel.shepherd@ee.doe.gov

Andy Walker
andy.walker@nrel.gov



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DOE/GO-102021-5627 • December 2021